

INVESTIGATING KINETIC OF NANO-AND MICRO-PARTICLES IN  
LIQUIDS BY USING OPTICAL TWEEZERS AND DIGITAL  
HOLOGRAPHIC TECHNIQUES



A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT  
FOR THE DEGREE OF PHILOSOPHY IN APPLIED PHYSICS  
FACULTY OF SCIENCE  
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG  
2018

KMITL-2018-SC-D-030-047

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.



COPYRIGHT 2018

FACULTY OF SCIENCE

**KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG**

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

|                   |                                                                                                                            |
|-------------------|----------------------------------------------------------------------------------------------------------------------------|
| Thesis Title      | Investigating Kinetic of Nano- and Micro-particles in Liquids by Using Optical Tweezers and Digital Holographic Techniques |
| Student Name      | Mr.Rittirong Nuansri                                                                                                       |
| Student ID        | 55650102                                                                                                                   |
| Degree            | Doctor of Philosophy (Applied Physics)                                                                                     |
| Department        | Physics                                                                                                                    |
| Year              | 2018                                                                                                                       |
| Thesis Advisor    | Asst. Prof. Dr. Prathan Buranasiri                                                                                         |
| Thesis Co-advisor | Professor H. Daniel Ou-Yang                                                                                                |

### Abstract

In this thesis, the kinetic of nano- and micro-particles in liquids was investigated by using optical tweezers (OT) and digital in-line holographic (DIH) techniques. The thesis was divided into two parts. Firstly, the fluorescent colloidal nanoparticles used for laser trapping in optical tweezers system was presented. It consists of aqueous fluorescent polystyrene (PS) solution, pluronic polymer and potassium chloride (KCl) mixed with poly ethylene glycol (PEG) for different PEG concentrations. Two optical tweezers systems were setup for the study of laser trapping. The first system, a conventional system, which is widely used in laser trapping that requires a fluorescent confocal microscope for observing the trapped nanoparticles. The second method was presented for the first time in this work. For this system, the trapped nanoparticles can be observed on the oscilloscope which is more convenient than that of the first system. However, the results obtained from both methods are in good agreement. In addition, a small capillary tube to be filled with the colloidal nanoparticles was developed and used in the second system. This capillary tube is possible to be used with the light sensitive camera which can be damage by a high light intensity being exposed to the camera. Secondly, the digital in-line holography based on Mach Zehnder interferometer (MZDIH) was setup for the determination of dynamic viscosity of the viscous oils. The spherical irons were used as the objects falling in the viscous oils. The hologram images of the iron falling

This material is reserved for educational use only, not allowed for commercial use.

along its entire path were recorded as a video file on the CMOS camera. The recorded hologram images were reconstructed on the holoviewer program via MATLAB. Then, the diameter and terminal velocity of the iron were obtained. Finally, the dynamic and kinematic viscosities of viscous oils were determined and compared with standard values. From the experimental results, it can be concluded that the MZDIH method is the simple and precise tool for determining the viscosity of fluids.

This thesis was presented the application of the optical technique both the optical tweezers (OT) and digital holographic (DH) techniques. These methods are the effective tools to be used for investigating the kinetic of particles in liquids as well as they could be used to apply in many various fields of the researches in further.

**Keywords:** optical tweezers or optical manipulation, optical systems, polymers, holography, hologram recording, Stokes equations.



## Acknowledgements

The accomplishment of the Philosophy doctoral degree of Science in Applied Physics could not complete well done by my effort only; however, it can be finished with the help from many people and supporting from many facilities also. First of all, I really appreciate to thank my advisor, Asst. Prof. Dr. Prathan Buranasi, who give a lot of valuable suggestions for performing in my research, and I had a good opportunity to practice doing research oversea at Lehigh university in USA by his assistance. Secondly, I would really like to thank my co-advisor, Professor H. Daniel Ou-Yang. He took care of me and taught both the necessary knowledges for using in the research and the general learning in daily life for being the American styles when I was in USA. Thirdly, I would like to say many thanks for the kindness of Professor Pichet Limsuwan, who is a professor in Physics at King Mongkut's University of Technology Thonburi. He helped to revise on my papers before submitting in order to publish in the international journals and also taught many things how to write the good paper as well as how to be a good teacher in the future. Next, I would like to thank all committee members for the valuable discussions and suggestions to improve my thesis. Lastly, I would like to thank the Science Achievement Scholarship of Thailand (SAST) to support the scholarships for studying in graduated degree for 5 years (2010-2014). Moreover, I would like to say a big thank my assistants for help me to do research in digital holography during the summer time. They consist of Sirichai Sartpan, the undergraduate student in Applied Physics of KMITL, and Vishal Singh and Bandaru Sai Kumar, who were the internship students from Indian Institute of Technology Delhi (IIT). Also, I cannot forget to thank all colleagues in Photon Dynamics Laboratory and friends, i.e., Hao Huang, Chantira Boonsri, Krittanon Sirorattanakul, and Thanyarat Thong-On, to give me the helps and suggestions.

Finally, I would like to especially thank my parents, Mr. Sommai Nuansri and Mrs. Chong Nuansri, for supporting and helping me in every way of my life since I was born until in the present. In addition, my sisters and other relatives encouraged and cheered me up to be strong for finishing in my Ph.D.

Mr. Rittirong Nuansri

# Table of Contents

|                                                                | Page     |
|----------------------------------------------------------------|----------|
| Abstract in English .....                                      | i        |
| Acknowledgements .....                                         | iii      |
| Table of Contents.....                                         | iv       |
| List of Tables .....                                           | vii      |
| List of Figures.....                                           | viii     |
| <b>Chapter 1 Introduction .....</b>                            | <b>1</b> |
| 1.1 Literature Reviews .....                                   | 1        |
| 1.2 Research Motivation.....                                   | 3        |
| 1.3 Objectives of the study.....                               | 5        |
| 1.4 Scopes of the study.....                                   | 5        |
| 1.5 Overview of the thesis.....                                | 6        |
| <b>Chapter 2 Overview of Theory .....</b>                      | <b>8</b> |
| 2.1 Principle of optical tweezers technique.....               | 8        |
| 2.1.1 Optical force acting on a particle .....                 | 10       |
| 2.1.1.1 Gradient force .....                                   | 10       |
| 2.1.1.2 Scattering force .....                                 | 11       |
| 2.1.2 Optical regime depending on the particle's size .....    | 12       |
| 2.1.2.1 Rayleigh regime .....                                  | 12       |
| 2.1.2.2 Ray optic regime .....                                 | 16       |
| 2.2 Principle of digital holographic technique .....           | 17       |
| 2.2.1 Holographic term.....                                    | 20       |
| 2.2.2 Method of reconstruction.....                            | 21       |
| 2.2.2.1 Huygens convolution method .....                       | 21       |
| 2.2.2.2 Angular spectrum method .....                          | 23       |
| 2.2.3 Digital holographic configurations.....                  | 26       |
| 2.2.3.1 Digital off-axis holographic (DOH) configuration ..... | 26       |
| 2.2.3.2 Digital in-lined holographic (DIH) configuration ..... | 27       |
| 2.3 Interaction on colloidal particles by polymers .....       | 28       |
| 2.4 Viscosity of fluids.....                                   | 29       |

|                                                                                                               |           |
|---------------------------------------------------------------------------------------------------------------|-----------|
| 2.5 Dynamic of a spherical particle in viscous fluids .....                                                   | 33        |
| <b>Chapter 3 Research methodology.....</b>                                                                    | <b>37</b> |
| 3.1 Development of the optical tweezers system for trapping of<br>colloidal nanoparticles in suspension ..... | 37        |
| 3.1.1 Optical tweezers system under microscope .....                                                          | 37        |
| 3.1.2 Optical tweezers system without microscope .....                                                        | 39        |
| 3.1.3 Materials and equipment used for trapping nanoparticles .....                                           | 41        |
| 3.1.4 The preparation of colloidal nanoparticles in suspension .....                                          | 45        |
| 3.1.5 Procedure for trapping colloidal nanoparticles .....                                                    | 46        |
| 3.2 Determination of viscosity of viscous oils by using Mach Zehnder<br>digital holography.....               | 50        |
| 3.2.1 Digital in-line holographic (DIH) system .....                                                          | 51        |
| 3.2.2 Materials and liquid chamber preparation.....                                                           | 52        |
| 3.2.3 The procedure for determination of viscous oils by<br>DIH method.....                                   | 55        |
| <b>Chapter 4 Experimental Results and Discussion .....</b>                                                    | <b>58</b> |
| 4.1 Trapping colloidal nanoparticles by optical tweezers.....                                                 | 58        |
| 4.1.1 Trapping colloidal nanoparticles under microscope .....                                                 | 58        |
| 4.1.2 Trapping colloidal nanoparticles without microscope .....                                               | 63        |
| 4.2 Determination of viscosity of lubricant oils by using Mach Zehnder<br>digital holography.....             | 68        |
| 4.2.1 Diameter measurement of spherical irons.....                                                            | 68        |
| 4.2.2 Determination of spherical iron velocity .....                                                          | 70        |
| 4.2.3 Determination of viscosity of the testing oils .....                                                    | 75        |
| <b>Chapter 5 Conclusions and Suggestions .....</b>                                                            | <b>79</b> |
| 5.1 Conclusions.....                                                                                          | 79        |
| 5.1.1 Trapping colloidal nanoparticles by optical tweezers.....                                               | 79        |
| 5.1.2 Determination of viscosity of lubricant oils by using Mach<br>Zehnder digital holography.....           | 80        |
| 5.2 Suggestions .....                                                                                         | 80        |
| References.....                                                                                               | 82        |
| Appendices .....                                                                                              | 86        |
| Appendix A .....                                                                                              | 87        |

|                        |     |
|------------------------|-----|
| Appendix B .....       | 97  |
| Author Biography ..... | 106 |



## List of Tables

| Table                                                                                                                                                   | Page |
|---------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 2.1 Lists of the dynamic viscosity units in the three most widely systems.....                                                                          | 32   |
| 2.2 Lists of the kinematic viscosity units in the three most widely systems.....                                                                        | 33   |
| 3.1 The spectral properties of 200 nm in diameter fluorescent microsphere<br>suspensions for preparing the samples.....                                 | 42   |
| 3.2 Compositions of materials used for preparing nanoparticles samples .....                                                                            | 46   |
| 3.3 The calibrated power of 532 nm laser by changing the optical density<br>number (OD) of a variable filter.....                                       | 49   |
| 3.4 The important properties of the viscous oils .....                                                                                                  | 54   |
| 4.1 The transmitted voltages of trapped nanoparticles under the optical system<br>without microscope (Fig. 3.3) of water and sample no. 1 to no. 4..... | 64   |
| 4.2 The transmitted voltages of trapped nanoparticles under the optical system<br>without microscope (Fig. 3.3) of sample no. 5 to no. 8 .....          | 65   |
| 4.3 Measured diameter of spherical irons by using the holoviewer via MATLAB<br>program.....                                                             | 69   |
| 4.4 The measured positions, falling time and velocity of the first iron falling<br>in all testing oils.....                                             | 71   |
| 4.5 The measured positions, falling time and velocity of the second iron falling<br>in all testing oils.....                                            | 72   |
| 4.6 The measured positions, falling time and velocity of the third iron falling<br>in all testing oils.....                                             | 73   |
| 4.7 The calculated dynamic and kinematic of all testing oils .....                                                                                      | 76   |
| 4.8 Comparing the kinematic viscosity from the standard value with<br>the experimental results of all testing oils contained in a liquid chamber .....  | 78   |

## List of Figures

| Figure                                                                                                                                                                                                              | Page |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 2.1 Diagram of the optical tweezers principles (a) laser beam is focused by an objective lens. (b) the momentum transfer to the object at the focused spot. ....                                                    | 9    |
| 2.2 Schematic of a nanosphere near the focus of a laser beam.....                                                                                                                                                   | 13   |
| 2.3 Description of the gradient force that perpendicular (a) and parallel (b) with laser propagation .....                                                                                                          | 16   |
| 2.4 Diagram of recording hologram by using digital in-line holography (DIH) based on Mach Zehnder system.....                                                                                                       | 18   |
| 2.5 The reconstruction of hologram by digital holographic technique. (a) no numerical lens and (b) using numerical lens.....                                                                                        | 19   |
| 2.6 The holographic term; (a) hologram recording, (b) hologram reconstruction with reference wave $E_R$ , and (c) hologram reconstruction with conjugate of reference wave $E_R^*$ .....                            | 21   |
| 2.7 Coordinating systems for numerical reconstruction .....                                                                                                                                                         | 23   |
| 2.8 The coordinating systems of wave vector $\vec{k}$ .....                                                                                                                                                         | 25   |
| 2.9 The flow chart of reconstruction algorithm.....                                                                                                                                                                 | 26   |
| 2.10 Diagram of the off-axis configuration .....                                                                                                                                                                    | 27   |
| 2.11 Diagram of (a) in-line digital holography and (b) Gabor digital holography. ....                                                                                                                               | 28   |
| 2.12 Schematic of: (a) polystyrene (PS) particles surrounded by PEG polymer (b) PS particles surrounded by pluronics polymer and (c) PS particles surrounded by pluronics polymer and PEG polymer.....              | 29   |
| 2.13 Velocity gradient of a fluid between smooth plates (Moving plate and stationary plate).....                                                                                                                    | 30   |
| 2.14 Diagram of a spherical particle falling in a viscous fluid and the forces acting on the particle .....                                                                                                         | 34   |
| 3.1 An optical tweezers system under fluorescent confocal microscope with 100X and 1.3 N.A. objective lens. A 1064 nm IR laser is a trapping laser, while a 488 nm fluorescent blue laser is an excited laser ..... | 38   |

## List of Figures (cont.)

| Figure                                                                                                                                                                                                              | Page |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 3.2 A schematic diagram of the optical tweezers system under fluorescent confocal microscope as shown in Fig.3.1 .....                                                                                              | 39   |
| 3.3 A setup of the optical tweezers system without microscope. By using the 532 nm green laser with the power up to 500 mW .....                                                                                    | 40   |
| 3.4 A schematic diagram of the optical tweezers system without microscope as shown in Fig.3.3. The green line represents a trapping laser of 532 nm wavelength.....                                                 | 41   |
| 3.5 All materials used for preparing the samples of colloidal nanoparticles coated by polymers in low KCl salt .....                                                                                                | 43   |
| 3.6 Dual Neutral Density filter wheel for changing the laser power .....                                                                                                                                            | 43   |
| 3.7 A rectangular capillary tube for containing the colloidal nanoparticles samples with the dimension of 2.0 x 0.1 mm, the thickness of glass of 0.1 mm, and the length of 100 mm .....                            | 44   |
| 3.8 (a) Oscilloscope, Tektronik; Model: TDS-2024 and (b) a periodic signal of trapped colloidal nanoparticles under the system without microscope .....                                                             | 44   |
| 3.9 Optical power meter for detecting the power of laser.....                                                                                                                                                       | 45   |
| 3.10 Diagram for trapping colloidal nanoparticles with 1064 nm IR laser under the optical tweezers system as illustrated in Fig. 3.1 .....                                                                          | 47   |
| 3.11 Process diagram for trapping colloidal nanoparticles under the optical tweezers system without microscope and objective lens as illustrated in Fig. 3.3 .....                                                  | 48   |
| 3.12 A digital in-line holography (DIH) system based on Mach Zehnder and a 635 nm diode laser is a light source .....                                                                                               | 51   |
| 3.13 (a) Schematic diagram of digital in-line holographic setup (DIH) based on Mach Zehnder interferometer and (b) the forces acting on the object moving in the viscous liquid contained in a liquid chamber ..... | 52   |
| 3.14 Stock of spherical irons about 1.5 mm in diameter .....                                                                                                                                                        | 53   |
| 3.15 A prepared liquid chamber for containing the viscous oils.....                                                                                                                                                 | 54   |

## List of Figures (cont.)

| Figure                                                                                                                                                                                                                                                                                                 | Page |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 3.16 The characteristics of viscous oils. From the left to the right; Lubricant oil (ZE-PRO32), Cold lubricant oil (SUNICE SL32D1), Gasoline engine oil, and Transformer oil (FR-3) .....                                                                                                              | 55   |
| 3.17 Diagram of procedure for determination of viscous oils by using DIH method .....                                                                                                                                                                                                                  | 56   |
| 4.1 Fluorescent images of colloidal nanoparticles in suspension trapped by a laser power of 30 mW at 1064 nm for different PEG contents of: (a) 10, (b) 20, (c) 30, (d) 40, (e) 45, (f) 50, (g) 60 $\mu$ l, and (h) without PEG .....                                                                  | 59   |
| 4.2 Fluorescent images of colloidal nanoparticles in suspension (Sample no.6) trapped by 1064 nm IR laser at different laser powers of: (a) 5, (b) 10, and (c) 15 mW .....                                                                                                                             | 61   |
| 4.3 Fluorescent images of colloidal nanoparticles in the suspension (Sample no.6) trapped by 1064 nm IR laser at different laser powers of: (d) 20, (e) 25, and (f) 30 mW .....                                                                                                                        | 62   |
| 4.4 $\ln$ [Transmitted light] in voltage unit determined phase separation of colloidal nanoparticles suspension as a function of optical density number (OD) of filter or changed power of trapping laser .....                                                                                        | 66   |
| 4.5 (a) – (c) the trapped nanoparticles images of the sample no.2, 6, and 7 at three OD number of filter; 1.04 (1.09 mW.), 0.54 (142.10 mW.), and 0.08 (374.10 mW.), respectively. The colloidal nanoparticles were confined in an optical focal region of 532 nm green laser without microscope ..... | 67   |
| 4.6 (a) Recorded hologram images, (b) reconstructed images, (c) intensity profile of recorded hologram images and (d) intensity profile of reconstructed images of a falling spherical iron in the lubricant oil (ZE-PRO32) .....                                                                      | 69   |
| 4.7 (a) Recorded hologram images and (b) reconstructed images showing the position of a spherical iron falling in the lubricant oil .....                                                                                                                                                              | 70   |
| 4.8 Variation of spherical iron velocity with falling distance of: (a) first irons, (b) second iron and (c) third iron in four different viscous oils.....                                                                                                                                             | 74   |

## List of Figures (cont.)

| Figure                                                                                                                                                                                                                        | Page |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 4.9 (a) Relationship of the terminal velocity of each spherical iron against the kinematic viscosity of oils. (b) comparing the kinematic viscosity between the experimental results and standard values of viscous oils..... | 77   |



# Chapter 1

## Introduction

### 1.1 Literature Reviews

Over many past years until the present, many fields of scientists or researchers have interested to develop works or invent techniques for investigating, manipulating, trapping, and even confining micro- or nano-particles in suspension as well as biological cells. There are many important techniques that have been used to apply for trapping or manipulating the objects in various fields of science, such as dielectrophoretic tweezers (DEP) [1], acoustic tweezers [2], magnetic tweezers [3], hydrodynamic trapping with microfluidic valving [4], including optical tweezers or laser trapping [5]. Each technique is suitable for using in different areas of researches or works, because these methods have the particular advantages or disadvantages dissimilarly, which depend on applying in the field properly. In this thesis, the optical tweezers (OT) or laser trapping method was applied to use the forces of radiation pressure of laser beam in order for confining the colloidal nanoparticles in suspension in the presence of both non-absorbing and absorbing polymers, even observing the behavior and investigating a nonlinear phase separation of multiply trapped colloidal nanoparticles in optical confinement. As well-known the optical tweezers technique since Arthur Ashkin discovered the acceleration and trapping of particles by radiation pressure for the first time in 1970 [6], this approach becomes as a significant tool, which can use to trap or manipulate objects like scissors or tweezers. Many applications can use this approach to apply in various objects in many fields such as trap a single micro-particle [7], confine multiple nanoparticles simultaneously [8-12], even study chromosome movement [13], and more recently trap red blood cells in living animals [14] in a tightly focused laser beam. For trapping multiple nanoparticles, many parameters of trapped particles were measured, including the interactions between colloidal particles [15-16], the properties and interactions of surrounded by absorbing polymers [17] as well as non-absorbing polymers [18] on the surface of a colloidal particle in suspension.

For another optical technique, it is the digital holography, which is a remarkable image processing tool. Since the holographic principle was explained by Dennis Gabor in 1948 [19], this technique has become an important optical method for research and industrial application. Producing a hologram requires two identical beams from the light source, such as a laser. The first wave without distortion or non-diffracted light, is called the reference beam. The second beam, passes through the sample and the wavefronts of the light diffract caused by the sample, is called the objective beam. The hologram patterns are recorded of both phases and amplitudes on a photographic film. In digital holography (DH), since the conventional hologram consumes a lot of holographic recording films, U. Schnars has been almost the first researcher to replace the holographic recording media by an electronic device as a charged-couple device detector (CCD), which this system is named digital holography (DH) [20]. In general, DH method is categorized into two kinds, on-axis (In-line) and off-axis configurations. The characteristics of the digital in-line geometry have the simplest setup. Here, the reference, object beam, and the recoding sensor are placed in the same axis. In the other configuration, the object and reference waves are at an angle with each other in order to avoid the noise incoming from the overlapping of both wavefronts [21]. Currently, the DH method has been found application in various fields because this technique can image both phases and amplitudes accurately and clearly in three dimensions (3D). The use of method depends on the practicability and the using process because of the number of reasons. For some examples of DH applications, biological cells such as Plankton and other marine organisms, bacteria and fruit flies, have been explored [22-23]. The density fluctuations of a standing wave in a thermoacoustic oscillation [24], and the phase compensation of spherical beam [25] have been analyzed by the hologram patterns as well. Besides, the fingerprint patterns of human can be observed and separated the difference by investigating the profile intensity fringes [26]. In this article, we focus to apply the DH tool for observing the kinetic of a spherical object falling in viscous fluids. There are numerous previous researches that have done in this field, for instance, measuring the velocity of particles flowing in microchannel [27-29], observing the flowing and structure mechanics of fluid [30-31], including the characterizing properties and scaling the size and shape of objects [32-36].

## 1.2 Research Motivation

Nowadays, there are various methods found by researchers around the world to apply for studying on the small objects both living and non-living samples. For example, the optical tweezers or optical trap (OT) is the one of an optical technique, which uses the radiation force of the laser to trap/confine the objects in the focal point, applied for controlling the small samples, including measuring the forces of trapped specimens. This technique usually is performed on a microscope with the objective lens of high numerical aperture (N.A.  $> 0.5$ ) and high magnification ( $\sim 40\times$  to  $100\times$ ) to easily obtain the intense focal point of the laser beam and observe the confined samples in a trap. Another popular optical technique is digital holography (DH), which the laser used in the system is separated into two beams, then they combined again and interfere each other with the difference pattern of wavefronts. The image of optical interference is recorded on CCD or CMOS camera. This method is called the image processing tool for recording the hologram (3D image) of the testing objects. In this thesis, I interest on studying the kinetic of small particles in the order of micro- to nano-meters suspended in liquids by using both mentioned techniques above.

For the first part in here, I apply the optical trap technique both the system under and without a microscope to study the kinetic of colloidal particles in the range of nanoscales suspended in liquids. The idea of this topic comes from something when soldiers have to work in the night time, a special goggles are used in order to amplify the intensity of light and allow them for seeing in the dark. The problem is if there were to be a sudden high intensity laser or light source shown, the amplification of the goggles may cause damage to the soldier's eyes. Also, electronics such as cameras and other devices that are light sensitive can be damaged by sudden high intensity lasers or light sources being exposed to the devices. I would like to see if the technique of colloidal cluster phase separation by optical trapping can be used as a mean to prevent the eyes or electronic devices from being damaged due to sudden high intensity light exposures. If a pair of night-vision goggles is designed to have some colloidal suspension as a part of the eye lenses, then maybe sudden high intensity laser exposure would cause the colloids to aggregate quickly and dissipate the light before it has the chance to damage the soldier's eyes. In my research, I performed experimentally how to obtain a good

This material is reserved for educational use only, not allowed for commercial use.

prepared colloidal suspension for using to confine the most multiple nanoparticles in an optical focused region of the optical tweezers system especially without the microscope, which is no objective lens.

For the second part, the lubricant oils of the four different kinematic viscosities used are 27.849 (Lubricant oil; ZE-PRO 32), 52.050 (Transformer oil; FR-3), 57.181 (Gasoline engine oil), and 70.428 (Cold lubricant oil; SUNICE SL-32D1) centi-Stokes (Measured at 40°C followed by ASTM D445). All lubricant oils used were supplied by the Goods and Exhibit Analysis Office, Excise Department of Thailand. The viscous oils in this study are important lubricants typically used on engine parts in vehicles as well as in industrial machinery. Choosing a suitable oil allows machinery users to protect moving engine parts in the normal operation. However, the user has to know the oil's parameters before use, particularly, the density and viscosity. The viscosity value is the most important characteristic governing the behavior and grade classification of oils. There are various ways to measure the viscosity, such as a cold cranking simulator (CCS), which is used to measure the dynamic viscosity ( $\eta$ , in the unit of centipoise) and the kinematic viscosity ( $\nu$ , in the unit of centistoke, cSt) following the standard of ASTM D445. These conventional methods are still accurate and precise; however, they have complicated operating procedures and use expensive equipment. Therefore, in my research, I propose an alternative way, Mach Zehnder digital in-line holography (MZDIH), to determine the dynamic viscosity ( $\eta$ , in the unit of mPa.s) and kinematic viscosity ( $\nu$ , in the unit of cSt). This method is simpler, compact, and less expensive than the conventional testing methods as mentioned above. In the experiment, the terminal velocity of a spherical iron particle ( $v_t$ ) falling in the different viscous lubricant oils contained in a liquid chamber was measured. Furthermore, the experimental values can then be used to determine the properties of the lubricant oils and also classify the commercial grade of the oils for their use in lubricating machine parts in the future.

### 1.3 Objectives of the study

- 1.3.1 To apply the optical tweezers and digital holographic techniques for investigating the kinetic of nano- and micro-particles in liquids.

- 1.3.2 To trap colloidal nanoparticles of samples in suspension at different volumes of PEG polymers by using optical tweezers technique both under and without microscope.
- 1.3.3 To investigate the motion of a spherical iron particle in viscous liquids contained in a liquid chamber by using digital In-line holographic technique (DIH) based on Mach Zehnder.
- 1.3.4 To determine the dynamic and kinematic viscosity of viscous liquids by using digital In-line holographic technique (DIH) based on Mach Zehnder.

#### 1.4 Scopes of the study

The scope of this thesis is focused on the application of optical techniques to investigate the kinetic of particles in liquids as described below.

- 1.4.1) The optical tweezers (OT) method set-up both under fluorescent confocal microscope with objective lens and without any microscope, is used to confine the colloidal nanoparticles coated by polymers in low salt suspension.
- 1.4.2) The prepared samples of eight different varying PEG polymers in suspension are trapped and observed under the system of both with fluorescent confocal microscope and without any microscope.
- 1.4.3) The non-linear phase separation of trapped-particles in optical focus is observed by plotting the curve between the transmitted voltages of trapped particles against the optical density number (OD) of filter.
- 1.4.4) The in-line digital holography (DIH) based on a Mach-Zehnder system, is applied to observe the motion of a spherical iron particle in four different viscosities of lubricant oils contained in a liquid chamber.
- 1.4.5) The terminal velocities of a spherical iron particle falling in different viscosities contained in a liquid chamber are determined.
- 1.4.6) The dynamic viscosity ( $\eta$ ) and kinematic viscosity ( $\nu$ ) of different lubricant oils are determined and compared with the standard values followed by the standard of ASTM D445.

## 1.5 Overview of the thesis

The structure in this thesis is divided into five chapters, named as follows;

Chapter 1: Introduction

Chapter 2: Overview of theory

Chapter 3: Research methodology

Chapter 4: Experimental results and Discussion

Chapter 5: Conclusions and Suggestions

The details of each chapter in the thesis are described briefly as follow.

Chapter 1 provides the literature reviews about applying the optical tweezers (OT) and digital holographic (DH) techniques to investigate the kinetic of particles in the range of nano- and micro-meters in liquids previously, as well as by using other methodologies in this field. Then, the research motivation why I have interested to focus on this topic is provided. This chapter is wrapped up by giving the objectives, scopes, benefits, and overview of the study.

Chapter 2 will describe the theories that are relevant to be used in the research. First, the principle of optical tweezers, which is the method used to confine, trap, or control the objects in the optical focus, is explained. Second, the interaction between particles and polymers in suspension is also described. Next, the digital holography (DH) technique, which is called the image processing method is provided, and the reconstruction process has been given. Moreover, the principle of a spherical particle moving in viscous liquids and the theory of the liquid viscosity will be also provided in this chapter.

Chapter 3 provide the details of methodology used in the research. The first section is started with explaining the set up of the optical tweezers (OT) both the system under fluorescent confocal microscope and without any microscope or objective lens. The materials and sample preparation in suspension and the procedure to trap the colloidal nanoparticles in suspension are described, respectively. For the second section, the digital in-line holographic (DIH) set up based on the Mach-Zehnder system is presented. The properties of liquids, the procedure of preparing a liquid chamber and the detail of a spherical iron particle used in the part are provided. In the end of this chapter, the process how to determine the viscosity of the lubricant oils is given thoroughly.

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

Chapter 4 presents the experimental results of the study. First, the images of trapped colloidal nanoparticles of prepared samples by optical tweezers both the system under fluorescent confocal microscope and without microscope are showed. Then, the non-linear phase separation of colloidal nanoparticles, trapped with the optical system without microscope, has been illustrated as a curve between the transmitted voltages of trapped particles against the different optical density number (OD) of filter. Second, the hologram images of a spherical iron particle falling in different viscosities of lubricant oils contained in a liquid chamber are captured at different positions along path of its motion and reconstructed by using the holoviewer program on MATLAB. Finally, the terminal velocity of a spherical iron particle, the dynamic and kinematic viscosities of lubricant oils are determined and presented as the curve.

Chapter 5 gives the conclusions of the study and the suggestions for further researches.

In the end of this thesis, the appendices are contained the articles published in the international journals. The first article is “Optical tweezer system with no fluorescent confocal microscope for trapping colloidal nanoparticles”. For the second one, it is entitled as “Determination of dynamic viscosity of viscous oils using Mach Zehnder digital holographic method”. Also, the biography of the author is placed in the last page of the thesis.

## Chapter 2

### Overview of Theory

This chapter concerned with the description of the principle of methodology and the relative theory in the research are explained. The component of this chapter consists of;

1. Principle of optical tweezers (OT) technique
2. Principle of digital holographic (DH) technique
3. Interaction of colloidal particles by polymers
4. Viscosity of fluids
5. Dynamic of a spherical particle in viscous fluids

The details of each section are given below.

#### 2.1 Principle of optical tweezers technique

Optical tweezers or optical traps (OT) uses the principle based on the radiation pressure of light. It uses light to trap, confine, or manipulate microscopic objects in a focused laser beam. In the biological sciences, these tools have been utilized for applying forces in the range of piconewton (pN) and measuring displacements in the nanometers (nm.) range of specimens ranging in size from about 10 nm to bigger than 100 nm. This technique has been known since the 17<sup>th</sup> century when Johannes Kepler explained the phenomenon of the direction of the comet's tail that always points opposite to the Sun. The reason is that the radiation pressure of the Sun pushes the small objects in those comets' tail away from. Then, in 1905 Albert Einstein explained about the photoelectric phenomenon that lights and other electromagnetic waves consist of particles, which are called photon. They have the momentum of light as shown below

$$p = \frac{h}{\lambda} \quad (2-1)$$

where  $p, h, \lambda$  represent the momentum of light, Planck's constant, and wavelength of light, respectively.

When the light incidents on any object, it transfers the momentum of photon to the object caused the forces acting on it. However, in the case of the Sun's light that incidents on the Earth, the radiation of the light (Intensity of the light) is really weak about  $0.5 \text{ nN/cm}^2$ . We cannot sense that the pressure of light is pushing us, while we stand outdoors on a day. For the optical tweezers technique, the beam of high laser power is focused strongly like a point on the objects. The force from the radiation pressure is much enough to trap small particles and move as following the laser. The most basic form of an optical trap is diagramed in Fig.2.1.

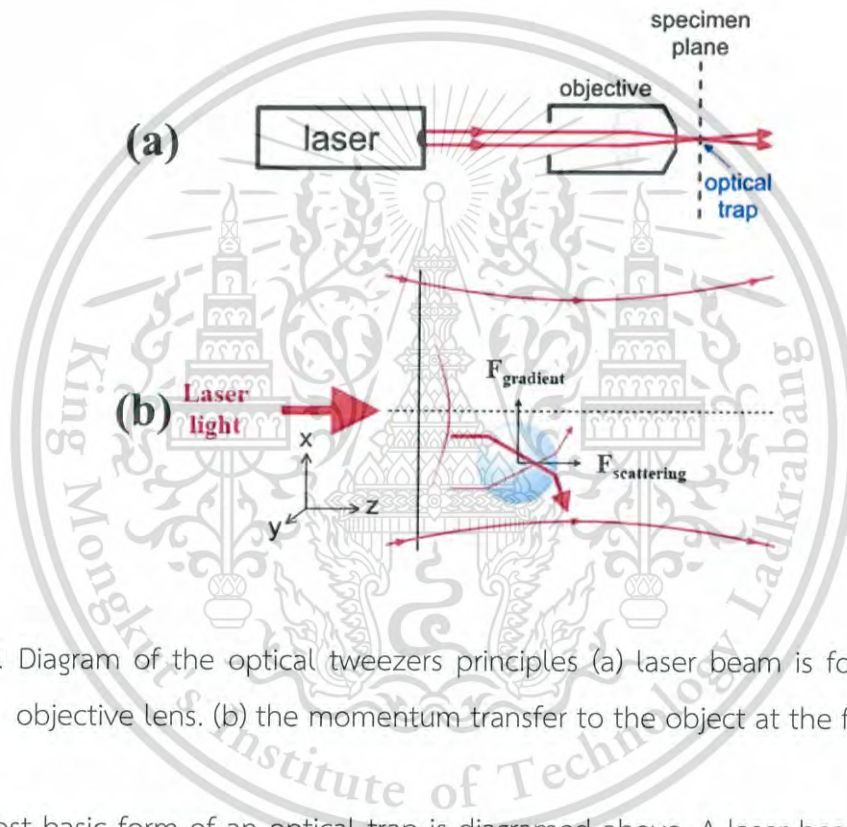


Fig. 2.1 Diagram of the optical tweezers principles (a) laser beam is focused by an objective lens. (b) the momentum transfer to the object at the focused spot

The most basic form of an optical trap is diagramed above. A laser beam is focused by a high-quality microscope objective to a spot in the specimen plane as shown in Fig. 2.1-a). This spot creates an "optical trap" which is able to hold a small particle at its center. In Fig. 2.1-b), the basic principle behind optical tweezers is the momentum transfer associated with bending light. Light carries momentum that is proportional to its energy and in the direction of propagation. Any change in the direction of light, by reflection or refraction, will result in a change of the momentum of the light. If an object bends the light, changing its momentum, conservation of momentum requires that the object must undergo an equal and opposite momentum change. This gives

rise to a force acting on the object. In a typical optical tweezers set up, the incoming light comes from a laser which has a Gaussian intensity profile. Basically, the light at the center of the beam is brighter than the light at the edges. When this light interacts with a bead, the light rays are bent according to the laws of reflection and refraction (Two example rays are shown above). The sum of the forces from all such rays can be split into two components: the scattering force, pointing in the direction of the incident light, and the gradient force, arising from the gradient of the Gaussian intensity profile and pointing in x-y plane towards the center of the beam. The gradient force is a restoring force that pulls the bead into the center. If the contribution to the scattering force of the refracted rays is larger than that of the reflected rays then a restoring force is also created along the z axis, yielding a stable trap. Next, the gradient force ( $F_{grad}$ ) and the scattering force ( $F_{scat}$ ) are detailed in the optical force principle acting on a particle in the trapping laser.

### 2.1.1 Optical force acting on a particle

In this section, the force from the trapping laser acting on a particle consists of two components such as the gradient force, which points to center of the focused spot or the highest intensity of the light gradient, and the scattering force, which points to the same direction of the incident light as detailed below:

#### 2.1.1.1 Gradient force

Gradient force is generated by inducing of the electromagnetic wave of light to the positive and negative ions inside the particles. They become a dipole from that the dipole is pulled into the highest light's intensity, which is the focal point. The incident light on a particle creates a dielectric response, due to the polarizability of the constituent atoms or ions. For one of these atoms or ions in a monochromatic, linearly polarized, continuous light field,  $E$ , the time-averaged induced dipole moment is:

$$\overline{p} = \alpha \cdot \overline{E} \quad (2-2)$$

where  $\vec{p}$  represents the polarizability of the particle to the surrounding medium,

$$\alpha = \alpha' + i \cdot \alpha'' = n_m^2 \tau^3 \left( \frac{n_c^2 - 1}{n_c^2 + 2} \right) \text{ is the relative complex,}$$

$n_{md}$  is the refractive index of a medium,

$n_p$  is the refractive index of a particle,

$$n_c \text{ is the ratio of } \frac{n_p}{n_{md}},$$

The interaction of the induced dipole with the electric field of the light creates an electrostatic potential as demonstrated below:

$$U = -\vec{p} \cdot \vec{E} \quad (2-3)$$

Thus, in a light field with a spatially varying intensity, there is a gradient:

$$\vec{F}_{grad} = -\nabla U = -\vec{p} \nabla E = -\alpha (E \cdot \nabla) \vec{E} \quad (2-4)$$

#### 2.1.1.2 Scattering force

The second force in an optical trap arises from the scattering of light and is a consequence of photons having momentum. This force acts in the direction of propagation of the light and is dependent on the light intensity rather than the gradient. The momentum of a single photon of energy  $\vec{E}$  is:

$$\vec{p} = \hbar \cdot \vec{k} = \frac{\vec{E} \cdot n_{md}}{c} \quad (2-5)$$

A beam of incident photons can be scattered from the particle, resulting in two impulses: one along the direction of light propagation and the other opposite the direction of the scattered photon. For isotropic scattering dependent on the size of the particle, the latter impulse has no preferred direction and results in a net force in the direction of light propagation. The change in momentum or force of a particle

can be calculated by considering the photon flux impinging on and leaving an object under the conservation of momentum:

$$\bar{F}_{scat} = \frac{n}{c} \iint (S_{in} - S_{out}) \cdot dA = \frac{n_{md} \sigma \langle S \rangle}{c} \quad (2-6)$$

where  $n_{md}$  is the refractive index of the surrounding medium,  $\langle S \rangle$  is the time-averaged Poynting vector,  $c$  is the speed of light and  $S$  is the particle's optical cross section.

### 2.1.2 Optical regime depending on the particle's size

In the consideration of the principle of optical tweezers, the particle is separated into two cases. Firstly, the radius of particles is much smaller than the wavelength of light ( $r < \lambda/10$ ), called Rayleigh particle. The Rayleigh regime is used to consider in this case. For another case, the radius of particles is much bigger than the wavelength of light ( $r > 10\lambda$ ), called Mie particle. The Ray optics regime is considered in this case.

#### 2.1.2.1 Rayleigh regime

In the Rayleigh regime, particles can be treated as a collection of dipoles polarized by the envelope of the light field forming the trap with the phase of the field being approximately constant throughout the particle. In the previous sections, equations were presented for the gradient and scattering force on small dielectric particles; however, in practice, it is difficult to exert sufficient force to trap a dielectric particle below 100 nm in size with current optics and laser limitations.

If the radius of a sphere is much smaller than the trapping laser wavelength in order of micrometer or nanometer, ( $r < \lambda/10$ ), the spherical nanoparticle can be considered as a dipole. The spherical object in this case is called "Rayleigh particles". In this regime, the Rayleigh scattering theory is used to calculate the optical force on the nanosphere. As shown in Fig. 2.2, a nanosphere with radius  $r$  and a refractive index  $n_p$  being illuminated by a beam of laser propagating along the  $z$ -axis in the positive direction were considered. The power of a laser beam is  $P$

and the refractive index of medium, which the nanosphere is suspended in, is  $n_{md}$ . The laser beam is a linearly polarized Gaussian beam in  $TEM_{00}$  mode with the radius of beam waist  $\omega_0$  at the focus. The polarization direction of the electric field of the laser is parallel to the  $x$ -axis. The center of the nanosphere is at  $\vec{r} = (x, y, z)$  and the center of the laser beam is located at the origin [37].

The wavefront of a Gaussian beam is flat at the center and its waist ( $1/e^2$  radius) spreads in accordance with:

$$\omega(z) = \omega_0 \left[ 1 + \left( \frac{\lambda_{md} z}{\pi \omega_0^2} \right)^2 \right]^{1/2} \quad (2-7)$$

where the wavelength of the laser in the medium is  $\lambda_{md} = \lambda_0 / n_{md}$ .

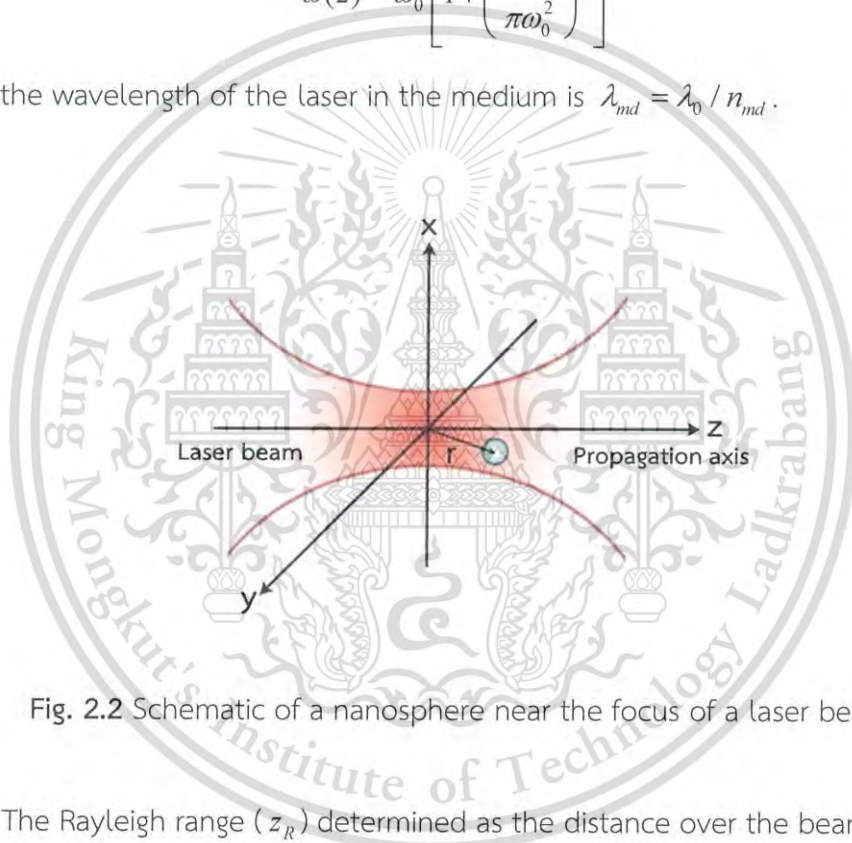


Fig. 2.2 Schematic of a nanosphere near the focus of a laser beam

The Rayleigh range ( $z_R$ ) determined as the distance over the beam radius spreads by a factor of  $\sqrt{2}$  is given by

$$z_R = \frac{\pi \omega_0^2}{\lambda_{md}} \quad (2-8)$$

The intensity distribution of the Gaussian beam is

$$I(x, y) = I_0 e^{-2(x^2 + y^2)/\omega^2} = \frac{2P}{\pi \omega^2} e^{-2(x^2 + y^2)/\omega^2} \quad (2-9)$$

where  $\omega = \omega(z)$  and  $P$  represents the power of the laser beam.

The numerical aperture ( $1/e^2$  points in  $k$ -space) of a Gaussian beam is

$$N.A. = \frac{\lambda_0}{\pi\omega_0} = n_{md} \frac{\lambda_{md}}{\pi\omega_0} \quad (2-10)$$

There are two components of the optical force of the focused laser beam acted on the nanosphere. The first one is the scattering force,  $\vec{F}_{scatt}(\vec{r})$ , which is proportional to the intensity of the laser and it is a nonconservative force. The other one is the gradient force,  $\vec{F}_{grad}(\vec{r})$ , which is proportional to the gradient of the intensity of the laser and is a conservative force. The gradient force forms a trapping potential for the nanosphere, while the scattering force tends to push the nanosphere away the trap. In order to form a stable trap, the  $\vec{F}_{grad}(\vec{r})$  should be larger than  $\vec{F}_{scatt}(\vec{r})$ .

The  $\vec{F}_{scatt}(\vec{r})$  force of the trapping laser [38] acted on a nanosphere is

$$\vec{F}_{scat}(\vec{r}) = \hat{z} \left( \frac{n_{md}}{c} \right) C_{scatt} I(\vec{r}) = \hat{z} \frac{128\pi^5 r_p^6}{3c\lambda_0^4} \left( \frac{n_c^2 - 1}{n_c^2 + 2} \right)^2 n_{md}^5 I(\vec{r}) \quad (2-11)$$

where  $c$  and  $C_{scatt}$  are the speed of light in vacuum and the scattering cross section, respectively. Due to the larger relative refractive index ( $m$ ), the  $\vec{F}_{scat}(\vec{r})$  force on a nanosphere in air is about 4.2 times bigger than the  $\vec{F}_{scat}(\vec{r})$  in water on the same nanosphere with the same intensity of laser. The number of scattered photons per second is

$$N_{scat} = \frac{\lambda_{md}}{h} |\vec{F}_{scat}| \quad (2-12)$$

where  $h$  is the Planck constant.

The  $\vec{F}_{grad}(\vec{r})$  force on the nanosphere [38] is

$$\vec{F}_{grad}(\vec{r}) = [\vec{p}(\vec{r}, t) \cdot \nabla] E(\vec{r}, t) = \frac{2\pi n_{md} r_p^3}{c} \left( \frac{n_c^2 - 1}{n_c^2 + 2} \right) \nabla I(\vec{r}) \quad (2-13)$$

where  $\vec{p}(\vec{r}, t)$  is the dipole of the nanosphere induced by the instantaneous electric field of the laser ( $\vec{E}(\vec{r}, t)$ ). A trapping potential formed by the  $\vec{F}_{grad}(\vec{r})$  force can be expressed as

$$V(\vec{r}) = \frac{2\pi n_{md} r_p^3}{c} \left( \frac{n_c^2 - 1}{n_c^2 + 2} \right) I(\vec{r}) \quad (2-14)$$

The total force acted on the nanosphere is  $\vec{F}(\vec{r}, t) = \vec{F}_{scatt}(\vec{r}) + \vec{F}_{grad}(\vec{r})$  and the minimum force along the  $z$ -axis is equal to  $F_z^{\min} = \min(F_z(\vec{r}))$  and must be negative in order to form a stable trap. Otherwise, the optical force of the laser will always push the nanosphere forward and the nanosphere will be not trapped in a focused of the laser. Because the  $\vec{F}_{grad}(\vec{r})$  force is proportional to  $r_p^3$  while  $\vec{F}_{scatt}(\vec{r})$  is proportional to  $r_p^6$ ; thereby, the gradient force decreases much slower than the scattering force. It is easier to obtain a negative minimum force ( $F_z^{\min}$ ) for a small nanosphere than a large sphere.

In order to trap or confine a nanosphere stably, the well depth should be at least 10 times larger than the average kinetic energy of the nanosphere. This is due to the fact that the kinetic energy of a nanosphere follows the Maxwell-Boltzmann distribution at thermal equilibrium. The nanosphere has a significant probability for its instantaneous kinetic energy to be much larger than its average kinetic energy. According to the energy equipartition theorem, the average kinetic energy of a nanosphere is equal to  $k_B T/2$  in each direction, where  $k_B$  and  $T$  are the Boltzmann constant and medium temperature, respectively. While the average kinetic energy depends on the radius of the nanosphere, the well depth of the trapping potential decreases as the radius of the nanosphere decreases. Therefore, if the size of the nanosphere is very small, it is difficult to trap it stably in the focused beam of a laser.

### 2.1.2.2 Ray optic regime

In this case, if the radius of a particle is much bigger than the trapping laser wavelength, ( $r > 10\lambda$ ), it is explained by Snell's law and conservation of momentum law. The spherical object in this case is called "Mie particles". We will consider light as a photon that has momentum inside  $p = h/\lambda$  that pass medium through particles with different refractive index. Momentum of light will refract from the direction of light propagation, then particles will move at the focal point of laser [37].

As shown in Fig. 2.3, the refraction of the rays by beads changes the momentum of the photons, equal to the change on the direction of the input and output rays. Conservation of momentum dictates that the momentum of bead changes by an equal but opposite amount, which results in the forces depicted by gray arrows. The net force on the bead is to the right, in the direction of the intensity gradient and slightly down.

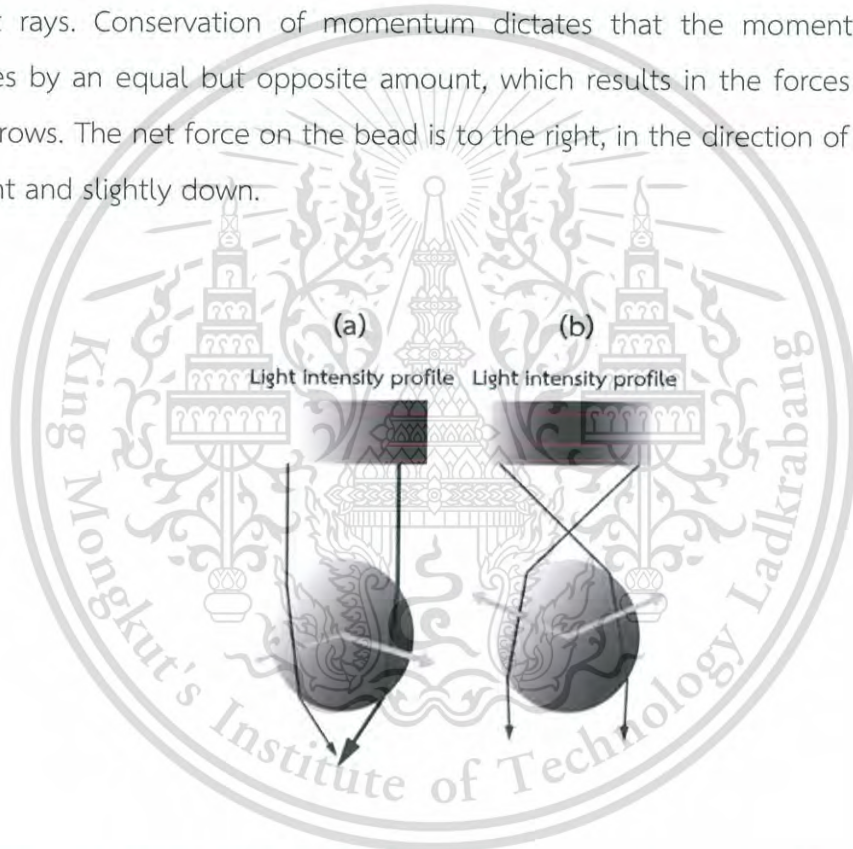


**Fig. 2.3** Description of the gradient force that perpendicular (a) and parallel (b) with laser propagation

In order to form a stable trap, the light must be focused, producing a three-dimensional intensity gradient. In this case, the bead is illuminated by a focused beam of light with a radial intensity gradient. Two representative rays are again refracted by the bead but the change momentum in this instance leads to a net force towards the focus. Gray arrows represent the forces. The lateral forces balance

each other out and the axial force is balanced by the scattering force, which decreases away from the focus. If the bead moves in the focused beam, the imbalance of optical forces will draw it back to the equilibrium position.

Particles are trapped by optical tweezers without damage or a little injured. That's suitable for using Optical Tweezers to study in biology such blood cell and microorganism. In addition, using Infrared laser can be reduced heat from liquid absorption in cells. Optical tweezers have been applied to trap a dielectric spherical particle and multi-spherical particles, bacteria, viruses, living and non-living cells, organelles, small metal particles, and even strands of DNA. Its applications still include tracking movement of bacteria, measurement of small forces, altering of cell membranes, and confinement for cell sorting. The physical of DNA and the molecular motors are two main topics studied by using optical traps. In both areas, a micron-sized glass or polystyrene bead is attached in a biological specimen to trap or control by optical tweezers. Researchers have been able to probe motor properties such as How much force can the motor produce? and What is the step size? By attaching a single molecular motor to a bead. Likewise, the beads are attached to the ends of DNA in order to measure the DNA's elasticities, as well as the forces under a phase transition of DNA.

## 2.2 Principle of digital holographic technique

Holography is the word of Greek language that consists of "holos" means total and "graphein" means recording or writing. When both words are merged as "holography", it means the recording images of wavefronts completely both phases and amplitudes of the interference patterns. The interference and diffraction of light are used to image and record the data from the objects on holographic film in three dimension (3D). This technique is found by Dennis Gabor in 1948, after that in 1971 he received the Nobel prize in physics from the topic of "Reflecting the general impact of holography on modern physics". The interference image is called "hologram", which is generated from the interference of two beam lights such as reference beam and object beam. The interference of these beams is occurred on a holographic film, and the film is taken to develop. Therefore, the holographic image (Hologram) inside the developed film can be observed by changing the vision

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

position. The hologram that recorded on holographic film is the conventional holographic technique.

By changing the recording medium, the hologram patterns that be marked on the electronic devices, i.e., Complementary metal oxide semiconductor (CMOS) or Charged couple detector (CCD) sensor, is called digital holography technique (DH) method as shown in Fig. 2.4. In the system, there are two beams separated by a beam splitter. An object beam passed through the objects, and the wavefronts of the beam diffract dependent on the objects' pattern. A reference beam from the other way will interfere with the object beam on the sensor's camera.

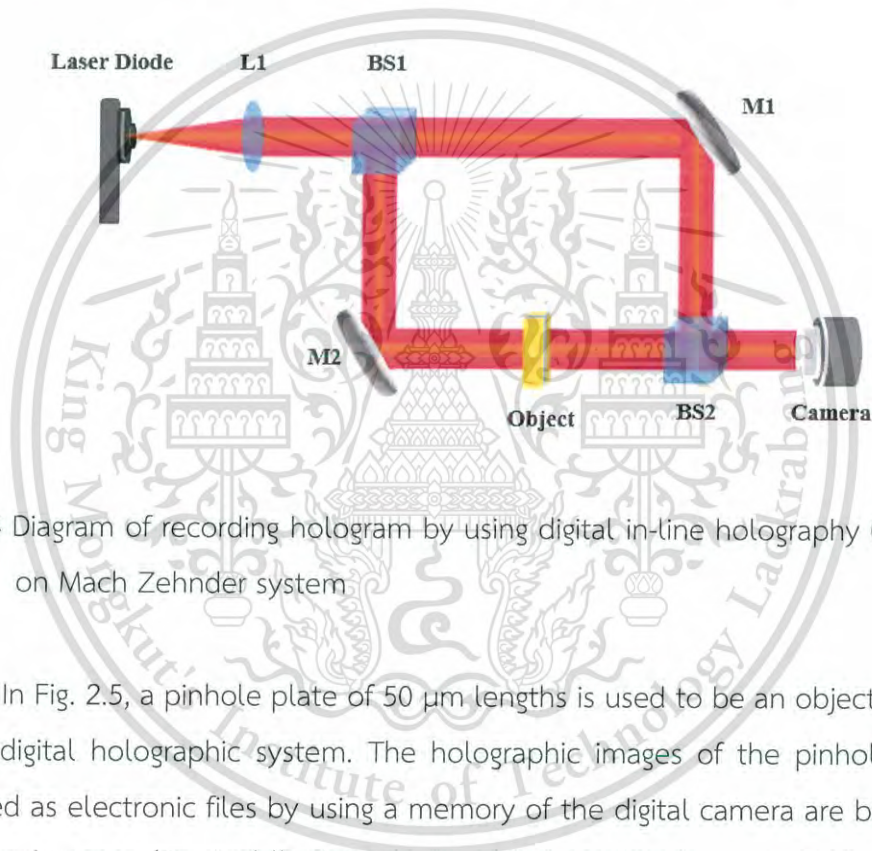


**Fig. 2.4** Diagram of recording hologram by using digital in-line holography (DIH) based on Mach Zehnder system

In Fig. 2.5, a pinhole plate of 50  $\mu\text{m}$  lengths is used to be an object for testing in the digital holographic system. The holographic images of the pinhole that are recorded as electronic files by using a memory of the digital camera are blur like the unfocused images (Fig. 2.5(a)). Then, in the digital holographic system the numerical lens is an important tool to focus the hologram like the image is on the focus point as demonstrated in Fig. 2.5(b).

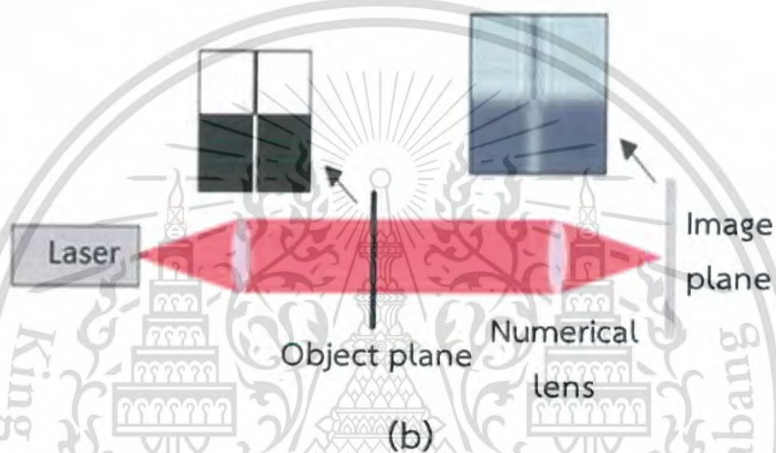
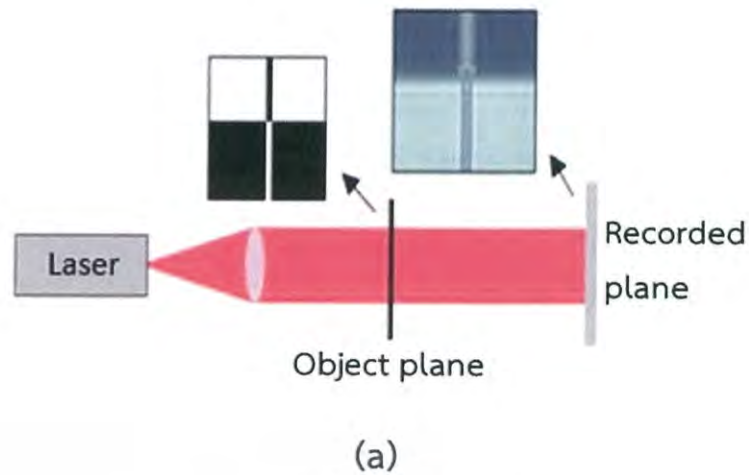


Fig. 2.5 The reconstruction of hologram by digital holographic technique. (a) no numerical lens and (b) using numerical lens

In holographic process, there are two important steps of this technique such as the recording and reconstructing steps. The first step is the experimental process, which the interference patterns are recorded by a camera's sensor in the DH system. All recorded images look indistinct like they are out-of-focus. Therefore, another step is the most important process to adjust the hologram images in the focus plane, which is the reconstruction method as those images are analyzed numerically on program. In this thesis, the CMOS sensor is utilized to record the hologram images, and for the reconstructing process, I will describe the methods of reconstruction in the next section.

Before start explaining the reconstruction methods, the holographic term is determined in the section 2.2.1.

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

### 2.2.1 Holographic term

The holographic term can be explained by using the electromagnetic waves of reference beam ( $E_R$ ) and object beam ( $E_o$ ) as shown in Fig. 2.5. The  $E_R$  and  $E_o$  are illumination of object field and reference field, respectively. The intensity of the interference field between  $E_R$  and  $E_o$  imaged on the holographic mediums is expressed by

$$\begin{aligned} I &= |E_R + E_O|^2 \\ &= |E_R|^2 + |E_O|^2 + E_R^* E_O + E_R E_O^* \end{aligned} \quad (2-15)$$

where  $E_O^*$  and  $E_R^*$  represent the conjugate pair of object field and reference field, respectively. For reconstruction, the reference field  $E_R$  (Reading beam) illuminated again on the hologram then the transmitted field is:

$$\begin{aligned} E &= E_R I \\ &= E_R |E_R + E_O|^2 \\ &= E_R |E_R|^2 + E_R |E_O|^2 + |E_R|^2 E_O + E_R^2 E_O^* \end{aligned} \quad (2-16)$$

From the equation (2-16), the first two terms are the non-diffracted wave pass through the hologram, which is called zero diffraction order. The third term is the reconstructed object wave, which forms the virtual image on the same side as the object. The last term is the distorted real image generated by spatial varying complex factor  $E_R^2$ . These last two terms are the complex object field and its conjugate called first order twin image. The hologram term is illustrated in Fig. 2.6(b).

To eliminate the distorted real image, the undistorted real can be generated by using conjugated reference beam  $E_R^*$  as described:

$$\begin{aligned} E &= E_R^* I \\ &= E_R^* |E_R + E_O|^2 \\ &= E_R^* |E_R|^2 + E_R^* |E_O|^2 + E_R^{*2} E_O + |E_R|^2 E_O^* \end{aligned} \quad (2-17)$$

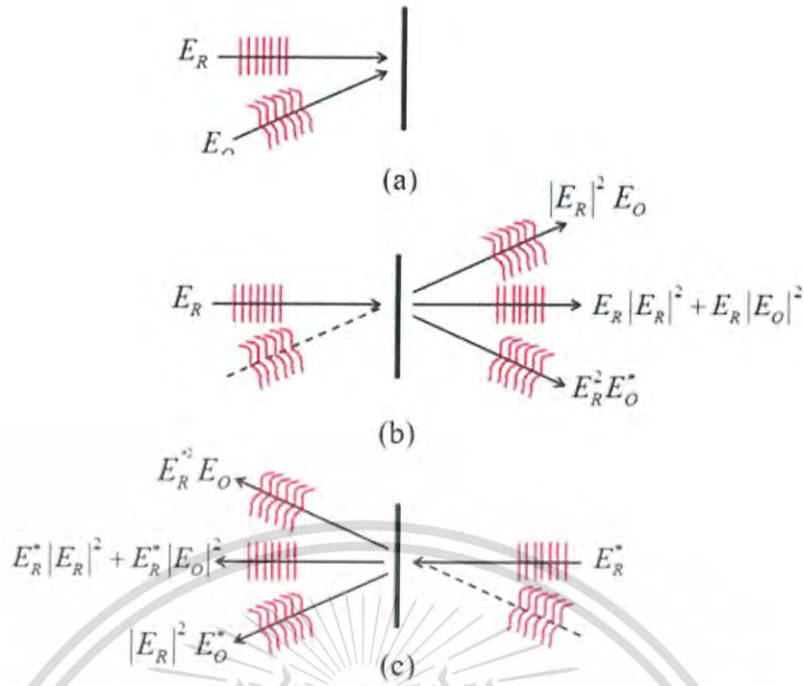


Fig. 2.6 The holographic term; (a) hologram recording, (b) hologram reconstruction with reference wave  $E_R$ , and (c) hologram reconstruction with conjugate of reference wave  $E_R^*$

## 2.2.2 Method of reconstruction

When the hologram images are recorded on the digital tools, those images are still out of focus or they are not clear. Then, all hologram images have to reconstruct in order to obtain the hologram in three dimensions clearly. In this process, there are two numerical methods for reconstructing recorded images, such as “Huygens convolution”, and “Angular momentum” methods [39-40]. Both methods are explained below in the section 2.2.2.1 and 2.2.2.2, respectively.

### 2.2.2.1 Huygens convolution method

Huygens convolution method (HCM) is the reconstructed method that based on Fresnel diffraction principle and convolution theorem. Suppose that  $h(x, y)$  represents two dimensional diffracted optical fields, which propagated along  $z$  direction to the recorded plane (Hologram plane) as shown in Fig. 2.7. By using Huygens – Fresnel principle, which explains the diffraction of light via aperture in rectangular coordinates, the diffracted optical field can be expressed as

$$h(x, y) = \frac{z}{j\lambda} \iint O(\xi, \eta) \frac{\exp(jk\rho)}{\rho^2} d\xi d\eta \quad (2-18)$$

where  $O(\xi, \eta)$  is the optical field at the object plane,

$\rho = [z^2 + (x - \xi)^2 + (y - \eta)^2]^{1/2}$  is the distance from any point on object plane  $(\xi, \eta)$  to the hologram plane  $(x, y)$ ,

$z$  is the propagation distance,

$k = 2\pi / \lambda$  is the wavenumber with the wavelength  $\lambda$ .

By using the convolution method, the hologram function can be written as

$$h(x, y) = \mathcal{F}^{-1} \{ \mathcal{F}[O(\xi, \eta)] \cdot \mathcal{F}[g(\xi, \eta, x, y)] \} \quad (2-19)$$

where the kernel  $g(\xi, \eta, x, y)$  is given by

$$g(\xi, \eta, x, y) = \frac{z}{j\lambda} \frac{\exp(jk\rho)}{\rho^2} \quad (2-20)$$

Due to the pixels size of recorded mediums (CMOS or CCD), it is very small compared with the propagated distance, the parameter  $\rho^2$  can be reduced to  $z^2$ . Thus, the kernel is expressed as

$$g(\xi, \eta, x, y) = \frac{\exp(jk\rho)}{j\lambda z} \quad (2-21)$$

The optical field at the image plane  $R(\xi', \eta')$  can be reconstructed by using inverse Fourier transform of filtered Huygens – Fresnel as:

$$R(\xi', \eta') = \mathcal{F}^{-1} \{ \mathcal{F}[h(x, y)] \cdot \mathcal{F}[g(\xi, \eta, x, y)] \} \quad (2-22)$$

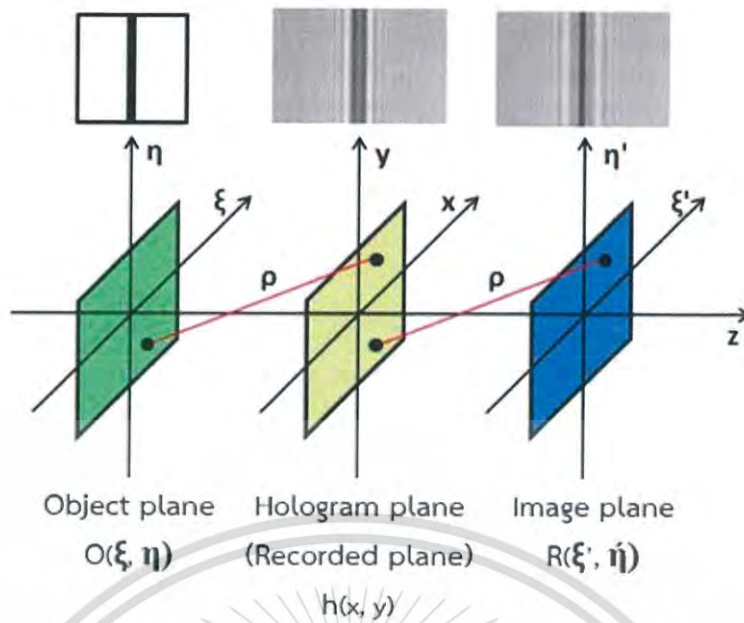


Fig. 2.7 Coordinating systems for numerical reconstruction

#### 2.2.2.2 Angular spectrum method

Angular spectrum method (ASM), the mathematical technique, is used to describe the optical field of the plane of propagated light and also used to reconstruct the digital hologram. This method uses Fourier transformation and inverse Fourier transformation to reconstruct digital hologram as the HCM, but it has the advantage in reconstructed distance. ASM can rightly reconstruct the digital hologram in nearer distance when compared with HCM.

Suppose that at plane  $z=0$  is the object plane  $(\xi, \eta)$  as shown in Fig. 2.7, the field of object plane  $O(\xi, \eta)$  has a two-dimensional Fourier transform that expressed by

$$\begin{aligned}
 O'(f_\xi, f_\eta; 0) &= \mathcal{F}\{O(\xi, \eta, 0)\} \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O(\xi, \eta, 0) \exp[-j2\pi(f_\xi \xi + f_\eta \eta)] d\xi d\eta
 \end{aligned} \tag{2-23}$$

and the inverse Fourier transform of its angular spectrum can be given by

$$\begin{aligned}
 O(\xi, \eta, 0) &= \mathcal{F}^{-1}\{O'(f_\xi, f_\eta; 0)\} \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O'(f_\xi, f_\eta; 0) \exp[-j2\pi(f_\xi \xi + f_\eta \eta)] df_\xi df_\eta
 \end{aligned} \tag{2-24}$$

where  $f_\xi$  and  $f_\eta$  are the components of spatial frequency. By consider as plane wave propagating with direction cosines as illustrated in Fig. 2.8, the component of spatial frequency can be given by

$$\alpha = \lambda f_\xi \quad \beta = \lambda f_\eta \quad \gamma = \sqrt{1 - (\lambda f_\xi)^2 - (\lambda f_\eta)^2} \tag{2-25}$$

Hence, the equation 2-23 becomes,

$$O'\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0\right) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O(\xi, \eta, 0) \exp[-j2\pi(\frac{\alpha}{\lambda} \xi + \frac{\beta}{\lambda} \eta)] d\xi d\eta \tag{2-26}$$

After the optical field propagate over distance  $z$ , the component in exponential will acquire a factor  $\exp\left(-j \frac{2\pi}{\lambda} \gamma z\right)$ . The angular spectrum of object field can be expressed by

$$\begin{aligned}
 O'\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; z\right) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O(\xi, \eta, 0) \exp[-j2\pi(\frac{\alpha}{\lambda} \xi + \frac{\beta}{\lambda} \eta)] \exp(-j \frac{2\pi}{\lambda} \gamma z) d\xi d\eta \\
 &= \mathcal{F}\left\{O(\xi, \eta, 0) \exp(-j \frac{2\pi}{\lambda} \gamma z)\right\}
 \end{aligned} \tag{2-27}$$

And its inverse Fourier transform is

$$\begin{aligned}
 O(\xi, \eta, z) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O'\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0\right) \exp[-j2\pi(\frac{\alpha}{\lambda} \xi + \frac{\beta}{\lambda} \eta)] \exp(-j \frac{2\pi}{\lambda} \gamma z) d\frac{\alpha}{\lambda} d\frac{\beta}{\lambda} \\
 &= \mathcal{F}^{-1}\left\{O'\left(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0\right) \exp(-j \frac{2\pi}{\lambda} \gamma z)\right\}
 \end{aligned} \tag{2-28}$$

Due to the wave propagate from object plane  $(\xi, \eta)$  to hologram plane  $(x, y)$  over a distance  $z$ , the optical field on hologram plane can be expressed

$$\begin{aligned}
h(x, y, z) &= O(\xi, \eta, z) \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} O'(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0) \exp[-j2\pi(\frac{\alpha}{\lambda}\xi + \frac{\beta}{\lambda}\eta)] \exp(-j\frac{2\pi}{\lambda}\gamma z) d\frac{\alpha}{\lambda} d\frac{\beta}{\lambda} \\
&= \mathcal{F}^{-1} \left\{ O'(\frac{\alpha}{\lambda}, \frac{\beta}{\lambda}; 0) \exp(-j\frac{2\pi}{\lambda}\gamma z) \right\} \\
&= \mathcal{F}^{-1} \left\{ \mathcal{F} \{ O(x, y, 0) \} \exp(-j\frac{2\pi}{\lambda}\gamma z) \right\}
\end{aligned} \tag{2-29}$$

Similarly, the optical field on reconstruction plane  $R(\xi', \eta')$  can be written in inverse Fourier transform form of hologram field

$$R(\xi', \eta', z) = \mathcal{F}^{-1} \left\{ \mathcal{F} \{ h(x, y, 0) \} \exp(-j\frac{2\pi}{\lambda}\gamma z) \right\} \tag{2-30}$$

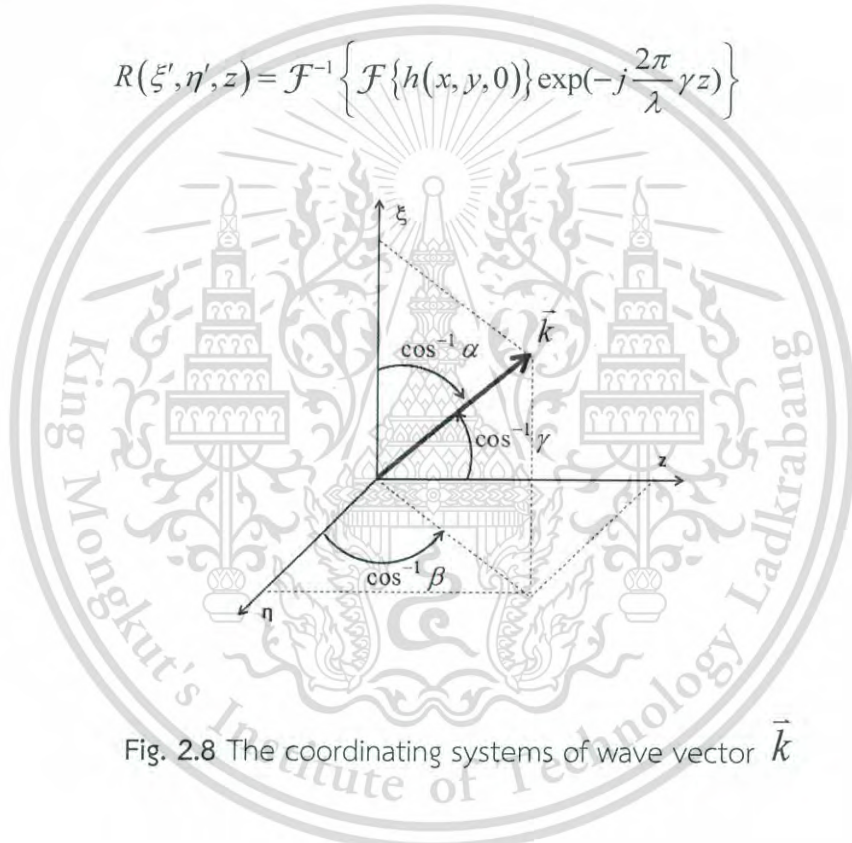


Fig. 2.8 The coordinating systems of wave vector  $\vec{k}$

As mentioned above both reconstruction methods, the ASM has more advantage than HCM. Therefore, ASM has been used to reconstruct the digital hologram in this thesis. A schematic flow chart diagram of the digital hologram reconstructed process is shown in Fig. 2.9. There are three mainly step processes in this digital hologram reconstructed algorithm. Firstly, compute the Fast Fourier Transformation (FFT) of hologram (FFT is the one function in MATLAB® program). Then, multiply the results from FFT by kernel  $g(z) = \exp\left(-j\frac{2\pi}{\lambda}\gamma z\right)$ . Lastly, the

reconstructed digital hologram is obtained by computing with Inverse Fast Fourier Transformation (IFFT) of the multiplied result.

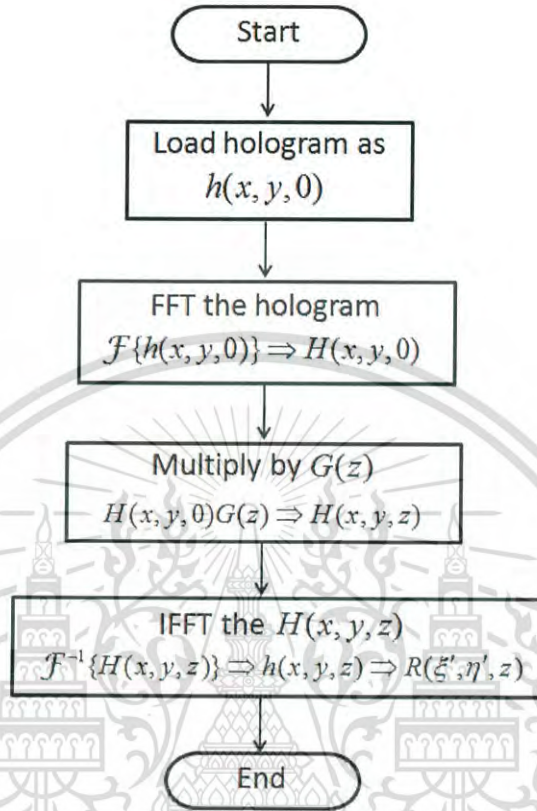


Fig. 2.9 The flow chart of reconstruction algorithm

### 2.2.3 Digital holographic configurations

The digital holographic technique can be sorted into two main configurations, depending on the interference angle between reference beam and object beam such as off axis and on axis or in-line configuration as explained below.

#### 2.2.3.1 Digital off-axis holographic (DOH) configuration

The off-axis configuration can be shown the diagram in Fig. 2.10, which the reference and object wave are interference with angle  $\theta$ . The maximum angle  $\theta_{\max}$  can be calculated by

$$\theta_{\max} = 2 \arcsin \left( \frac{\lambda}{4\Delta x} \right) \approx \frac{\lambda}{2\Delta x} \quad (2-31)$$

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

where  $\lambda$  and  $\Delta x$  are wavelength of the recording light and resolution of recording medium, respectively. The angle  $\theta$  in this configuration can be up to 180 degrees by using photographic film as the recording medium with the resolution  $\Delta x$  up to 0.2  $\mu\text{m}$ . However, the maximum resolution of imaging sensor (CCD or CMOS) is in order of 5  $\mu\text{m}$ . Therefore, the maximum angle in this case (the wavelength of light source in this thesis is 635 nm) is about 3.6 degree.

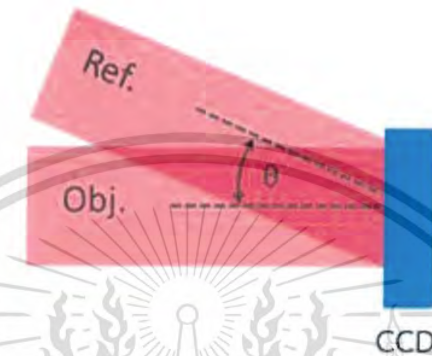


Fig. 2.10 Diagram of the off-axis configuration

#### 2.2.3.2 Digital in-line holographic (DIH) configuration

The recording angle of digital holography is factually close to 0 degree and called in-line configuration as shows in Fig. 2.11(a). Moreover, there are the other one configuration called Gabor configuration, which is invented by D. Gabor, who the first invent holography technique. As shown in Fig 2.11(b), the light illuminates to obstacle and there are two consider wave in this configuration. Firstly, the light diffracts at the edge of obstacle called object wave. Secondly, the other part of light that not scatter on obstacle called reference wave. These two waves interfere on sensor of camera like the other configurations. However, in this thesis called Gabor configuration as in-line configuration because most of research call this configuration as in-line.

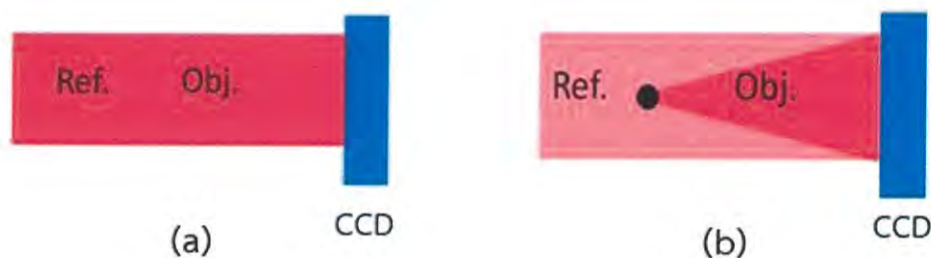


Fig. 2.11 Diagram of (a) in-line digital holography and (b) Gabor digital holography

### 2.3 Interaction of colloidal particles coated by polymers

Colloidal particles suspended in aqueous suspensions usually carry positive more than negative charges around them. If the dilution is too great, there appears to be some aggregation each other particles in suspension like in Fig. 2.12(a). The figure 2.12 was described previously in ref. [41] that shown the schematic of Polystyrene particles surrounded by polymers. The polymers generate the repulsive-attractive forces of the interactions between colloidal particles in suspensions. Absorbing surfactant, Pluronic PEG-PPG-PEG triblock, is a short polymer used to add in suspension for absorbing on a particle surface. The middle PPG section is hydrophobic chain which anchors on the sphere surface, while the two PEG sides, hydrophilic chain, extent like brushes into the aqueous environment [17]. These brushes generate the repulsive force, which prevent the aggregation between particle interactions as shown in Fig. 2.12(b). On the other hand, in order to produce the attractive force between particles, Poly (ethylene glycol) (PEG) as long chain of neutral polymer, non-absorbing polymer, are added properly in the suspensions. The brushes of Pluronic coated on the PS surface can bind with the crowding of PEG polymer to introduce more attractive forces between PS particles when they are trapped in a focused beam of laser. The sizes of the polymer are characterized by the gyration radius ( $R_g$ ). In this research, the  $R_g$  is about 5 nm. for the 14kD Pluronic, 14 nm. for the 35kD PEG, and also the molecular structure of both polymer types is shown on the right in Fig. 2.12. For applying the colloidal suspension to trap multiple particles, the generated repulsive-attractive forces of the interactions between particles in the presence of polymers are helpful. While the colloidal particles are confined in a focused laser, lots of particles can move close up in a trap easily

caused by binding each other between the PEG brushes of Pluronic and the PEG chains. However, when there is no light acting in the suspension, the repulsive force renders the colloidal stability. In another way, by adding low concentration of KCl salt in suspension, the negative charges of salt ( $\text{Cl}^-$ ) interact with the positive charges around particles as mentioned above, they can move closer each other by producing attractive force.

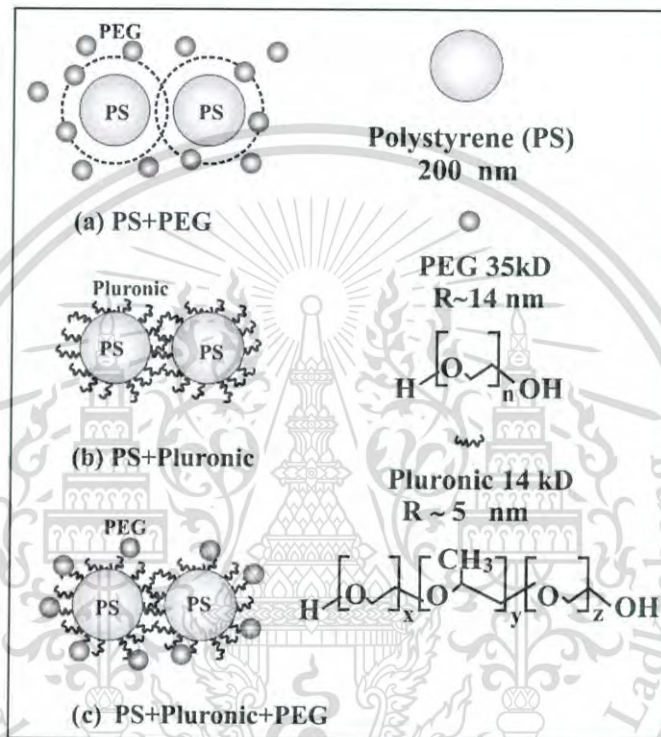


Fig. 2.12 Schematic of: (a) polystyrene (PS) particles surrounded by PEG polymer (b) PS particles surrounded by pluronics polymer and (c) PS particles surrounded by pluronics polymer and PEG polymer

## 2.4 Viscosity of fluids

Viscosity is the properties that resists the motion of a fluid. When the fluid moves, there is produced a shear stress in it, which denoted by the Greek letter ( $\tau$ ). The magnitude of the shear stress depends on the viscosity of the fluid, denoted by the Greek letter  $\eta$  (Eta). Shear stress can be determined as the force required to slide one unit area layer of a substance over another. Therefore,  $\tau$  (tau) is a force divided

by an area that parallel with the flow and can be measured in the units of newtons per square meter ( $\text{N/m}^2$ ) or pounds per square foot ( $\text{lb/ft}^2$ ). In a fluid such as oil, water, or other common liquids, the magnitude of the shear stress is directly proportional to the velocity that change between different positions in the fluid. In Fig. 2.13, the concept of the change of velocity in a fluid by experiencing a thin layer of fluid between two surfaces. The first one is a stationary surface and the second one is a moving surface. An elementary condition that exists when a real fluid contacts with the surface of a boundary is that the fluid has the same velocity as the boundary. Then, the fluid in contact with the lower surface has a zero velocity, but the velocity,  $v$ , becomes when it in contact with the upper surface as illustrated in Fig. 2.13 [42].

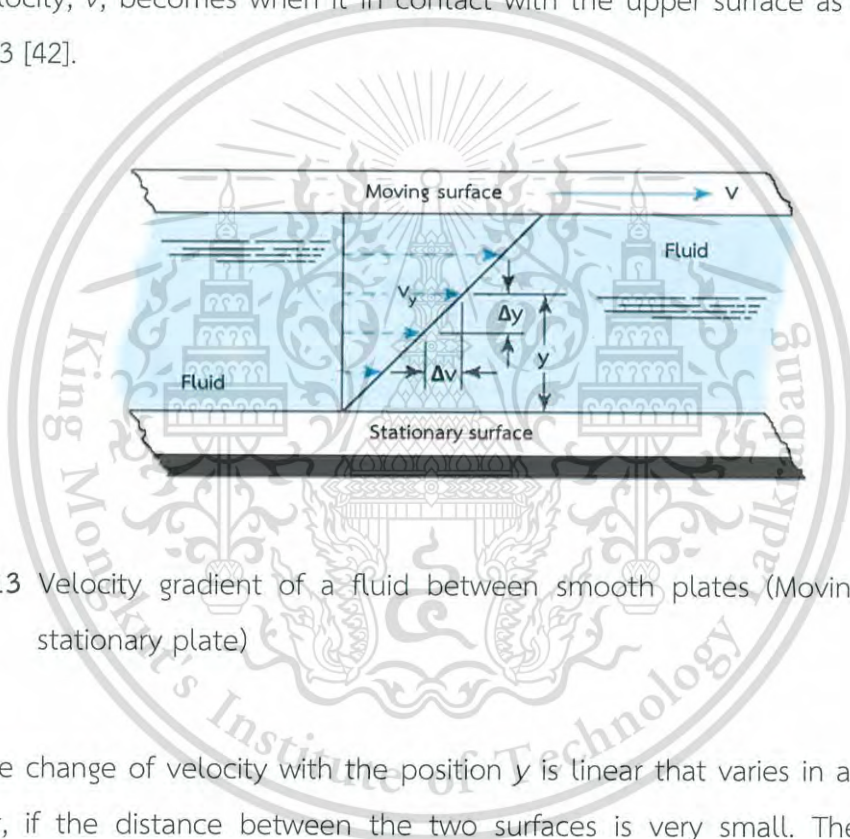


Fig. 2.13 Velocity gradient of a fluid between smooth plates (Moving plate and stationary plate)

The rate change of velocity with the position  $y$  is linear that varies in a straight-line manner, if the distance between the two surfaces is very small. The change of velocity can be measured the *velocity gradient* or the *shear rate* and is determined as  $\Delta v / \Delta y$ . In general, the relationship of the velocity gradient is directly proportional to the shear stress in the fluid and can be expressed mathematically as

$$\tau = \eta (\Delta v / \Delta y) = \eta \left( \frac{\Delta y}{\Delta v} \right) \quad (2-32)$$

where  $\eta$  is the dynamic viscosity that is the proportionality constant of the fluid. From the equation, it can be imagined the physical explanation by stirring a fluid

with a glass rod. The force of stirring causes a velocity gradient to be generated in the fluid. For a cold oil with a high magnitude of viscosity, it is required a greater force than to stir in water with the lower viscosity. This can be indicated that there is the higher shear stress in the cold oil.

There are many different unit systems to determine the dynamic viscosity ( $\eta$ ) of a fluid. The units of  $\eta$  can be obtained by substituting the SI units of the parameters in Eq. 2-32 as follows.

$$\eta = \frac{N}{m^2} \times \frac{m}{m/s} = \frac{N \cdot s}{m^2} \quad (2-33)$$

Because another name of  $N/m^2$  is Pa, the unit of dynamic viscosity can also be rewritten as

$$\eta = Pa \cdot s \quad (2-34)$$

When the dynamic viscosity is sometimes combined with other parameters, especially a density of the fluid ( $\rho_f$ ), it is expressed in the unit of kilogram ( $kg$ ) rather than newton ( $N$ ) to be convenient for using. Since  $1N$  is equal to  $1 \text{ kg} \cdot m/s^2$ , then  $\eta$  can be expressed as

$$\eta = N \times \frac{s}{m^2} \times \frac{kg \cdot m}{s^2} \times \frac{s}{m^2} = \frac{kg}{m \cdot s} \quad (2-35)$$

Therefore, either  $N \cdot s/m^2$ ,  $Pa \cdot s$ , or  $kg/m \cdot s$  may be used in the SI unit for the determination of dynamic viscosity of the fluid. Generally, there are the most three unit system used to determine the dynamic viscosity as presented in Table 2.1. In my thesis, the SI unit of  $kg/m \cdot s$  is used for determination of viscous oils because it is related to the unit of kinematic viscosity in centistoke ( $cSt$ ) as following the ASTM D445 standard and will be mentioned below.

**Table 2.1** Lists of the dynamic viscosity units in the three most widely systems

| Unit system               | Dynamic viscosity units                                                                       |
|---------------------------|-----------------------------------------------------------------------------------------------|
| International system (SI) | $N.s/m^2, Pa.s, kg/m.s$                                                                       |
| U.S. Customary System     | $lb.s/ft^2$ or $slug/ft.s$                                                                    |
| cgs system (obsolete)     | $poise = dyne.s/cm^2 = g(cm.s) = 0.1 Pa.s$<br>$centipoise = poise/100 = 0.001 Pa.s = 1 mPa.s$ |

In fluid mechanics, there are many calculations that involve the ratio of the dynamic viscosity to the density of the fluid. As a matter convenience, the kinematic viscosity, denoted by  $\nu$  (nu) is determined as

$$\nu = \eta / \rho_f \quad (2-36)$$

$\nu$  is another property of the fluid because  $\eta$  and  $\rho_f$  are both properties of the fluid.

The SI units of kinematic viscosity can be derived by substituting the SI units of dynamic viscosity ( $kg/m.s$ ) and density ( $kg/m^3$ ) of the fluid in Eq. 2-36:

$$\begin{aligned} \nu &= \frac{\eta}{\rho_f} = \eta \left( \frac{1}{\rho_f} \right) \\ \nu &= \frac{kg}{m.s} \times \frac{m^3}{kg} = m^2/s \end{aligned} \quad (2-37)$$

The kinematic viscosity units in the three most widely systems are listed in Table 2.2. For the convenient use in my thesis, the unit of kinematic viscosity in cgs system is used to determine the kinematic viscosity of lubricant oils because they were measured by following the ASTM D445 standard in centistoke (cSt) unit from the supplier.

**Table 2.2** Lists of the kinematic viscosity units in the three most widely systems

| Unit system               | Dynamic viscosity units                                                                        |
|---------------------------|------------------------------------------------------------------------------------------------|
| International system (SI) | $m^2/s$                                                                                        |
| U.S. Customary System     | $ft^2/s$                                                                                       |
| cgs system (obsolete)     | $stoke = cm^2/s = 1 \times 10^{-4} m^2/s$<br>$centistoke = stoke/100 = 1 \times 10^{-6} m^2/s$ |

## 2.5 Dynamic of a spherical particle in viscous fluids

When a spherical object falls vertically in a fluid, it gradually moves through the fluid. By the layers of the fluid that be in front of the object, they flow to the space that the object passed through, which the flow doesn't spin. The gravitational force ( $F_g$ ) pushes the spherical object falling down in the direction of motion. However, there are two forces acting on the object in the direction opposite to the motion's direction. They are a buoyant force ( $F_b$ ) and a viscous drag force ( $F_d$ ) as illustrated in Fig. 2.14.

From the Newton's law of motion, the motion of a spherical particle can be written as the equation 2-38;

$$F_g - F_b - F_d = ma \quad (2-38)$$

where  $m$ ,  $a$ , and  $g$  are the mass of a spherical particle in the unit of kg, the acceleration of s spherical particle falling in a fluid and the gravitational acceleration of the earth in the unit of  $m/s^2$ , respectively.

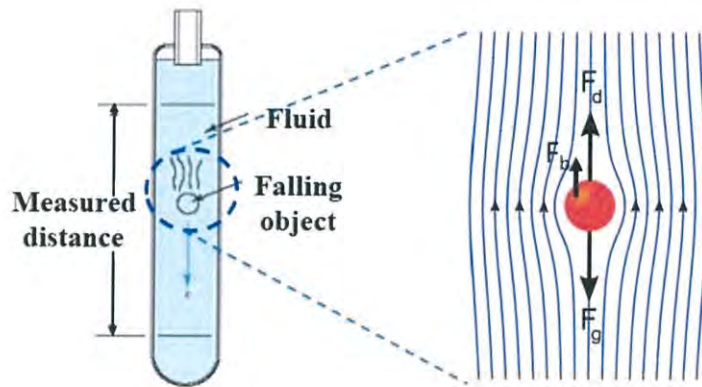


Fig. 2.14 Diagram of a spherical particle falling in a viscous fluid and the forces acting on the particle

A spherical particle moving in a fluid feels a frictional force in a direction opposite to its direction of motion. The magnitude of this force depends on the geometry of the object, its velocity, and the internal friction of the fluid. A measure for the internal friction is given by the dynamic viscosity " $\eta$ ". For a sphere of radius " $r$ " moving at velocity " $v$ " in an infinitely extended fluid of dynamic viscosity, in 1845 Sir George Stoke desired an expression for the mathematical equation of the frictional force, which is proved from the Stokes equation [43].

$$F_d = 6\pi\eta r * v \quad (2-39)$$

Under the particular condition of the  $F_d$  force, this law is mentioned the force acting on a small and sphere object, as it falls down through a viscous medium under the influence of the gravitational force " $F_g$ ". The gravitational force can be expressed as the equation below;

$$F_g = mg = \rho_o V_o g \quad (2-40)$$

Due to those conditions specified above of the object, the Reynolds number in the system has small, therefore the flow of liquid remains laminar [44]. Laminar flow is defined as a condition where fluid particles move along in smooth paths in laminar. This material is reserved for educational use only, not allowed for commercial use.

(fluid layers gliding over one another). Where  $\eta$ ,  $r$ ,  $v$ ,  $\rho_o$ ,  $V_o$ , and  $g$  represent the dynamic viscosity of a fluid in kg/m-s unit, the radius of a sphere in meter unit (m), the constant velocity (m/s), the density of the object (kg/m<sup>3</sup>), the volumes of the object (m<sup>3</sup>), and the gravitational constant, respectively.

For another force exerted on an object in upward direction, it is the bouyant force ( $F_b$ ) as is described by the principle of Archimedes [45]. The buoyant force is equal to the weight of the fluid, which equal to the volume of the spherical particle as well. Because all parts of the object immerse in the fluid, the mathematic equation of the bouyant force can be expressed as equation 2-41.

$$F_b = \rho_f * V_o * g = \rho_f \left( \frac{4}{3} \pi r^3 \right) g \quad (2-41)$$

Where  $\rho_f$ ,  $V_o$ , and  $r$  represent the density of the fluid (kg/m<sup>3</sup>), the volumes of the object (m<sup>3</sup>), and the radius of a sphere in meter unit (m), respectively.

When a small stationery spherical particle is released into a viscous liquid, the particle at a constant velocity experiences forces both upward and downward that must be in balance by Newton's 3<sup>rd</sup> law of motion. The Eq. 2-38 can be rewritten as;

$$F_g - F_b - F_d = 0 \quad (2-42)$$

Then, the Eq. 2-42 is substituted all forces acting on a spherical particle falling through the viscous fluid by the Eq. 2-39 to 2-41 as illustrated above. It can be expressed as;

$$\rho_o \left( \frac{4}{3} \pi r^3 \right) g - \rho_f \left( \frac{4}{3} \pi r^3 \right) g - 6\pi\eta r * v_t = 0 \quad (2-43)$$

Therefore, by equating and solving all mathematic forces, the terminal or constant velocity ( $v_t$ ) can be expressed as the equation below.

$$v_t = (\rho_o - \rho_f) \frac{2}{9} \frac{r^2 g}{\eta} \quad (2-44)$$

where  $\rho_o$ ,  $\rho_f$ ,  $r$ , and  $\eta$  represent the object's density, the fluid's density, the radius of the spherical object, and the dynamic viscosity of fluids, respectively. The dynamic viscosity of a fluid can, therefore, be determined by measuring the rate of the terminal velocity of a particle. The factor conversion to obtain the kinematic viscosity can be followed by Eq. 2-45, which is explained in ASTM D445 (Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids, and Calculation of Dynamic Viscosity).

$$\eta = \nu \cdot \rho_f \cdot 10^{-3} \quad (2-45)$$

where  $\eta$  is the dynamic viscosity of a liquid in mPa.s unit,

$\nu$  is the kinematic viscosity of a liquid in mm<sup>2</sup>/s or cSt unit,

$\rho_f$  is the density of a liquid at the same temperature used for the determination of the kinematic viscosity.

By considering a flow of a spherical particle falling through viscous liquids in a microchannel or between parallel plates, there is the force of surface tension to recognize the apparent stress in the surface layer of a liquid. Normally, the surface tension is an energy associated with an interface of liquid-liquid or liquid-air. Because the surface of liquids behaves like a membrane, the liquid surface may form a curvature between small channels, where the liquid drop can look more or less rounded [46]. Therefore, the speed of the liquids at the center is the maximum, and the speed of the liquid gradually decreases until it reaches a minimum at the channel's surface. For this reason, the speed of a particle falling through a liquid contained in a small channel is slower than if it were moving through a liquid contained in a bigger one, because of the surface tension between the liquid and the container.

## Chapter 3

### Research methodology

In this chapter, I deal with the research methodology, materials and relevant equipment used in this thesis. The section of this chapter is divided into two main parts;

1. Development of the optical tweezers (OT) system for trapping of colloidal nanoparticles in suspension.
2. Determination of viscosity of viscous oils by using Mach Zehnder digital holographic method.

All details of research methodologies in each section are explained below.

#### 3.1 Development of the optical tweezers system for trapping of colloidal nanoparticles in suspension

##### 3.1.1 Optical tweezers system under microscope

The optical system that was used to confine or trap the colloidal nanoparticles in suspensions is an optical tweezers or optical trap. At the tightly focused laser beam, the number of nanoparticles can be confined and separated the phase of the particles in suspensions. In this thesis, the experimental process is divided in two sessions. The first section is the optical system set under the florescent confocal microscope with a high numerical aperture objective lens, 100X with N.A 1.3, which can trap the particles easily as the system shown in Fig. 3.1 and the schematic diagram shown in Fig. 3.2.

From the figure as shown below, this system is widely used to trap the particles easily. A 1064 nm Nd:YAG laser (Changchun New Industries Optoelectronics Tech.) with a maximum laser power of 30 mW was used as a trapping beam. It was expanded by the beam expander BE1 and passed to a half-wave plate ( $\lambda/2$ ). The half-wave plate rotated the polarization direction of the 1064 nm laser beam and the intensity of the beam could be varied continuously. The adjusted intensity 1064 nm laser beam reflected at the mirror M1 and passed to the dichroic mirror (DM). At the same time a blue laser beam at 488 nm emitted from an argon ion laser (Showa

Optronics, GLG3135) was allowed to pass through the beam expander BE2 and reflected at the DM. The 1064 nm laser beam could pass through the DM while the 488 nm laser beam reflected at the DM. Both laser beams were reflected at the mirror M2 and collimated by a pair of telescope lenses. The beams were reflected at the mirror M3 to pass into an oil-immersion objective lens (100X, N.A.= 1.3, Olympus) in order to focus tightly the laser beams to obtain a laser beam diameter of 1  $\mu\text{m}$ . The fluorescent colloidal nanoparticles were trapped by the 1064 nm laser beam and excited by the 488 nm laser beam to emit the green fluorescent light in the wavelength of 508 nm. The green fluorescent light of trapped particles was collected by a condensing lens and reflected by a beam splitter BS. It was passed through a filter and recorded by a CCD camera with a resolution of 10 pixels per 1  $\mu\text{m}$ . Then, it was monitored by the software (Olympus, Fluoview FV 1000) and displayed on a computer.

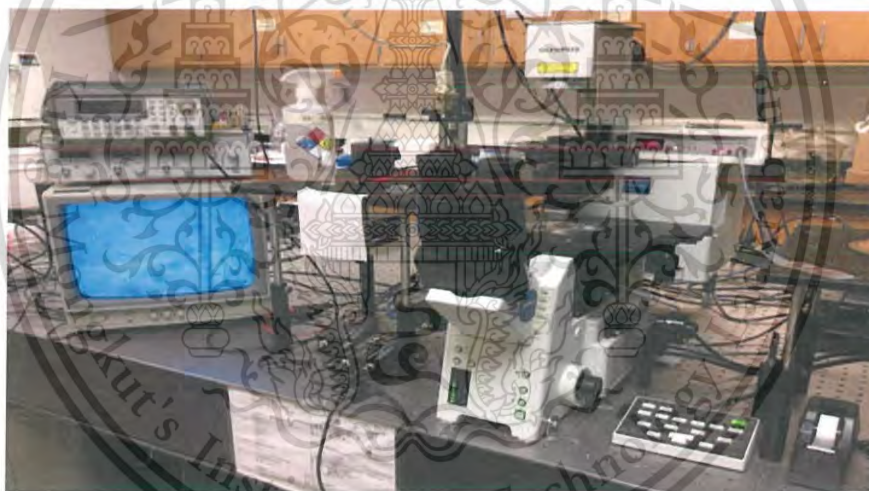


**Fig. 3.1** An optical tweezers system under fluorescent confocal microscope with 100X and 1.3 N.A. objective lens. A 1064 nm IR laser is a trapping laser, while a 488 nm fluorescent blue laser is an excited laser

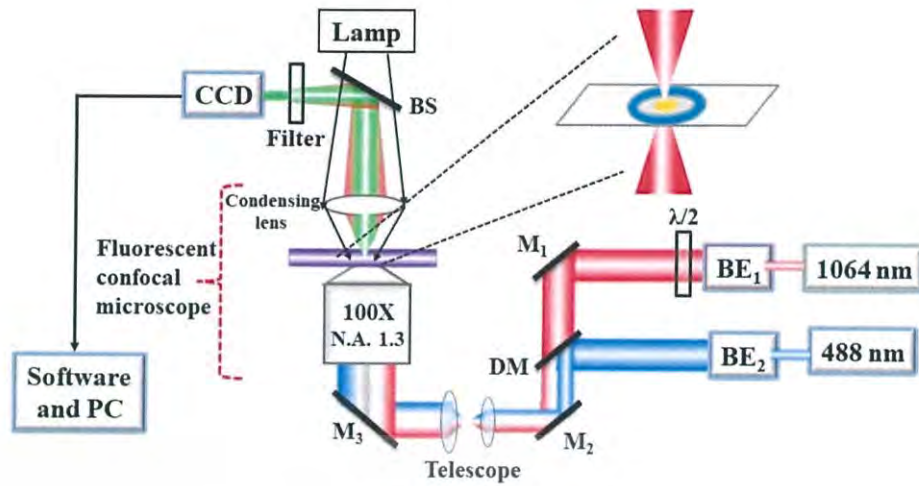


Fig. 3.2 A schematic diagram of the optical tweezers system under fluorescent confocal microscope as shown in Fig.3.1

### 3.1.2 Optical tweezers system without microscope

For the second system, the optical tweezers without any objective lens or microscope was setup to observe trapping of colloidal nanoparticles, which is the main purpose of this part. In the experiment, a new setup for trapping the colloidal particles without confocal microscope in weakly focused laser beam was developed, which is no objective lens. A real setup of this system was shown in Fig. 3.3 and a schematic diagram of the system was illustrated in Fig. 3.4.

A diode pumped-Nd:YAG laser (Laserglow) with a double frequency at a wavelength of 532 nm was used as a light source. The laser light was passed to a variable filter for adjusting the laser intensity. The optical density (OD) numbers of the filter can be varied from 3.0 to 0.08 in order to increase the laser output power from 0.370 to 374.100 mW. The laser output power was measured using a laser power meter with 0.001 resolution (Ophir Photonics, NOVA) connected behind the filter.

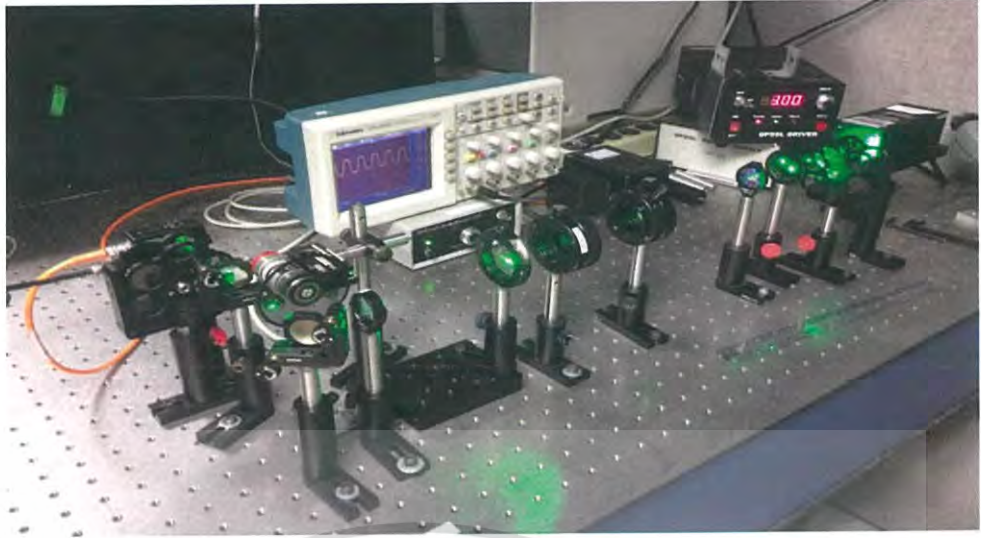


**Fig. 3.3** A setup of the optical tweezers system without microscope. By using 532 nm green laser with the power up to 500 mW

The laser beam with a diameter ( $D_1$ ) of 6 mm passed through a short focal length lens  $L_1$  and expanded to a diameter ( $D_2$ ) of 20 mm by a long focal length lens  $L_2$ . Then, the laser beam was focused by lens  $L_3$  to obtain a beam diameter of 1  $\mu\text{m}$  and passed through the colloidal nanoparticles which filled in a rectangular quartz capillary tube (Vitrocom Technical Glass). The dimension (width  $\times$  length  $\times$  height) of the capillary tube was 0.1  $\times$  2  $\times$  100  $\text{mm}^3$ . It was mounted on the sample stage in the vertical direction in which the side 2  $\times$  100  $\text{mm}^2$  was perpendicular to the laser beam. That is the laser beam passed through the thickness 0.1 mm of colloidal nanoparticles and trapped nanoparticles in the focused area. The transmitted light passed through lens  $L_4$  and chopped by an optical chopper to obtain periodic light signals. The light signal was focused by lens  $L_5$  and detected by an optical detector. The detected light signal was converted into the voltage signal and the signal-to-noise ratio was enhanced by a lock-in amplifier (Stanford Research, SR-830). Finally, the periodic voltage signal was monitored by an oscilloscope (Tektronix, TDS 2024).

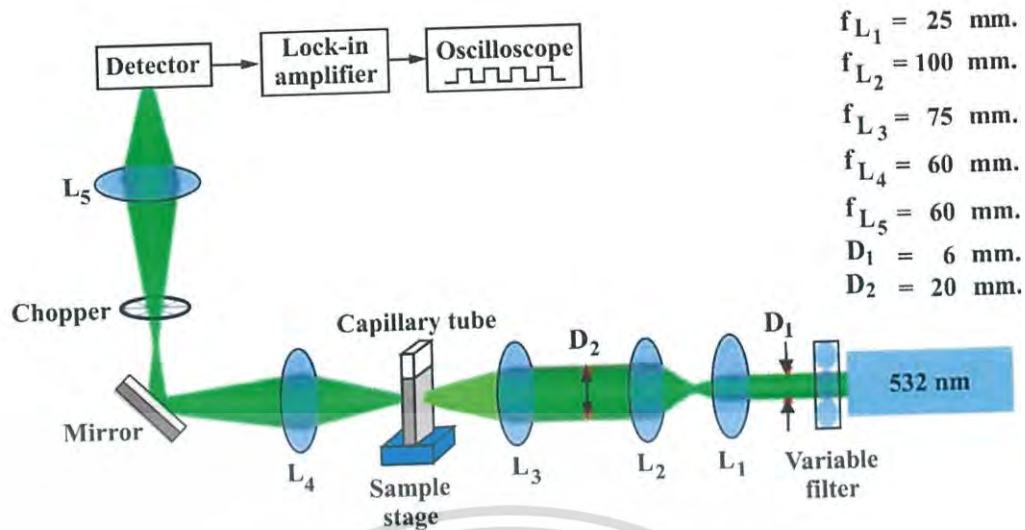


Fig. 3.4 A schematic diagram of the optical tweezers system without microscope as shown in Fig.3.3. The green line represents a trapping laser of 532 nm wavelength

### 3.1.3 Materials and equipment used for trapping nanoparticles

In this section, materials used for preparing the colloidal nanoparticles samples coated by polymers in low potassium chloride (KCl) salt and some important necessary tools are presented below.

#### ➤ Fluorescent polystyrene particles of 200 nm in diameter

The fluorescent microspheres are made of polystyrene and are dyed with green, red or blue fluorescent dyes. The dyes are incorporated into the polymer matrix (not surface dyed). They are packaged in deionized water with trace amounts of surfactant preservative to inhibit aggregation and promote stability. They are packaged as aqueous suspensions at 1% solids by weight. They have a refractive index of 1.59 and a density of  $1.06 \text{ g/cm}^3$ . The particles must be thoroughly dispersed before use. The suspension can be resuspended by gently inverting, rolling or swirling the bottle, followed by a brief (15 second) immersion in a low power ultrasonic bath. The microspheres can be dispensed using the dropper tip or by using a clean pipette. A clean pipette can be used to take samples from the bottle. Shaking the bottle is not recommended, as the product may foam.

**Table 3.1** The spectral properties of 200 nm in diameter fluorescent microsphere suspensions for preparing the samples

| Spectral Properties of Fluorescent Microspheres |                        |                      |                   |
|-------------------------------------------------|------------------------|----------------------|-------------------|
| Specified Color                                 | Excitation Maxima (nm) | Emission Maxima (nm) | Stokes Shift (nm) |
| Green                                           | 468 (blue)             | 508 (green)          | 40                |
| Red                                             | 542 (green)            | 612 (red)            | 70                |
| Blue                                            | 365 (UV)               | 447 (blue)           | 82                |
|                                                 | 388 (UV-violet)        | 447 (blue)           | 59                |
|                                                 | 412 (violet)           | 473 (blue)           | 61                |

➤ *Pluronic polymer*

Pluronic polymer (14 kD, Sigma-Aldrich) at 1% by volume was added in the suspension in order for protecting aggregation between particle-particle surface. It is a kind of an absorbing polymer, which has a short length of its chain. Its structure consists of PEG-PPG-PEG triblock.

➤ *Potassium chloride (KCl)*

Potassium chloride (KCl) with 100 mM and 74.5513 g/mol molecular weight (SigmaUltra, Minimum 99.0%) were added in the suspension to generate the force between the particles moved close each other; however, they are not aggregated by protecting with Pluronics.

➤ *Poly (ethylene glycol) or PEGs*

For increasing more attraction force between nanoparticles and making them to hold each other as well as in the suspension, Poly (ethylene glycol) or PEGs at 10% by volume,  $M_w = 35000$  g/mol, density ( $\rho$ ) =  $1.20$  g/cm<sup>3</sup> (Sigma- Aldrich) were added properly. PEG polymer has a long length of its chain and it is a non-absorbing polymer.



Fig. 3.5 All materials used for preparing the samples of colloidal nanoparticles coated by polymers in low KCl salt

➤ *Dual Neutral Density filter wheel*

A Dual Neutral Density filter wheel was used for varied the laser power. The optical densities of the filter are from 0.04 to 2.5 in 0.1 increments. Each wheel contains 6 different filter positions of 1.0 inch in diameter as presented in Fig .3.6.



Fig. 3.6 Dual Neutral Density filter wheel for changing the laser power

➤ *Rectangular capillary tubes*

The rectangular capillary tubes for containing the prepared colloidal samples were utilized as a chamber. The dimension of the tube is  $2.0 \times 0.1$  mm with the thickness of glass of 0.1 mm and the length is 100 mm as presented in Fig. 3.7.

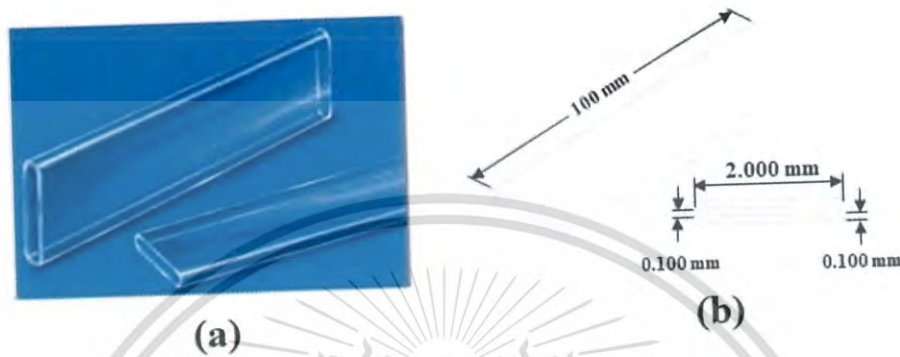


Fig. 3.7 A rectangular capillary tube for containing the colloidal nanoparticles samples with the dimension of  $2.0 \times 0.1$  mm, the thickness of glass of 0.1 mm, and the length of 100 mm

➤ *Oscilloscope*

The oscilloscope, Tektronik; Model: TDS-2024, was used to measure the voltages of the transmitted signal light of trapped nanoparticles in the trapped area under the system without microscope. The result was presented as a periodic signal on the display as presented in Fig. 3.8.

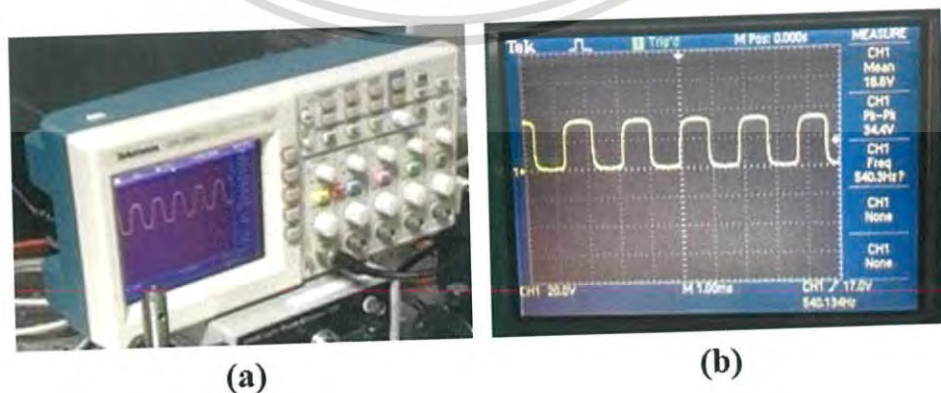


Fig. 3.8 (a) Oscilloscope, Tektronik; Model: TDS-2024 and (b) a periodic signal of trapped colloidal nanoparticles under the system without microscope

### ➤ Optical power meter

The optical power meter was used to detect the power of laser in the process of calibrating the incident power as seen in Fig. 3.9. Its brand is Ophir Photonics; NOVA display-ROHS, P/N; 7201500 and S/N; 690670, with 0.001 resolution.



Fig. 3.9 Optical power meter for detecting the power of laser

### 3.1.4 The preparation of colloidal nanoparticles in suspension

To enhance the number of nanoparticles in the optical trap, the samples have to be prepared by adding polymers with low KCl salt in suspension. The materials and prepared samples are detailed in Table 3.2. The green fluorescence polystyrene particles of 200 nm in diameter with the concentration of 1% by weight and Pluronic polymers with the concentration of 1% by volume were fixed the volume at 50  $\mu\text{L}$  and 12  $\mu\text{L}$ , respectively. Potassium chloride (KCl) salt with 100 mM molecular weight was fixed the volume at 12  $\mu\text{L}$  as well. However, the poly ethylene glycol (PEG) polymer with the concentration of 10% v/v was varied the volume from 10  $\mu\text{L}$  to 60  $\mu\text{L}$ . Then, all parameters were mixed in a plastic microtube in the ratio as shown in the table below.

Table 3.2 Compositions of materials used for preparing nanoparticles samples

| Sample no. | Volume of parameters ( $\mu\text{l}$ ) |                    |               |                | Total volume ( $\mu\text{l}$ ) |
|------------|----------------------------------------|--------------------|---------------|----------------|--------------------------------|
|            | Dyed PS<br>1% w/w                      | Pluronic<br>1% v/v | KCl<br>100 mM | PEG<br>10% v/v |                                |
| 1          | 50                                     | 12                 | 12            | 10             | 84                             |
| 2          | 50                                     | 12                 | 12            | 20             | 94                             |
| 3          | 50                                     | 12                 | 12            | 30             | 104                            |
| 4          | 50                                     | 12                 | 12            | 40             | 114                            |
| 5          | 50                                     | 12                 | 12            | 45             | 119                            |
| 6          | 50                                     | 12                 | 12            | 50             | 124                            |
| 7          | 50                                     | 12                 | 12            | 60             | 134                            |
| 8          | 50                                     | -                  | -             | -              | 50                             |

### 3.1.5 Procedure for trapping colloidal nanoparticles

In order to obtain the purpose for observing the colloidal nanoparticles trapped both systems of under fluorescent confocal microscope and without any microscope, the processes in the research are followed the step below;

1. Prepare samples; the concentrations of all parameters were fixed as 1.0 wt% PS particles, 1.0 v/v% Pluronic, 100 mM KCl, and 10 v/v% PEG, respectively. the volumes of PEGs are varied, but the other parameters are not changed as shown in Table 3.2.
2. The prepared samples must be shaken thoroughly every time to ensure all parameters be compatible as adding Pluronic, KCl, and PEGs, respectively.
3. All samples were prepared immediately prior to use as the suspension may not be stable for long periods of time.
4. The 10  $\mu\text{l}$  of each sample (Sample no. 1-8) was sucked and dropped on a glass slide and cover with a cover glass. It was placed under fluorescent confocal microscope (Olympus, IX-81) in the system as shown in Fig. 3.1.

5. The colloidal particles of samples were trapped at tightly focused IR laser with 30 mW under the optical system with fluorescent confocal microscope (Fig. 3.1).
6. While the nanoparticles in suspension were trapped, the dyed fluorescence coated on the surface of a particle were excited by 488 nm laser and emitted as 508 nm wavelength. The fluorescent green images were illuminated which can observe the trapped particles at the focused laser beam on the monitor.
7. The size of trapped colloidal nanoparticles of those samples was measured and compared.
8. Vary the power of trapping laser (1064 nm IR laser) in the system under fluorescent confocal microscope from 5, 10, 15, 20, 25, and 30 mW, respectively.

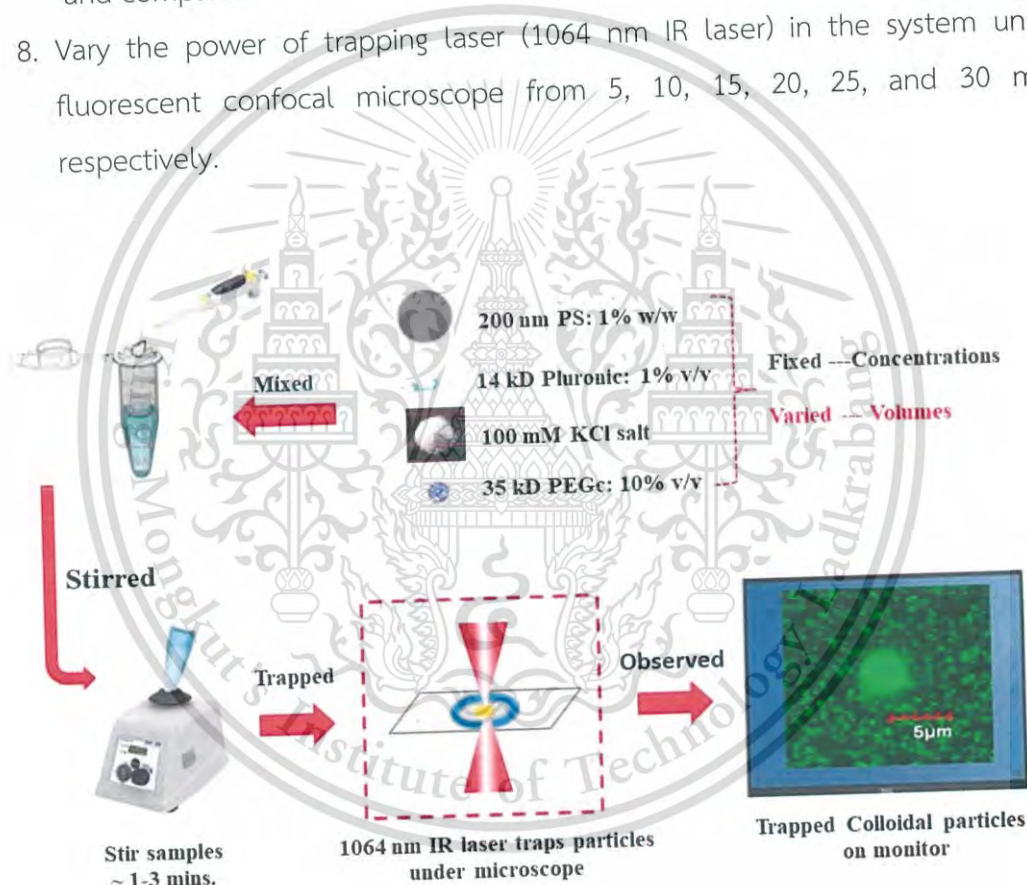


Fig. 3.10 Diagram for trapping colloidal nanoparticles with 1064 nm IR laser under the optical tweezers system as illustrated in Fig. 3.1

9. All prepared samples (Table. 3.2) were brought again to trap in the optical setup without objective lens and microscope (Fig. 3.3).
10. Before trapping the samples, the power of laser was calibrated by changing the OD number of Dual Neutral wheels, both filter no.1 and no.2 as shown the calibrated results below in Table 3.3.
11. The power of laser was detected by using the optical power meter, Ophir Photonics; NOVA display-ROHS, P/N; 7201500 and S/N; 690670, with 0.001 resolution as shown in Fig. 3.9.
12. The optical density (OD) number of filter was changed from 3.0 to 0.08 as detained in Table 3.3 in order to increase the laser intensities or laser power from  $\sim 0.3$  to  $\sim 400$  mW. measured by an optical power meter.
13. The samples were sucked full into the rectangular tube by capillary force, and sealed it with vacuum grease both end sides, then put the tube on the sample's stage.

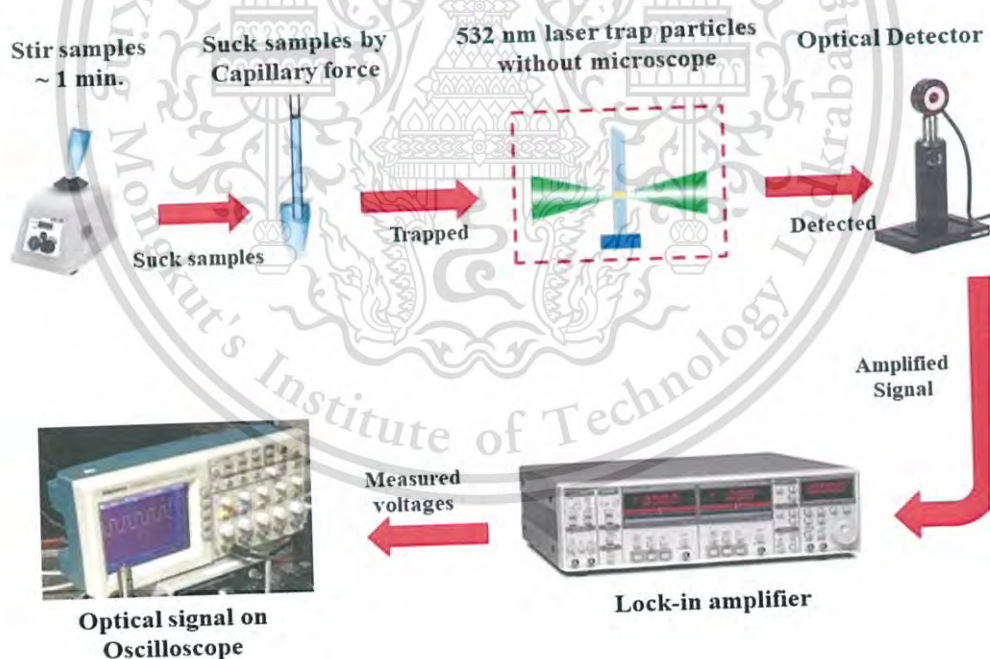


Fig. 3.11 Process diagram for trapping colloidal nanoparticles under the optical tweezers system without microscope and objective lens as illustrated in Fig. 3.3

**Table 3.3** The calibrated power of 532 nm laser by changing the optical density number (OD) of a variable filter

| No. | Optical density number (OD) |             |           | Power (mW) |
|-----|-----------------------------|-------------|-----------|------------|
|     | Filter no.1                 | Filter no.2 | OD. total |            |
| 1   | 2.50                        | 0.50        | 3.00      | 0.370      |
| 2   | 2.50                        | 0.20        | 2.70      | 0.795      |
| 3   | 2.50                        | 0.04        | 2.54      | 0.970      |
| 4   | 2.00                        | 0.50        | 2.50      | 2.347      |
| 5   | 2.00                        | 0.30        | 2.30      | 3.883      |
| 6   | 2.00                        | 0.20        | 2.20      | 4.070      |
| 7   | 2.00                        | 0.04        | 2.04      | 6.255      |
| 8   | 1.50                        | 0.40        | 1.90      | 10.360     |
| 9   | 1.50                        | 0.20        | 1.70      | 13.620     |
| 10  | 1.50                        | 0.04        | 1.54      | 16.820     |
| 11  | 1.00                        | 0.30        | 1.30      | 27.720     |
| 12  | 1.00                        | 0.20        | 1.20      | 36.720     |
| 13  | 1.00                        | 0.04        | 1.04      | 44.890     |
| 14  | 0.50                        | 0.50        | 1.00      | 52.860     |
| 15  | 0.50                        | 0.40        | 0.90      | 87.730     |
| 16  | 0.50                        | 0.20        | 0.70      | 115.700    |
| 17  | 0.50                        | 0.10        | 0.60      | 137.400    |
| 18  | 0.50                        | 0.04        | 0.54      | 142.100    |
| 19  | 0.04                        | 0.40        | 0.44      | 221.900    |
| 20  | 0.04                        | 0.30        | 0.34      | 223.600    |
| 21  | 0.04                        | 0.20        | 0.24      | 297.400    |
| 22  | 0.04                        | 0.10        | 0.14      | 352.200    |
| 23  | 0.04                        | 0.04        | 0.08      | 374.100    |

14. Using the optical chopper, the transmitted light of trapped fluorescent nanoparticles in the optical focused beam are changed into periodic signals. The lock-in amplifier amplified and converted the signals to voltages, which monitored on the oscilloscope as shown in Fig. 3.8.
15. The transmitted voltages of trapped colloidal nanoparticles were recorded by an oscilloscope and all samples were repeated 3 runs at each OD number.
16. A curve of transmitted voltages was plotted against the optical number density (OD) of the variable filter.
17. Nonlinear phase separation of colloidal nanoparticles of prepared samples was investigated in terms of transmitted voltages of the intensities of the laser power.
18. The sample no. 2, 6 and 7 in Table 3.2 were selected to confirm trapping of nanoparticles by using the optical tweezers system without microscope at three different OD numbers at 1.04 (1.09 mW), 0.54 (142.10 mW), and 0.08 (374.10 mW), respectively.
19. The images of the trapped multiple nanoparticles of these samples at the focal area were captured on the screen by using CMOS camera (Cannon, EOS-70D).

The experimental results of all prepared samples trapped under both system of under fluorescent confocal microscope and without any microscope are presented as the green fluorescent images of trapped nanoparticles. The non-linear phase separation of particles is also plotted as a curve. All results in this part will be shown in the section 4.1.

### 3.2 Determination of viscosity of viscous oils by using Mach Zehnder digital holography

In this section, the experiment for observing a spherical iron falling in viscous oils contained in a liquid chamber, the digital holographic system, the materials specification, as well as the procedure in this work were detailed thoroughly.

### 3.2.1 Digital in-line holographic (DIH) system

A real system of the experimental setup is presented in Fig. 3.12 and a schematic diagram is also shown in Fig. 3.13. The Mach Zehnder Digital Holographic (MZDH) system was used to be a methodology for determining the viscosity of viscous oils by observing a spherical iron travelling in different lubricant oils contained in a liquid chamber.

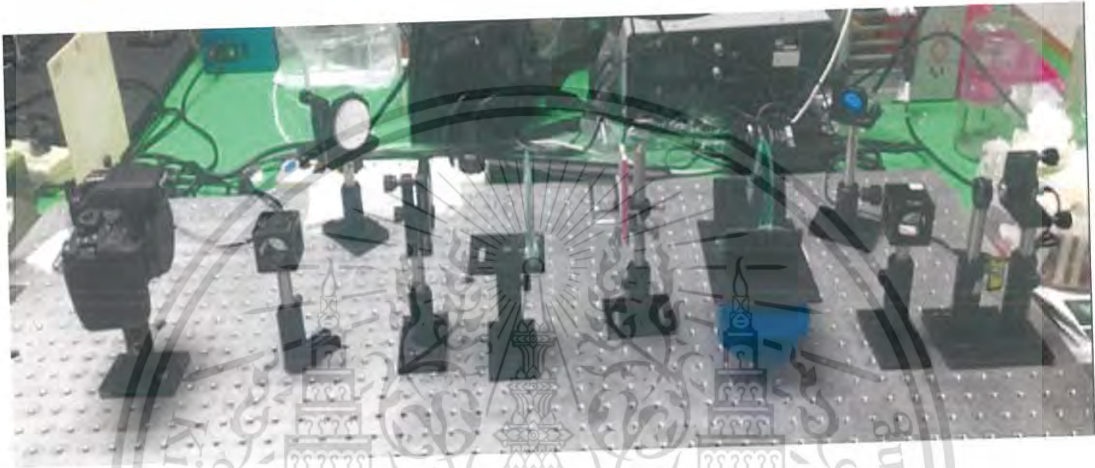


Fig. 3.12 A digital in-line holography (DIH) system based on Mach Zehnder and 635 nm diode laser is a light source

In the MZDH system, the light source was a laser diode with 635 nm wavelength at a power of 1 mW (LDM115G/633/1). A convex lens  $L_1$ ,  $f_1 = 200$  mm, was used to collimate the laser beam that propagates in the z-axis from the light source. Then, the laser beam of about 20 mm in diameter was separated into two identical beams, the reference beam and the object beam, by a beam splitter  $BS_1$ . The reference beam, without any distortion, is reflected at mirror  $M_1$ , while the object beam is reflected at mirror  $M_2$ . The object beam was a short focal length convex lens  $L_2$ ,  $f_2 = 10$  mm, and a long focal length expanded convex lens  $L_3$  and  $L_4$ ,  $f_{3,4} = 200$  mm to cover the whole volume of liquid chamber. Then, the transmitted beam passed through the object was collimated again by concave lens  $L_5$ ,  $f_5 = -200$  mm to generate the parallel beam. Finally, the two beams were recombined at the beam splitter  $BS_2$ , and the hologram patterns were recorded on the CMOS camera (Canon EOS 700D, Japan,  $5184 \times 3456$  pixels,  $4.29 \mu\text{m}$ . pixel pitch). The numerically

reconstructed distance ( $R$ ) based on the Huygens-Fresnel principle was found to be 400 mm.

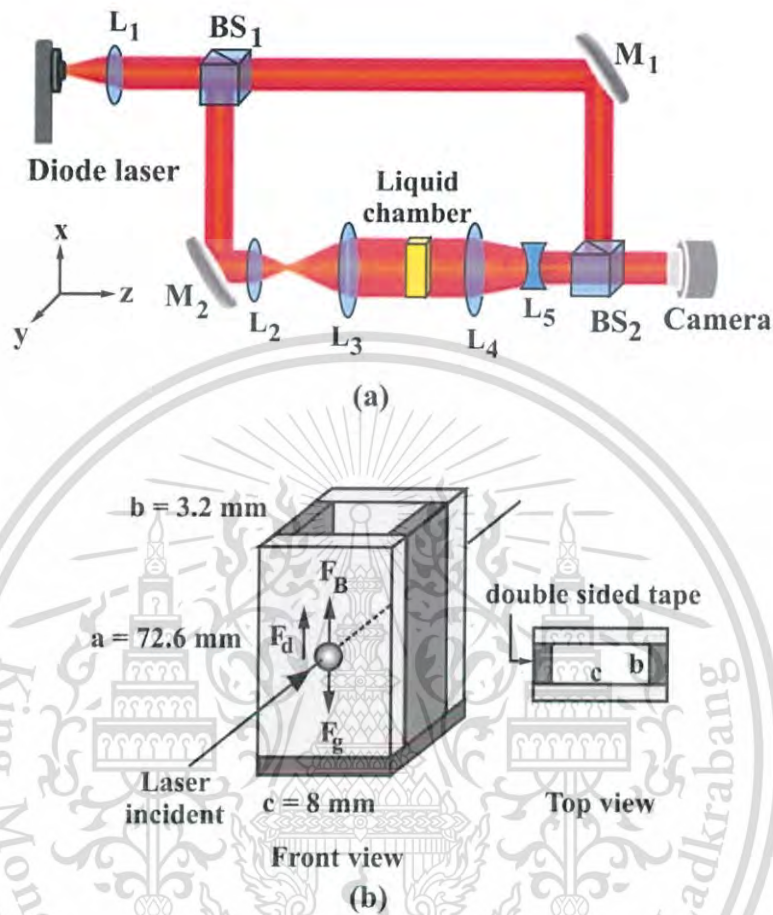


Fig. 3.13 (a) Schematic diagram of digital in-line holographic setup (DIH) based on Mach Zehnder interferometer and (b) the forces acting on the object moving in the viscous liquid contained in a liquid chamber

### 3.2.2 Materials and liquid chamber preparation

This section is provided all materials and equipment used for determination of viscosity of viscous oils. The important materials consist of spherical irons, liquid chamber and viscous oils for testing. For other equipment such as a plastic dropper, a tweezers, beakers, tissues, ethanol and etc., they are not shown here.

➤ *Stock of spherical irons*

Three spherical irons were selected from the stock to be testing particles. Each one has a diameter of about 1.50 mm and a density of  $7.00 \text{ g/cm}^3$ . The particle size was measured by a digital Vernier caliper (STAINLESS HARDENED Brand) with 0.01 mm resolution. The average diameter of the iron was found to be  $1.50 \pm 0.02 \text{ mm}$ .

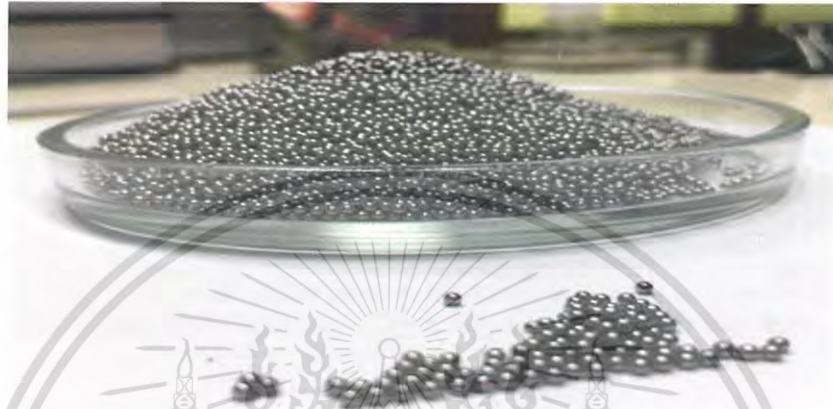


Fig. 3.14 Stock of spherical irons about 1.5 mm in diameter

➤ *A liquid chamber*

A liquid chamber was prepared by using two glass slides, each one of glass slides having a dimension (length x width x thickness) of  $76.2 \times 25.4 \times 1.5 \text{ mm}^3$  (SAIL, No. 7101). They were attached with two layers of double sided tape foam with 3.2 mm thick (3M, 4026 Natural PUR Foam) between the slides and sealed at the bottom by hot melted adhesion glue. Fig. 3.13(b) shows the diagram of liquid chamber with a volume ( $a \times b \times c$ ) of  $72.6 \times 3.2 \times 8 \text{ mm}^3$ .

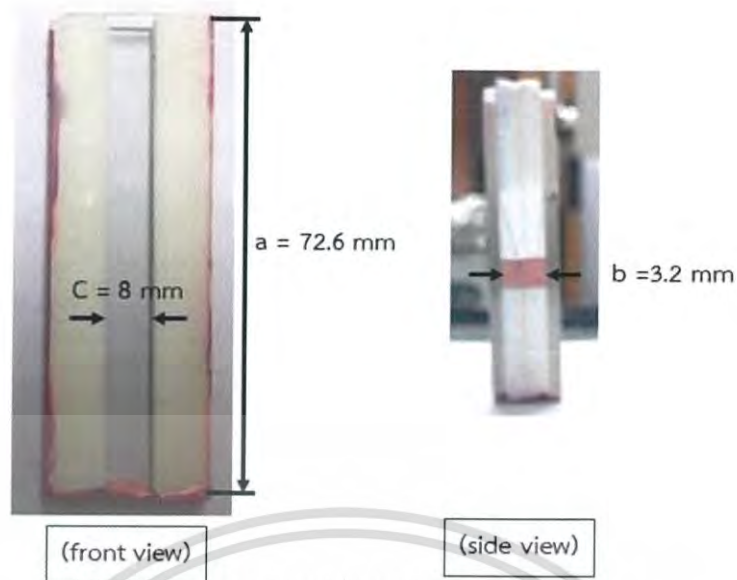


Fig. 3.15 A prepared liquid chamber for containing the viscous oils

➤ *Viscous oils*

Viscous oils used in this study were supplied by the Goods and Exhibit Analysis Office, Excise Department of Thailand. The properties and the characteristics of each oil are given in Table 3.4 and Fig. 3.16, respectively. The values of density ( $\rho_f$ ) at 15°C and the kinematic viscosity ( $\nu$ ) at 40°C were obtained from ASTM D1298 and ASTM D445, respectively.

Table 3.4 The important properties of the viscous oils

| Oils                             | Properties of oils                     |                       |
|----------------------------------|----------------------------------------|-----------------------|
|                                  | $\rho_f$ @15°C<br>(g/cm <sup>3</sup> ) | $\nu$ @40°C<br>(cSt.) |
| Lubricant, (ZE-PRO32)            | 0.87154                                | 27.849                |
| Transformer, (FR-3)              | 0.92478                                | 52.050                |
| Gasoline Engine                  | 0.87398                                | 57.181                |
| Cold Lubricant, (SUNICE SL-32D1) | 0.95870                                | 70.428                |

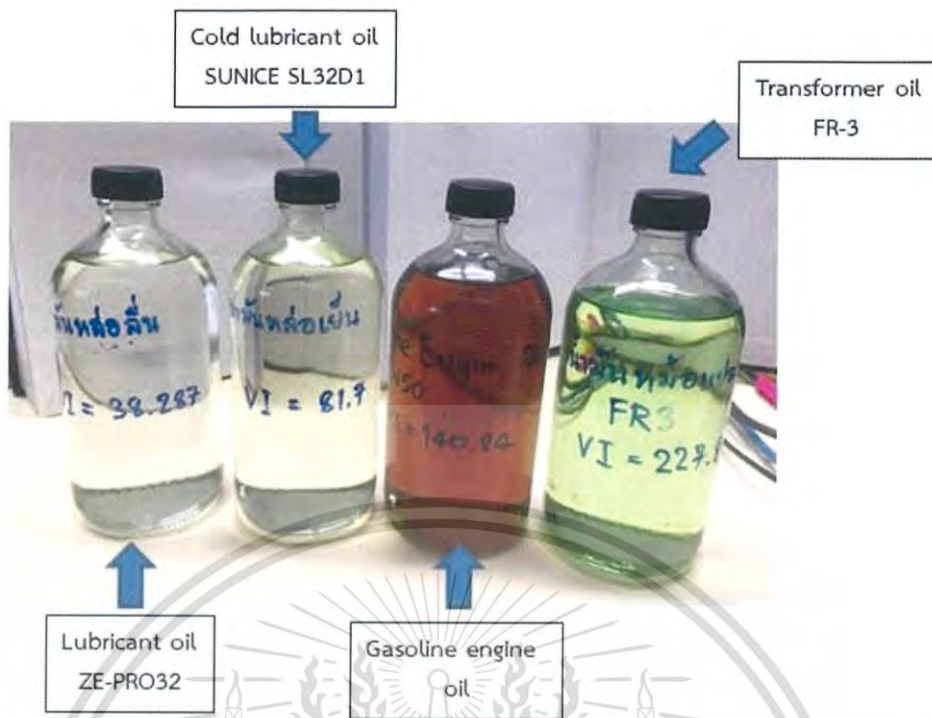


Fig. 3.16 The characteristics of viscous oils. From the left to the right; Lubricant oil (ZE-PRO32), Cold lubricant oil (SUNICE SL32D1), Gasoline engine oil, and Transformer oil (FR-3)

### 3.2.3 The procedure for determination of viscous oils by DIH method

For the last section in this chapter, the procedure for observing the dynamic of a spherical iron particle falling in viscous oils contained in a liquid chamber were detailed below;

1. Set up the digital in-line holography based on Mach Zehnder system as shown in Fig. 3.12 and the diagram of the system in Fig. 3.13.
2. Fill the lubricant oil (ZE-PRO 32) almost full in the 8 mm widths of a liquid chamber by a plastic dropper and mount it on the sample stage in the object beam of the system.
3. Wipe the outer surface of a liquid chamber by ethanol and ensure it is dry and clean for the laser light pass through clearly along path the chamber.

4. Release the first iron particle by a tweezers into the lubricant oil that contained in the liquid chamber already, at the same time records the falling of the particle as a video file by using a CMOS camera (Cannon, EOS 70D).
5. Release the second and the third spherical irons in the lubricant oil and record the video file again for falling of the second and the third particles in the lubricant oil, respectively.
6. Change a new liquid chamber and repeat step no. 2-5 for the other oils; Transformer oil, Gasoline engine oil, and Cold lubricant oil, respectively.
7. Cut images from the recorded videos of all three ions falling in every testing oils. The images were captured at 10, 20, 30, 40, 50, 60 mm of the position along the liquid chamber path from the top to the bottom.
8. Record the falling times ( $t$ ) at every captured position of each iron and repeat the same process for the other testing oils.
9. Take all captured images to reconstruct the hologram images, then the diameter of the spherical irons ( $D$ ) and the position of the iron falling through the oils are measured accurately at high resolution by using the holoviewer program via MATLAB.

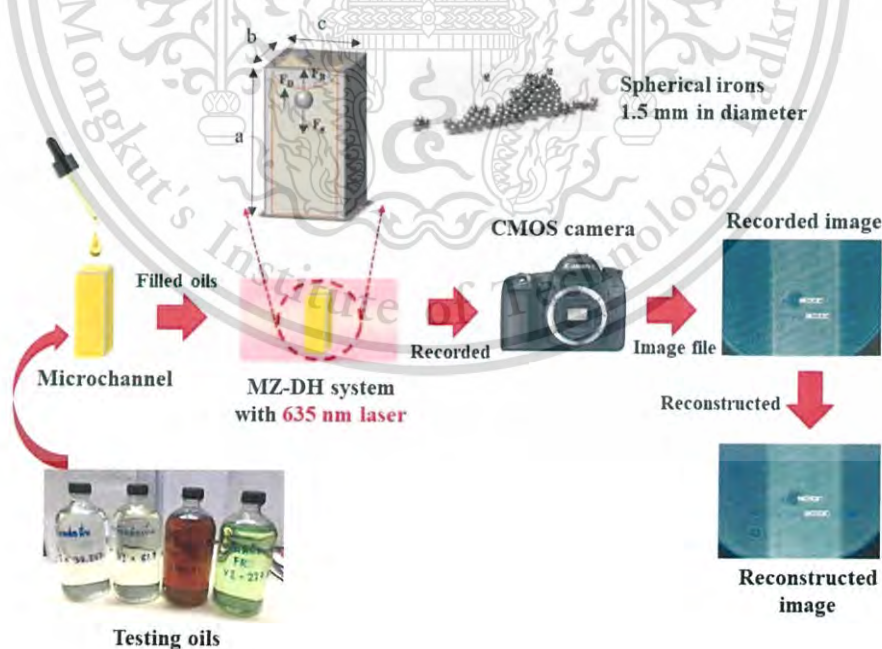


Fig. 3.17 Diagram of procedure for determination of viscous oils by using DIH method

10. The velocity of the irons falling in all testing oils is calculated by using the relationship between the position (P) and the falling time (t),  $v = P/t$ .
11. Plot curve between the velocity (v) of three ions falling in all testing oils in y-axis and the measured position (P) in x-axis by using the origin program, then using linear function to fit the curve in order for observing the trend of the iron velocity along the liquid chamber path.
12. Assumed that the slope of the curve from step no. 11 tends to be linear, then the terminal velocity ( $v_t$ ) can be obtained from the average velocity from every position.
13. Average the diameter of spherical irons measured in step no.9 to find out the radius (r) of each spherical iron.
14. Take all parameters to determine the dynamic viscosities ( $\eta$ , kg/m.s) by using the equation 2-33 as described in Chapter 2. Then, convert the unit of  $\eta$  from kg/m.s to mPa.s;  $1 \text{ kg/m.s} = 1000 \text{ mPa.s}$ .
15. Find out the kinematic viscosities ( $\nu$ , cSt = mm<sup>2</sup>/s) by following the standard of ASTM D445,  $\eta = \rho_f * \nu * 10^{-3}$ .
16. Plot curve between  $v_t$  (mm/s) of all irons against the standard kinematic viscosities ( $\nu$ , cSt) of all testing oils to observe the trend of aspherical iron velocity in different viscosities of oils.
17. Compare the kinematic viscosity of experimental results and the standard values (followed by ASTM D445) on a curve, also find out the percentage error of  $\nu$ .

**Note;** The ambient temperature in our experiments is about 25°C (Room temperature). Therefore, the oils' temperature in the experiments is assumed the same as ambient temperature.

The experimental results of a spherical iron falling in four different viscous oils contained in a liquid chamber are presented as the hologram images. The terminal velocities of the spherical irons are plotted as a curve versus the measured positions of a liquid chamber. The dynamic and kinematic viscosities of oils are also computed and compared. All results in this part will be shown and discussed in section 4.2.

For the next chapter, all experimental results of this thesis will be reported and discussed, respectively.

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

## Chapter 4

# Experimental Results and Discussion

All experimental results of my thesis are presented in this chapter and discussion about the results is also given. The details are divided into two main parts. The first part gives the results of trapping colloidal nanoparticles by using optical tweezers technique. For the second part, determination of viscosity of viscous oils evaluated by observing the motion of a spherical iron particle are shown. The experimental results of both parts are presented as images, data and also plotted on a curve as following below.

### 4.1 Trapping colloidal nanoparticles by optical tweezers

After getting the samples of the colloidal nanoparticles as detailed in Table 3.2, the first thing we would like to observe is the interactions of colloidal nanoparticles of all samples caused by adding parameters in the suspensions, especially varying the volumes of 10 % v/v Poly (ethylene glycol) (PEG). In this section, I divided the experimental results into two sub-section both trapping samples under fluorescent confocal microscope and without any microscope.

#### 4.1.1 Trapping colloidal nanoparticles under microscope

The 10  $\mu\text{l}$  of each prepared sample as detailed in Table 3.2 (Sample no.1-8) were sucked by a small pipette to drop on a glass slide mouthed on the sample stage under confocal fluorescent microscope (Olympus, IX-81) and covered by a cover glass. Then, they were trapped by a 1064 nm ND:YAG IR laser with 30 mW at the focal point focused by the 100X objective lens (Fig. 3.1). Under this system, the trapped nanoparticles were observed by eyepiece of the microscope. The fluorescent signal of the trapped nanoparticles was amplified by a photo multiplier tube (PMT) and the fluorescent images were recorded by CCD camera at the resolution of 10 pixels per 1  $\mu\text{m}$  as illustrated in Fig. 4.1(a)-(h). From the images, the bright green color is the colloidal nanoparticles suspended in the aqueous solution, which excited by 488 nm blue laser and emitted as 508 nm wavelength. At the trapping area, it is the multiple trapped nanoparticles confined simultaneously.

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

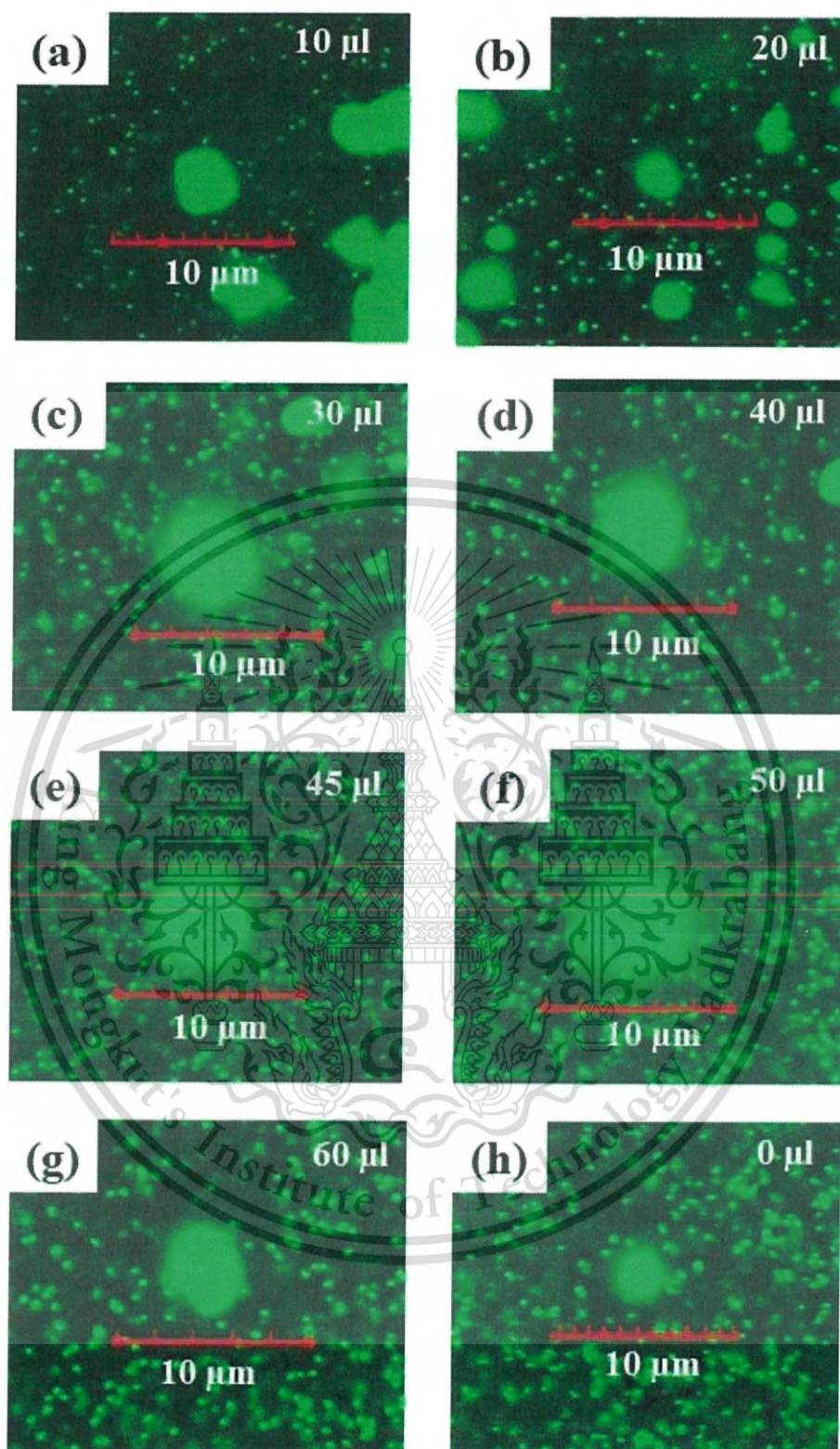


Fig. 4.1 Fluorescent images of colloidal nanoparticles in suspension trapped by a laser power of 30 mW at 1064 nm for different PEG contents of: (a) 10, (b) 20, (c) 30, (d) 40, (e) 45, (f) 50, (g) 60  $\mu\text{l}$ , and (h) without PEG

Fig. 4.1(a)–(d) corresponds to the PEG contents of 10, 20, 30, and 40  $\mu\text{l}$ , respectively. It is seen that many big bright green lumps are observed indicating that the colloidal nanoparticles still aggregate itself in the unstable solution. Therefore, the particles cannot be confined steadily at the trapping area. When the PEG was added up to 45 and 50  $\mu\text{l}$  (Sample no. 5 and 6), the particles were confined easily at the same time in a trap, and the solution is stable, since there is no aggregation between particle-particle as shown in Fig. 4.1(e)–(f). A big group of trapped nanoparticles at the center was observed due to the high intensity of trapping laser, and large attractive force between particles as previously described. However, for solution added with 60  $\mu\text{l}$  PEG (Sample no. 7) and the solution without an addition of PEG (Sample no. 8), the solution is stable, the amount of the colloidal nanoparticles in the trapping area decreased. It results in the decrease of trapped particles as seen in Fig. 4.1(g)–(h). To confirm the results, as shown in Fig. 4.1, the experiments for each sample were repeated for 10 times at the laser power of 30 mW. It was found that similar results were obtained. The diameter of bright green circle in Fig. 4.1(f) was determined using ImageJ program and repeated for 5 times. Then, the average diameter of trapped particles was determined and found to be  $5.89 \pm 0.26 \mu\text{m}$ .

It is seen from Fig. 4.1 that the sample no.6 (Fig. 4.1 (f)) with a PEG content of 50  $\mu\text{l}$  shows the best laser trapping with a laser power of 30 mW. Therefore, further experiments were carried out for different laser powers of 5, 10, 15, 20, 25, and 30 mW in order to observe the behavior of particles, which the power of trapping laser was varied. As shown in the Fig. 4.2 and 4.3, the first row of the figure is two dimensions of trapped nanoparticles and the second row presents the three dimensions of each image on the left plotted by using the Fluoview software, which is installed in the system. The fluorescent images of colloidal nanoparticles in the suspension (Sample no.6) trapped by laser at different laser powers of 5, 10, 15, 20, 25, and 30 mW were presented respectively from Fig 4.2(a)–(c) and Fig. 4.3 (d)–(f). It is clearly observed that at a high laser power of 25 mW and higher, more trapping of colloidal nanoparticles. Hence, it can be concluded that the diameter of trapped particles at the center increases with increasing the laser power.

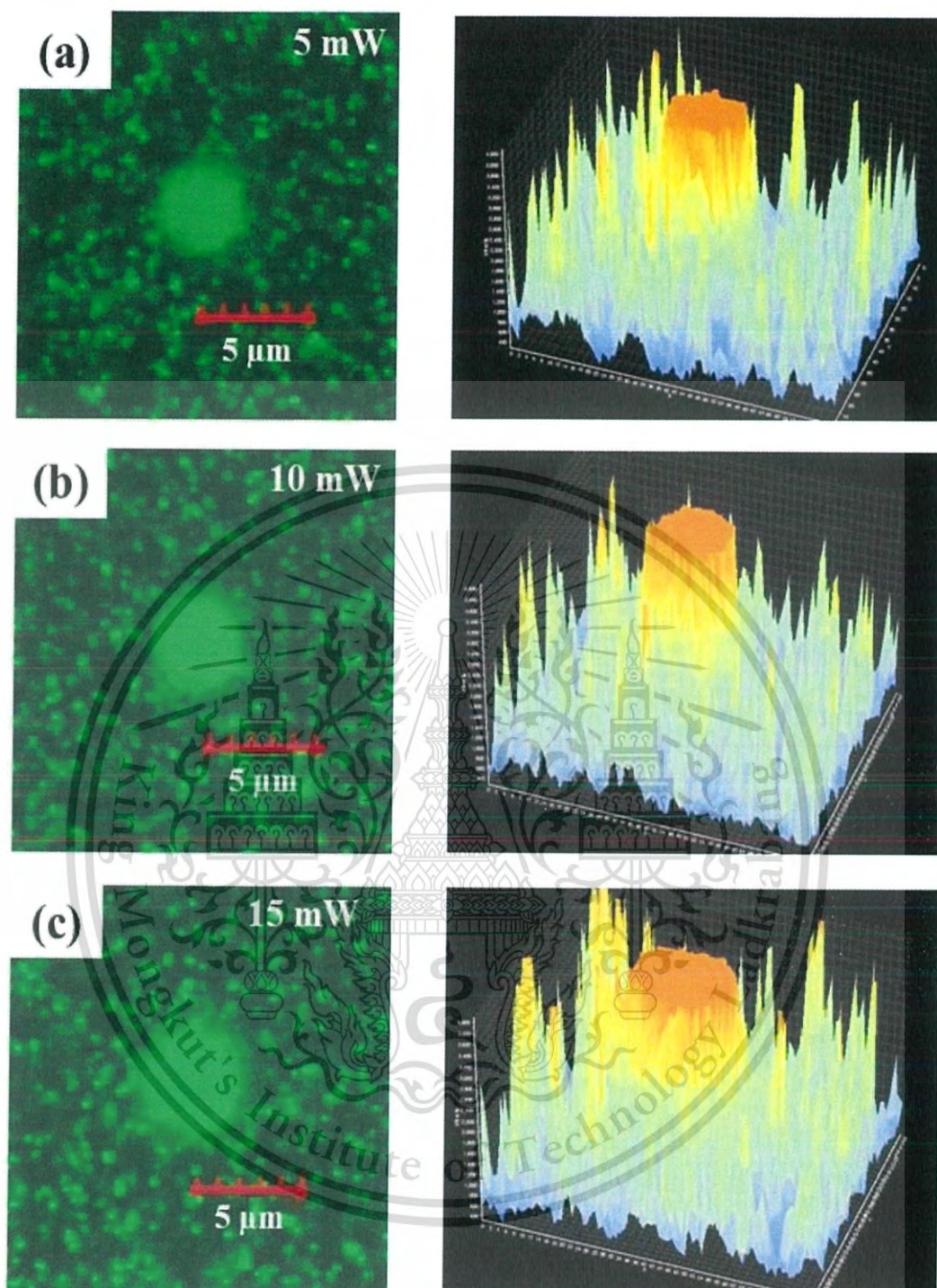


Fig. 4.2 Fluorescent images of colloidal nanoparticles in suspension (Sample no.6) trapped by 1064 nm IR laser at different laser powers of: (a) 5, (b) 10, and (c) 15 mW

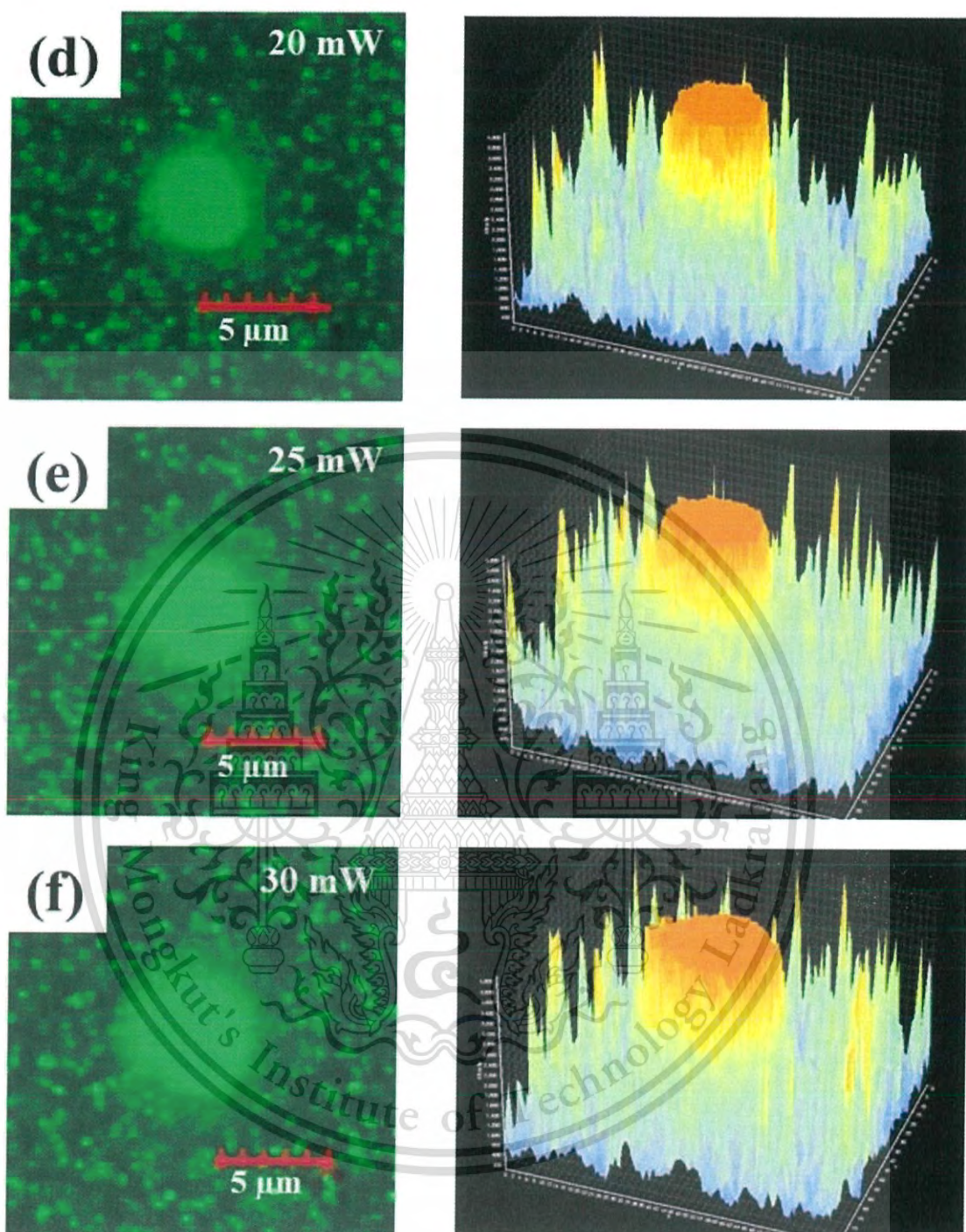


Fig. 4.3 Fluorescent images of colloidal nanoparticles in the suspension (Sample no.6) trapped by 1064 nm IR laser at different laser powers of: (d) 20, (e) 25, and (f) 30 mW

#### 4.1.2 Trapping colloidal nanoparticles without microscope

As referred to the experimental setup in Fig. 3.3, the colloidal nanoparticles of each sample in Table 3.2 was used to trap by 532 nm Nd:YAG laser. The laser output power was varied by a variable filter with optical density (OD) numbers from 3.0 to 0.08 corresponding to the laser output powers from 0.370 to 374.100 mW as presented in Table 3.3. The transmitted light was finally converted into the voltage signal and measured by an oscilloscope. All samples were performed for 3 runs at different laser power, and the transmitted voltages of all were averaged, then collected as presented in Table 4.1 to 4.2.

Then, all experimental results in Table 4.2 and 4.3 were summarized to plot a curve of  $\ln[\text{Transmitted light}]$  (V) versus increasing of the optical density number (OD) or decreasing of laser power as shown in Fig. 4.5. In this curve, it can be obtained the aim of my research for investigating nonlinear phase separation of colloidal nanoparticles in an optical confinement. For sample no.7 and 8 (Added 60  $\mu\text{l}$  PEG and No PEG, respectively), the curve is linear the whole line from low to high of power compared with calibrated water line (Blue cycle dot). On the other hand, for low PEG volumes added (Sample No.1 – 5) the curve is nonlinear. These curves are linear at low intensity of laser (High OD number more than 1.0); however, they trend to be bent after less than 1.0 OD or about more than 30 mW. Even though they can be seen the nonlinear curve of samples added low PEG at high power, the trend of these curves is not stable because colloidal particles of these samples are aggregated solution observed under fluorescent confocal microscope as seen above in Fig. 4.1(a)-(d). The big cluster compared with a PS particle's size (200 nm in diameter) in suspension is easy to be trapped and also easy to lose away from focal point. For another reason, it is due to the weak intensity at the focal point of the optical system affected to confine multiple colloidal particles hardly. As the sample no.6 (50  $\mu\text{l}$  PEG added), the solution is stable as seen in Fig. 4.1(f) observed under confocal fluorescent microscope. Because of this reason, the particles are easy to be trapped in the optical focal area and the size of trapped colloidal nanoparticles is stable, not lose out after trapped at high intensity power.

**Table 4.1** The transmitted voltages of trapped nanoparticles under the optical system without microscope (Fig. 3.3) of water and sample no. 1 to no. 4

| no. | OD.<br>number | Power<br>(mW) | Transmitted voltages of trapped particles (V) |           |           |           |           |
|-----|---------------|---------------|-----------------------------------------------|-----------|-----------|-----------|-----------|
|     |               |               | water                                         | no.1      | no.2      | no.3      | no.4      |
|     |               |               | -                                             | 10 ul PEG | 20 ul PEG | 30 ul PEG | 40 ul PEG |
| 1   | 3.00          | 0.370         | 0.186                                         | 0.160     | 0.133     | 0.147     | 0.141     |
| 2   | 2.70          | 0.795         | 0.236                                         | 0.170     | 0.176     | 0.178     | 0.179     |
| 3   | 2.54          | 0.970         | 0.264                                         | 0.186     | 0.189     | 0.174     | 0.166     |
| 4   | 2.50          | 2.347         | 0.462                                         | 0.301     | 0.227     | 0.258     | 0.259     |
| 5   | 2.30          | 3.883         | 0.696                                         | 0.405     | 0.311     | 0.342     | 0.359     |
| 6   | 2.20          | 4.070         | 0.899                                         | 0.505     | 0.375     | 0.427     | 0.439     |
| 7   | 2.04          | 6.255         | 1.070                                         | 0.587     | 0.450     | 0.495     | 0.508     |
| 8   | 1.90          | 10.360        | 1.773                                         | 0.943     | 0.713     | 0.807     | 0.812     |
| 9   | 1.70          | 13.620        | 2.343                                         | 1.217     | 0.977     | 1.029     | 1.061     |
| 10  | 1.54          | 16.820        | 3.157                                         | 1.349     | 1.169     | 1.249     | 1.344     |
| 11  | 1.30          | 27.720        | 5.147                                         | 1.927     | 1.987     | 2.013     | 2.141     |
| 12  | 1.20          | 36.720        | 6.730                                         | 2.102     | 2.568     | 2.486     | 2.891     |
| 13  | 1.04          | 44.890        | 8.047                                         | 2.213     | 2.578     | 2.998     | 3.729     |
| 14  | 1.00          | 52.860        | 9.277                                         | 2.241     | 2.640     | 3.619     | 4.174     |
| 15  | 0.90          | 87.730        | 14.300                                        | 2.449     | 4.160     | 4.296     | 5.943     |
| 16  | 0.70          | 115.700       | 19.167                                        | 2.112     | 4.380     | 3.993     | 6.223     |
| 17  | 0.60          | 137.400       | 22.433                                        | 1.886     | 4.460     | 4.328     | 6.671     |
| 18  | 0.54          | 142.100       | 22.833                                        | 1.823     | 3.564     | 4.048     | 5.620     |
| 19  | 0.44          | 221.900       | 34.067                                        | 2.883     | 5.547     | 6.046     | 6.438     |
| 20  | 0.34          | 223.600       | 34.067                                        | 2.953     | 5.166     | 6.451     | 6.500     |
| 21  | 0.24          | 297.400       | 43.767                                        | 3.991     | 6.074     | 8.023     | 7.460     |
| 22  | 0.14          | 352.200       | 50.000                                        | 5.713     | 6.129     | 8.653     | 6.933     |
| 23  | 0.08          | 374.100       | 51.267                                        | 5.996     | 6.720     | 7.537     | 7.654     |

**Table 4.2** The transmitted voltages of trapped nanoparticles under the optical system without microscope (Fig. 3.3) of sample no. 5 to no. 8

| no. | OD.<br>number | Power<br>(mW) | Transmitted voltages of trapped particles (V) |           |           |        |
|-----|---------------|---------------|-----------------------------------------------|-----------|-----------|--------|
|     |               |               | no.5                                          | no.6      | no.7      | no.8   |
|     |               |               | 45 ul PEG                                     | 50 ul PEG | 60 ul PEG | No PEG |
| 1   | 3.00          | 0.370         | 0.146                                         | 0.141     | 0.180     | 0.159  |
| 2   | 2.70          | 0.795         | 0.186                                         | 0.168     | 0.185     | 0.168  |
| 3   | 2.54          | 0.970         | 0.164                                         | 0.182     | 0.219     | 0.181  |
| 4   | 2.50          | 2.347         | 0.246                                         | 0.400     | 0.358     | 0.283  |
| 5   | 2.30          | 3.883         | 0.334                                         | 0.592     | 0.520     | 0.396  |
| 6   | 2.20          | 4.070         | 0.406                                         | 0.756     | 0.655     | 0.493  |
| 7   | 2.04          | 6.255         | 0.487                                         | 0.908     | 0.778     | 0.578  |
| 8   | 1.90          | 10.360        | 0.755                                         | 1.122     | 1.289     | 0.967  |
| 9   | 1.70          | 13.620        | 0.955                                         | 1.398     | 1.622     | 1.268  |
| 10  | 1.54          | 16.820        | 1.098                                         | 1.770     | 1.914     | 1.517  |
| 11  | 1.30          | 27.720        | 1.868                                         | 2.787     | 3.406     | 2.492  |
| 12  | 1.20          | 36.720        | 2.509                                         | 4.187     | 4.490     | 3.744  |
| 13  | 1.04          | 44.890        | 2.929                                         | 4.247     | 5.549     | 4.490  |
| 14  | 1.00          | 52.860        | 3.199                                         | 4.307     | 6.329     | 5.043  |
| 15  | 0.90          | 87.730        | 4.641                                         | 4.448     | 10.260    | 7.942  |
| 16  | 0.70          | 115.700       | 4.444                                         | 4.369     | 13.622    | 10.379 |
| 17  | 0.60          | 137.400       | 3.783                                         | 3.811     | 15.656    | 12.244 |
| 18  | 0.54          | 142.100       | 3.222                                         | 3.378     | 17.122    | 12.444 |
| 19  | 0.44          | 221.900       | 3.721                                         | 3.496     | 24.667    | 18.456 |
| 20  | 0.34          | 223.600       | 3.567                                         | 3.478     | 23.567    | 18.456 |
| 21  | 0.24          | 297.400       | 3.591                                         | 3.026     | 28.000    | 24.356 |
| 22  | 0.14          | 352.200       | 4.197                                         | 2.939     | 30.678    | 28.267 |
| 23  | 0.08          | 374.100       | 4.268                                         | 2.822     | 29.956    | 28.700 |

Therefore, it can be concluded from the curve in Fig. 4.5 that the sample no.6, added 60  $\mu\text{l}$  PEG in suspension, is the best sample to be trapped the colloidal nanoparticles under the weak intensity at focused laser beam. However, it still requires the high intensity of laser power more than 30 mW (Less than 1.0 OD number of filter) to be used.

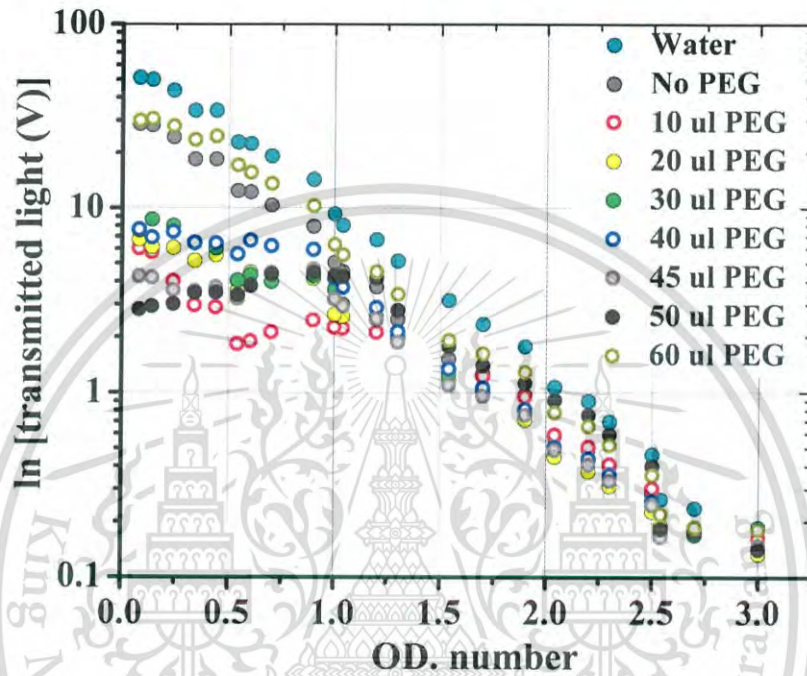


Fig. 4.4  $\ln$  [Transmitted light] in voltage unit determined phase separation of colloidal nanoparticles suspension as a function of optical density number (OD) of filter or changed power of trapping laser

Moreover, to confirm the experimental results of trapped colloidal nanoparticles of all samples as shown in the curve, the images of trapped colloidal nanoparticles under the system without microscope were captured. In the system as shown in Fig.3.3, the mirror was removed out and placed a screen to observe the incident light on it. A CMOS camera (Cannon, EOS-70D) was used to take the images of trapped colloidal nanoparticles of sample No. 2, 6, and 7 at three different OD number (1.04 OD, 0.54 OD, and 0.08 OD, respectively) as illustrated in Fig. 4.5.

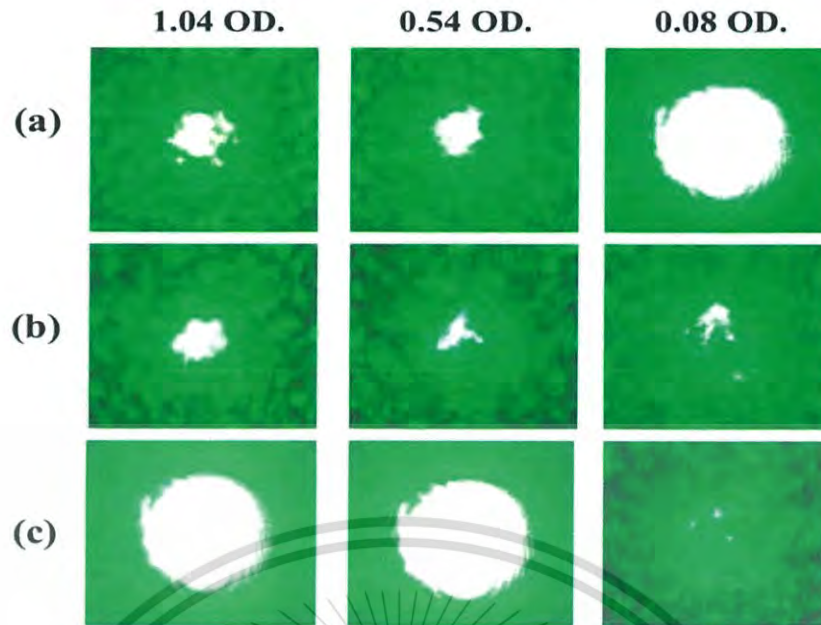


**Fig. 4.5** (a) – (c) the trapped nanoparticles images of the sample no.2, 6, and 7 at three OD number of filter; 1.04 (1.09 mW.), 0.54 (142.10 mW.), and 0.08 (374.10 mW.), respectively. The colloidal nanoparticles were confined in an optical focal region of 532 nm green laser without microscope

As seen in Fig. 4.5, the bright white area in the middle of each image represents the focused beam of trapping laser, and the green region represents the amounts of nanoparticles in suspension. In Fig. 4.5(a) under low PEG volume added (20 ul PEG), the nanoparticles move gradually into the focal point. They can be observed from the green area at the center on the first row (0.08 OD, 374.10 mW) at the highest intensity of laser. However, they still have a small bright part for low intensity power on the second and third rows (1.04OD; 1.09 mW and 0.54 OD; 142.10 mW). For sample no.7, only PS particles, the colloidal nanoparticles cannot be trapped in the focused beam as all of laser power shown in Fig 4.5(c). Lastly in Fig 4.5(b), it can be observed clearly that the green color cover almost area in the center for all images, especially at the highest laser intensity (0.08 OD, 374.10 mW). This result can be implied that the particles are easy trapped to be in the focal point and blocked the laser light, which cannot emit through the trapped particles. Because of that reason, we can observe distinctly the nonlinear phase separation of

colloidal nanoparticles in an optical confinement of the samples added 45  $\mu\text{L}$  - 50  $\mu\text{L}$  of 10%v/v PEG in the mixtures, especially at high laser intensity (More than 30 mW).

The results obtained by this system is in good agreement with those of fluorescent confocal microscope system. However, the second system as proposed in this work is much more convenient to be used as optical tweezers in observing the trapping colloidal nanoparticles.

## 4.2 Determination of viscosity of lubricant oils by using Mach Zehnder digital holography

The experimental results of a spherical iron particle falling in different lubricant oils contained in a liquid chamber tracked by MZDIH system are displayed. In this section, there are three main parts are provided such as diameter measurement of spherical iron, determination of spherical iron velocity, and determination of viscosity of the oils as following below.

### 4.2.1 Diameter measurement of spherical irons

Among four viscous oils used in this work, the lubricant oil (ZE-PRO32) is transparent. Therefore, it was used for the diameter measurement of spherical irons. It was filled in the liquid chamber which placed in the object arm of the interferometer as shown in Fig.3.12. In the experiment, three spherical irons were collected from the stock to be the testing particles. The first spherical iron particle was dropped into the liquid chamber. The hologram images of the particle falling along its entire path were recorded as a video file on the CMOS camera (Canon EOS 700D, Japan, 5184  $\times$  3456 pixels, 4.29  $\mu\text{m}$ . pixel pitch). Then, the recorded hologram images were reconstructed on the holoviewer program via MATLAB by using the reconstructing distance of 400 mm. Fig. 4.6(a) and (b) show the typical recorded hologram images and the reconstructed images of a falling spherical iron at any position in the lubricant oil. However, it is noted that all the experiments in this work were performed at the room temperature (27°C).

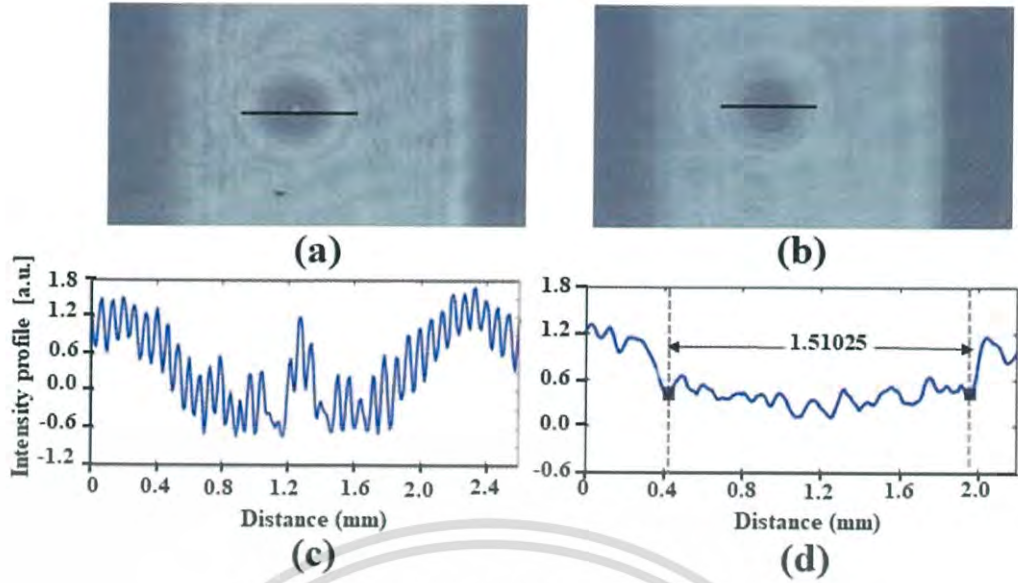


Fig. 4.6 (a) Recorded hologram images, (b) reconstructed images, (c) intensity profile of recorded hologram images and (d) intensity profile of reconstructed images of a falling spherical iron in the lubricant oil (ZE-PRO32)

The holoviewer program via MATLAB was used to reconstruct the image as shown in Fig. 4.6(b) and the diameter of a spherical iron was determined accurately as seen in Fig. 4.6(d). The experiments were carried for three times of each spherical iron and the results are given in Table 4.3. The average diameter of the first spherical iron was found to be 1.51251 mm. The similar experiments were performed for the second and third spherical irons, and the results are also given in Table 4.3 below.

Table 4.3 Measured diameter of spherical irons by using the holoviewer via MATLAB program

| No.     | Diameter (mm)        |                      |                      |
|---------|----------------------|----------------------|----------------------|
|         | 1 <sup>st</sup> iron | 2 <sup>nd</sup> iron | 3 <sup>rd</sup> iron |
| 1       | 1.51025              | 1.49987              | 1.52108              |
| 2       | 1.51509              | 1.49891              | 1.52315              |
| 3       | 1.51218              | 1.50006              | 1.51057              |
| average | 1.51251              | 1.49961              | 1.51827              |

It is seen that the diameter of spherical irons obtained by DIH method agree with that measured by the Vernier caliper. In addition, it should be pointed out that DIH method can be used for diameter measurement with very high accuracy (5 decimal points).

#### 4.2.2 Determination of spherical iron velocity

To determine the velocity of spherical irons, each one was dropped into the liquid chamber and the hologram images were recorded as a video file on the CMOS camera (Canon, EOS 700D, Japan,  $5184 \times 3456$  pixels,  $4.29 \mu\text{m}$ . pixel pitch).

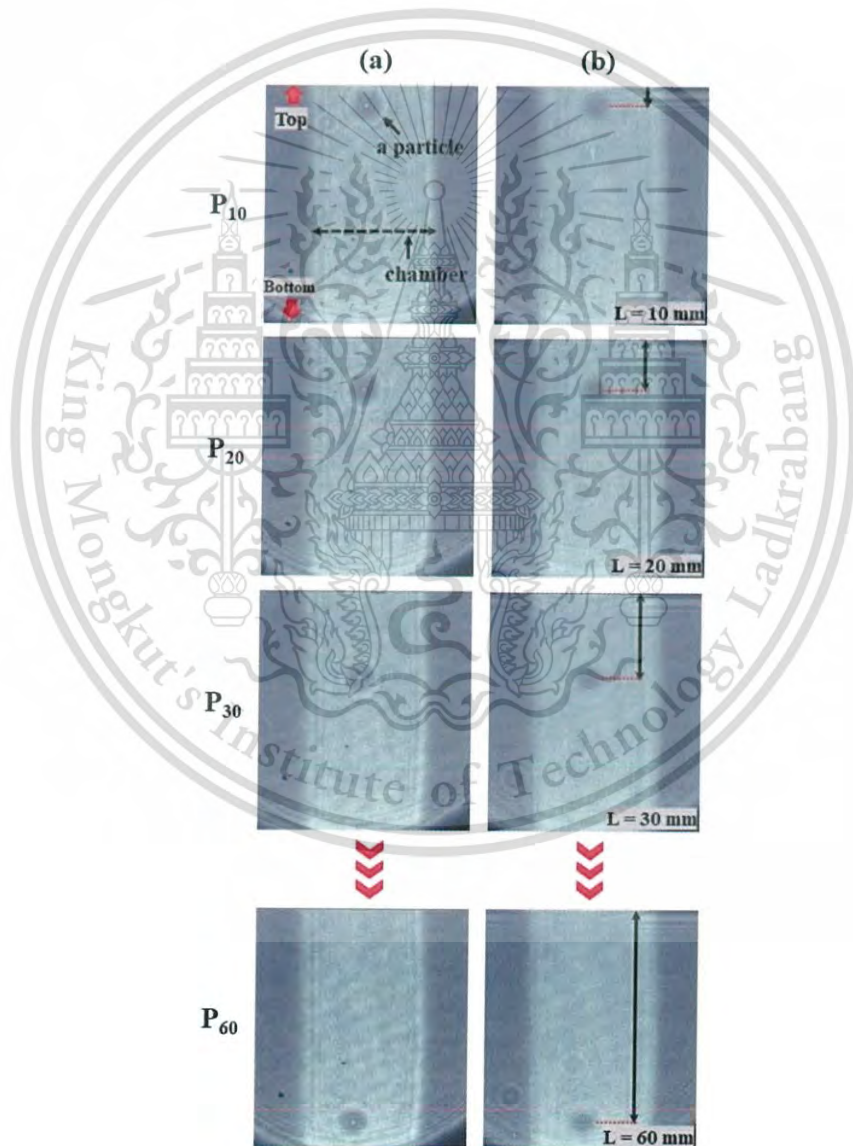


Fig. 4.7 (a) Recorded hologram images and (b) reconstructed images showing the position of a spherical iron falling in the lubricant oil

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

The video files of a spherical iron falling in the liquid chamber were captured as an image at different positions (P) along the liquid chamber of 10, 20, 30, 40, 50, and 60 mm as denoted by  $P_{10}$ ,  $P_{20}$ , ...,  $P_{60}$ , respectively. Then, the falling times (t) at any measured position were obtained and the velocity of spherical iron was determined. Fig. 4.7(a) and 4(b) show the recorded and reconstructed hologram images of a spherical iron falling in liquid chamber filled with the lubricant oil. The typical values of measured velocity and time at different positions of the first spherical iron falling in all testing oils are given in Table 4.4. Similar experiments were performed with the second and the third spherical irons and the results are given in Table 4.5 to 4.6 below.

**Table 4.4** The measured positions, falling time and velocity of the first iron falling in all testing oils

| Lubricant oil (ZE-PRO32) |       |          | Transformer oil (FR-3) |          |
|--------------------------|-------|----------|------------------------|----------|
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.042 | 237.520  | 0.067                  | 148.956  |
| 20                       | 0.084 | 238.875  | 0.133                  | 150.612  |
| 30                       | 0.125 | 240.168  | 0.198                  | 151.404  |
| 40                       | 0.167 | 240.010  | 0.269                  | 148.502  |
| 50                       | 0.209 | 238.996  | 0.334                  | 149.872  |
| 60                       | 0.250 | 239.982  | 0.403                  | 148.982  |
| Averaged of v            |       | 239.259  |                        | 149.721  |
| Gasoline engine oil      |       |          | Cold lubricant oil     |          |
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.077 | 129.984  | 0.103                  | 97.431   |
| 20                       | 0.154 | 129.609  | 0.202                  | 98.865   |
| 30                       | 0.232 | 129.291  | 0.301                  | 99.567   |
| 40                       | 0.310 | 129.157  | 0.403                  | 99.226   |
| 50                       | 0.383 | 130.414  | 0.501                  | 99.736   |
| 60                       | 0.458 | 131.011  | 0.603                  | 99.561   |
| Averaged of v            |       | 129.911  |                        | 99.064   |

**Table 4.5** The measured positions, falling time and velocity of the second iron falling in all testing oils

| Lubricant oil (ZE-PRO32) |       |          | Transformer oil (FR-3) |          |
|--------------------------|-------|----------|------------------------|----------|
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.042 | 236.952  | 0.068                  | 146.852  |
| 20                       | 0.085 | 235.395  | 0.137                  | 145.685  |
| 30                       | 0.128 | 235.051  | 0.203                  | 147.923  |
| 40                       | 0.172 | 232.982  | 0.276                  | 144.988  |
| 50                       | 0.214 | 234.085  | 0.341                  | 146.654  |
| 60                       | 0.254 | 236.541  | 0.406                  | 147.742  |
| Averaged of v            |       | 235.168  |                        | 146.641  |
| Gasoline engine oil      |       |          | Cold lubricant oil     |          |
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.080 | 125.024  | 0.107                  | 93.622   |
| 20                       | 0.158 | 126.540  | 0.211                  | 94.666   |
| 30                       | 0.240 | 125.020  | 0.314                  | 95.641   |
| 40                       | 0.323 | 123.850  | 0.422                  | 94.858   |
| 50                       | 0.398 | 125.622  | 0.528                  | 94.620   |
| 60                       | 0.486 | 123.544  | 0.621                  | 96.641   |
| Averaged of v            |       | 124.933  |                        | 95.008   |

**Table 4.6** The measured positions, falling time and velocity of the third iron falling in all testing oils

| Lubricant oil (ZE-PRO32) |       |          | Transformer oil (FR-3) |          |
|--------------------------|-------|----------|------------------------|----------|
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.042 | 237.025  | 0.066                  | 151.052  |
| 20                       | 0.085 | 236.520  | 0.130                  | 153.524  |
| 30                       | 0.125 | 239.541  | 0.195                  | 153.654  |
| 40                       | 0.169 | 236.851  | 0.263                  | 152.005  |
| 50                       | 0.209 | 239.021  | 0.327                  | 152.687  |
| 60                       | 0.252 | 237.658  | 0.387                  | 154.852  |
| Averaged of v            |       | 237.769  |                        | 152.962  |
| Gasoline engine oil      |       |          | Cold lubricant oil     |          |
| P (mm)                   | t (s) | v (mm/s) | t (s)                  | v (mm/s) |
| 10                       | 0.077 | 129.320  | 0.100                  | 100.321  |
| 20                       | 0.153 | 130.522  | 0.200                  | 99.852   |
| 30                       | 0.228 | 131.645  | 0.295                  | 101.641  |
| 40                       | 0.306 | 130.855  | 0.406                  | 98.472   |
| 50                       | 0.381 | 131.224  | 0.492                  | 101.544  |
| 60                       | 0.455 | 131.855  | 0.595                  | 100.800  |
| Averaged of v            |       | 130.904  |                        | 100.438  |

Then, all experimental data from Table 4.4 to 4.6 were collected to plot a curve between the measured positions (mm) in x-axis and the iron particle velocity (mm/s) in y-axis. The curve of all spherical irons in lubricant oil, transformer oil, gasoline engine oil and cold lubricant oil are illustrated in Fig. 4.8. It is clearly observed that the velocity is constant in the falling path for all spherical irons in all viscous oils. Hence, the average velocity values are assumed to be terminal velocity for spherical irons which will be used for the determination of dynamic viscosity as shown in Table 4.7.

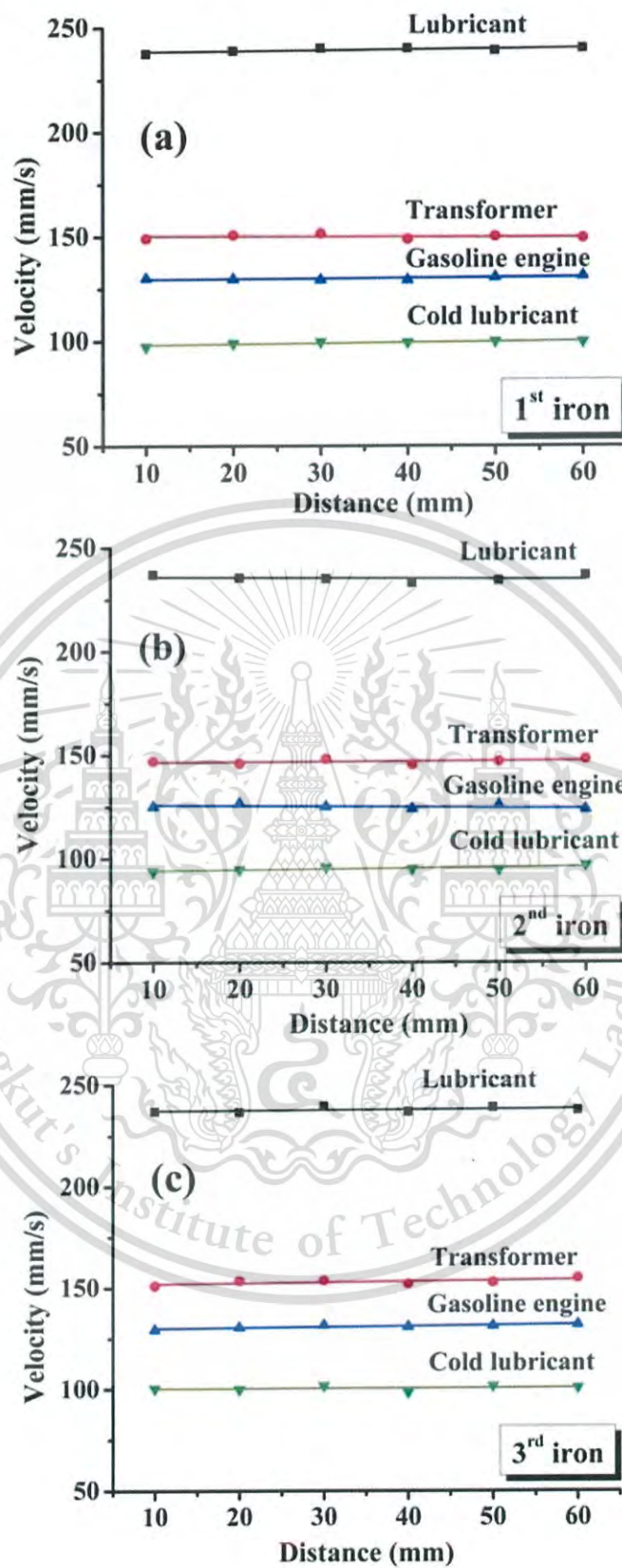


Fig. 4.8 Variation of spherical iron velocity with falling distance of: (a) first irons, (b) second iron and (c) third iron in four different viscous oils

This material is reserved for educational use only, not allowed for commercial use.

Forbidden to modify the content, and cite the document when use.

### 4.2.3 Determination of viscosity of the testing oils

For the last part, to obtain the main purpose of the study, both dynamic viscosity ( $\eta$ ) and kinematic viscosity ( $\nu$ ) of four testing oils was determined. The dynamic viscosity can be obtained by using the Eq. (2-33) as mentioned in chapter 2 and is shown again below;

$$\eta = (\rho_0 - \rho_f) \frac{2}{9} \frac{r^2 g}{v_t}$$

where  $\eta$  is dynamic viscosity of the oil (kg/m.s),

$\rho_0$  is density of the iron = 7000 kg/m<sup>3</sup>

$\rho_f$  is density of the oil (obtained from Table 3.4),

$r$  is average radius of the iron (obtained from Table 4.3),

$g$  is gravitational constant = 9.80665 m/s<sup>2</sup> and,

$v_t$  is terminal velocity of an iron falling in the oil (obtained from the average velocity in Table 4.4 to 4.6)

Then, the dynamic viscosity ( $\eta$ ) of all four viscous oils using three spherical irons were determined in the unit of kg/m.s. The calculated  $\eta$  was converted to the SI unit, mPa.s by using the convert factor; 1 kg/m.s = 1000 mPa.s.

Finally, the kinematic viscosity of the oil can be obtained by using the relationship between dynamic viscosity ( $\eta$ , in mPa.s unit) and kinematic viscosity ( $\nu$ , in cSt unit) as given by:  $\eta = \rho_f \nu \times 10^{-3}$ . Therefore, the kinematic viscosity of all four viscous oils were calculated and the results are given Table 4.7.

Table 4.7 The calculated dynamic and kinematic of all testing oils

| Testing oils                     | The calculated viscosities of oils |                         |                      |
|----------------------------------|------------------------------------|-------------------------|----------------------|
|                                  | $V_t$<br>(mm/s)                    | $\eta$ @25°C<br>(mPa.s) | $\nu$ @25°C<br>(cSt) |
| 1 <sup>st</sup> iron             |                                    |                         |                      |
| Lubricant, (ZE-PRO32)            | 239.259                            | 31.925                  | 36.630               |
| Transformer, (FR-3)              | 149.721                            | 50.574                  | 54.687               |
| Gasoline Engine                  | 129.911                            | 58.773                  | 67.247               |
| Cold Lubricant, (SUNICE SL-32D1) | 99.064                             | 76.008                  | 79.282               |
| 2 <sup>nd</sup> iron             |                                    |                         |                      |
| Lubricant, (ZE-PRO32)            | 235.168                            | 31.928                  | 36.635               |
| Transformer, (FR-3)              | 146.641                            | 50.759                  | 54.887               |
| Gasoline Engine                  | 124.933                            | 60.077                  | 68.739               |
| Cold Lubricant, (SUNICE SL-32D1) | 95.008                             | 77.907                  | 81.263               |
| 3 <sup>rd</sup> iron             |                                    |                         |                      |
| Lubricant, (ZE-PRO32)            | 237.769                            | 32.370                  | 37.141               |
| Transformer, (FR-3)              | 152.961                            | 49.880                  | 53.937               |
| Gasoline Engine                  | 130.904                            | 58.772                  | 67.247               |
| Cold Lubricant, (SUNICE SL-32D1) | 100.438                            | 75.540                  | 78.794               |

From the calculated dynamic viscosity ( $\eta$ ) in Table 4.7, for example the lubricant oil, the  $\eta$  as obtained from three spherical irons are 31.925, 31.928 and 32.370 mPa.s, respectively, which are in good agreement. The dynamic viscosity for lubricant oil, transformer oil, gasoline engine oil and cold lubricant oil are approximately 31.925, 50.574, 58.77 and 76.008 mPa.s, respectively. Therefore, the cold lubricant oil gives the highest dynamic viscosity.

To compare the results obtained in this work with those of standard values of ASTM D445 as given Table 3.4, it is necessary to convert the dynamic viscosity ( $\eta$ ) into the kinematic viscosity ( $\nu$ ) as mentioned above. The kinematic viscosity ( $\nu$ ) of all four viscous oils obtained from three spherical irons are also displayed in Table 4.7. All experimental results were collected to plot as a line curve as presented in Fig 4.9. From Fig. 4.9(a), it can be seen that the terminal velocity of a spherical iron tends to

decrease exponentially with increasing the kinematic viscosity of oils. Also, it is clearly observed that the kinematic viscosity of all four viscous oils obtained from the first, second and third spherical irons are approximately equal.

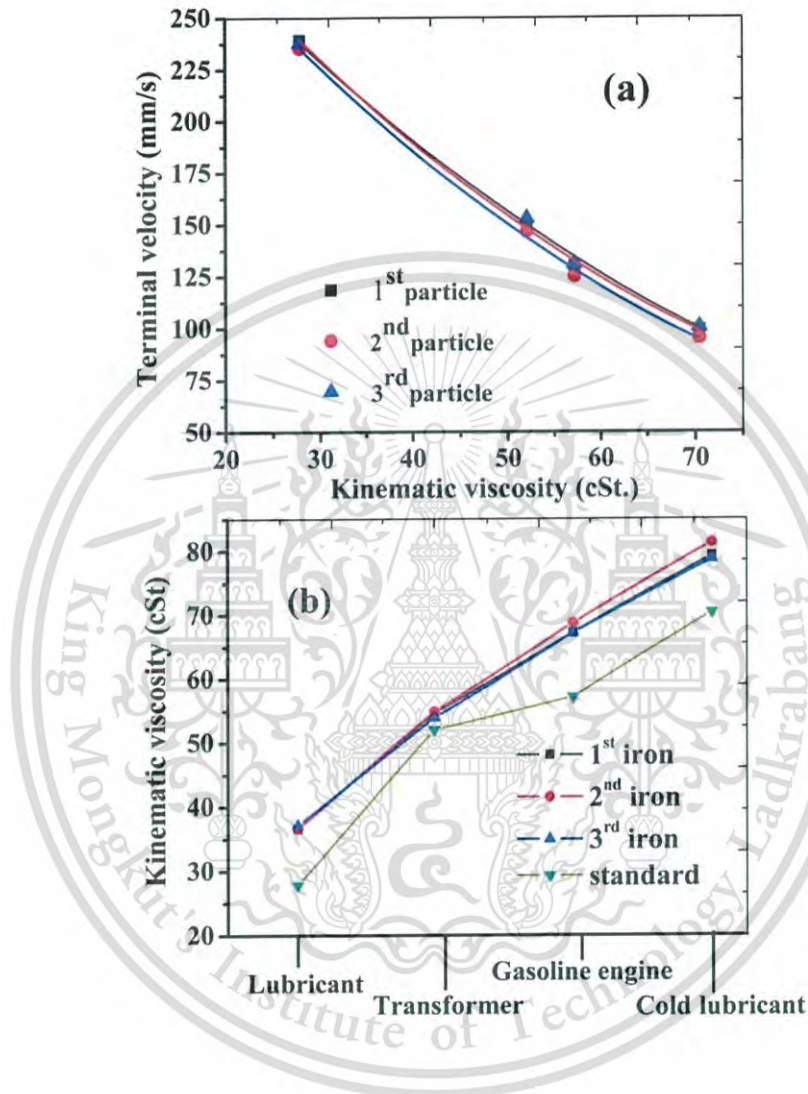


Fig.4.9 (a) Relationship of the terminal velocity of each spherical iron against the kinematic viscosity of oils. (b) comparing the kinematic viscosity between the experimental results and standard values of viscous oils

Furthermore, as shown in Fig 4.9(b), the kinematic viscosity values obtained in this work are higher than those of standard values as given in Table 3.4. The difference in kinematic viscosity values are due to the temperature difference of the

viscous oils. Since all the experiments in this work were performed at 27°C while the standard measurements were carried out at 40°C. However, it is observed that the higher viscous oil temperature results in the lower kinematic viscosity.

**Table 4.8** Comparing the kinematic viscosity from the standard value with the experimental results of all testing oils contained in a liquid chamber

| Oils                     | Experimental results      |                       | Standard values       | % error<br>$v$ |
|--------------------------|---------------------------|-----------------------|-----------------------|----------------|
|                          | $\eta$ , @25°C<br>(mPa.s) | $v$ , @25°C<br>(cSt.) | $v$ , @40°C<br>(cSt.) |                |
| Lubricant oil (ZE-PRO32) | 27.022                    | 31.005                | 27.849                | 11.33          |
| Transformer oil (FR-3)   | 52.658                    | 56.941                | 52.050                | 9.40           |
| Gasoline engine oil      | 56.202                    | 64.306                | 57.181                | 12.46          |
| Cold lubricant oil       | 74.424                    | 77.630                | 70.428                | 10.23          |

In addition, comparing the experimental results and the standard value are obtained and presented in Table 4.8. The error percentage of kinematic viscosities of all testing oils is found to be about 10%. The error might come from the oils' temperature during the measuring process as mentioned above. Other factors to make the error might come from the oil densities during the measuring process under different temperatures as well. However, all experimental results are agreeable with the theory of the dynamic of a spherical particle falling in viscous fluids and the Stokes' equation as mentioned in section 2.4. Despite the discrepancies, the DH method is simpler and more compact a system when compared with the conventional tools used to determine the parameters of viscous liquids.

## Chapter 5

# Conclusions and Suggestions

In the last chapter, I wrapped up the thesis by providing the conclusions and suggestions about the study. The detail here is separated into two main parts as described below.

### 5.1 Conclusions

As mentioned along the whole thesis under the topic of “investigating kinetic of nano- and micro-particles in liquids by using optical tweezers and digital holographic techniques”; now, the thesis is ended by the conclusions. In this section, the conclusion is separated as two parts; 1: trapping colloidal nanoparticles by using optical tweezers technique and 2: determination of viscosity of lubricant oils by using Mach Zehnder digital holographic technique.

#### 5.1.1 Trapping colloidal nanoparticles by using optical tweezers

In the past years, all the optical tweezers systems used for the laser trapping of colloidal nanoparticles require a fluorescent confocal microscope for observing the trapped nanoparticles. In this work, a new optical tweezers system without the use of fluorescent confocal microscope was developed and proposed for the first time. For this system, the variable filter was used for adjusting the laser power while the colloidal nanoparticles to be studied were prepared properly by coating with polymers in low KCl salt and filled in a quartz rectangular capillary tube with a dimension of  $0.1 \times 2 \times 100 \text{ mm}^3$ . By this system, a small device has been used, that is a small rectangular capillary tube for the use in laser trapping. After the system was used for laser trapping and the results were obtained as presented in Section 4.2, I expect to use the developed small device, that is a small capillary tube filled with colloidal nanoparticles in suspension, with a night-vision goggle for protection the damage from the high light intensity in the future.

### 5.1.2 Determination of viscosity of lubricant oils by using Mach Zehnder Digital Holography

For determination of viscosity of lubricant oils, the digital in-line holographic technique based on Mach Zehnder system (MZDIH) was developed for observing a spherical iron particle falling in lubricant oils. The hologram patterns of the samples recorded by CMOS sensor were reconstructed numerically based on the Huygens-Fresnel principle on the holoviewer program via MATLAB. The diameter of spherical irons and the position of a particle falling along the liquid chamber path, were measured easily and accurately in high resolution. From the analyzed results, the terminal velocity of the particle was obtained, which agrees well with the Stokes theory. Finally, the dynamic viscosity ( $\eta$ ) and kinematic viscosity ( $\nu$ ) of lubricant oils were determined and compared with the standard values (followed by ASTM D445). From the experimental results, it can be concluded that this method is the simple and precise tool for the determination of viscosity of fluids. Furthermore, by using this tool instead of the conventional methods, it could be applied in the future to indicate other important parameters, properties, as well as grade grad classification of lubricants oils.

## 5.2 Suggestions

Lastly, the suggestions about the problems during the study, the error of experimental results, as well as the understanding in the theory are given. Those factors are described below and could be helpful for improving to do better researches in the future.

For developing the optical tweezers system to trap colloidal nanoparticles in suspension without microscope. There are many important factors that have to be improved. Firstly, the ratio of all parameters added in preparing samples are still not properly much. They still require high laser power more than 30 mW for trapping multi-nanoparticles simultaneously in a focused area. The size of trapped particles is small compared to the use for producing as a part of a goggle's lens to protect the eyes from the damage of high light intensity. Secondly, the samples have to be prepared and shaken prior to the use. In contrast, the colloidal nanoparticles kept long period of times will aggregate each other like a lump in suspension. Finally, the gradient force at focused area in the optical tweezers system without microscope is

This material is reserved for educational use only, not allowed for commercial use.

not enough to trap nanoparticles well. Moreover, the laser power is required high intensity for trapping nanoparticles and overcome the Brownian motion of them. Then, it still has to be developed in the future.

For determination of viscosity of viscous oils by using Mach Zehnder digital holographic technique, the experimental results of viscosity are still error from the standard value. Those error percentages of about 10% might come from the different temperatures during the measuring process (@25°C in our research, @40°C followed by ASTM D445). During the process of releasing a spherical iron in a viscous oil contained in a liquid chamber, it is hard to control the iron particle falling in the middle of the chamber. From that reason, the surface tension interacted on the chamber surface and the iron dominates in the system. Then, the particle velocity would smaller than the real one and affect to the calculated viscosity of oils. In addition, the recording equipment requires for high resolution to analyze the hologram images more precisely.



## References

- [1] Son, M. Choi, S. Ko, K. H. Kim, M. H. Lee, S.-Y. Key, J. Yoon, Y.-R. Park, I. S. and Lee, S. W. 2016. "Characterization of the Stiffness of Multiple Particles Trapped by Dielectrophoretic Tweezers in a Microfluidic Device." *Langmuir* 32: 922-927.
- [2] Yu, Y. Qiu, W. Chiu, B. and Sun, L. 2015. "Feasibility of Multiple Micro-Particle Trapping- Simulation Study." *Sensors* 15: 4958-4974.
- [3] Yan, J. Skoko, D. and Marko, J. F. 2004. "Near-field magnetic tweezer manipulation of single DNA molecules." *Phys. Rev. E* 70(011905): 1-5.
- [4] Zhou, Y. Basu, S. Wohlfahrt, K. J. Lee, S. F. Klennerman, D. Laue, E. D. Seshia, A. A. 2016. "A microfluidic platform for trapping, releasing and super-resolution imaging of single cells." *Sensors Actuators B: Chem.* 232: 680-691.
- [5] Ashkin, A. Dziedzic, J. M. Bjorkholm, J. E. and Chu, S. 1986. "Observation of a single-beam gradient force optical trap for dielectric particles." *Opt. Lett.* 11(5): 288-290.
- [6] Ashkin, A. 1970. "Acceleration and Trapping of Particles by Radiation Pressure." *Phys. Rev. Lett.* 24(156): 156-159.
- [7] Wei, M.-T. and Chiou, A. 2005. "Three-dimensional tracking of Brownian motion of a particle trapped in optical tweezers with a pair of orthogonal tracking beam and the determination of the associated optical force constants." *Opt. Express* 13(15): 5798-5806.
- [8] Junio, J. Ng, J. Cohen, J. A. Lin, Z. F. and Ou-Yang, H. D. 2011 "Ensemble method to measure the potential energy of nanoparticles in an optical trap." *Opt. Lett.* 36(8): 1497-1499.
- [9] Fu, J. Zhan, Q. Lim, M. Y. Li, Z. and Ou-Yang, H. D. 2013. "Potential energy profile of colloidal nanoparticles in optical confinement." *Opt. Lett.* 38(20): 3995-3998.
- [10] Ling, L. Huang, L. Fu, J. Guo, H. Li, J. Ou-Yang, H. D. and Li, Z.-Y. 2013. "The properties of gold nanospheres studied with dark field optical trapping." *Opt. Express* 21(5): 6618-6624.

## References (cont.)

- [11] Junio, J. Park, S. Kim, M.-W. and Ou-Yang, H. D. 2010. "Optical bottles: A quantitative analysis of optically confined nanoparticle ensembles in suspension." *Solid State Communications* 150: 1003-1008.
- [12] Junio, J. Cohen, J. A. and Ou-Yang, H. D. 2016. "Osmotic Bulk Modulus of Charged Colloids Measured by Ensemble Optical Trapping." *J. Phys. Chem. B* 120: 9187-9194.
- [13] Berns, M. W. Wright, W. H. Tromberg, B. J. Profeta, G. A. Andrews, J. J. and Walter, R. J. 1989. "Use of a laser-induced optical force trap to study chromosome movement on the mitotic spindle." *Proc. Natl. Acad. Sci. U. S. A.* 86: 4539-4543.
- [14] Zhong, M.-C. Wei, X.-B. Zhou, J.-H. Wang, Z.-Q. and Li, Y.-M. 2013. "Trapping red blood cells in living animals using optical tweezers." *Nature Communication* 4(1768): 1-7.
- [15] Croker, J. C. and Grier, D. G. 1994. "Microscopic Measurement of the Pair Interaction Potential of Charge-Stabilized Colloid." *Phys. Rev. Lett.* 73(2): 352-355.
- [16] Mellor, C. D. Sharp, M. A. Bain, C. D. and Ward, A. D. 2005. "Probing interactions between colloidal particles with oscillating optical tweezers." *J. Appl. Phys.* 97(103114).
- [17] Li, J.-T. Caldwell, K. D. and Rapoport, N. 1994. "Surface Properties of Pluronic-Coated Polymeric Colloids." *Langmuir* 10: 4475-4482.
- [18] Kim, S. Y. and Zukoski, C. F. 2011. "Role of polymer segment-Particle Surface Interactions in Controlling Nanoparticle Dispersions in Concentrated Polymer Solutions." *Langmuir* 27: 10455-10463.
- [19] Gabor, G. 1948. "A new microscopic principle." *Nature* 166: 777-778.
- [20] Schnars, U. and Jüptners, W. 1994 "Direct recording of holograms by a CCD target and numerical reconstruction." *Appl. Opt.* 33(2): 179-181.
- [21] Micó, V. Ferreira, C. Zalevsky, Z. and García, J. 2010. "Basic principles and applications of digital holographic microscopy." *Micros. Sci., Technol. Applic. Educ.* 1411-1418.

## References (cont.)

- [22] Sun, H. Hendry, D.C. Player, M.A. and Watson, J. 2007. "In situ underwater electronic holographic camera for studies of plankton." *IEEE J. Oceanic Eng.* 32(2): 373-382.
- [23] Xu, W. Jericho, M. H. Meinertzhagen†, I. A. and Kreuzer, H. J. 2001. "Digital in-line holography for biological applications." *PNAS* 98(20): 11301-11305.
- [24] Penelet, G., Leclercq, M. Wassereau, T. and Picart, P. 2016. "Measurement of density fluctuations using digital holographic interferometry in a standing wave thermoacoustic oscillator." *Exp. Therm. Fluid Sci.* 70: 176-184.
- [25] Sánchez-Ortiga,1, E. Ferraro, P. Martínez-Corral, M. Saavedra, G. and Doblas, A. 2011. "Digital holographic microscopy with pure-optical spherical phase compensation." *J. Opt. Soc. Am.* 28(7): 1410-1417.
- [26] Plaipichit, S. and Buranasiri, P. 2014. "Moisture effect of fingerprint using total internal reflection digital in-line holography.", *Opt. Eng.* 53(11): 11235.
- [27] Khatmullina, L. and Isachenko, I. 2017. "Settling velocity of microparticles of regular shapes." *Mar. Pollut. Bull.* 114: 871-880.
- [28] Yang, Y. and Kang, B. S. 2015. "Development and validation of digital holographic particle velocity measurement system for rotation flows." *Optik* 126: 2223-2227.
- [29] Hinsch, K. D. 2002. "Holographic particle image velocimetry." *Meas. Sci. Technol.* 13(7): R61-72.
- [30] Garcia-Sucerquia, J. Xu, W. Jericho, S.K. Jericho, M.H. and Kreuzer, H.J. 2008. "4-D imaging of fluid flow with digital in-line holographic microscopy." *Optik* 119: 419-423.
- [31] Desse, J.M. Picart, P. and Tankam, P. 2012. "Digital color holography applied to fluid and structural mechanics." *Opt. Lasers Eng.* 50: 18-28.
- [32] Ash III, W.M. and Kim, M.K. 2008. "Digital holography of total internal reflection." *Opt. Express* 16(13): 9811-9820.
- [33] Murata, S. and Yasuda, N. 2000. "Potential of digital holography in particle measurement." *Opt. & Laser Technol.* 32: 567-574.
- [34] Trolinger, J.D. 1975. "Particle Field Holography." *Opt. Eng.* 14(5): 383-392.

## References (cont.)

- [35] Vössing, H.-J. Borrmann, S. and Jaenicke, R. 1998. "In-line holography of cloud volumes applied to the measurement of raindrops and snowflakes." *Atmos. Res.* 49: 199-212.
- [36] Darakis, E. Khanam, T. Rajendran, A. Kariwala, V. Naughton, T.J. and Asundi, A.K. 2010. "Microparticle characterization using digital holography." *Chem. Eng. Sci.* 65: 1037-1044.
- [37] Tongcang Li, B.S. 2011. "Fundamental tests of physics with optically trapped microspheres." Ph.D. Thesis of The University of Texas at Austin.
- [38] Harada, Y. and Asakura, T. 1996. "Radiation forces on a dielectric sphere in the Rayleigh scattering regime." *Optics Communications*. 124 (1996): 529-541.
- [39] Kim, M.K. 2011. **Digital Holographic Microscopy**. New York: Springer.
- [40] Schnars, U. and Jueptner, W. 2005. **Digital Holography**. New York: Springer Berlin Heidelberg.
- [41] Fu, J. and Ou-Yang, H. D. 2014. "Einstein's osmotic equilibrium of colloidal suspensions in conservative force fields." *Proc. SPIE* 9164, 91641V.
- [42] Mott, R.L. 1994. **Applied Fluid Mechanics**. 4<sup>th</sup> ed. New York: Macmillan Publishing Company.
- [43] Ansonge, R. and Sonar, T. 2009. **Mathematical Models of Fluid Dynamics**. Germany: Wiley-VCH Verlag GmbH & Co. KGaA.
- [44] Vennard, J.K. 1961. **Elementary Fluids Mechanics**. New York and London: John Wiley & Sons, Inc.
- [45] Serway, R.A. and Jewett, J.W. 2014. **Physics for Scientists and Engineers with Modern Physics**. USA.: CENGAGE LEARNING.
- [46] Hughes, W.F. and Brighton, J.A. 1991. **Theory and problems of Fluid dynamics**. Singapore: McGraw-Hill, Inc.



## Appendix A

1<sup>st</sup> journal

Published by Ukrainian Journal of Physical Optics

“Optical tweezer system with no fluorescent confocal microscope for trapping colloidal nanoparticles”



# Optical tweezer system with no fluorescent confocal microscope for trapping colloidal nanoparticles

<sup>1</sup> R. Nuansri, <sup>1</sup> P. Buranasiri, <sup>1,2</sup> P. Limsuwan and <sup>3</sup> H.D. Ou-Yang

<sup>1</sup> Department of Physics, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand, [opticslaser@yahoo.com](mailto:opticslaser@yahoo.com)

<sup>2</sup> Department of Physics, Faculty of Science, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand

<sup>3</sup> Department of Physics, Lehigh University, Bethlehem, Pennsylvania 18015, USA, [hdo0@lehigh.edu](mailto:hdo0@lehigh.edu)

Received: 28.05.2018

**Abstract.** We describe two optical tweezer systems for the studies of laser trapping of fluorescent colloidal nanoparticles (NPs). The first one, conventional optical tweezer system widely used in laser trapping, requires a fluorescent confocal microscope for observing trapped NPs. The second system, with no microscope, is presented for the first time in this work. The quantity of trapped NPs for this system is estimated from the transmitted laser light intensity that passes through the fluorescent colloidal NPs. Then the transmitted laser light is converted into the voltage signal and measured by an oscilloscope. A small capillary tube to be filled by the colloidal NPs is developed and used in the second system. This tube can be used with light-sensitive cameras for which a danger of damaging by high light intensities exists. Finally, we show that the results obtained using the both tweezer systems are in good agreement.

**Keywords:** optical tweezers, laser trapping, fluorescent particles, pluronic polymers

**PACS:** 42.66.-V

**UDC:** 535.214

## 1. Introduction

In the recent years, many researchers have been interested in the techniques aimed at investigating, manipulating, trapping and even confining micro- and nanoparticles (NPs) in suspensions and biological cells. There are many important techniques used for trapping or manipulating these objects in various fields of science. These are dielectrophoretic tweezer [1], acoustic tweezer [2], magnetic tweezer [3], hydrodynamic trapping with microfluidic valving [4], optical tweezer and laser trapping [5]. Each of these techniques is suitable for different research areas and has its particular advantages or drawbacks that determine proper applications.

Optical tweezers represent a well-known technique ever since A. Ashkin has discovered acceleration and trapping of particles by radiation pressure in 1970 [6]. The approach has become a significant tool for trapping particles, which resembles a scissor or a tweezer. The technique can be used for various objects, e.g. trapping single micro-particles [5–7], simultaneously confining multiple NPs [8–12], studying chromosome movements [13], and recent approaches for trapping red blood cells in living animals [14] in tightly focused laser beams. In order to trap multiple NPs, many parameters of trapped particles have been studied, including those defining the interactions between colloidal particles [15, 16], the properties and the interactions of particles surrounded by absorbing [17] or non-absorbing [18] polymers, and the properties of colloidal particle surfaces in suspensions.

In connection with numerous applications of optical tweezers in different areas, we have suggested an optical tweezer device to be attached to the light-sensitive camera lenses for which there is a danger of damaging from a sudden and high intensities of light exposed at the camera. If a high-intensity light exposes the camera lenses, some colloidal NPs in the device behave as a part of the camera lens. Then the device should cause the colloidal NPs to aggregate quickly and dissipate the light before it damages the camera lenses.

In the present work, we build and describe the two following optical tweezer systems for trapping colloidal NPs in suspension: (1) a system with a fluorescent confocal microscope and (2) a system with no fluorescent confocal microscope. The second optical tweezer is suggested for the first time. In addition, we develop and use in the second system a small capillary tube to be filled with the colloidal NPs. This capillary tube is aimed to be used with the light-sensitive cameras that can be damaged by high intensities.

## **2. Theory**

### ***2.1. Optical forces acting on nanospherical particles***

When a radiation pressure from a laser beam is used for trapping particles, there are two force components that act on these particles. The first component is a trapping optical gradient force of a laser which acts perpendicular to the direction of light propagation. The other one is a scattering force directed along the direction of laser light propagation. When trapping a nanospherical particle of which size is much smaller than the light wavelength of a trapping laser, one can assume that the NP represents a simple dipole [19]. The particles are pulled towards the focus of laser beam by the optical gradient force and, at the same time, they are pushed away from the focus by the scattering force. If small particles need to be confined in a trap in an easy and stable manner, the optical gradient force must be large enough if compared to the light scattering force due to momentum transfer of electromagnetic wave. The intensity of trapping laser is required to be high enough in order to overcome the effect of Brownian motion [8, 9]. Furthermore, by using the objective lens with high numerical apertures, one can focus the laser beam tightly [20]. Finally, when confining multiple particles simultaneously at a focal point, one has to consider particle–particle and particle–light interactions. This is unlike the case of trapping of a single microparticle, where only the effect of laser trapping on a particle is relevant [8].

As a result, for the optical tweezer system without microscope, the optical gradient force of the laser is weak compared to the scattering force and the thermal effect from the Brownian motion. This leads to forward movement of NPs along the direction of laser light propagation. Hence, the colloidal NPs in the suspension are added to polymers in order to decrease the effect of the Brownian motion. This is described in Section 2.

### ***2.2. Interaction of colloidal particles with polymers***

In this work, polystyrene (PS), a pluronic polymer, and poly-ethylene glycol (PEG) are used when preparing the solution of colloidal particles for investigations of the laser trapping. Therefore the interaction of colloidal particles with the polymers should be discussed.

Usually, the colloidal particles suspended in an aqueous solution carry positive charges around their surface more than negative ones. Fig. 1a shows the PS colloidal particles suspended in an aqueous solution and mixed with PEG, which represents a non-absorbing polymer. There is some aggregation of the particles in the suspension. If the PS colloidal particles are mixed with the pluronic polymer (a so-called PEG–PPG–PEG triblock – see Fig. 1b), the middle PPG section which is hydrophobic is chain-anchored on a spherical surface, while the two PEG sides of the

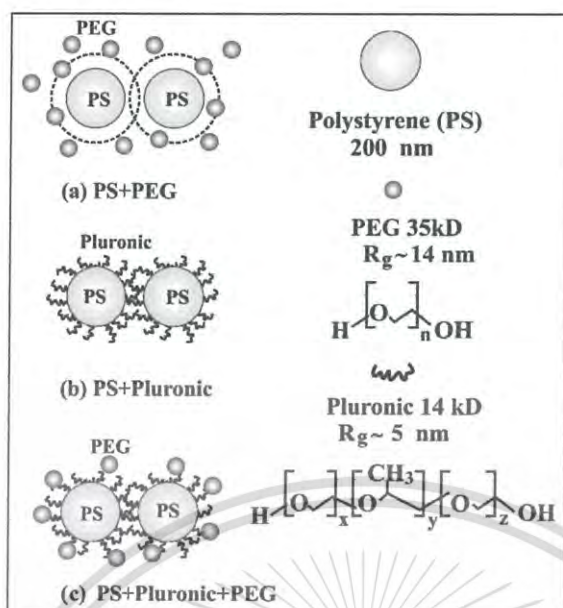


**Fig. 1.** Schemes of PS particles surrounded by PEG polymer (a), pluronic polymer (b) and pluronic polymer with PEG polymer (c).

pluronic polymer are like brushes in an aqueous environment [17]. These brushes generate a repulsive force that prevents aggregation due to particle interactions. In order to enhance the attractive force acting among the particles coated by the pluronic polymer in solution, a non-absorbing PEG polymer with neutral long chains is added to the solution, as shown in Fig. 1c. The brushes of pluronic coated on the PS surface can be bound, along with crowding PEGs, as described previously in Ref. [21]. The size of the polymers is characterized by a so-called gyration radius  $R_g$ . The  $R_g$  parameters of 14 kD pluronic and 35 kD PEG are about 5 and 14 nm, respectively.

To increase the force of attraction among the particles in some other way, a potassium chloride KCl can be added to the suspension. Then the negative charges of the salt ( $\text{Cl}^-$ ) interact with the positive charges around the particles as mentioned above and become move closer to each other due to the attractive force. If one applies the colloidal suspension for trapping multiple particles by a focused laser, the repulsive and attractive forces among the particles generated in the presence of polymers are helpful. While the colloidal particles are trapped in a focused laser beam, many particles can move closer in a trap. This is caused by the effect of binding that appears between the pluronic and PEG chains. In addition, the repulsive force renders stability of the solution when there is no light acting on it.

### 3. Experimental procedures

#### 3.1. Material and sample preparations

1.0 wt. % aqueous fluorescent microsphere suspension made of the PS and dyed with a green fluorescent dye (Thermo Scientific) was used as a starting solution for the laser trapping. The particles of the fluorescent microsphere suspension had spherical shapes, with a diameter of 200 nm. 50  $\mu\text{l}$  of a dyed PS aqueous solution was added to 12  $\mu\text{l}$  of the pluronic polymer (Sigma-Aldrich) with the volume concentration 1%. Since the PS NP surfaces were coated by the pluronic polymer, the mixed solution was shaken in order to protect aggregation of the NPs. A potassium

chloride KCl (100 mM 12  $\mu$ l; Sigma-Aldrich) was added to the solution to make the NPs move close to each other and to increase the attractive force among the NPs. To make the NPs hold each other well in the suspension, we added PEG (10% by volume; Sigma-Aldrich) of seven different volumes (10, 20, 30, 40, 45, 50 and 60  $\mu$ l) and shaken the solution once again. All the samples were prepared immediately prior to their use as a suspension of colloidal NPs for laser trapping, because they could not be stable for a long enough time. The samples thus prepared were denoted as #1 to #7 (see Table 1). Finally, the sample #8 referred to a pure dyed PS solution.

**Table 1.** Compositions of materials used for preparing our colloidal NP samples.

| Sample # | Volume of materials, $\mu$ l |                 |            |             | Total volume, $\mu$ l | Volume fraction, $\phi$ |       |
|----------|------------------------------|-----------------|------------|-------------|-----------------------|-------------------------|-------|
|          | Dyed PS 1% w/w               | Pluronic 1% v/v | KCl 100 mM | PEG 10% v/v |                       | Particles               | PEG   |
| 1        | 50                           | 12              | 12         | 10          | 84                    | 0.60                    | 2.70  |
| 2        | 50                           | 12              | 12         | 20          | 94                    | 0.53                    | 4.83  |
| 3        | 50                           | 12              | 12         | 30          | 104                   | 0.48                    | 6.55  |
| 4        | 50                           | 12              | 12         | 40          | 114                   | 0.44                    | 7.96  |
| 5        | 50                           | 12              | 12         | 45          | 119                   | 0.42                    | 8.58  |
| 6        | 50                           | 12              | 12         | 50          | 124                   | 0.40                    | 9.15  |
| 7        | 50                           | 12              | 12         | 60          | 134                   | 0.37                    | 10.16 |
| 8        | 50                           | —               | —          | —           | 50                    | 1.00                    | —     |

### 3.2. Experimental

In this work, two alternative optical tweezer systems are used for trapping the colloidal NPs in suspensions: (1) a conventional system with a fluorescent confocal microscope and (2) a novel system with no microscope.

Fig. 2 shows a schematic diagram of our optical tweezer system equipped with a fluorescent confocal microscope. This system is widely used to trap the particles [9]. 10  $\mu$ l of each of the samples #1 to #8 was sucked and dropped on a glass slide, and covered with a cover glass. It was placed under a fluorescent confocal microscope (Olympus, IX-81). A beam of a 1064 nm Nd:YAG laser (Changchun New Industries Optoelectronics Tech.) with a maximum power 30 mW was used as a trapping beam. It was expanded by a beam expander BE<sub>1</sub> and passed onto a half-wave plate denoted as  $\lambda/2$ . This plate rotated the polarization direction of the laser beam so that its intensity

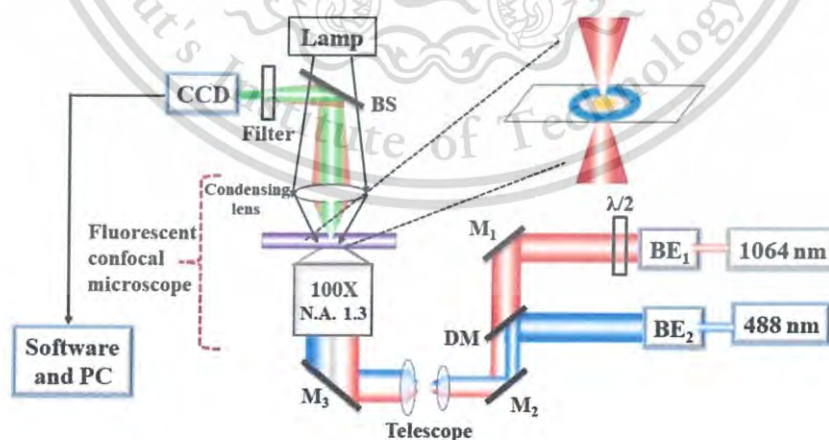


**Fig. 2.** Schematic diagram of our optical tweezer system built using a microscope with a 100X objective lens.

could be varied continuously. The 1064 nm laser beam of adjusted intensity was reflected by a mirror  $M_1$  and passed to a dichroic mirror (DM). At the same time, a blue beam emitted from an argon-ion laser at 488 nm (Showa Optronics, GLG3135) was allowed to pass through a beam expander  $BE_2$  and was reflected at the mirror DM. The 1064 nm laser beam could pass through the mirror DM, while the 488 nm beam was reflected by it. The both were reflected at a mirror  $M_2$  and collimated by a pair of telescope lenses. Then the beams were reflected at a mirror  $M_3$  to pass into an oil-immersion objective lens (100X, the numerical aperture 1.3; Olympus) in order to focus tightly the laser beams and obtain the laser-beam diameter 1  $\mu\text{m}$ . The fluorescent colloidal NPs were trapped by the 1064 nm beam and excited by the 488 nm beam to emit a green fluorescent light at the wavelength of 508 nm. The green fluorescent light of the trapped particles was collected by a condensing lens and reflected by a beam splitter BS. It passed through a filter and was recorded by a CCD camera with a resolution of 10 pixel per 1  $\mu\text{m}$ . Then, the signal was monitored by software (Olympus, Fluoview FV 1000) and displayed on a computer monitor.

In case of our second optical tweezer system suggested for trapping the colloidal NPs, there is no confocal microscope and no objective lens, so that the laser beam is weakly focused. A scheme of this system is illustrated in Fig. 3. A diode-pumped Nd:YAG laser (Laserglow) with a doubled frequency (532 nm) was used as a light source. The laser light passed onto a variable filter for adjusting laser intensity. The optical density numbers of the filter can be varied from 3.0 to 0.08 in order to increase the output laser power from 0.370 to 374.100 mW. This power was measured using a laser power meter with the resolution of 0.001 (Ophir Photonics, NOVA), which was connected behind the filter.

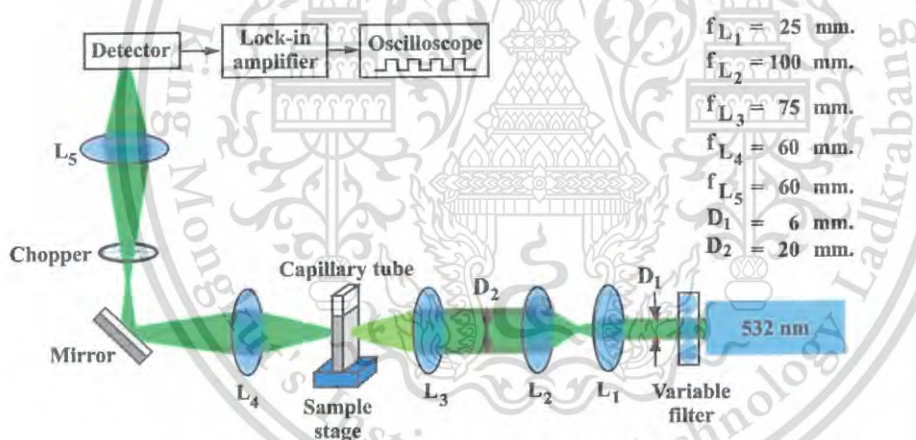


**Fig. 3.** Schematic diagram of our optical tweezer system built with no microscope.  $L_1$  ( $f_{L_1}$ ) to  $L_5$  ( $f_{L_5}$ ) denote lens and their focal lengths.

The laser beam with a diameter  $D_1$  (6 mm) passed through a short focal-length lens  $L_1$  and was expanded to a diameter  $D_2$  (20 mm) by a long focal-length lens  $L_2$ . Then the laser beam was focused by a lens  $L_3$  to obtain a beam diameter of 1 mm and passed through the colloidal NPs filling a rectangular quartz capillary tube (Vitrocom Technical Glass). The dimensions of the capillary tube (width  $\times$  length  $\times$  height) were equal to  $0.1 \times 2 \times 100\text{ mm}^3$ . It was mounted on a sample stage in a vertical direction, where the side  $2 \times 100\text{ mm}^2$  was perpendicular to the laser beam. In other words, the laser beam passed through the colloidal NPs with the thickness of 0.1 mm and trapped the NPs in the focused area.

The transmitted light passed through a lens  $L_4$  and was chopped by an optical chopper to obtain a periodic light signal. This signal was focused by a lens  $L_5$  and detected with an optical detector. The detected signal was converted into a voltage signal and the signal-to-noise ratio was enhanced by a lock-in amplifier (Stanford Research, SR-830). Finally, the periodic voltage signal was monitored by an oscilloscope (Tektronix, TDS 2024).

#### 4. Results and discussion

As seen from Fig. 2, the colloidal NPs in each sample mentioned in Table 1 fill the capillary tube. It is mounted on the sample stage at the focal point of the 100X objective lens under the fluorescent confocal microscope. Then the NPs are trapped by the 1064 nm Nd:YAG laser with the power of 30 mW. The trapped particles are observed through the eyepiece of the microscope and the fluorescent images are recorded with the CCD camera. Fig. 4 displays fluorescent images of the colloidal NPs.

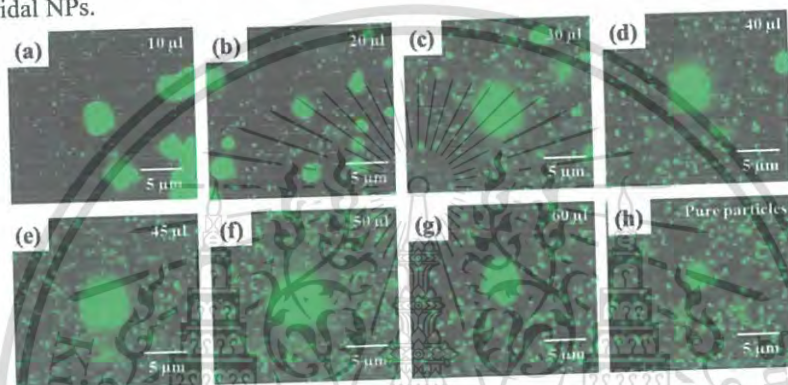


Fig. 4. Fluorescent images of colloidal NPs in the suspension trapped using the laser power of 30 mW at 1064 nm for different PEG contents: 10 (a), 20 (b), 30 (c), 40 (d), 45 (e), 50 (f) and 60  $\mu$ l (g). Panel (h) corresponds to the case when no PEG is used.

A bright green colour in Fig. 4 corresponds to the colloidal NPs suspended in the aqueous solution. This colour appears since the green fluorescent dye coated on the PS NPs is excited by the blue 488 nm laser and emits the green light at 508 nm. There are multiply trapped particles confined simultaneously at the trapping area.

The images shown in Fig. 4a–d correspond respectively to the PEG contents 10, 20, 30 and 40  $\mu$ l. Here many big bright-green lumps are observed, thus indicating that the colloidal NPs still aggregate themselves in the unstable solution. Therefore the particles cannot be confined steadily at the trapping area. When we add up to 45 and 50  $\mu$ l of PEG (samples #5 and #6), the particles are confined easily in the trap. The solution becomes stable, since there is no particle–particle aggregation (see Fig. 4e, f). Big trapped NPs are observed at the centre due to a high light intensity of the trapping laser and large attractive force acting among the particles, as described above. The solution is also stable in cases of the solution where 60  $\mu$ l of PEG is added (sample #7) and the solution where no PEG is present (sample #8). Nevertheless, the amount of the colloidal particles in the trapping area decreases. This results in decreasing numbers of the trapped particles, as seen from Fig. 4g, h. This fact is caused by a significant increase in the total volume of the solution, which results in decreasing volume fraction of the particles (see Table 1).

To confirm further the results presented in Fig. 4, we have repeated the experiments for each sample 10 times at the laser power of 30 mW. In all the cases we have obtained the similar results. The diameter of the bright green circle seen from Fig. 4f has been repeatedly (5 times) determined

using an ImageJ program. Then the average diameter of the trapped particles has been determined. It is equal to  $5.89 \pm 0.26 \mu\text{m}$ .

As seen from Fig. 4, the sample #6 with the PEG content equal to  $50 \mu\text{l}$  reveals the best laser trapping at the laser power of  $30 \text{ mW}$ . Therefore, further experiments with this sample have been carried out for different laser powers ( $5, 10, 15, 20, 25$  and  $30 \text{ mW}$ ). Fig. 5 shows the appropriate fluorescent images of the colloidal NPs in the suspension trapped by the laser. It is clearly seen that still more trapping of the colloidal NPs occurs beginning from  $25 \text{ mW}$  and at higher laser powers. Hence, one can conclude that the diameter of the particles trapped at the centre increases with increasing laser power.

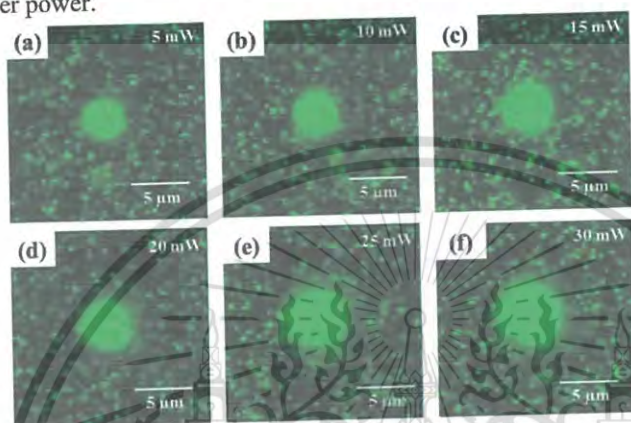


**Fig. 5.** Fluorescent images of trapped colloidal NPs in the suspension (sample #6), as observed at different laser powers:  $5$  (a),  $10$  (b),  $15$  (c),  $20$  (d),  $25$  (e) and  $30 \text{ mW}$  (f).

We have also trapped the colloidal NPs for each of the samples mentioned in Table 1 using the  $532 \text{ nm}$  Nd:YAG laser (see the experimental setup displayed in Fig. 3). Here the output laser power has been changed by a variable filter, with the optical density numbers changing from  $3.0$  down to  $0.08$ . This corresponds to the output laser powers in the region  $0.370\text{--}374.100 \text{ mW}$ . The transmitted light is finally converted into the voltage signal and measured by the oscilloscope. Fig. 6 shows the logarithm of the transmitted light measured in the units of electrical voltage as a function of optical density number, as obtained for the cases of colloidal NPs placed in the suspensions with different PEG contents ( $10, 20, 30, 40, 45, 50$  and  $60 \mu\text{l}$ ). The dependences of the

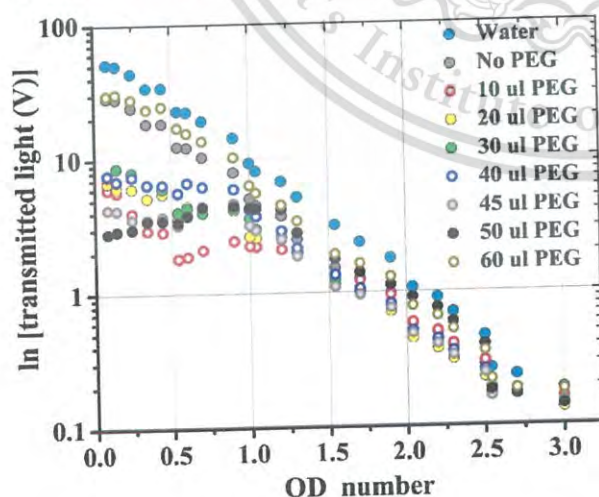


**Fig. 6.** Dependences of transmitted light intensity measured in the units of voltage logarithm on the optical power measured in the units of optical density (OD) number of filter, as measured for different PEG contents ( $10, 20, 30, 40, 45, 50$  and  $60 \mu\text{l}$ ), with water and with no PEG.

voltage on the optical density number, which have been measured for the colloidal NPs with no PEG and with the pure water, are also shown in Fig. 6. It should be pointed out that the case of water has been studied for reference.

Our results demonstrate that, in the region of high optical density numbers (1.0–3.0) that corresponds to the region of low laser powers, the voltage changes linearly with the optical density number. This confirms that the colloidal NPs are not trapped in this region. When the optical density number decreases from 1.0 to 0.08, the voltage tends to decrease due to increasing trapping of colloidal NPs. Furthermore, the sample #6 with 50  $\mu\text{l}$  of PEG shows a smooth variation of the voltage, thus indicating stable trapping of the NPs under this condition.

Finally, we are to notice that the results obtained using the second optical tweezer system agree well with those obtained using a common confocal microscope system. However, our second system with no microscope is much more convenient for using as an optical tweezer and observing the trapping of colloidal NPs.

## 5. Conclusion

All of the optical tweezer systems used till now for laser trapping of the colloidal NPs have required a fluorescent confocal microscope for observing the trapped NPs. In this work, we have developed a novel optical tweezer system that does not make use of a fluorescent confocal microscope. In this system, the variable filter is used for adjusting the laser power while the colloidal NPs under study are filled in a rectangular capillary quartz tube with the dimensions of  $0.1 \times 2 \times 100 \text{ mm}^3$ . The transmitted light that passes through the colloidal NPs is converted into a voltage signal and measured by an oscilloscope. Our system appears to be much more convenient when used for the observations of trapped NPs than the conventional optical tweezer systems.

## References

1. Son M, Choi S, Ko H K, Kim H M, Lee S-Y, Key J, Yoon Y-R, Park I S and Lee S W, 2016. Characterization of the stiffness of multiple particles trapped by dielectrophoretic tweezers in a microfluidic device. *Langmuir*. **32**: 922–927.
2. Yu Y, Qiu W, Chiu B and Sun L, 2015. Feasibility of multiple micro-particle trapping – simulation study. *Sensors*. **15**: 4958–4974.
3. Yan J, Skoko D and Marko J. F, 2004. Near-field magnetic tweezer manipulation of single DNA molecules. *Phys. Rev. E*. **70**: 011905.
4. Zhou Y, Basu S, Wohlfahrt K J, Lee S F, Klenerman D, Laue E D and Seshia A A, 2016. A microfluidic platform for trapping, releasing and super-resolution imaging of single cells. *Sensors Actuators B: Chem.* **232**: 680–691.
5. Ashkin A, Dziedzic J M, Bjorkholm J E and Chu S, 1986. Observation of a single-beam gradient force optical trap for dielectric particles. *Opt. Lett.* **11**: 288–290.
6. Ashkin A, 1970. Acceleration and trapping of particles by radiation pressure. *Phys. Rev. Lett.* **24**: 156–159.
7. Wei M-T and Chiou A, 2005. Three-dimensional tracking of Brownian motion of a particle trapped in optical tweezers with a pair of orthogonal tracking beam and the determination of the associated optical force constants. *Opt. Express*. **13**: 5798–5806.
8. Junio J, Ng J, Cohen J A, Lin Z F, and Ou-Yang H D, 2011. Ensemble method to measure the potential energy of nanoparticles in an optical trap. *Opt. Lett.* **36**: 1497–1499.
9. Fu J, Zhan Q, Lim M Y, Li Z and Ou-Yang H D, 2013. Potential energy profile of colloidal nanoparticles in optical confinement. *Opt. Lett.* **38**: 3995–3998.

10. Ling L, Huang L, Fu J, Guo H, Li J, Ou-Yang H D and Li Z-Y, 2013. The properties of gold nanospheres studied with dark field optical trapping. *Opt. Express*. **21**: 6618–6624.
11. Junio J, Park S, Kim M-W and Ou-Yang H D, 2010. Optical bottles: A quantitative analysis of optically confined nanoparticle ensembles in suspension. *Solid State Commun.* **150**: 1003–1008.
12. Junio J, Cohen J A and Ou-Yang H D, 2016. Osmotic bulk modulus of charged colloids measured by ensemble optical trapping. *J. Phys. Chem. B*. **120**: 9187–9194.
13. Berns M W, Wright W H, Tromberg B J, Profeta G A, Andrews J J and Walter R J, 1989. Use of a laser-induced optical force trap to study chromosome movement on the mitotic spindle. *Proc. Natl. Acad. Sci. U. S. A.* **86**: 4539–4543.
14. Zhong M.-C, Wei X.-B, Zhou J.-H., Wang Z.-Q and Li Y.-M, 2013. Trapping red blood cells in living animals using optical tweezers. *Nature Commun.* **1768**: 1–7.
15. Croker J C and Grier D G, 1994. Microscopic measurement of the pair interaction potential of charge-stabilized colloid. *Phys. Rev. Lett.* **73**: 352–355.
16. Mellor C D, Sharp M A, Bain C D and Ward A D, 2005. Probing interactions between colloidal particles with oscillating optical tweezers. *J. Appl. Phys.* **97**: 103114.
17. Li J-T, Caldwell K D and Rapoport N, 1994. Surface properties of pluronic-coated polymeric colloids. *Langmuir*. **10**: 4475–4482.
18. Kim S Y and Zukoski C F, 2011. Role of polymer segment-Particle Surface Interactions in Controlling Nanoparticle Dispersions in Concentrated Polymer Solutions. *Langmuir*. **27**: 10455–10463.
19. Ashkin A, 1992. Forces of a single-beam gradient laser trap on a dielectric sphere in the ray optics regime. *Biophys. J.* **61**: 569–582.
20. Harada Y and Asakura T, 1996. Radiation forces on a dielectric sphere in the Rayleigh scattering regime. *Opt. Commun.* **124**: 529–541.
21. Fu J and Ou-Yang H D, 2014. Einstein's osmotic equilibrium of colloidal suspensions in conservative force fields. *Proc. SPIE*. **9164**: 91641V.

R. Nuansri, P. Buranasiri, P. Limsuwan and H.D. Ou-Yang. 2018. Optical tweezer system with no fluorescent confocal microscope for trapping colloidal nanoparticles. *Ukr.J.Phys.Opt.* **19**: 150 – 158. doi: 10.3116/16091833/19/3/150/2018

**Анотація.** Описано дві системи оптичного пінцета для вивчення лазерного захоплення флуоресцентних колоїдних наночастинок (НЧ). Перша або звичайна система оптичного пінцета, яку широко застосовують для лазерного захоплення, вимагає флуоресцентного конфокального мікроскопа для спостереження захоплених НЧ. Другу систему без мікроскопа вперше представлено в цій роботі. Кількість захоплених НЧ для цієї системи оцінено з інтенсивності лазерного світла, яке проходить крізь флуоресцентні колоїдні НП. Далі пройдене лазерне світло перетворюється на сигнал напруги і вимірюється осцилографом. Для другої системи розроблено та використано невелику капілярну трубку, наповнену колоїдними НЧ. Цю трубку можна використовувати разом зі світлочутливими камерами, для яких є загроза пошкодження через високу інтенсивність світла. Нарешті, продемонстровано добре узгодження результатів, одержаних за допомогою обох систем пінцета.

## Appendix B

2<sup>nd</sup> journal

Published by American Journal of Applied Sciences

“Determination of Dynamic Viscosity of Viscous Oils using  
Mach Zehnder Digital Holographic Method”



# Determination of Dynamic Viscosity of Viscous Oils using Mach Zehnder Digital Holographic Method

Rittirong Nuansri, Pichet Limsuwan and Prathan Buranasiri

Department of Physics, Faculty of Science,  
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

## Article history

Received: 04-06-2018

Revised: 10-07-2018

Accepted: 13-07-2018

## Corresponding Author:

Rittirong Nuansri

Department of Physics, Faculty

of Science, King Mongkut's

Institute of Technology

Ladkrabang, Bangkok 10520,

Thailand; Email:

kmitl.apl@gmail.com

**Abstract:** The digital in-line holography based on Mach Zehnder interferometer (MZDIH) was setup for the determination of dynamic viscosity of the viscous oils. The spherical irons were used as the falling objects in the viscous oils. The hologram images of the iron falling along its entire path were recorded as a video file on the CMOS camera. The recorded hologram images were reconstructed on the holoviewer program via MATLAB. Then, the diameter and velocity of the iron were obtained. Finally, the dynamic viscosity of viscous oils were determined and compared with standard values. From the experimental results, it can be concluded that the MZDIH method is the simple and precise tool for determining the dynamic viscosity of fluids.

**Keywords:** Holography, Dynamic Viscosity, Stokes Equation

## Introduction

Since the holographic principle was explained by Dennis Gabor (Gabor, 1948), this technique has become an important optical method for research and industrial application. Producing a hologram requires two identical beams from a coherent light source, such as a laser. The first wave without distortion or non-diffracted light, is called the reference beam. The second beam, which passes through the object and the wavefronts of the light diffract caused by the object, is called the object beam. The hologram patterns are recorded of both phases and amplitudes on a photographic film. In Digital Holography (DH), since the conventional hologram consumes a lot of holographic recording films, the holographic recording media has been replaced by a Charged-Couple Device Detector (CCD) (Schnars and Jüptner, 1994). Generally, DH method is categorized into two kinds, on-axis (in-line) and off-axis configurations. The characteristics of the digital in-line geometry have the simplest setup. Here, the reference beam, object beam and the recording sensor are placed in the same axis. In the other configuration, the object and reference waves are at an angle with each other in order to avoid the noise incoming from the overlapping of both wavefronts (Micó *et al.*, 2010). Currently, the DH method has found application in various fields because this technique can be determined both phases and amplitudes accurately and clearly in three dimensions (3D). For example, the plankton and other marine

organisms as well as bacteria and fruit flies have been explored using the DH method (Sun *et al.*, 2007; Xu *et al.*, 2001). The density fluctuations of a standing wave in a thermoacoustic oscillation (Penelet *et al.*, 2015) and the phase compensation of spherical beam (Sánchez-Ortiga *et al.*, 2011) have been analyzed by the hologram patterns as well. The fingerprint patterns of human can also be observed and separated by investigating their profile intensity fringes (Plaipichit and Buranasiri, 2014). A number of previous researches have used the DH method for measuring the velocity of particles flowing through liquids in microchannel (Khatmullina and Isachenko, 2016), observing the flow and mechanics of fluid (Desse *et al.*, 2012). These groups have also characterized the fluid's properties and adjusted the size and shape of objects traveling in the liquids (Murata and Yasuda, 2001; Darakis *et al.*, 2009).

In this research, the kinematic viscosities of the four different lubricant oils used are 27.849, 52.050, 57.181 and 70.428 centi-Stokes (Measured at 40°C followed by ASTM D445). The lubricants used were supplied by the Goods and Exhibit Analysis Office, Excise Department of Thailand. The fluids used in this study are important lubricants typically used on engine parts in vehicles as well as in industrial machinery. Choosing a suitable oil allows machinery users to protect moving engine parts in the normal operation. However, the user has to know the oil's parameters before use, particularly, the density and viscosity. The viscosity value is the most important characteristic governing the behavior and grade

classification of oils. There are various ways to measure the viscosity, such as a cold cranking simulator (CCS), which is used to measure the dynamic viscosity ( $\eta$ , in the unit of centipoise) and the kinematic viscosity ( $\nu$ , in the unit of centistoke, cSt) following the ASTM D445 standard. These conventional methods are still accurate and precise; however, they have complicated operating procedures and use expensive equipment. Therefore, in our research, we propose an alternative way, Mach Zehnder digital in-line holography (MZDIH), to find out the dynamic viscosity ( $\eta$ , in the unit of mPa.s) and kinematic viscosity ( $\nu$ , in the unit of cSt.). This method is simpler, compact and less expensive than the conventional testing methods as mentioned above. In the experiment, the terminal velocity of a particle ( $v_t$ ) moving in different viscous lubricant oils contained in a liquid chamber was measured. Furthermore, the experimental values can then be used to determine the properties of the lubricant oils and also classify the commercial grade of the oils for their use in lubricating machine parts.

## Theoretical Backgrounds

### *Dynamic of a Particle in Fluids*

In non-compressible liquids, since the layers of the internal textures of the liquids have the relative activity to each other, the liquids have an internal resistant force. That force is called the viscous force or drag force, with direction opposite to the direction of particle motion. The drag force was determined by Sir George Stoke in 1845 (Collinson and Roper, 1995) and given by equation:

$$F_d = 6\pi\eta rv_t \quad (1)$$

where  $\eta$ ,  $r$ ,  $v_t$  are dynamic viscosity, radius of the sphere and constant velocity, respectively. This law says that the force acting on a small spherical object, as it falls down through a viscous medium. Under the influence of the gravitational force:

$$F_g = \rho_o V_o g \quad (2)$$

where  $\rho_o$ ,  $V_o$  and  $g$  are density of the object, volume of the spherical object and the gravitational constant, respectively. Due to the conditions of the object specified above, the Reynolds number in the system is small, therefore the flow of liquid remains laminar (Mott, 1994). The bouyant force as described by the principle of Archimedes (Serway and Jewett, 2014), is exerted on the object in the upward direction and given by:

$$F_B = \rho_f V_o g \quad (3)$$

When a small stationary spherical particle is released into a viscous liquid, the particle at a constant velocity ( $v_t$ ) experiences forces both upward and downward that must be in balance by Newton's 3rd law of motion. The dynamic viscosity can be expressed by equation:

$$\eta = (\rho_o - \rho_f) - \frac{2r^2g}{9v_t} \quad (4)$$

where  $\rho_o$ ,  $\rho_f$ ,  $r$  and  $\eta$  are object density, fluid density, radius of the spherical object and dynamic viscosity of the fluid, respectively.

Another force acting to a particle falling through the liquid in a small channel is the surface tension of the liquid in the channel. This force was recognized from the apparent stress in the surface layer of a liquid during its flow in a liquid chamber or between parallel plates.

Normally, the surface tension is an energy associated with an interface of liquid-liquid or liquid-air. Because the surface of liquids behaves like a membrane, the liquid surface may form a curvature between small channels, where the liquid drop can look more or less rounded (Hughes and Brighton, 1991). Therefore, the speed of the liquids at the center is maximum and the speed of liquid gradually decreases until it reaches a minimum at the liquid chamber surface. For this reason, the speed of a particle falling through a liquid contained in the liquid chamber is slower than moving through a liquid contained in a bigger one, because of the surface tension between the liquid and the container.

### *Reconstruction Method of Digital Holography*

In this work, the principle of Fresnel diffraction and convolution theory of hologram reconstruction was described (Kim, 2011; Schnars and Jueptner, 2005). By assuming a parameter that propagates along the z-axis to the sensor plane ( $U(x,y)$ ) represents the two dimensional (2-D) diffraction of optical fields based on the Huygens-Fresnel principle. The diffraction of light through the optical filter in the rectangular coordinates can be shown as the optical diffraction equation:

$$U(x,y) = \frac{z}{j\lambda} \iint O(\xi,\eta) \frac{\exp(jkr)}{r^2} d\xi d\eta \quad (5)$$

where  $O(\xi, \eta)$  represents an optical field in two dimensions at the object plane,  $r$  equals to  $[z^2 + (x-\xi)^2 + (y-\eta)^2]^{1/2}$ , which is the displacement from any point on the object plane ( $O(\xi, \eta)$ ) to the recording or sensor plane ( $x, y$ ) and  $z$  is the propagation distance of the optical field as shown in Fig. 1. The hologram function can be expressed using the convolution technique as illustrated in Equation 6:



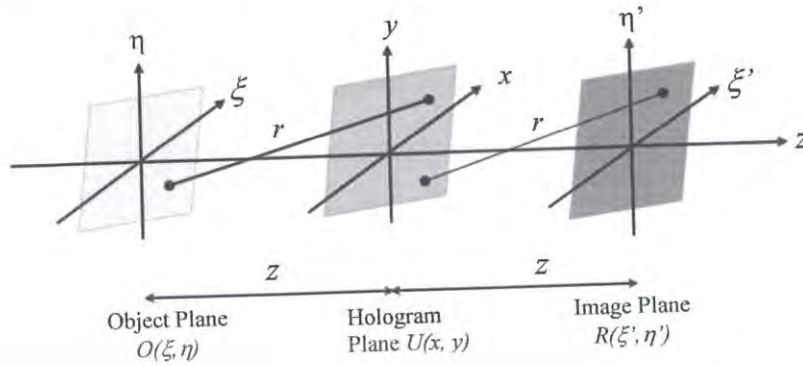


Fig. 1: A coordinate system for the numerical reconstruction of recorded images by digital holographic technique

$$U(x, y) = F^{-1}\{F[O(\xi, \eta)] \cdot F[\zeta, \eta, x, y]\} \quad (6)$$

where the Kernel's equation is given by  $g(\zeta, \eta, x, y) = \frac{z \exp(jkr)}{j\lambda r^2}$  and  $k$  represents the wavenumber of light, which equals  $2\pi/\lambda$ . Because the size of the recording sensor is very small compared to the distance of light propagation,  $r^2$  is reduced to  $z^2$ . Hence, this equation can be rewritten as  $g(\zeta, \eta, x, y) = \frac{\exp(jkz)}{jkz}$ . By utilizing the inverse Fourier transform of the filtered Huygens-Fresnel principle, the optical field at the image plane  $(R(\xi', \eta'))$  can be reconstructed as:

$$R(\xi', \eta') = F^{-1}\{F[O(x, y)] \cdot F[g(\zeta, \eta, x, y)]\} \quad (7)$$

The holograms recorded by the sensor are transferred to a computer and reconstructed based on the Huygens-Fresnel principle as shown in the Equation 7.

## Experimental Method

### Experimental Setup

Fig. 2(a) shows the Mach Zehnder Digital Holographic (MZDH) system used for measuring the dynamic viscosity of a spherical iron object travelling in the viscous oil.

In the MZDH system, the light source was a laser diode with 635 nm wavelength at a power of 1 mW (LDM115G/633/1). A convex lens  $L_1$ ,  $f_1 = 200$  mm, was used to collimate the laser beam that propagates in the z-axis from the light source. Then, the laser beam of about 20 mm in diameter was separated into two identical beams, the reference beam and the object beam, by a beam splitter  $BS_1$ . The reference beam, without any distortion, is reflected at mirror  $M_1$ , while the object beam is reflected at mirror  $M_2$ .

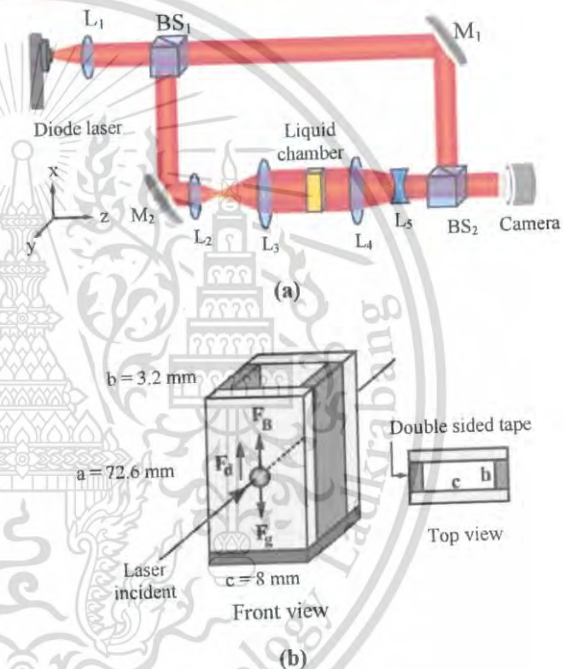


Fig. 2: (a) Schematic diagram of digital in-line holographic setup (DIH) based on Mach Zehnder interferometer and (b) the forces acting on the object moving in the viscous liquid contained in the liquid chamber

The object beam was a short focal length convex lens  $L_2$ ,  $f_2 = 10$  mm and a long focal length expanded convex lens  $L_3$  and  $L_4$ ,  $f_{3,4} = 200$  mm to cover the whole volume of liquid chamber. Then, the transmitted beam passed through the object was collimated again by concave lens  $L_5$ ,  $f_5 = -200$  mm to generate the parallel beam. Finally, the two beams were recombined at the beam splitter  $BS_2$  and the hologram patterns were recorded on the CMOS camera (Canon EOS 700D, Japan,  $5184 \times 3456$  pixels,  $4.29 \mu\text{m}$ . pixel pitch).

The numerically reconstructed distance (R) based on the Huygens-Fresnel principle as mentioned in section 2.2 was found to be 400 mm.

Materials and Sample Preparation

Three spherical irons, each one with a diameter of about 1.50 mm and a density of 7.00 g/cm<sup>3</sup> were used as the object. The object size was measured by a digital Vernier caliper with 0.01 mm resolution. The average diameter of the object was found to be 1.50 ± 0.02 mm.

The liquid chamber was prepared by using two glass slides, each one having a dimension (length x width x thickness) of 76.2 × 25.4 × 1.5 mm<sup>3</sup> (SAIL, No. 7101). They were attached with two layers of double sided tape foam with 3.2 mm thick (3M, 4026 Natural PUR Foam) between the slides and sealed at the bottom by hot melted adhesion glue. Figure 2b shows the diagram of liquid chamber with a volume (a × b × c) of 72.6 × 3.2 × 8 mm<sup>3</sup>.

The viscous oils used in this study were supplied by the Goods and Exhibit Analysis Office, Excise Department of Thailand. The properties of the oils are given in Table 1. The values of density (ρ<sub>f</sub>) at 15°C and the kinematic viscosity (ν) at 40°C were obtained from ASTM D1298 and ASTM D445, respectively.

Table 1: Properties of the viscous oils used in the experiment

| Oils                     | Density at 15°C (g/cm <sup>3</sup> ) | Kinematic viscosity at 40°C (cSt.) |
|--------------------------|--------------------------------------|------------------------------------|
| Lubricant oil (ZE-PRO32) | 0.87154                              | 27.849                             |
| Transformer oil (FR-3)   | 0.92478                              | 52.050                             |
| Gasoline engine oil      | 0.87398                              | 57.181                             |
| Cold lubricant oil       | 0.95870                              | 70.428                             |

Results and Discussion

Diameter Measurement of Spherical Iron

Among four oils used in this work, the lubricant oil is transparent. Therefore, it was used for the diameter measurement of spherical iron. It was filled in the liquid chamber which placed in the object arm of the interferometer as shown in Fig. 2(a). The first spherical iron object was dropped into the liquid chamber. The hologram images of the object falling along its entire path were recorded as a video file on the CMOS camera (Canon EOS 700D, Japan, 5184×3456 pixels, 4.29 μm. pixel pitch). Then, the recorded hologram images were reconstructed on the holoviewer program via MATLAB by using the reconstructing distance of 400 mm. Figs. 3(a) and 3(b) show the typical recorded hologram images and the reconstructed images of a falling spherical iron at any position in the lubricant oil. However, it is noted that all the experiments in this work were performed at the room temperature (27°C).

The holoviewer program via MATLAB was used to analyze the image as shown in Figure 3(d) and the diameter was determined. The experiments were carried for three times and the results are given in Table 2. The average diameter of the first spherical iron was found to be 1.51251 mm. The similar experiments were performed for the second and third spherical irons and the results are also given in Table 2. It is seen that the diameter of spherical iron obtained by DIH method agree with that measured by the Vernier caliper. In addition, it should be pointed out that DIH method can be used for diameter measurement with very high accuracy (5 decimal points).

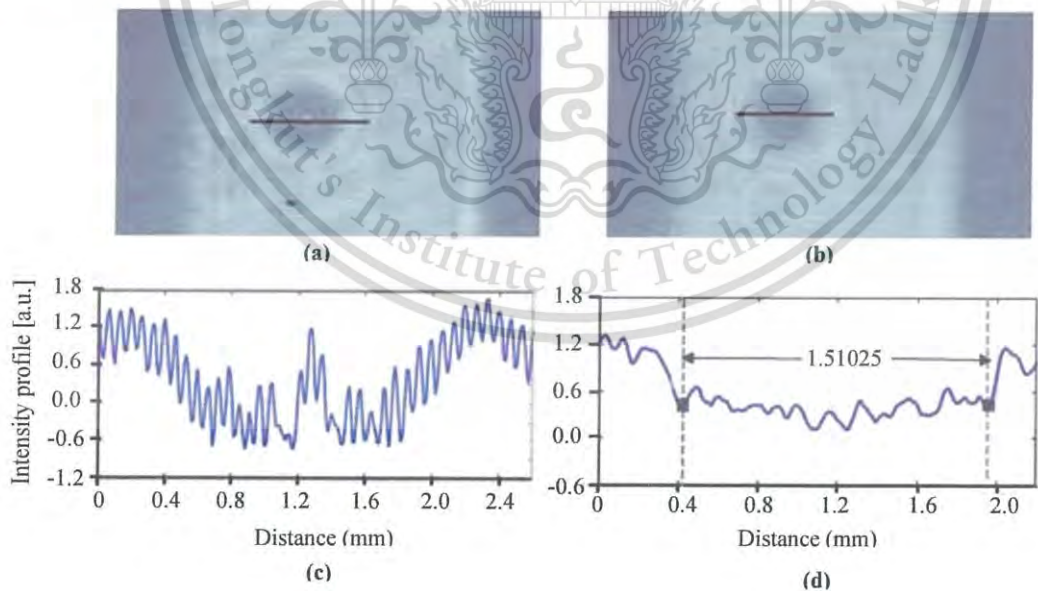


Fig. 3: (a) Recorded hologram images, (b) reconstructed images, (c) intensity profile of recorded hologram images and (d) intensity profile of reconstructed images of a falling spherical iron in the lubricant oil

Determination of Spherical Iron Velocity

To determine the velocity of spherical irons, each one was dropped into the liquid chamber and the hologram images were recorded as a video file on the CMOS camera (Canon, EOS 700D, Japan, 5184 × 3456 pixels, 4.29 μm. pixel pitch). The video files of a spherical iron falling in the liquid chamber were captured as an image at different positions (P) along the liquid chamber of 10, 20, 30, 40, 50 and 60 mm as denoted by P<sub>10</sub>, P<sub>20</sub>,..., P<sub>60</sub>, respectively. Then, the falling times (t) at any measured position were obtained and the velocity of spherical iron was determined. Figs. 4(a) and 4(b) show the recorded and reconstructed hologram images of a spherical iron falling in liquid chamber filled with the lubricant oil. The typical values of measured velocity and time at different positions of three spherical irons falling in the lubricant oil are given in Table 3.

Similar experiments were performed with transformer oil, gasoline engine oil and cold lubricant oil but the results are not given here. However, the relationship between velocity and distance for all spherical irons in lubricant oil, transformer oil, gasoline engine oil and cold lubricant oil are illustrated in Fig. 5. It is clearly observed that the velocity is constant in the falling path for all spherical irons in all viscous oils. Hence, the average velocity values are assumed to be terminal velocity for spherical irons which will be used for the determination of dynamic viscosity as shown in Table 4.

Determination of Dynamic Viscosity of the Oils

The dynamic viscosity of the oils was determined from Equation (4):

$$\eta = (\rho_o - \rho_f) \frac{2}{9} \frac{r^2 g}{v_t}$$

where:  
η = Dynamic viscosity of the oil (kg/m.s)  
ρ<sub>o</sub> = Density of the iron = 7000 kg/m<sup>3</sup>  
ρ<sub>f</sub> = Density of the oil (obtained from Table 1)  
r = Radius of the iron (obtained from Table 2)  
g = Gravitational constant = 9.80665 m/s<sup>2</sup>  
v<sub>t</sub> = Terminal velocity of an iron falling in the oil (obtained from Table 3)

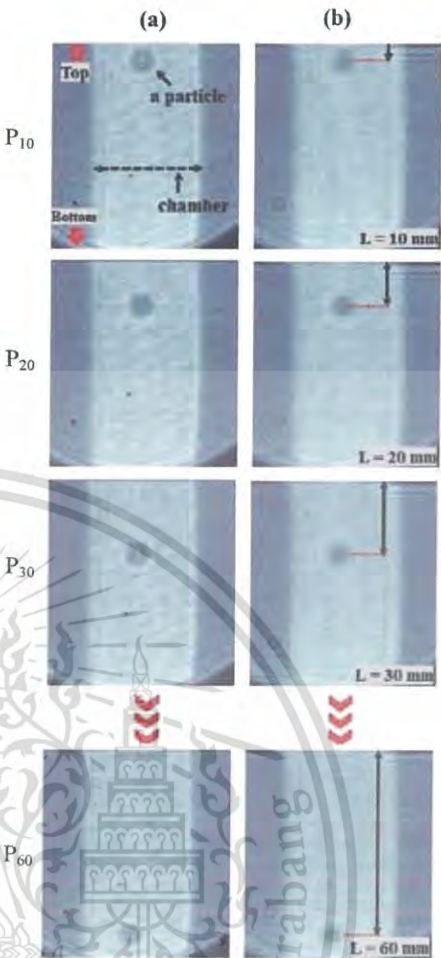


Fig. 4: (a) Recorded hologram images and (b) reconstructed images showing the position of a spherical iron falling in the lubricant oil

Table 2: Measured diameter of spherical irons

| No.     | Diameter (mm)        |                      |                      |
|---------|----------------------|----------------------|----------------------|
|         | 1 <sup>st</sup> iron | 2 <sup>nd</sup> iron | 3 <sup>rd</sup> iron |
| 1       | 1.51025              | 1.49987              | 1.52108              |
| 2       | 1.51509              | 1.49891              | 1.52315              |
| 3       | 1.51218              | 1.50006              | 1.51057              |
| Average | 1.51251              | 1.49961              | 1.51827              |

Table 3: Measured velocity and time at different positions of spherical irons falling in the lubricant oil

| Position (mm) | 1 <sup>st</sup> iron |         | 2 <sup>nd</sup> iron |         | 3 <sup>rd</sup> iron |         |
|---------------|----------------------|---------|----------------------|---------|----------------------|---------|
|               | t(s)                 | v(mm/s) | t(s)                 | v(mm/s) | t(s)                 | v(mm/s) |
| 10            | 0.042                | 237.520 | 0.042                | 236.952 | 0.042                | 237.025 |
| 20            | 0.084                | 238.875 | 0.085                | 235.395 | 0.085                | 236.520 |
| 30            | 0.125                | 240.168 | 0.128                | 235.051 | 0.125                | 239.541 |
| 40            | 0.167                | 240.010 | 0.172                | 232.982 | 0.169                | 236.851 |
| 50            | 0.209                | 238.996 | 0.214                | 234.085 | 0.209                | 239.021 |
| 60            | 0.250                | 239.982 | 0.254                | 236.541 | 0.252                | 237.658 |
| Average       |                      | 239.259 |                      | 235.168 |                      | 237.769 |

**Table 4:** Dynamic viscosity ( $\eta$ ) and kinematic viscosity ( $\nu$ ) of four viscous oils.

| Oils                 |                             |                 |                     |                    |
|----------------------|-----------------------------|-----------------|---------------------|--------------------|
| Parameters           | Lubricant oil               | Transformer oil | Gasoline engine oil | Cold lubricant oil |
| 1 <sup>st</sup> iron | Average radius = 0.75626 mm |                 |                     |                    |
| $v_t$ (mm/s)         | 239.259                     | 149.721         | 129.911             | 99.064             |
| $\eta$ (mPa.s)       | 31.925                      | 50.574          | 58.773              | 76.008             |
| $\nu$ (cSt)          | 36.630                      | 54.687          | 67.247              | 79.282             |
| 2 <sup>nd</sup> iron | Average radius = 0.74981 mm |                 |                     |                    |
| $v_t$ (mm/s)         | 235.168                     | 146.641         | 124.933             | 95.008             |
| $\eta$ (mPa.s)       | 31.928                      | 50.759          | 60.077              | 77.907             |
| $\nu$ (cSt)          | 36.635                      | 54.887          | 68.739              | 81.263             |
| 3 <sup>rd</sup> iron | Average radius = 0.75914 mm |                 |                     |                    |
| $v_t$ (mm/s)         | 237.769                     | 152.961         | 130.904             | 100.438            |
| $\eta$ (mPa.s)       | 32.370                      | 49.880          | 58.772              | 75.540             |
| $\nu$ (cSt)          | 37.141                      | 53.937          | 67.247              | 78.794             |

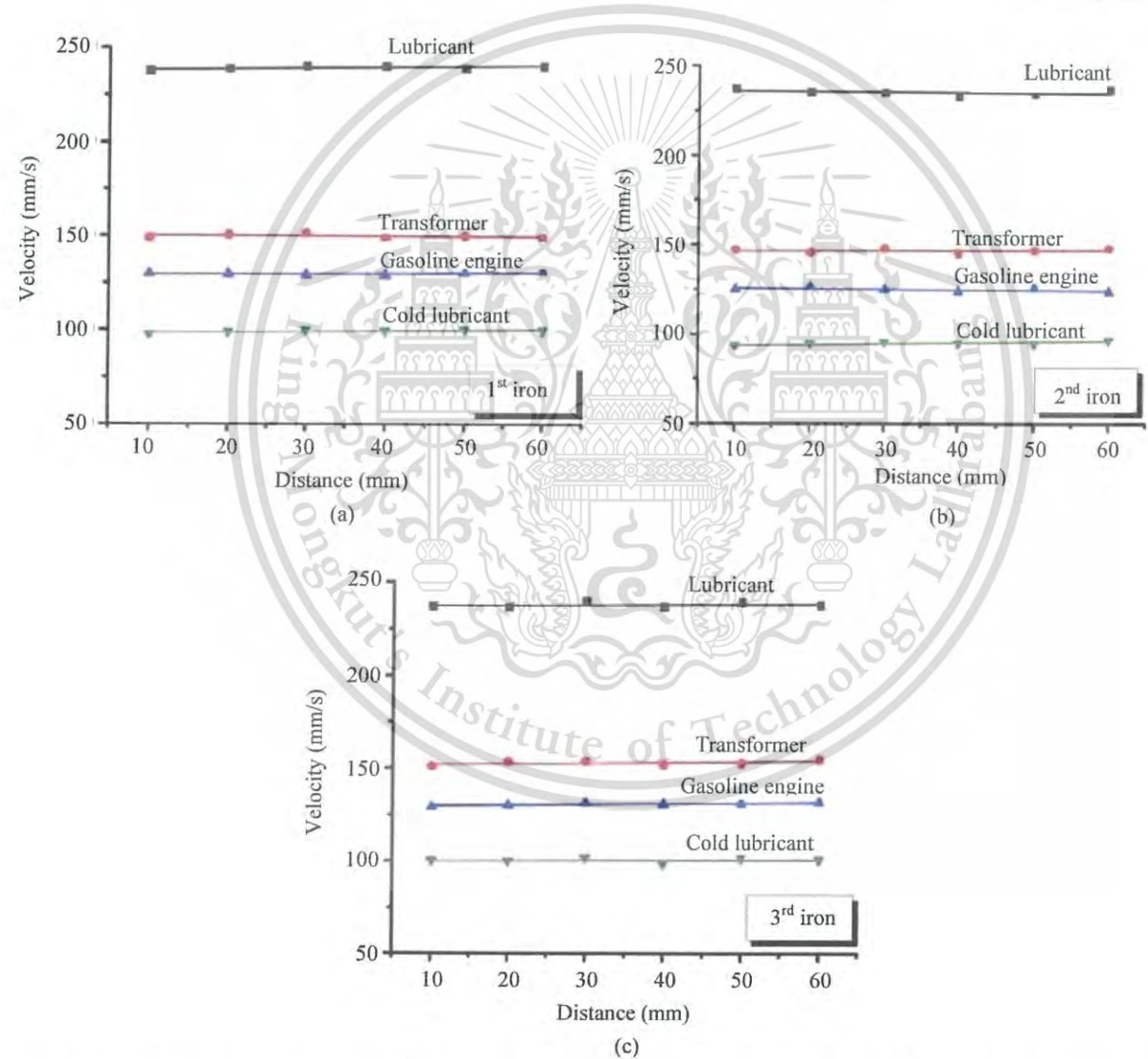


**Fig. 5:** Variation of spherical iron velocity with falling distance of: (a) first irons, (b) second iron and (c) third iron in four different viscous oils

Then, the dynamic viscosity of all four viscous oils using three spherical irons were determined and the results are given Table 4.

The relationship between dynamic viscosity ( $\eta$ , in mPa.s unit) and kinematic viscosity ( $\nu$ , in cSt unit) is given by:

$$\eta = \rho_f \nu \times 10^{-3} \quad (8)$$

Therefore, the kinematic viscosity of all four viscous oils were calculated and the results are given Table 4.

From the dynamic viscosity ( $\eta$ ) given in Table 1, for example the lubricant oil, the  $\eta$  as obtained from three spherical irons are 31.925, 31.928 and 32.370 mPa.s, respectively, which are in good agreement. The dynamic viscosity for lubricant oil, transformer oil, gasoline engine oil and cold lubricant oil are approximately 31.925, 50.574, 58.773 and 76.008 mPa.s, respectively. Therefore, the cold lubricant oil gives the highest dynamic viscosity.

To compare the results obtained in this work with those of standard values of ASTM D445 as given Table 1, it is necessary to convert the dynamic viscosity ( $\eta$ ) into the kinematic viscosity ( $\nu$ ) by Equation (7) as mentioned above. The kinematic viscosity ( $\nu$ ) of all four viscous oils obtained from three spherical irons are displayed in Fig. 6.

From Fig. 6, it is clearly observed that the kinematic viscosity of all four viscous oils obtained from the first, second and third spherical irons are approximately equal.

Furthermore, it is seen that the kinematic viscosity values obtained in this work are higher than those of standard values as given in Table 1. The difference in kinematic viscosity values are due to the temperature difference of the viscous oils. Since all the experiments in this work were performed at 27°C while the standard measurements were carried out at 40°C. However, it is observed that the higher viscous oil temperature results in the lower kinematic viscosity.

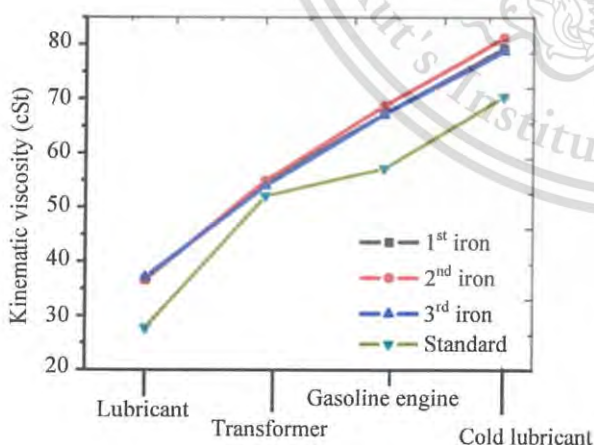


Fig. 6: Comparing the kinematic viscosity between the experimental results and standard values for four viscous oils

## Conclusion

The digital in-line holographic based on Mach Zehnder interferometer was setup for the determination of dynamic viscosity of four viscous oils. In the system, the liquid chamber filled with the viscous oil to be studied was developed. Three spherical irons of about the same diameter were used as the falling objects in the liquid chamber. The hologram images of the spherical iron falling along its entire path were recorded as a video file on the CMOS camera. The recorded hologram images were reconstructed on the holoviewer program via MATLAB. Then, the diameter and velocity of the spherical iron were obtained. Finally, the dynamic viscosity ( $\eta$ ) of all four viscous oils were determined. It can be concluded that this method is the simple and precise tool for the determination of dynamic viscosity of fluids.

## Acknowledgement

Rittirong Nuansri would like to thank Dr. Witoon Yindeesuk, Head of Physics Department for providing all facilities to make this work complete. This article has been supported the reconstructed tool from Department of Physics, Michigan Technological University, U.S.A.

## Funding Information

This work was financially supported by the Department of Physics, King Mongkut's Institute of Technology Ladkrabang.

## Author's Contributions

**Rittirong Nuansri:** Carried out the experimental setup, collected all the measurement data and prepared the original manuscript.

**Pichet Limsuwan:** Helped in writing the manuscript.

**Prathan Buranasiri:** Read and approved the manuscript.

## Ethics

This article is original and contains unpublished material. It is confirmed that all authors have read and approved the manuscript and there are no ethical issues involved.

## References

- Collinson, C. and T. Roper, 1995. Particle Mechanics. Elsevier Ltd., Oxford, pp: 30. ISBN: 0-340-61046-8.
- Darakis, E., T. Khanam, A. Rajendran, V. Kariwala and T.J. Naughton *et al.*, 2009. Microparticle characterization using digital holography. Chemical Eng. Sci., 65: 1037-1044. DOI: 10.1016/j.ces.2009.09.057

- Desse, J.M., P. Picart and P. Tankam, 2011. Digital color holography applied to fluid and structural mechanics. *Optics Lasers Engineering*, 50: 18-28. DOI: 10.1016/j.optlaseng.2011.06.018
- Gabor, D., 1948. A new microscopic principle. *Nature*, 161: 777-778. DOI: 10.1038/161777a0
- Hughes, W.F. and J.A. Brighton, 1991. *Theory and Problems of Fluid Dynamics*. McGraw-Hill, Inc., Singapore, pp: 5. ISBN: 0-07-031117-x
- Khatmullina, L. and I. Isachenko, 2016. Settling velocity of microparticles of regular shapes. *Marine Pollution Bulletin*, 114: 87-880. DOI: 10.1016/j.marpolbul.2016.11.024
- Kim, M.K., 2011. *Digital Holographic Microscopy*. Springer, New York, USA, ISBN-10: 978-1-4419-7792-2, pp: 47-50.
- Micó, V., C. Ferreira, Z. Zalevsky and J. García, 2010. Basic principles and applications of digital holographic microscopy. *Microscopy: Science, Technology, Applications and Education*, 1411-1418.
- Mott, R.L., 1994. *Applied Fluid Mechanics*. 4th Edn., Macmillan Publishing Company, New York, ISBN-10: 0-02-384231-8, pp: 477.
- Murata, S. and N. Yasuda, 2001. Potential of digital holography in particle measurement. *Optics Laser Technology*, 32: 567-574.
- Penelet, G., M. Leclercq, T. Wassereau and P. Picart, 2015. Measurement of density fluctuations using digital holographic interferometry in a standing wave thermoacoustic oscillator. *Experimental Thermal Fluid Science*, 70: 176-184. DOI: 10.1016/j.expthermflusci.2015.09.012
- Plaipichit, S. and P. Buranasiri, 2014. Moisture effect of fingerprint using total internal reflection digital in-line holography. *Optical Engineering*, 53: 112315. DOI: 10.1117/1.OE.53.11.112315
- Sánchez-Ortiga, E., P. Ferraro, M. Martínez-Corral, G. Saavedra and A. Doblas, 2011. Digital holographic microscopy with pure-optical spherical phase compensation. *Optical Society America*, 28: 1410-1417. DOI: 10.1364/JOSAA.28.001410
- Schnars, U. and W. Jueptner, 2005. *Digital Holography*. Springer Berlin Heidelberg, New York, ISBN-10: 3-540-21934-x, pp: 44-54.
- Schnars, U. and W. Jüptners, 1994. Direct recording of holograms by a CCD target and numerical reconstruction. *Applied Optics*, 33: 179-181.
- Serway, R.A. and J.W. Jewett, 2014. *Physics for Scientists and Engineers with Modern Physics*. 9th Edn., CENGAGE LEARNING, USA, ISBN-13: 978-1-133-95399-9, pp: 423-425.
- Sun, H., D.C. Hendry, M.A. Player and J. Watson, 2007. In situ underwater electronic holographic camera for studies of plankton. *IEEE J. Oceanic Engineering*, 32: 373-382. DOI: 10.1109/JOE.2007.891891
- Xu, W., M.H. Jericho, I.A. Meinertzhagen and H.J. Kreuzer, 2001. Digital in-line holography for biological applications. *PNAS* 98: 11301-11305. DOI: 10.1073/pnas.191361398

## Author Biography

**Name :** Mr.Rittirong Nuansri  
**Date of Birth :** July 21, 1984  
**Address :** 83 Moo 9, Prutiew sub-district, Khaophanom district, Krabi 81140  
**Education :**

1990-1999 Primary and secondary school at Banbangriang school, Krabi Thailand  
 2000-2002 High school at Ammartpanichnukul school, Krabi Thailand  
 In Science-Mathematic Program  
 2003-2006 King Mongkut's Institute of Technology Ladkrabang, Bangkok Thailand  
**B.Sc. Applied Physics**, Scientific Instrument and Industrial  
**Thesis :** Microwave Induced Plasma at Atmospheric Pressure  
**Advisor :** Asst. Prof. Warawoot Thowladda  
**GPA :** 3.44 (2<sup>nd</sup> Class honor)  
 2010-2011 King Mongkut's Institute of Technology Ladkrabang, Bangkok Thailand  
**M.Sc. Applied Physics**  
**Thesis :** Multi Higher-Order Anisotropic Self-Diffraction in Cerium Doped Barium Titanate Crystal  
**Advisor :** Asst. Prof. Prathan Buranasiri  
**GPA :** 3.77

**Scholarship** Science Achievement Scholarship of Thailand (2010-2014)

### Academic Publications

1. Optical tweezer system with no fluorescent confocal microscope for trapping colloidal nanoparticles (Published in *Ukrainian Journal of Physical Optics*)
2. Determination of Dynamic Viscosity of Viscous Oils using Mach Zehnder Digital Holographic Method (Published in *American Journal of Applied Sciences*)