Report of Cooperative Education

Reduction of Steam Loss and Study of the Efficiency of Hot Oil Furnace in Purified Terephthalic Acid Production

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รายงานสหกิจศึกษาฉบับสมบูรณ์

การลดไอน้ำสูญเสียและการศึกษาประสิทธิภาพของเตาเผาในกระบวนการผลิตกรดเทเรฟทาลิกบริสุทธิ์

โสภณัฐ หัตถกิจจานุกิจ

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ABSTRACT

This project aims at enhancement energy efficiency in terms of reduction of steam loss and study the efficiency of hot oil furnace in a purified terephthalic acid production. One of causes of the steam loss in PTA production is the failures of steam traps. Two types of steam trap failure are cold failure which is accumulation of condensate in the steam trap and leak failure of steam trap. For steam traps which are cold failure, the possible causes of steam trap failure of heat exchanger 102 are high load of condensate and unsuitable type of steam trap. This steam trap should be used the mechanical steam trap and larger capacity. The possible causes of steam trap failure of dryer 304 and heat exchanger 504 are inability to discharge air and blocking the orifice from dirt. These steam traps should be checked air venting, cleaned, and removed dirt at steam traps. The possible causes of steam trap failure of heat exchanger 901 are high backpressure of steam trap, inability to discharge air, and blocking from dirt. For recommendation, the controlled temperature of heat exchanger 901 should increase and steam trap should be checked air venting, cleaned, and removed dirt at steam traps. The possible causes of steam trap failure of steam jacketed drum 509 and heater steam drum 1206 are low differential pressure and unsuitable types of steam traps. These steam traps should be used the mechanical steam traps. For steam trap which is leak failure, the possible causes of steam trap failure of dryer 304 are damage of internal part of steam trap and blocking from dirt. This steam trap should be checked internal part of steam trap, cleaned, and removed dirt at steam trap. In hot oil furnace system, excess oxygen in flue gas is a variable which affects the efficiency of hot oil furnace. After create the correlation between furnace efficiency and excess oxygen by STAT program, it was found that the optimum excess oxygen was 3.0% and the furnace efficiency was 93%. When excess oxygen was adjusted with controlling other variables related furnace efficiency to constant in order to test the optimum excess oxygen from STAT program, optimum excess oxygen was 1.3% which was the normal operation and the furnace efficiency was 89%. The errors of optimum excess oxygen from STAT program come from an average value of lower heating value of flue gas (900 BTU/SCF) and mass flow rate of hot oil (620 ton/h).

Keywords: Steam loss, Steam trap, Furnace efficiency, Excess oxygen

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TABLE OF CONTENTS

Page

Part II: Study the efficiency of hot oil furnace.

CHAPTER III. RESEARCH METHODOLOGIES

Part I: Reduction steam loss from purified terephthalic acid production.

Part II: Study the efficiency of hot oil furnace.

CHAPTER IV. RESULTS AND DISCUSSION

Part I: Reduction steam loss from purified terephthalic acid production.

Part II: Study the efficiency of hot oil furnace.

CHAPTER V. CONCLUSIONS AND SUGGESTIONS

Part I: Reduction steam loss from purified terephthalic acid production.

Part II: Study the efficiency of hot oil furnace.

APPENDIX

APPENDIX C EXAMPLES OF CALCULATION

APPENDIX REGRESSION EQUATION FROM MINITAB PROGRAM

LIST OF FIGURES

Page

Page

LIST OF TABLES

CHAPTER I

INTRODUCTIONS

Part I: Reduction steam loss from purified terephthalic acid production.

1.1 Background

Purified terephthalic acid is necessary feedstock for production of polyester fiber, polyethylene terephthalate acid and film. The purified terephthalic acid produced from SCG Chemical is high productivity and sold both inside and outside country. Therefore, purified terephthalic acid production should be high quality and low cost in order to compete with another company. For this reason, the company provides the policy to reduce the cost of production so as to create consistency for the company.

Siam Mitsui PTA Company Limited (SMPC) is a joint venture between SCG Chemical Company and Mitsui Chemicals Inc. (MCI), Japan. The SMPC produces and distributes the purified terephthalic acid which is the raw material to produce polyester products. The SMPC produces purified terephthalic acid about 1 million tons per year. The SMPC has 3 plants in Map Ta Phut Industrial Estate. Each plant includes two production units that are crude terephthalic acid unit (CTA unit) and purified terephthalic acid unit (PTA unit).

The purified terephthalic acid production process used a lot of energy to produce the product. The sources of energy that use in the PTA production are fuel gas, steam and electrical energy. The steam is the important energy used for the production process such as heating the product at dryer, preheating the raw materials. The steam which is purchased from the power plant divides into two types of steam that are low pressure steam (15 kg/cm^2) and medium pressure steam (25 kg/cm^2). The cost of steam is about 150 million baht per year. In the recent year, the steam consumption has increased. The cause of increasing of steam loss is steam loss. Therefore, the production engineers need to find the causes of steam loss and find the recommendations in order to reduce steam loss.

1.2 Objective

To reduce steam loss in PTA plant 2

1.3 Scope of Work

1.3.1 To study the steam system in PTA plant 2

1.3.2 To study principles of steam traps

1.3.3 To find the equipment which loss the steam in PTA plant 2

1.3.4 To find the causes of steam loss and recommendations to reduce steam loss

1.4 Expected Output

The causes and recommendations to reduce steam loss in PTA plant 2

Part II: Study the efficiency of hot oil furnace.

1.1 Background

The purified terephthalic acid production process does not only use the steam to heat the process stream but hot oil is the important heating medium to heat the process stream. Most of hot oil users are used for preheating the terephthalic acid powder (TA-powder) from crude terephthalic acid unit. TA-powder which is the solid phase is heated by steam and hot oil in order to dissolve in water into liquid phase before it is fed to PTA reactor. After hot oil was used, it is transferred to hot oil furnace in order to heat up again. Source of energy in hot oil furnace is heat of combustion of fuel gas. In each year, the cost of fuel gas is about 170 million baht per year. Therefore, hot oil furnace should be operated at high efficiency in order to reduce the fuel gas consumption. Increasing of the hot oil efficiency relates with the excess oxygen in flue gas. This project studies about adjusting the excess oxygen in order to enhancement the furnace efficiency and reduce the fuel gas consumption in hot oil furnace.

1.2 Objective

To study the efficiency of hot oil furnace in PTA plant 2

1.3 Scope of Work

1.3.1 To study the hot oil furnace system in PTA plant 2

1.3.2 To study the effect of adjustment of percent oxygen excess on the furnace efficiency

1.3.3 To find the optimum excess oxygen in hot oil furnace in PTA plant 2

1.4 Expected Outputs

1.4.1 Enhancement of hot oil furnace efficiency in PTA plant 2

1.4.2 The value of optimum percent oxygen excess of hot oil furnace in PTA plant 2

CHAPTER II

LITERATURE REVIEWS

Part I: Reduction steam loss from purified terephthalic acid production.

2.1 Purified terephthalic acid (PTA) production process (SMPC Company, 2004)

Siam Mitsui PTA Company (SMPC) produces purified terephthalic acid (PTA) powder about 1 million ton per year with an hourly design rate of 44.1 ton per hour. The SMPC is located in Rayong province and has three PTA plants. Each PTA plant consists of two major units which are Crude Terephthalic Acid (CTA) unit and Purified Terephthalic Acid (PTA) unit.

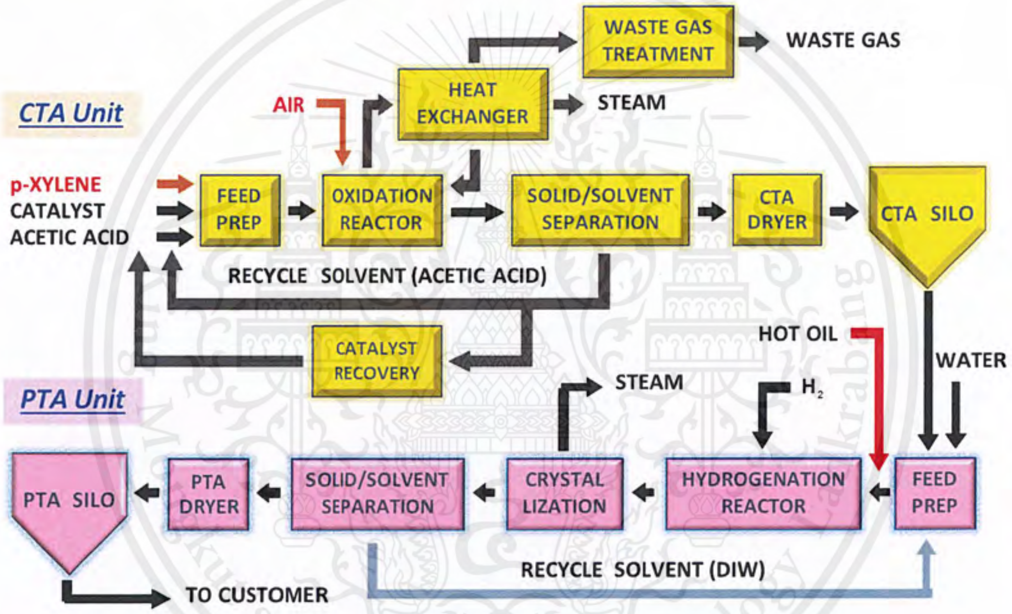


Figure 2.1 Flow diagram of purified terephthalic acid (PTA) production (SMPC Company, 2004)

In CTA unit, production process is used for catalytic liquid phase air oxidation of paraxylene. Acetic acid solvent, paraxylene, catalyst solution and air are continuously fed to the CTA reactor. The catalyst solution consists of cobalt acetate, manganese acetate and tetrabromoethane. Exothermic heat is removed by condenser. In the reaction, water is formed which is separated from acetic acid by overhead of distillation column in order to keep the water concentration in the reactor.

Products from the reactor are depressurized and cooled and then terephthalic acid is precipitated. Precipitated terephthalic acid is centrifuged to remove acetic acid and dried at CTA dryer. The dried solids that are TA-powder are conveyed to the CTA silos.

4-Carboxy benzaldehyde (4-CBA) is the main impurity in TA-powder. 4-CBA is changed to para-toluic acid (p-TA) by hydrogenation reaction that can be dissolved in water. In PTA unit, crude terephthalic acid is dissolved in water at high temperature and pressure. The sources of heat come from hot oil and steam. The reaction in PTA reactor is hydrogenation reaction which converts 4-CBA to p-TA. The p-TA dissolved in water is removed by rotary filters. The purified terephthalic acid is crystallized by depressurizing and dried at PTA dryer. The dried solids that are PTA-powder are conveyed to the PTA silos and then they are sold to customers.

2.2 Energy loss of steam system (กรมพัฒนาพลังงานทดแทนและอนุรักษ์พลังงาน, 2550)

Steam system consists of three parts that are stream generation, steam distribution and steam using. Therefore, the sources of energy loss of steam system can come from three parts same as steam system which are energy loss from stream generation, energy loss from steam distribution and energy loss from steam using.

Energy loss from stream generation depends on boiler efficiency, combustion improvement, rate of heat transfer both hot and cold sides. The many factors that affect the boiler efficiency are excess energy loss from flue gas, heat transfer between two surfaces, improper fuel/air ratio, fuel burners which lack proper maintenance and energy loss from the wall of boiler.

Energy loss from steam distribution comes from leaking of steam, improper pipe insulation, improper steam trap and return of condensate. Returning of condensate not only saves the fuel but saves water and increases life time of boiler. Improper type or size of steam trap affects to decrease the efficiency and life time of steam trap. Energy loss from steam using comes from poor heat transfer of surface, improper steam trap and insufficient insulation.

2.3 Steam trap

Steam is water that was changed into gas phase. Steam is colorless and used to deliver energy. Advantages of steam are low toxicity, ease of transportability, high efficiency, high heat capacity, and low cost with respect to the other substances. Steam trap is the automatic valve that discharges condensate and non-condensable gases and prevents the live steam passing through steam trap. The basic considerations to determine the size of steam traps, you should know or calculate the condensate loads, safety factor, differential pressure and maximum allowable pressure.

2.3.1 Objectives of steam traps (Armstrong International, 2011)

Objectives of steam traps are condensate discharge from equipment, not allow the escape of steam and discharge air and non-condensable gas. In addition, steam trap should provide many characteristics.

1. Minimized steam loss from steam trap
2. Long service life and save money on maintenance
3. Steam trap should be resistant the corrosion.
4. Air and carbon dioxide venting should be set up. The air reduces heat transfer of the steam. And, the carbon dioxide can form in carbonic acid.
5. Operation against back pressure. Steam trap should be operated under the pressurized return line.
6. Seam trap should be operated in dirty steam that passes through strainer screens. Solid particles can cause the erosion problem.

2.3.2 Types of steam traps (Spirax Sarco Limited Company, n.d.)

Steam trap can divide into three types that are classified by International Standard ISO 6704:1982. Types of steam traps are mechanical steam trap, thermodynamic steam trap and thermostatic steam trap. Mechanical steam traps are operated by changing in fluid density between steam and condensate. These steam traps include ball float trap and inverted bucket trap. Both steam traps have a float that is a moving part. Thermodynamic steam traps are considered the phenomenon of flash steam from condensate. These steam traps include disc, impulse and labyrinth steam traps. In thermostatic steam trap, the temperature of saturated steam is determined by pressure. When saturated steam gave up latent heat, condensate is formed at steam temperature. A result of any heat loss, the temperature of the condensate will reduce below the steam temperature. A thermostatic trap will remove the condensate at low temperature. As steam reaches the trap, the temperature of steam trap will increase and then the steam trap closes.

1. Thermostatic steam traps

Principles of thermostatic steam trap is the differential temperature of steam and condensate that effects to the expansion of metal or phase changing from liquid to gas. These types of steam traps are divided into two types that are bimetallic steam trap and balance pressure steam trap.

a. Bimetallic steam trap

Bimetallic steam trap uses the expansion of a straight metal. Two strips of different metals are welded together. The two strips deflect after heating by steam temperature.

The bimetallic steam trap should be operated at a constant temperature of steam. When pressure and temperature were varying, this steam trap is not suitable. The expansion of single bimetal strip is small, which is slowly close and open the valve. The performance of steam trap can be determined by the differential temperature between the steam saturated curve and trap operating temperature curve. The ideal trap operating temperature curve will be nearly and below the steam saturated curve.

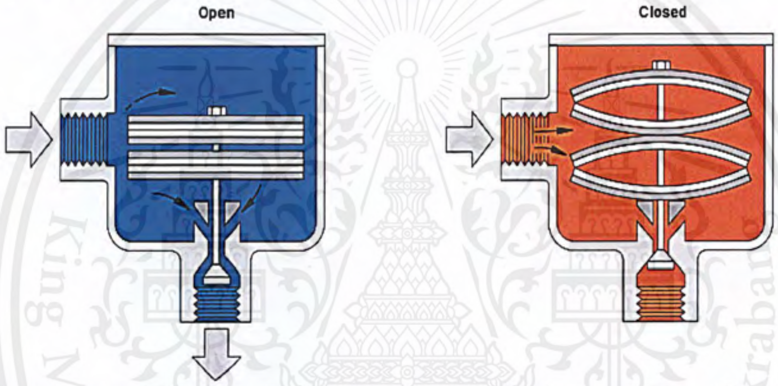


Figure 2.2 Bimetallic steam trap with two leaf element (Spirax Sarco Limited Company, n.d.)

Advantages of the bimetallic steam trap

1. The steam trap can adjust to the discharge temperature.
2. The steam trap can be installed in any position.
3. The steam trap can fully open when temperature of steam trap was cool. Therefore, the steam trap is good for air venting on start-up load.
4. The steam trap can be damaged by water hammer.
5. The failure mode of trap is opened.
6. Energy efficient

Disadvantages of the bimetallic steam trap

1. Dirt particles can prevent tight valve closing.
2. The condensate discharge temperature does not follow the saturated temperature.

3. The steam trap slowly responds to discharge condensate when condensate load was changed.

4. Difficult to check at field

5. Frequent adjustment is necessary for fluctuating pressures.

b. Liquid expansion steam trap

The liquid expansion steam trap is the simple thermostatic traps which shown in Figure 2.3. In liquid expansion steam trap, the element contains the oil which expands when is heated in order to close the valve of the trap. The adjustment allows the temperature of the trap discharge between 60°C and 100°C, which is ideally suited trap to discharge air and cold condensate.

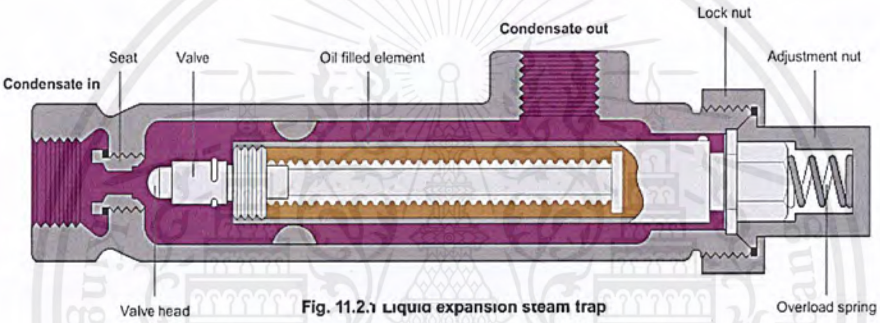


Figure 2.3 Liquid expansion steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the liquid expansion steam traps

1. The steam trap can discharge condensate at low temperature.
2. The steam trap is fully opened when it was cold.
3. The steam trap can discharge air on start-up load.
4. The steam trap can be installed in any position.
5. The failure mode of trap is opened.

Disadvantages of the liquid expansion steam traps

1. The tube of element can be damaged by corrosion of condensate.
2. If the temperature of discharge condensate is 100 °C or below, it should not be used on applications.
3. The steam trap slowly responds to discharge condensate when the condensate load was changed.
4. Dirt particles can block the tight close.
5. Difficult to check at field

c. Balanced pressure steam trap

The operation of balanced pressure steam trap is the balance pressure in the capsule. Inside the capsule contains a special liquid and water. The boiling point of mixture is below the water. In hot condition of condensate, the mixture in capsule vaporizes to the vapor phase. The vapor pressure increases in capsule and expands to close the valve. In cold condition of condensate, the mixture in the capsule does not vaporize that effects to low vapor pressure and then valve is opened. Therefore, air and condensate will be removed. The differential concentration of special liquid in the water causes the difference in boiling points. The tin wall of a capsule can quickly respond to open and close the valve.

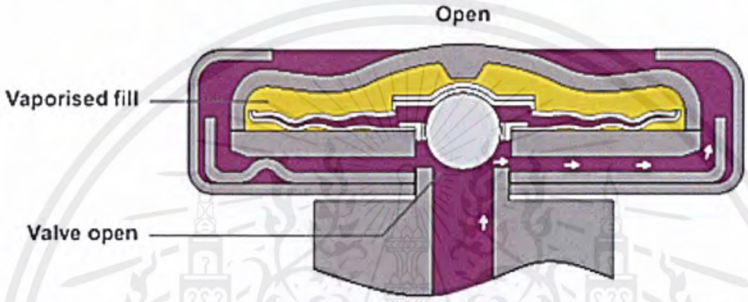


Figure 2.4 Balanced pressure steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the balanced pressure steam trap

1. The steam trap is small, light and has a large capacity.
2. The steam trap is fully opened when it was cold and can discharge air on start-up load.
3. The capsule and valve seat are easily removed and replaced which does not remove the trap from the line.
4. The failure mode of trap is opened.

Disadvantages of the balanced pressure steam trap

1. If the discharge condensate temperature does not drop below the steam temperature, the steam trap will not open.
3. Steam trap slowly responds to discharge condensate when condensate load was changed.
4. Dirt particles can block the tight close.
5. Difficult to check at field

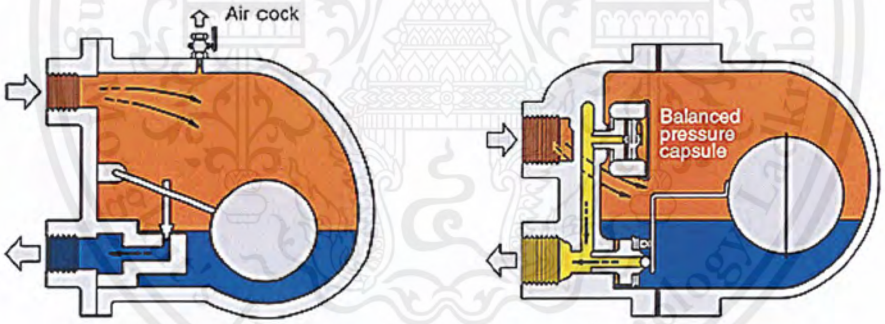
2. Mechanical steam traps

The operation of mechanical steam trap depends on the difference in density between condensate and steam. These type include ball float steam trap and inverted bucket steam trap.

a. Ball float steam trap

The ball float steam trap operates by differential density between condensate and steam. In the trap, ball float can rise or dip which depends on the level of condensate. After condensate flowed through the trap, the level of condensate increases and pushes a ball float to rise. Effects of a ball floating are opening a valve and removing air and condensate to condensate return line. Conventional ball float steam trap has an air cock to vent the air. But modern trap uses a thermostatic air vent, which can remove the air automatically.

The operation of thermostatic air vent is same as the balanced pressure capsule. A thermostatic air vent is located at the top of the steam trap that is above the condensate level. When air or non-condensable gas accumulated in the trap, the temperature in the trap decreases. Then, thermostatic air vent opens to remove the condensate.



(a) (b)

Figure 2.5 Float trap with air cock (a), Float trap with thermostatic air vent (b)

(Spirax Sarco Limited Company, n.d.)

Advantages of the float steam trap

1. The steam traps can continuously discharge the condensate at steam temperature that follows the saturated temperature.
2. Free float is the one moving part.
3. If the steam trap has air venting, it can discharge air freely.
4. The steam trap is simple construction and can be operated at high pressure.
5. Energy efficient

Disadvantages of the float steam trap

1. The free-float can be damaged by water hammer.

2. The steam trap should be installed correct position (Tolerance angle for installation -5°).

3. The steam trap is large and heavy.

4. The failure mode of trap is closed.

5. If the steam trap is higher differential pressure, the free-float can close because steam trap is designed to balance between pressure force and buoyancy force of float.

b. Inverted bucket steam trap

The operation of inverted bucket steam trap consists of an inverted bucket that is the moving part. An inverted bucket is connected by a lever to a valve. A small air vent hole is the important part which removes air and steam from the inverted bucket.

The action of inverted bucket steam trap is as follows. First, the inverted bucket is lying on the bottom that is pulling a valve open. The condensate flows and fills up the inverted bucket. The inverted bucket sinks that effects to open a valve. Then, condensate is continually discharged. When steam arrived, the inverted bucket floats and effects to close a valve. After that, steam in the inverted bucket condenses to liquid phase or is removed through an air vent hole. As a result, the inverted bucket sinks again. Accumulated condensate is discharged and the cycle is repeated again. Air in the inverted bucket is removed through an air vent hole into the head of steam trap for passing the air through the valve. The large air vent hole is the faster air and steam removal. The valve of this steam trap is opened by the weight of an inverted bucket and closed by steam pressure. The design of steam trap closing is forced by buoyancy force when steam was holding. Therefore, these two properties are the parameters to determine the discharge capacity and operating pressure of steam trap.

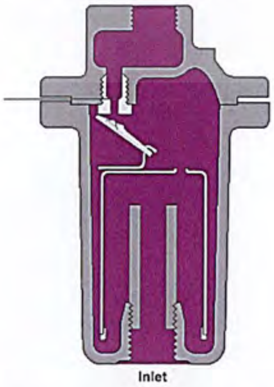


Figure 2.6 Inverted bucket steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the inverted bucket steam trap

1. The steam trap is simple construction and can be operated at high pressure.
2. The steam trap can discharge the condensate at steam temperature that follows the saturated temperature.
3. The steam trap can be used for an applications where steam locking occurs.
4. The failure mode of steam trap is opened.

Disadvantages of the inverted bucket steam trap

1. The steam trap can slowly discharge air because inverted bucket has a small size of hole.
2. The failure mode of trap is unpredictable which can be opened or closed.
3. The steam trap should be installed in correct position.
4. If the steam trap is not enough water holding in the trap, steam can leak through the outlet valve.
5. If the steam trap is higher differential pressure, the inverted bucket trap can close.

3. Thermodynamic steam traps

Principles of thermodynamic steam trap depends on the dynamics of water and flash steam. This type of steam trap is robust and can operate at high temperature and pressure.

a. Traditional thermodynamic steam trap (Disc steam trap)

Traditional thermodynamic steam trap or disc steam trap relies on the formation of flash steam that comes from hot condensate. The flash steam is generated by arriving at high temperature and pressure. A moving part is a disc that stays above the control chamber or cap.

At start-up, the disc is raised by condensate pressure which removes cool condensate immediately. When hot condensate arrived the chamber, the flash steam is generated by dropping pressure. The flash steam is high velocity that causes a low pressure under the disc. The disc is closed to the seat because the top of disc is more force than the underside and then condensate cannot be removed. After the flash steam at the top of disc condenses, the pressure at the top of disc will decrease. The disc is raised by condensate pressure under the disc.

The increasing of backpressure at discharge reduces the dynamic effect. Therefore, the design of steam trap should be individually designed which is suitable for the maximum allowable backpressure of their steam trap. The disc steam trap can be removed the air.

If a steam trap contains a lot of air, steam trap should be discharged the air by separating air vent with parallel the trap.

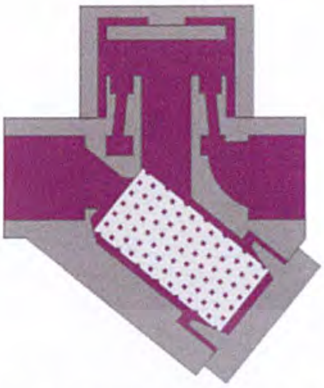


Figure 2.7 Disc steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the disc steam trap

1. The steam trap is small size and light weight and can be installed in any position.
2. The steam trap is suitable for wide pressure range.
3. The steam traps can discharge the condensate at steam temperature.
4. Easily to check at field

Disadvantages of the disc steam trap

1. If backpressure is more than 50% of inlet pressure, the steam trap can be opened by backpressure.
2. Steam can loss at normal operation and increases by atmospheric effects.
3. Cycle of steam trap operation increases due to clog of dirt particles
4. The steam trap is intermittent operation which effects to quick wear of disc.

b. Labyrinth steam trap

This steam trap is a simple design that consists of baffles and can be adjusted by a hand wheel. When hot condensate arrived the trap, the flash steam is generated by decreasing pressure in each of baffle. The flash steam in expansion chambers prevents the escape of hot condensate. After the temperature of condensate decreases until flash steam does not occur, the condensate will pass through the trap as the water. The baffle plates can be adjusted by changing the position relative to the body and size of the orifice.

Labyrinth steam trap has not the moving part which is controlled by pressure and temperature of condensate. The trap can continuously discharge condensate.

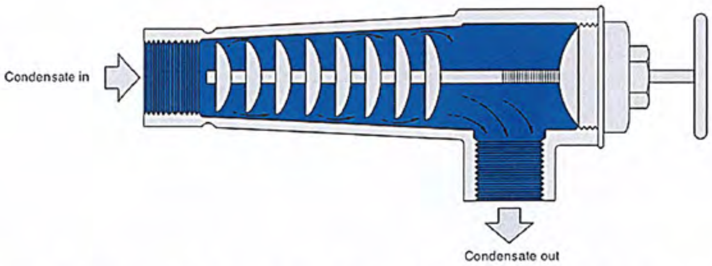


Figure 2.8 Labyrinth steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the labyrinth steam trap

The steam trap does not have automatic part. That is little mechanical failure.

Disadvantages of the labyrinth steam trap

The steam trap can be adjusted by manual. If steam trap setting is not correct, steam leaking or waterlogging will occur.

c. Impulse steam trap

The impulse seam trap is directly operated from temperature and pressure of the steam. This type consists of orifice, a piston disc, a main valve, and valve body. Condensate pushes under the disc and passes around the piston disc to the chamber. The pressure upper the piston disc is less than under that causes the piston disc lift the main valve. So, condensate can discharge through the orifice and main valve.

When the temperature of condensate increased, condensate will form the flash steam. The pressure of flash steam at upper piston disc is higher than under which effects to close a main valve. In each opening of a main valve, a small amount of condensate is discharged. At high condensate load, a main valve should be wide in order to discharge the condensate. The impulse steam trap can continuously discharge the condensate.

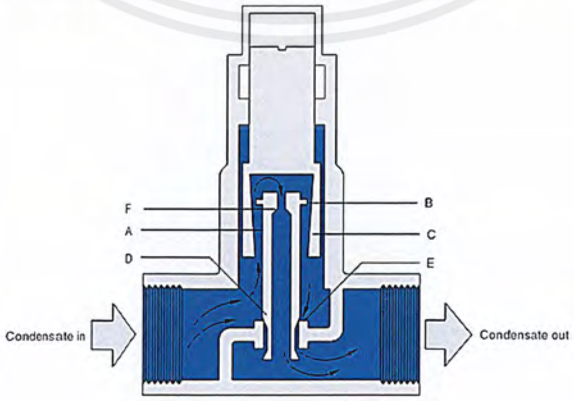


Figure 2.9 Impulse steam trap (Spirax Sarco Limited Company, n.d.)

Advantages of the impulse steam trap

1. The steam trap can be installed in any position.
2. The steam trap quickly responds to discharge the condensate when condensate load was changed.
3. They will work over a wide range of steam pressures without any change in valve size.
4. The failure mode of trap is opened.
5. The steam trap is good air venting.

Disadvantages of the impulse steam trap

1. Impulse steam trap can close when backpressure was more than 40% of inlet pressure.
2. Difficult to check at field because condensate is continuously discharged.
3. The steam trap is easily effected by dirt particles.
4. Steam can loss at normal operation

Table 2.1 Comparison the types of steam traps

Characteristic	Inverted bucket	Float	Thermostatic	Thermodynamic
Method of operation	Intermittent	Continuous	Intermittent	Intermittent
Energy conservation	Excellent	Good	Fair	Poor
Corrosion resistance	Excellent	Good	Good	Excellent
Vent air and CO_2 at steam temperature	Yes	No	No	No
Vent air capability	Poor	Good	Excellent	Poor
Operation against back pressure	Excellent	Excellent	Excellent	Poor
Handles dirt	Excellent	Poor	Fair	Poor
Physical size	Large	Large	Small	Small
Failure mode	Open	Closed	Open/close	Open/close

2.3.3 The steam trap selection process (Blue Bell, 2014)

Many factors used to select the steam trap are divided into several level.

Table 2.2 Steam trap selection criteria (Blue Bell, 2014)

First level criteria	Satisfy primary requirements
• Safety • Efficiency • Service life	Three types of steam traps can be good performance in this criteria when installation and steam trap size were properly.
Second level criteria	Affect overall utility
• Easily checking • Sensitivity to backpressure • Resistance to freeze damage • Dirt sensitivity • Installation versatility • Air venting • Responsiveness to changing loads • Resistance to shock vibration and water hammer • Predominant failure mode • Discharge mode • Condensate discharge temperature relative to saturation curve • Magnitude of condensate subcooling • Ease of maintenance	Each steam trap has different design that effects to differ in prominent and weakness points. The second criteria will help user to evaluate on installation or life cycle costs.
Third level criteria	Commercial considerations
• Product availability • Post-sales service • Warranty • Price	This criteria is based on the commercial which helps the user to select steam trap supplier.

For Table 2.2, each factor can be described in Table 2.3.

Table 2.3 Steam trap selection factors (Blue Bell, 2014)

Steam trap selection factors	Description
Safety	A good designed steam trap of steam trap manufacturer can produce the product safety. The Standard American Nation Standard Institute (ANSI) describes design and testing of steam trap which effects to the product safety.
Service life	The lifetime of steam trap is decreased when pressure and temperature were increased. Hot condensate can cause the corrosive and erosive problems. The designer should design the steam trap to prevent the problems by using the hardened materials.
Efficiency	The most steam traps which are failed to close do not loss steam when steam trap failed. The considerations of steam traps are both efficiency and functions. The stand point of thermostatic steam trap is efficiency because it can discharge the condensate at low temperature. The condensate will accumulate and prevent live steam passing through the trap. However, thermal efficiency of equipment is more important than efficiency of steam trap.
Ease of checking	Some types of steam traps can be observed the operation by listening the steam trap. The opening and closing of trap can be modulate or slower. Steam trap should be checked in order to know the steam trap condition. The float and thermodynamic steam traps can be investigated the conditions by listening. But, thermostatic steam traps are difficultly investigated.
Sensitivity to back pressure	When the condensate was discharged to the condensate return system, the backpressure can occur. The condensate discharge temperature of bimetallic steam trap decreases when the backpressure increased. The efficiency of thermodynamic steam trap decreases when backpressure was more than 50% of inlet pressure.

Table 2.3 Steam trap selection factors (Continued) (Blue Bell, 2014)

Steam trap selection factors	Description
Resistance to freeze damage	Some steam traps are susceptible to damage by freezing more other types of steam traps because of the difference on their design and materials. The bucket and float traps are not suitable because they can be damaged by freezing problem of condensate in the trap. But, bimetallic and thermostatic steam traps are suitable for this condition.
Dirt sensitivity	Dirt particles can clog and prevent to close the valve of steam trap. Therefore, live steam can leak and damage the seat of valve. Some thermostatic, thermodynamic and bucket steam traps have a small pore to discharge the condensate.
Installation versatility	Thermostatic and thermodynamic types of steam traps can be installed both horizontal and vertical directions. Mechanical steam trap is not flexible installation. Therefore, users need to know specific models for installation in either horizontal or vertical installations.
Air venting	Air should be removed from pipe line and equipment at start-up condition. If air can be quickly removed, the temperature of equipment will quickly reach the target temperature. Thermostatic type can quickly remove the air. While thermodynamic steam trap and bucket trap slowly remove the air. When equipment had many times to start and shutdown, the steam traps that can quickly vent the air are considered.
Responsiveness to changing load	Not all trap types can discharge condensate when condensate load was changed. Mechanical and thermodynamic steam traps can quickly respond to discharge condensate. Thermostatic steam trap needs to cool the condensate before trap opens and discharges a lot of condensate.

Table 2.3 Steam trap selection factors (Continued) (Blue Bell, 2014)

Steam trap selection factors	Description
Resistance to shock, vibration and water hammer	Although, design of steam system efforts to reduce vibration level, shock and water hammer. But, these causes are hardly eliminated at start-up condition. Thermodynamic and bimetallic steam traps are very rugged. The float trap can be damaged from these causes.
Predominant failure mode	Most steam traps are closed by clogging with dirt particles. But, some cases of steam traps can be opened. When thermodynamic and bimetallic steam traps damaged, the traps fail open. Inverted bucket trap can fail open or close. A trap that fails close will not loss of live steam. A trap that fails open will not affect the process conditions. A trap that fails open is more desirable than fails close because the process conditions can be maintained.
Discharge mode	The discharge mode of thermodynamic steam trap is cycle operation that is easily checked in the steam trap conditions. The discharge mode of float steam trap is continuous which can quickly respond when the load of condensate was changed.
Condensate discharge temperature relative to the saturation curve	Condensate discharge temperature is the temperature of condensate at inlet of steam trap coming from the equipment. The opening and closing cycle should occur at the condensate temperature which is close to the saturated temperature. The saturated temperature will be changed as the changing of steam pressure. Mechanical and thermodynamic steam traps can discharge the condensate at the saturation curve.

Table 2.3 Steam trap selection factors (Continued) (Blue Bell, 2014)

Steam trap selection factors	Description
Magnitude of condensate subcooling	Subcooling is the differential temperature between condensate and saturated temperature of steam. In the process, condensate should be discharged at the temperature that it forms in order to control the process parameters. A little of subcooling temperature is about 2-3 °F that called hot traps. Hot traps can discharge all condensate arriving the trap. A large of subcooling temperature is about 30 °F. The cold traps will improve overall system efficiency.
Ease of maintenance	Several manufacturers design the steam trap for simplify maintenance.

2.3.4 Factors that affect capacity of steam trap (Blue Bell, 2014)

Capacity of steam trap can be divided into three factors that are orifice or seat size, differential pressure between the inlet and outlet ends and temperature of condensate.

Table 2.4 Factors that effect a capacity of steam trap (Blue Bell, 2014)

Factors	Description
Orifice or seat size	The design of steam trap is carefully designed to determine the size of orifice and seat. The size of orifices of thermodynamic and mechanical steam traps are unchanged. But, the size of orifice of thermostatic steam trap can be changed depending on the temperature of condensate in steam trap.
Differential pressure	The amount of condensate that passes through the orifice depends on differential pressure between inlet steam trap and condensate return line. In some installations, the differential pressure may vary that effects to the condensate discharging.
Condensate temperature	The capacity of steam trap based on the condensate temperature. The discharge capacity increases when condensate temperature decreased with respect to steam temperature.

2.3.5 Installation guidelines (J.C. King and D. M. Sneed, 1985)

Steam trap should be installed in the correct installation. The following are general guidelines to install the steam trap.

1. The location of steam trap should be easily and quickly to remove or replace. The upstream and downstream should be installed the valves.

2. A test discharge with valve should be installed after the trap in condensate return systems.

3. Inlet and outlet piping size should be larger or equal to the size of steam trap. Some manufactures designed the steam traps with multiple inlets and outlets. All inlets and outlets that are not used must be closed.

4. The designing of steam trap used stainless steel in construction that is lighter and more compact.

5. Steam and condensate lines should be inclined. The improper installation may cause the water hammer that can damage the instrument and equipment. When discharge line stayed high level, check valve should be installed at the discharge of steam trap.

6. Steam traps that are float and inverted bucket should be installed in correct direction. When disc steam trap was installed in horizontal, the life of disc steam trap is doubled.

7. When steam valve was closed, the inlet pressure of steam trap may be less than the outlet pressure. Therefore, vacuum breakers should be installed to allow atmospheric pressure into the trap. Thermostatic trap should be installed in order to release the vapor locking.

8. Float and thermostatic traps should be used when the condensate load frequently changes. If they are installed at steam space, the all condensate that is formed will be released.

9. The traps that are not enough air venting and improper installation may cause the air locking. The traps should be installed near the source of condensate. The traps that are undersized is not effective to discharge condensate.

10. Water hammer can occur when high pressure condensate was discharged to low pressure condensate. The high pressure condensate can flash in low pressure line. Therefore, the condensate cannot be discharged to return line.

11. Bypass valve of steam trap can be opened when steam trap needed to maintain or replace. When bypass valve was opened, steam and condensate are quickly released to return line which loss the energy.

2.3.6 Fundamentals concerning trap (Blue Bell, 2014)

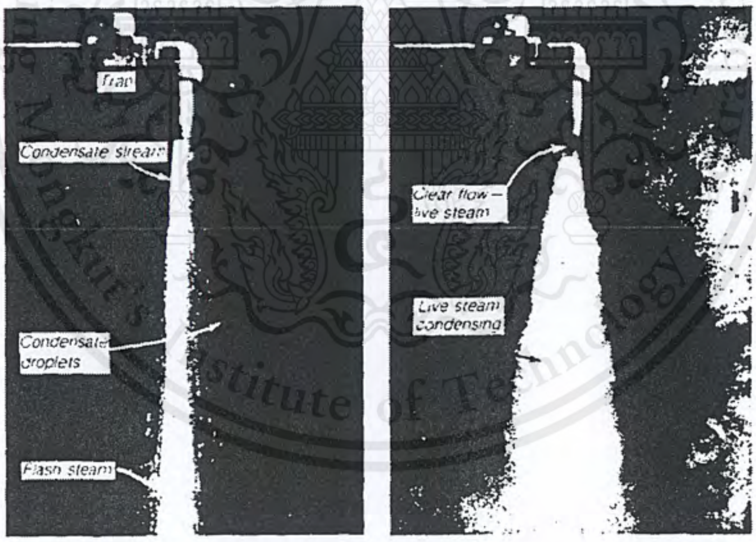
Steam trap inspection is process to investigate the performance of steam trap. If steam trap is same performance, it can be decided to O.K. If steam trap is not same performance, it can be decided that the trap may be faulty or incorrect installation. Three techniques that are used to investigate the steam trap are slight, sound and temperature.

1. Slight

Observation the condensate discharge can determine the working of steam trap. Training and experience is necessary for this technique. Observers should know about the difference between flash and live steam.

Flash steam is the lazy vapor that is formed when hot condensate is exposed to the atmosphere. The condensate will re-evaporate that is white cloud. The discharge of flash steam will be mixed with the hot condensate that does not re-evaporate.

Live steam is steam that is higher temperature, higher velocity discharge and clear flow. When live steam was discharged to the atmospheric condition, the live steam is condensed that can see in the visible cloud.



(a) (b)

Figure 2.10 Illustration of difference between flash steam (a) and live steam (b) (Blue Bell, 2014)

2. Sound detection

Sound detection technique is simple method to inspect the working of steam trap. Some steam traps operate in cycle. An inspector hears the cycle of part in steam trap such as disc, inverted bucket and piston disc. If condensate volume is low, the sound detection technique will be hard to detect. The industrial stethoscope is the simple and effective device.

3. Temperature measurement

Temperature measurement technique is useful for inspection the performance of steam trap. When condensate temperature was cool, the steam trap may have some problems such as flow blocking in the pipe. When condensate temperature was hot, the steam trap may leak the live steam.

2.3.7 Failures of steam traps

The reliability of steam can be improved by focusing on the performance of steam traps in order to successfully drain the condensate. The condensate which cannot be removed in the steam distribution causes the erosion and water hammer. In surveying the steam trap, an assessment of each trap's condition will be labeled either good or failed. In failed condition, failed traps can be labeled either cold failures or hot failures. Failures of steam trap can be caused by trap damage, debris or wear, or incorrect application or installation of the steam trap.

1. Cold failure

Cold failures of steam traps should be considered the highest priority. Cause of cold steam trap is the condensate which does not adequately drain to the condensate return line. Possible causes of cold failures are negative pressure different, under sizing, steam locking, high backpressure, inability to discharge air, debris or deposits and so on.

2. Hot failure

Hot failures which occur from leaking of live steam do not present the same safety issues as cold failure. Although, the steam leaking is inefficient, however condensate can be still discharged. The benefit of hot failure solving is economics-related. Possible causes of hot failures are backwards installation, incorrect orientation, oversizing and so on.

Part II: Study the efficiency of hot oil furnace.

2.1 Combustion principles (TSI Incorporated, 2004)

Combustion occurs when fuel reacted with the oxygen in the air as shown in Figure 2.11. One of products of combustion is heat used in the equipment. Other products are carbon dioxide and water. The combustion reaction is exothermic reaction. Combustion efficiency can be easy to enhance by monitoring the gases in the stack or flue gas which can conserve the fuel.

When complete combustion occurs, combustion efficiency will be high. Complete combustion takes place when fuel had already burned and did not have the unburned fuel. Complete combustion will occur when the mixture of fuel and air (fuel/air ratio) was suitable under the appropriate conditions of turbulent and temperature.

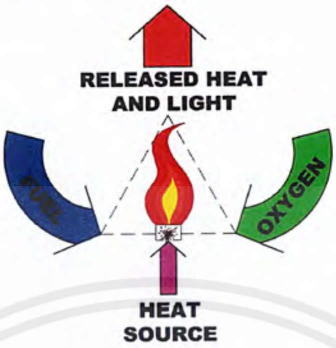


Figure 2.11. Three components of combustion (Newnhem, 2012)

The heat which is released from combustion reaction is called heat of combustion. For example, combustion of methane is shown:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 + 8026\, kJ/mol$$

$$CH_4 + 1.5O_2 \rightarrow 2H_2O + CO + 519.7\, kJ/mol$$

Combustion of methane which is complete combustion has products only carbon dioxide and water. But, incomplete combustion, the products from the reaction are carbon monoxide and water. Amount of air supplied for the complete combustion is greater than incomplete combustion. From both reactions, released heat of incomplete combustion is less than the complete combustion. Thus, combustion reaction should be completed in order to get the maximum heat of combustion.

In theoretically, stoichiometric combustion can be suitable ratio of fuel to air which is lower heat loss from the combustion system. But the fact, stoichiometric combustion has many factors that effects the combustion system. Therefore, the heat loss from the combustion system cannot provide the 100% efficiency. In real practice, increasing the amounts of air can ensure the burning all of the fuel in order to provide the complete combustion. Excess air is the amount of air added to the combustion reaction for certain all energy.

In the combustion reaction, some chemicals are formed such as CO (Carbon monoxide), NO (Nitric oxide), NO_2 (Nitrogen dioxide), SO_2 (Sulfur dioxide), soot and ash that should be minimized and measured. These products are harmful to the environment. The combustion analysis is an essential step to control the combustion process in order to achieve high combustion efficiency and low toxic chemicals emission.

2.1.1 Fuel/air ratio (Michael Biarnes, Bill Freed and Jason Esteves, 2013)

Fuel/air ratio is the ratio of fuel to air during combustion reaction. The optimum fuel/air ratio is the stoichiometric ratio takes place when the fuel and oxygen in the combustion reaction balanced each other out perfectly.

2.1.2 Excess air and excess oxygen (Michael Biarnes, Bill Freed and Jason Esteves, 2013)

In combustion process uses the amount of air that is excess oxygen relative to stoichiometric combustion. Stoichiometric combustion depends on the oxidation reaction in each fuel which is different in fuel compositions.

The excess air can be measured in term of coefficient of excess air (λ). The coefficient of excess air (λ) is defined as a ratio of air that supplies to the combustion reaction to the air that needs to react with fuel in stoichiometric combustion. If the coefficient of excess air (λ) is 1, the amount of air is same as the air in stoichiometric combustion. If the coefficient of excess air (λ) is less than 1, the amount of air in combustion reaction is less than the air in stoichiometric combustion and is considered to be incomplete combustion. If the coefficient of excess air (λ) is more than 1, the amount of air in combustion reaction is more than the air in stoichiometric combustion and represents excess of air. Excess air depends on the types of fuels (Gas, liquid, solid fuels). The amount of air required complete combustion of gaseous and liquid fuels is less than solid fuels.

In complete combustion, the furnace chamber is fired in excess air. Excess air is increasing the amount of air that contains both oxygen and nitrogen. The increasing amount of air in furnace chamber can increase the mixing of the oxygen in air, reacting with the fuel. The increasing of fuel and oxygen mixing will improve the combustion efficiency. Excess air can react with more amount of fuel until the combustion is complete which decreases the amount of carbon monoxide that occurs in the incomplete combustion.

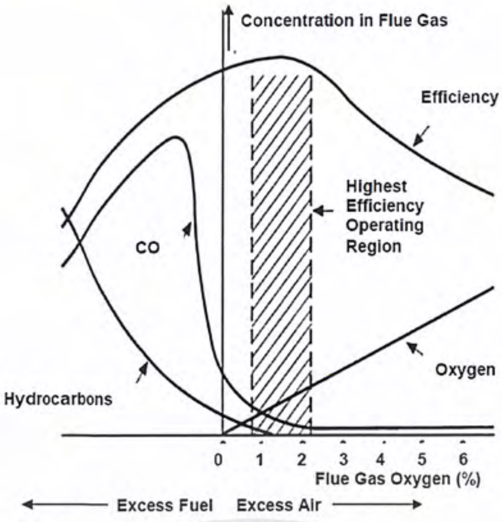


Figure 2.12 The effects of oxygen concentration in the flue gas (Michael Biarnes, n.d.)

The largest heat loss or energy loss comes from products of combustion or flue gas. Heat loss from flue gas cannot eliminate because flue gas is heated in the combustion reaction and some heat is carried into the atmosphere. The heat loss from flue gas can be reduced by reducing the excess air that reacts with the fuel in the furnace. When the excess air and temperature of flue gas increased, the heat loss from flue gas increases.

2.1.3 Unburned fuel loss

If the amount of air that supplied to the furnace is less than the stoichiometric air, the results is decreasing of released heat from the fuel combustion due to unburned fuel and incomplete combustion. The deficient air in combustion can produce carbon monoxide and hydrogen in the products of combustion, which refer to combustible substances. The increasing of combustible substance depends on decreasing of amount of air that is less than the stoichiometric combustion.

In practice, some trace levels of unburned fuel appear in the flue gas stream even with some amount of excess air, due to imperfect mixing of fuel and air at the burner or other burner conditions. As a result, combustion processes are not operated at the stoichiometric point. Instead, combustion processes are operated with sufficient excess air to keep the amount of combustibles minimized. Combustibles levels of a few hundred parts per million (ppm) in the flue gas have an insignificant effect on efficiency.

2.1.4 Formation of carbon monoxide (Grzegorz Wielgosiski, 2012)

One of the incomplete combustion products is carbon monoxide that is highly toxic. Carbon monoxide in the incomplete combustion is formed by imperfect mixing between fuel and oxygen. The reversible reaction of carbon dioxide can produce the carbon monoxide. Carbon monoxide is the first products of the pyrolysis fuel. Then, carbon monoxide is oxidized with oxygen to carbon dioxide in gas phase reaction. The amount of carbon monoxide content in good combustion is in the range of 20-50 ppm. If the mixing between fuel and air is not good, the amount of carbon monoxide content is approximately 1,000 ppm or more.

2.1.5 Formation of nitrogen oxides (Grzegorz Wielgosiski, 2012)

The nitrogen oxides are formed in the combustion process. The forms of nitrogen oxide formation are NO (Nitric oxide), NO_2 (Nitrogen dioxide) and N_2O (Nitrous oxide). Nitric oxide is the basic nitrogen oxide compound that is formed by combustion reaction.

Excess air in combustion reaction effects to decrease flame temperature. Thus, the efficiency also decreases too. In radiant section, the fuel gas and oxygen are combustion turbulence, causes dissociation of oxygen and then oxygen ions react with nitrogen in the air forming NO and NO_2. Therefore, more excess air supplies to combustion reaction, the more nitrogen oxides occur. On the other hand, less excess air supplies to combustion reaction, the less nitrogen oxides occur.

2.2 Process heaters Furnaces

2.2.1 Process heaters Furnaces (Metek, 2012)

Process heater or direct-fired heater uses hot flue gas from combustion reaction to heat the process stream in the tube which is called furnace or fired heater. Furnace can be divided into four sections, which are radiant section, convection section, shield section and stack and breeching sections.

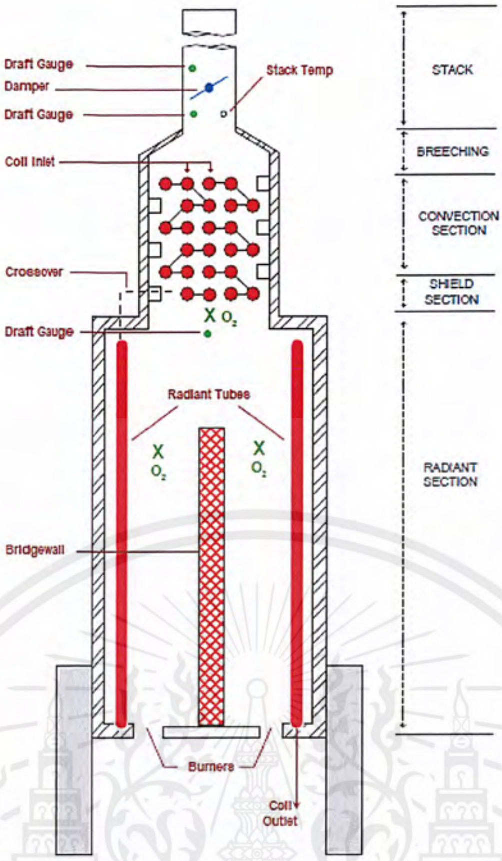


Figure 2.13 Sections of a process heater (Metek, 2012)

1. Radiant section

The radiant tubes directly receive radiant heat from burners. The tubes are either horizontal or vertical that are located on the wall of furnace. Approximately 85% of the heat is received from radiant section. This section can be called firebox.

2. Convection section

The feed is preheated in the convection section before transferring to radiant section. The heat of flue gas which cannot transfer in radiant section is removed in convection section in order to reduce the temperature before going to the stack. Too much heat picked up in the convection section is a sign of too much draft.

3. Shield section

The shield section is below the convection section. The shield section consists of rows of tubes in order to shield the convection tubes from the direct radiant heat. The bridgewall temperature is the temperature of the flue gas that is removed heat from radiant section before hitting the convection section.

4. Stack and breeching sections

The transition between convection section and stack is the breeching. The flue gas temperature from the combustion reaction at stack should be reduce by controlling the heat recovery. Many important factors are controlling the flue gas temperature such as acid dew point temperature.

2.2.2 Types of furnaces (Karl Kolmetz, 2010)

Furnace is the equipment that produces and supplies the heat to process. Furnace can refer to direct furnace. Furnace is the high temperature equipment. The heat which is produced at the burner is transferred to a process through tubular coils.

1. Vertical cylindrical furnace

This type is suitable for hot oil heater and some process that the duties are small about 150 MBtu/h. The tubes of this type are installed vertically round of the burners that are located on the bottom floor of the furnace. The tubes are parallel to the flame. This type can be designed without or with convection section.

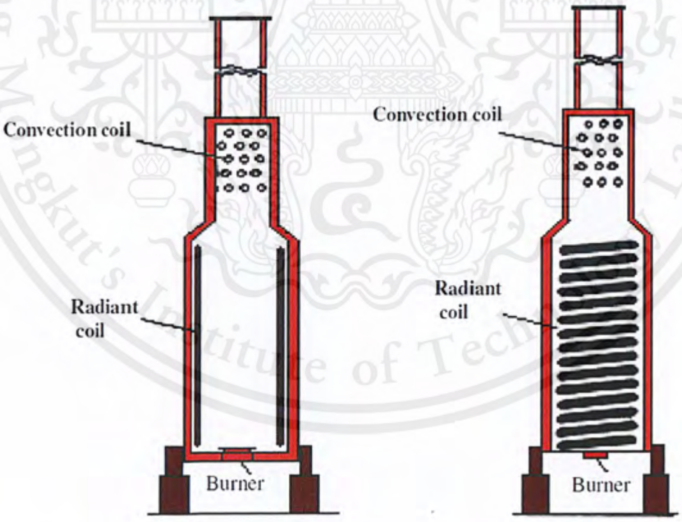


Figure 2.14 Vertical cylindrical furnace (Karl Kolmetz, 2010)

2. Horizontal tube cabin furnace

This type includes the radiation and convection. Tubes are installed horizontally while the burner is located on the bottom of furnace. The flame is not straight and parallel to the wall of furnace. The first layer of tubes in convection section that directly contacts with the radiation section is shield tubes. In cabin of large furnace can be installed a center wall that divides into two zones of the radiation section. The duty of this type is 20-50 million kcal/h.

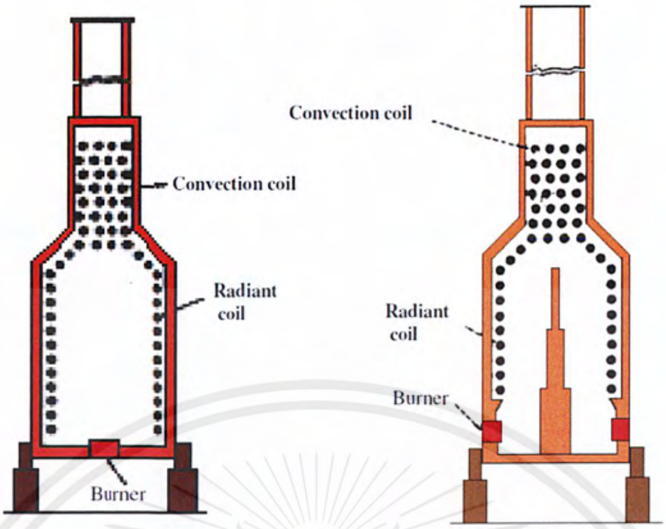


Figure 2.15 Horizontal tube cabin furnace (Karl Kolmetz, 2010)

3. Hoop-tube furnace

The tubes in radiation section is bent like as U-shape with vertically oriented. This type is designed to use when the pressure drop was very low. This type can use in the catalytic reformers. In limitation, the furnace can use for vapor phase of the feed stream. Hoop-tube furnace has duty about 13-25 million kcal/h.

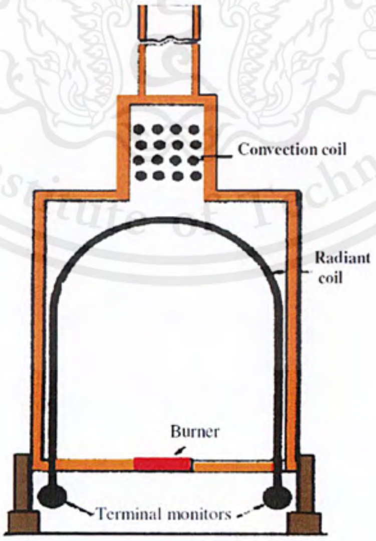


Figure 2.16 Hoop-tube furnace (Karl Kolmetz, 2010)

4. Vertical tube box furnace

The tubes of this type are installed vertically along the wall in radiation section. Radiant tubes are arranged in a single row in each combustion cell and fired from both sides of the row. This arrangement has a uniform distribution of heat transfer around the tube. This type is suitable for large forced-draft burners.

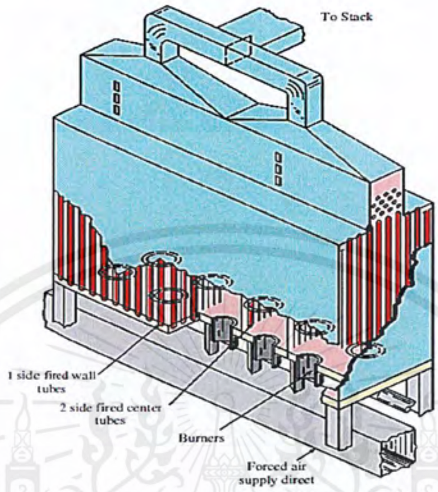


Figure 2.17 Vertical tube box furnace (Karl Kolmetz, 2010)

5. Horizontal tube box furnace

The radiant and convection sections are separated by bridge wall. Bridge wall can provide the good direction of flame and transfer the smoke into flue stack. Burners are firing from the floor along the both sides of the bridge wall. Horizontal tube box furnace has duty about 8-30 million kcal/h.

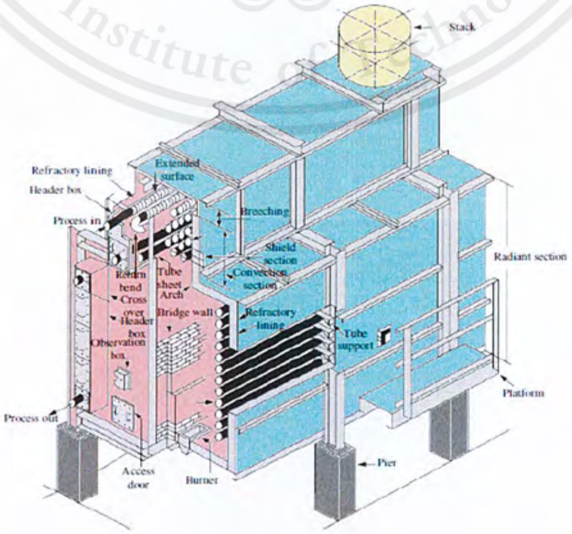


Figure 2.18 Horizontal tube box furnace (Karl Kolmetz, 2010)

6. Multiple cell heater

Two-cell horizontal tube box has high efficiency and duty is about 25-65 million kcal/h.

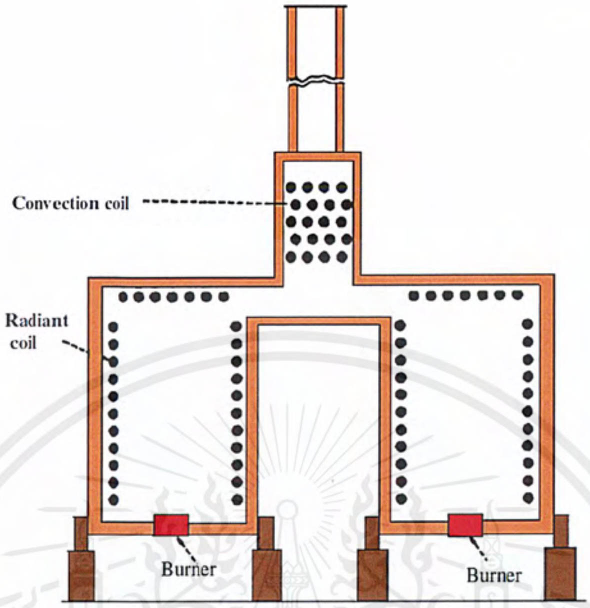


Figure 2.19 Multiple cell heater (Karl Kolmetz, 2010)

7. Helical coil furnace

This type is commonly used when pressure drop is limited. Many helical coil furnace can only have a radiant section.

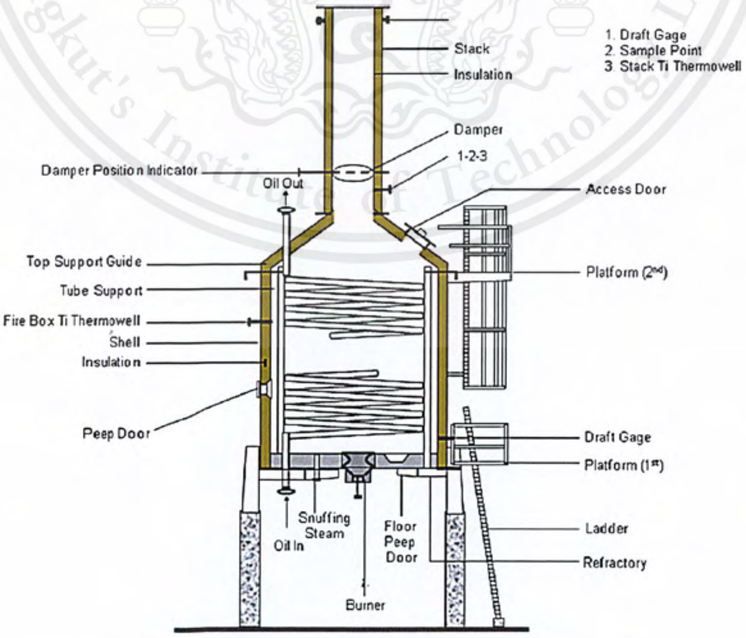


Figure 2.20 Helical coil furnace (Karl Kolmetz, 2010)

2.3 Furnace Efficiency (American petroleum institute 560. 2001)

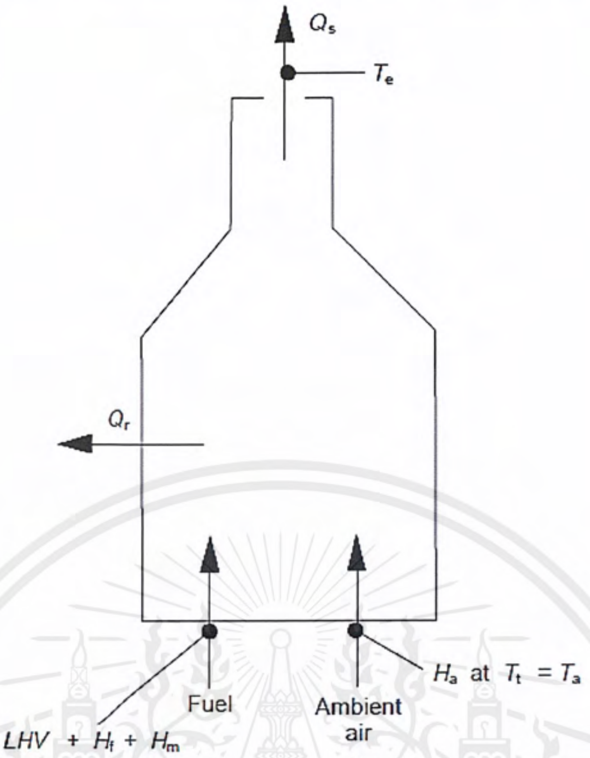


Figure 2.21 Typical furnace arrangement with non-preheated air

(American petroleum institute 560. 2001)

For the arrangements in Figure 2.21, the furnace efficiency (based on the lower heating value of the fuel) can be determined by the following equation:

$$\text{Efficiency} = \frac{\text{Total heat absorbed}}{\text{Total heat input}} \times 100 \qquad (2.1)$$

Also,

$$\text{Efficiency} = \frac{\text{Total heat input - Total heat losses}}{\text{Total heat input}} \times 100 \qquad (2.2)$$

Therefore,

$$e = \frac{(LHV+H_a+H_f+H_m)-(Q_r+Q_s)}{(LHV+H_a+H_f+H_m)} \times 100 \qquad (2.3)$$

Where:

e = Furnace efficiency (%)

LHV = Lower heating value of the fuel burned (Btu/lb.)

H_a = Air sensible heat correction (Btu/lb.)

H_f = Fuel sensible heat correction (Btu/lb.)

H_m = Atomizing medium sensible heat correction (Btu/lb.)

Q_r = Assumed radiation heat loss (Btu/lb.)

Q_s = Calculated stack heat loss (Btu/lb.)

2.4 Heat exchanger (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Heat exchanger is the equipment that is used for transferring heat from one fluid phase to another fluid phase. The heat transfer between two fluid phases may or may not contact together. The fluid can be one compound or mixtures. The applications of heat exchanger are heating or cooling of fluid, evaporation or condensation of fluid and recovering the heat from system.

Heat transfer which occurs in heat exchanger is convection in fluid phase and conduction in the wall between two fluids. The rate of heat transfer depends on overall heat transfer coefficient and magnitude of differential temperature.

2.4.1 Heat exchanger analysis (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Heat exchanger which operates for long periods of time and does not change conditions can be steady. The kinetic and potential energy of fluid stream is negligible because of no change the velocities and elevations. The specific heat of fluids that change following the temperature can constant at average value. The heat transfer in axial is negligible. And, the heat exchanger is perfect insulation that does not have heat loss to the surrounding. Therefore, from the first law of thermodynamics, the rate of heat transfer of hot fluid equals to the rate of heat transfer of cold fluid.

$$\dot{Q}=\dot{m}_c c_{p,c} (T_{c,\,out} - T_{c,\,in}) \tag{2.4}$$

$$\dot{Q}=\dot{m}_h c_{p,h} (T_{h,\,in} - T_{h,\,out}) \tag{2.5}$$

Where the subscripts *c* and *h* stand for cold and hot fluids, respectively, and

$\dot{m}_c$, $\dot{m}_h$ = Mass flow rates (kg/h)

$c_{p,c}$, $c_{p,h}$ = Specific heat capacities (kJ/kg $^{\circ}$C)

$T_{c,\,in}$, $T_{h,\,in}$ = Inlet temperatures ($^{\circ}$C)

$T_{c,\,out}$ $T_{h,\,out}$ = Outlet temperatures ($^{\circ}$C)

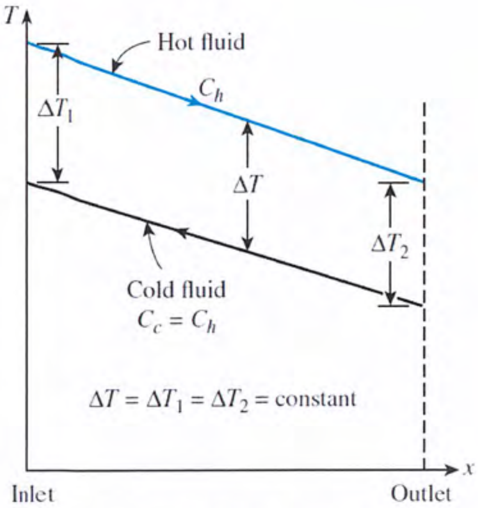


Figure 2.22 Temperature change of cold and hot fluids in heat exchanger

(Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Two special types of heat exchangers are condensers and reboilers. Phase of one fluids are changed and can be determined the heat transfer rate as Equation 2.6.

$$\dot{Q}=\dot{m}h_{fg} \tag{2.6}$$

Where $\dot{m}$ is the rate of evaporation or condensation of the fluid and h_{fg} is the enthalpy of vaporization of the fluid at the specified temperature or pressure.

The conditions are useful to note that heat exchanger may be operated. The temperature distribution can show in Figure 2.23. The heat capacity rate of hot and cold streams are shown in Equation 2.7 and 2.8. The heat capacity rate of hot stream is higher than the cold stream. In conditions, the hot stream is condensing from vapor to liquid phase and the temperature of hot stream is nearly constant. While the temperature of cold stream increases. When condensation was formed, the heat capacity rate of hot stream is nearly to infinity. When evaporation occurred, the heat capacity rate of cold stream is nearly to infinity too.

$$C_c=\dot{m}_c c_{p,c} \tag{2.7}$$

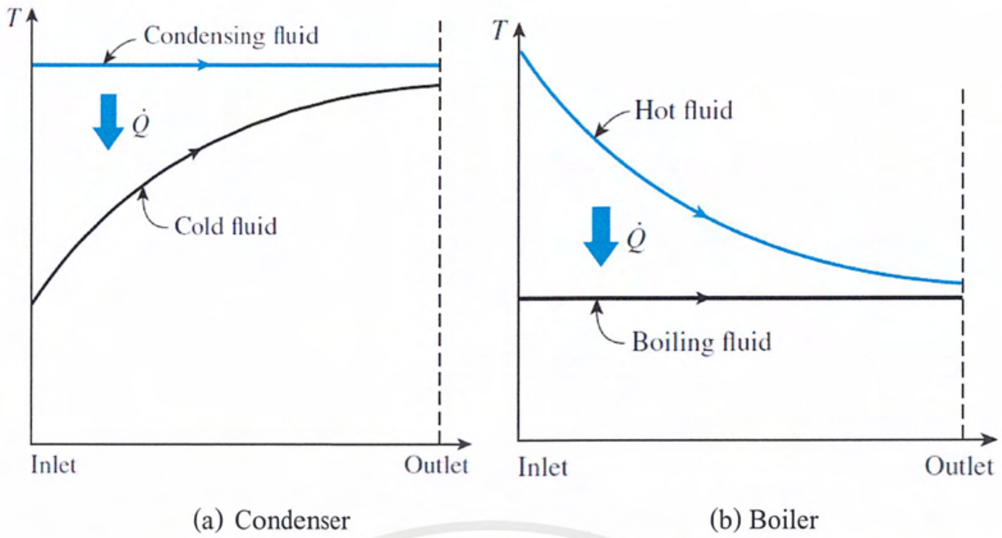
$$C_h=\dot{m}_h c_{p,h} \tag{2.8}$$

Where the subscripts c and h stand for cold and hot fluids, respectively, and

C_c, C_h = Heat capacity rates (kJ/°C)

$\dot{m}_c$, $\dot{m}_h$ = Mass flow rates (kg/h)

$c_{p,c}$, $c_{p,h}$ = Specific heats (kJ/kg °C)



(a) Condenser (b) Boiler

Figure 2.23 Variations of fluid temperature in a heat exchanger when one of the fluids condenses or boils (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

CHAPTER III

RESEARCH METHODOLOGIES

Part I: Reduction steam loss from purified terephthalic acid production.

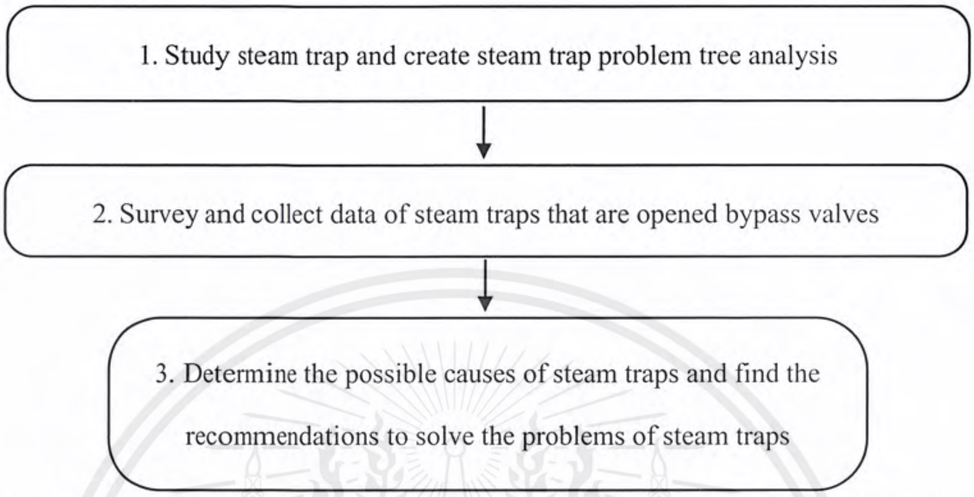


Figure 3.1 Step diagram of reducing steam loss from purified terephthalic acid (PTA) production

3.1 Study steam trap and create steam trap problem tree analysis

In CTA and PTA units used a lot of energy to produce the purified terephthalic acid. In part of reduction steam loss, the steps to study about steam loss include:

Step 1: Study on purified terephthalic acid production process

Step 2: Study on steam system and condensate return system in PTA plant 2

Step 3: Study on principles and operations of steam traps

Step 4: Create steam trap problem tree analysis

3.2 Survey and collect data of steam traps that are opened bypass valves

Steam traps in CTA and PTA unit were observed by operator to check the condition of steam traps. Data of the steam traps that have problems was found from the design data of steam traps. The design data of steam traps can be divided into two parts. First, the design data of steam traps are designed by Mitsui Chemical that is a SMPC's specification. Second, the design data of steam traps are designed by Yarway Company that is Yarway's specification. The data of steam traps was shown in Table 3.1.

Table 3.1 Specifications and actual condition of steam trap

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification							
Yarway's specification							
Actual condition							

S.F. is safety factor.

Types of steam traps in actual conditions are observed by operators. The inlet pressure of steam traps can read at the pressure gauge at local. The backpressure are assumed to equal the design data. Differential pressure is the differential pressure between inlet and outlet of steam trap. Condensate load of actual condition can be determined by heat balance calculation.

3.2.1 Calculate the actual condensate load

Step 1: Calculate the absorbed heat from process in actual condition

The absorbed heat from process of actual condition may be different with design data because the some process parameters such as inlet process temperature, mass flow rate of process do not equal to the design data. Therefore, the calculation of actual condensate load is necessary to determine the capacity of steam traps.

$$\dot{Q}_{absorbed,process} = \dot{m}_{process} c_{p,process} (T_{process,outlet} - T_{process,inlet}) \qquad (3.1)$$

Where $\dot{Q}_{absorbed,process}$ = Heat absorbed from process stream (kJ/h)

$\dot{m}_{process}$ = Mass flow rate of process stream (kg/h)

$c_{p,process}$ = Specific heat capacity of process stream (kJ/kg*K)

$T_{process,inlet}$ = Temperature of inlet process stream (°C)

$T_{process,outlet}$ = Temperature of outlet process stream (°C)

Step 2: Calculate the mass flow rate of condensate

Some equipment in PTA plant use steam to heat the process stream. The condensate load can be calculated from the latent heat of steam that is transferred to the process stream.

$$\dot{Q}_{absorbed,process} = \dot{m}_{steam} h_{fg} \tag{3.2}$$

Where $\dot{Q}_{absorbed,process}$ = Heat absorbed from process stream (kJ/h)

$\dot{m}_{steam}$ = Mass flow rate of steam (kg/h)

h_{fg} = The latent heat of steam (kJ/kg)

3.3 Determine the possible causes of steam traps and find the recommendations to solve the problems of steam traps

Step 1: Finding the steam trap manufacturer to check the steam traps

In the present, the steam traps that used in SMPC belong to Yarway and TLV Companies. The Yarway Company supplied all steam traps at first created plants. After that, some steam traps were damaged and then steam traps were changed by TLV Company. Therefore, steam trap observers in this project come from TLV Company.

Step 2: Use steam trap problem tree analysis to find the problems of steam traps.

Then, use the principles of steam trap such as types of steam traps, installation and so on to find the recommendations in order to reduce steam loss.

Part II: Study the efficiency of hot oil furnace.

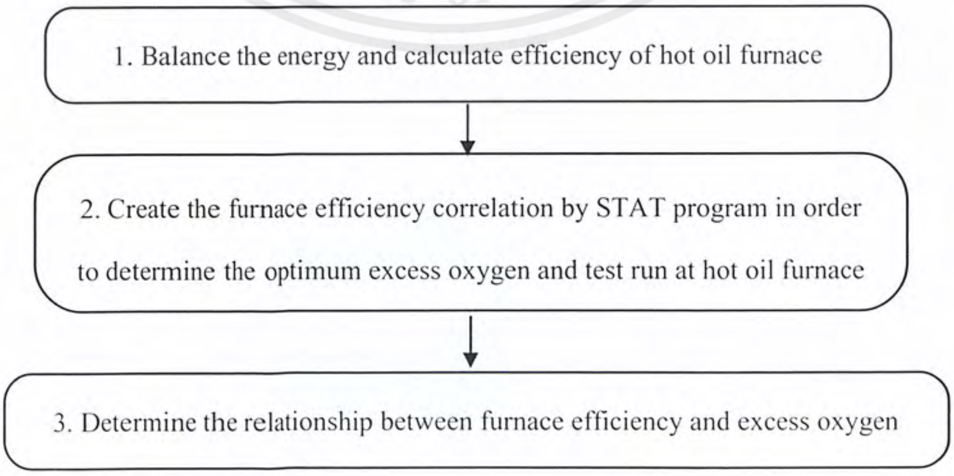


Figure 3.2 Step diagram of study of hot oil furnace efficiency

3.1 Balance the energy and calculate efficiency of hot oil furnace

Step 1: Study on purified terephthalic acid production

Step 2: Study the hot oil furnace system in PTA plant 2

Step 3: Calculate the energy balance and efficiency of hot oil furnace

Hot oil furnace have many parameters which relate with the furnace efficiency. Tag number in each parameter was searched in P&ID. The value of parameters come from historical data which were found in PI process book program.

This project used the data 2 years ago which was 1 January 2016 – 30 August 2017. The data came from PI process program and experience of operator and production engineer.

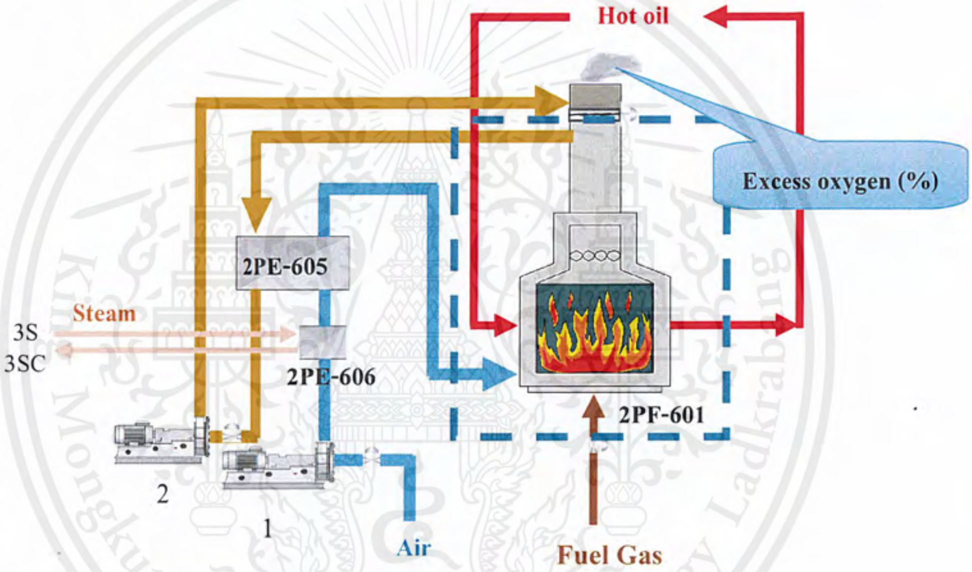


Figure 3.3 Flow diagram of hot oil furnace

Note: 3S = Steam at pressure 3 kg/cm^2

3SC = Condensate return line at pressure 1 kg/cm^2

Step 1: Determine heat of inlet air

$$\dot{Q}_{air,inlet} = \dot{m}_{air} c_{p,air} (T_{air} - T_{ref,air}) \tag{3.3}$$

Where $\dot{Q}_{air,inlet}$ = Energy of inlet air (kJ/h)

$c_{p,air}$ = Specific heat capacity of air (kJ/kg*K)

Step 2: Determine released heat of fuel gas

$$\dot{Q}_{\text{fuel}} = \dot{m}_{\text{fuel}}\text{LHV} \qquad (3.4)$$

Where $\dot{Q}_{\text{fuel}}$ = Heat released from fuel gas (kJ/h)

LHV = Lower heating value of the fuel (kJ/kg)

Step 3: Determine absorbed heat of hot oil

$$\dot{Q}_{\text{hot oil}} = \dot{m}_{\text{hot oil}}c_{\text{p,hot oil}}(T_{\text{hot oil,outlet}} - T_{\text{hot oil,inlet}}) \qquad (3.5)$$

Where $\dot{Q}_{\text{hot oil}}$ = Heat of hot oil (kJ/h)

$c_{\text{p,hot oil}}$ = Specific heat capacity of hot oil (kJ/kg*K)

Step 4: Determine efficiency of hot oil furnace

$$\text{Efficiency} = \frac{\text{Total heat absorbed}}{\text{Total heat input}} \times 100 \qquad (3.6)$$

3.2 Create the furnace efficiency correlation by STAT program in order to determine the optimum excess oxygen and test run at hot oil furnace

Regression equation from minitab program

Step 1. Collect data that use in minitab program are mass flow rate of hot oil, temperature of inlet hot oil and fuel gas/air ratio and furnace efficiency because other parameters are controlled. These data have used since 1 January 2016 until 30 August 2017.

Step 2. Use response surface to determine the efficiency model. Independent variables of efficiency equation are mass flow rate of hot oil, temperature of inlet hot oil, and fuel gas/air ratio.

Step 3. Create the graph between furnace efficiency and fuel gas/air ratio. Mass flow rate of hot oil, temperature of inlet hot oil and lower heating value are controlled.

Where Mass flow rate of hot oil = 620 ton/h

Temperature of inlet hot oil = 280 °C

Lower heating value = 900 BTU/SCF

Step 4. Select the optimum fuel gas/air ratio that is highest furnace efficiency.

Step 5. Test runs the optimum excess oxygen from efficiency correlation at hot oil furnace. When fuel gas/air ratio decreased, the amount of air increase which affects to increase the excess oxygen in flue gas. In control system, the values of percent excess oxygen in flue gas depend on fuel gas/air ratio. Therefore, in experiment, increasing of percent excess oxygen is controlled about 0.5% per day by changing the fuel gas/air ratio until it equals to 5% that is maximum capacity of air compressor.

3.3 Determine the relationship between furnace efficiency and excess oxygen

Create graph between furnace efficiency and excess oxygen in each day in order to observe changing of furnace efficiency.

CHAPTER IV

RESULTS AND DISCUSSIONS

Part I: Reduction steam loss from purified terephthalic acid production.

4.1 Steam trap problem tree analysis

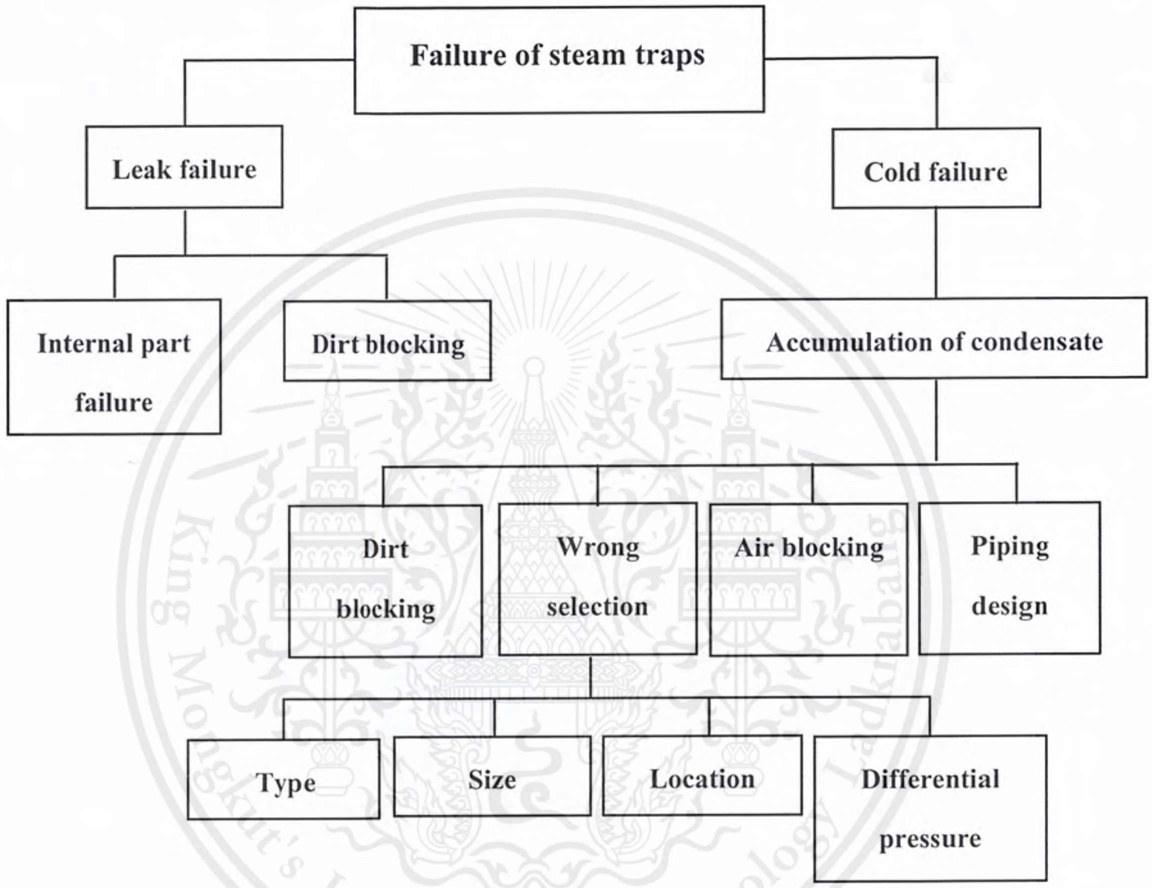


Figure 4.1 Steam trap problem tree analysis

From study on principles of steam trap, it was found that failure of steam traps can be divided into two cases which are leak failure and cold failure. The possible causes of leak failure are internal part failure and blocking from dirty particles. The result of leak failure is steam leakage which affects cost loss, safety and environment. The possible causes of cold failure are blocking from dirty particles, wrong steam trap selections including type, size, location and differential pressure of steam traps, air blocking and piping design. The result of cold failure is accumulation of condensate which affects about maintenance cost, safety and product reliability.

4.2 List of steam traps that bypass valves of steam traps are opened

CTA and PTA units have some of steam traps that are opened bypass valves. If the operators closed the bypass valves of steam traps, the temperature of process stream cannot control to the set point temperature. When bypass valves of steam traps were opened, steam losses at the bypass valves of steam traps. The equipment which bypass valves of steam traps are opened were shown in Table 4.1.

Table 4.1 Equipment which bypass valves of steam traps are opened

Units	Equipment	Steam trap tags
CTA unit	Heat exchanger 102 (2TE-102)	ST-1109
	Dryer 304 (2TM-304)	ST-1304
	Steam jacketed drum 509 (2TD-509)	ST-1511
	Heat exchanger 901 (2TE-901)	ST-1903
PTA unit	Dryer 404 (2PM-404)	ST-2415
	Heat exchanger 504 (2PE-504)	ST-2504
	Heater steam drum 1206 (2PD-1206)	ST-2201

4.3 Possible causes and recommendations of seven steam traps

1. Heat exchanger 102

Table 4.2 Specifications and actual condition of steam trap of heat exchanger 102

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	float	22	10.5	11.5	350	2	700
Yarway's specification	Impulse	-	-	11.5	-	3.4	1,200
Actual condition	Impulse	12	10.5	1.5	548 (Calculate)	-	-

S.F. is safety factor.

Specification of steam trap in PTA plant is divided into 2 sources which are SMPC's specification and Yarway's specification. SMPC's specification is the first specification of steam trap when PTA plant was built at the first time. Yarway's specification is the specification of steam trap manufacture which supplied to SMPC.

From Table 4.2, differential pressure of heat exchanger 102 which was designed by SMPC was 11.5 kg/cm^2. But differential pressure which was designed by Yarway Company was 1.5 kg/cm^2 and less than SMPC's specification. When differential pressure decreased, the discharge condensate load would be decreased. Therefore, the discharge condensate load from design data was decreased to 520 kg/h. In the actual condition, the condensate load was 548 kg/h which came from calculation. The condensate load of actual condition that was higher than designed capacity affected to condensate cannot discharge to the condensate return line and then accumulate in heat exchanger. Accumulation of condensate decreases the heat transfer area, which is the contact area between steam and process stream, affects to decrease the temperature of process stream. For this problem, steam trap used in heat exchanger 102 should be the mechanical steam trap (Inverted bucket trap, free float trap) and larger size in order to support the condensate load because impulse steam trap cannot continuously discharge the condensate and slowly respond to change with condensate load.

2. Dry 304

Table 4.3 Specifications and actual condition of steam trap of dryer 304

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	float	4.7	1-2	2.7-3.7	4,996	2	9,992
Yarway's specification	float	-	-	3.7	-	2.8	14,000
Actual condition	float	7.2	1-2	5.2-6.2	7,700	-	-

S.F. is safety factor.

From Table 4.3, dryer 304 used float type that was same as SMPC and Yarway's specifications. Inlet pressure and condensate load of actual condition were 7.2 kg/cm^2 and 7,700 kg/h respectively that were higher than both designed specifications. When bypass valve of the steam trap was closed, the temperature of process stream decreased. Although the capacity of the steam trap was enough but bypass valve was necessary opened because steam trap had the problems that might be come from inability air venting and orifice blocking from dirty particles. The steam trap should be checked air venting and cleaned the steam trap in order to remove dirty particles.

3. Steam jacketed drum 509

Table 4.4 Specifications and actual condition of steam trap of steam jacketed drum 509

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	disc	3.2	1	2.2	50	3	150
Yarway's specification	disc	-	-	2.2	-	4.8	240
Actual condition	disc	1.8	1	0.8	55	-	-

S.F. is safety factor.

From Table 4.4, steam jacketed drum 509 used disc type that was same as SMPC and Yarway's specifications. Differential pressure of steam trap was 0.8 kg/cm^2 that was lower than design because of low inlet pressure. The possible causes might come from the low differential pressure and unsuitable type of steam trap which affects to accumulate the condensate in steam jacketed drum 509. In recommendation, steam trap should be changed types of steam traps to mechanical steam trap because it can operate at high backpressure and frequently changing with condensate load. When the steam trap is changed to the mechanical steam trap, condensate will be drained continuously. Thus, condensate is not accumulated in the heat exchanger.

4. Heat exchanger 901

Table 4.5 Specifications and actual condition of steam trap of heat exchanger 901

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	float	3.2	1	2.2	3,069	2	6,138
Yarway's specification	float	-	-	2.2	-	4.2	13,000
Actual condition	float	3	1	2	4,109 (Calculate)	-	-

S.F. is safety factor.

From Table 4.5, steam trap in actual condition was float trap which was the same type as designed data from SMPC and Yarway Companies. Heat exchanger 901 cannot close the bypass valve of steam trap because process temperature cannot control. Possible causes of steam trap might be come from inability to discharge air, orifice blocking from dirty particles or low differential pressure. Steam trap should be checked the air venting and cleaned. When stream trap operated at low differential pressure, the condensate cannot be discharged to condensate return line. Therefore, temperature of process stream should be controlled that is higher than current temperature in order to increase the steam pressure which supplies to equipment. Increasing of inlet steam pressure affects to increase the differential pressure and amount of discharged condensate.

5. Dryer 404

Table 4.6 Specifications and actual condition of steam trap of dryer 404

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	float	2.5-4	1-2	0.5-3	8,080	2	16,160
Yarway's specification	float	-	-	1.5-2	-	4.3-5	35,000-40,000
Actual condition	float	3.6	1-2	1.6-2.6	13,000	-	-

S.F. is safety factor.

According to a TLV technician survey, dryer 404 leaked about 220 ton/h or 200,000 baht/year. The actual condition of steam trap was under designed data of SMPC and Yarway's specifications. Leaking of live steam that passed through the steam trap might come from internal part was damaged by erosion at orifice and dirty particles which blocked the orifice. The problem of steam trap can be solved by checking the steam trap. If internal part of steam trap damages, steam trap should be replaced to the new one. If the orifice is blocked by dirty particles, steam trap should be cleaned in order to get rid of the dirty particles.

6. Heat exchanger 504

Table 4.7 Specifications and actual condition of steam trap of heat exchanger 504

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	float	9.4	3.2	6.2	1,024	2	2,048
Actual condition	float (TLV)	10.4	3.2	7.2	1,217 (Calculate)	-	-

S.F. is safety factor.

Heat exchanger 504 used float trap from TLV Company. The steam trap cannot close bypass valve because temperature of process cannot be controlled at target temperature. When bypass valve of the steam trap was closed, the temperature of process stream was decreasing and pressure of inlet steam was increasing in order to maintain the process temperature. For capacity of steam trap, the steam trap can drain the condensate at actual condition. The possible causes of steam traps might be come from inability discharge air and blocking from dirty particles. The steam trap should be checked and cleaned in order to confirm that dirty particles do not block the air cock in the steam trap.

7. Heater steam drum 1206

Table 4.8 Specifications and actual condition of steam trap of heater steam drum 1206

Specification	Type	Inlet pressure (kg/cm^2)	Back pressure (kg/cm^2)	Differential pressure (kg/cm^2)	Condensate flow (kg/h)	S.F.	Designed capacity (kg/h)
SMPC's specification	disc	22	10.5	11.5	329	2	658
Yarway's specification	Impulse	-	-	11.5	-	4	1,300
Actual condition	Impulse	17	10.5	6.5	407 (Calculate)	-	-

S.F. is safety factor.

From Table 4.8, the inlet pressure of steam trap was less than design of SMPC's specification which resulted in decreasing differential pressure. Capacity of steam trap was enough but cannot close the bypass valve of steam trap because the temperature of process stream cannot be controlled at target temperature. The possible causes might come from the low differential pressure and unsuitable type of steam trap. Steam trap should be changed to the mechanical steam trap in order to continuously discharge the condensate and increased the inlet pressure by increasing controlled temperature of process stream.

Part II: Study the efficiency of hot oil furnace.

4.1 Furnace efficiency

Hot oil furnace of PTA plant has two furnaces that are used to heat the process in PTA unit of plant 2 and 3. The hot oil furnace of plant 2 used fuel gas to generate the heat. But, Plant 3 used methane gas from anaerobic unit to generate the heat. The parameters that are used to calculate the furnace efficiency of PTA unit of plant 2 include:

1. Mass flow rate of fuel gas	(kg/h)
2. Mass flow rate of inlet hot oil	(kg/h)
3. Mass flow rate of inlet air	(kg/h)
4. Inlet hot oil temperature	(°C)
5. Outlet hot oil temperature	(°C)
6. Inlet air temperature	(°C)
7. Lower heating value of fuel gas	

The mass flow rate of fuel gas and air are controlled by percent excess oxygen of outlet flue gas and outlet hot oil temperature in cascade control. The temperature of outlet hot oil is 313 °C. The fuel gas that is used in hot oil furnace is purchased from PTT Public Company Limited. In normal operation, oxygen content in outlet flue gas is controlled at 1.3% and the furnace efficiency is 88.88%.

4.2 Correlation of hot oil furnace efficiency and furnace parameters

Parameters that were used to find the correlation were inlet hot oil flow rate, temperature of inlet hot oil and fuel gas/air ratio. The correlation came from minitab program by using response surface of design of experiment. The correlation of furnace efficiency shown in Equation 4.1.

Conditions Mass flow rate of inlet hot oil = 620 ton/h
Outlet hot oil temperature = 313 °C
Lower heating value of fuel gas = 900 BTU/SCF

$$\text{Eff} = 1935-(8.408*\text{Temp})-(3.005*\text{Flow})+(68.16*\text{F/A})-(0.000587*\text{Flow}*\text{Flow})-(4.148*\text{F/A}*\text{F/A})+(0.01337*\text{Temp}*\text{Flow}) \quad (4.1)$$

When Eff = Furnace efficiency (%)
Temp = Temperature of inlet hot oil (°C)
F/A = Fuel gas/air ratio

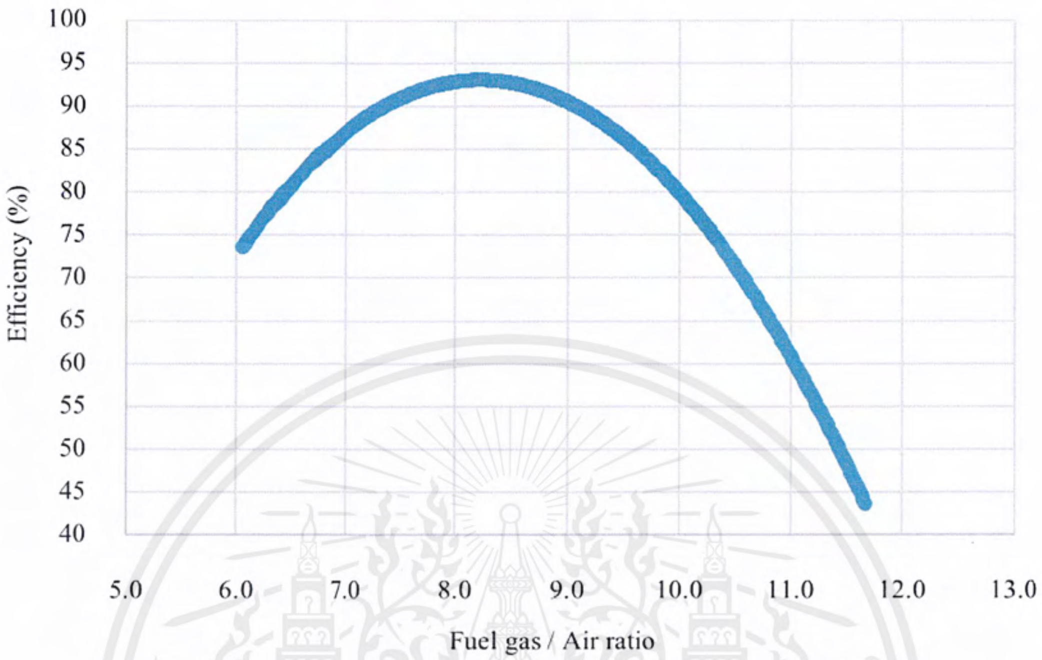


Figure 4.2 Correlation between efficiency and fuel gas/air ratio

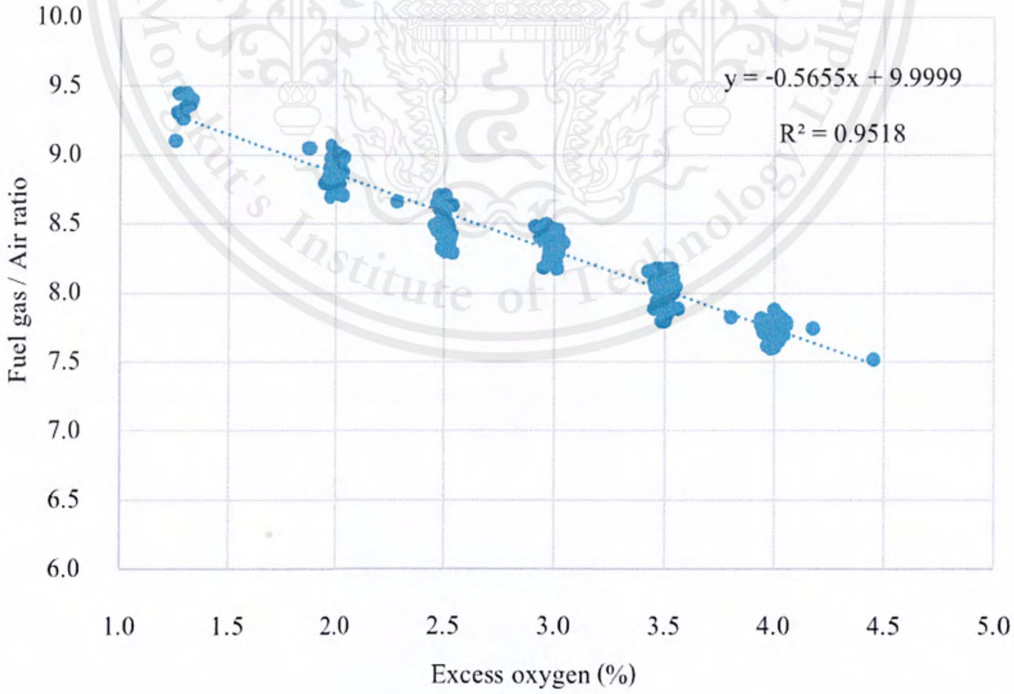


Figure 4.3 Correlation between fuel gas/air ratio and excess oxygen (%)

From Figure 4.2, graph relationship of furnace efficiency and fuel gas/air ratio looks like parabola. The maximum furnace efficiency from correlation was 93% which fuel gas/air ratio and excess oxygen equal to 8.3 and 3.0% respectively. When fuel gas/air ratio was higher or lower than 8.3, the furnace efficiency decreased. In comparison, the furnace efficiency from actual and correlation at 9.3 fuel gas/air ratio are 88.88 % and 88.80% which are similar values. Therefore, the optimum excess oxygen from minitab program is 3.0%.

4.3 Testing results and relationship between furnace efficiency and excess oxygen

From the experimental data, the parameters and the efficiency of hot oil furnace of plant 2 were shown in Table 4.9.

Table 4.9 Calculated results of hot oil furnace efficiency

Date	Fuel gas flow rate (kNm^3/h)	Air flow rate (kg/h)	F/A (%)	Percent excess oxygen (%)	Released heat from fuel gas (kWatt)	Heat from inlet air (kWatt)	Absorbed heat from hot oil (kWatt)	Furnace efficiency (%)
19/10/17	1,617.7	20,919.7	9.26	1.30	15.1	1.5	14.7	88.7
20/10/17	1,612.1	21,705.9	8.89	2.00	14.9	1.6	14.7	89.4
21/10/17	1,597.0	22,298.1	8.58	2.37	14.8	1.6	14.7	89.7
22/10/17	1,606.0	23,038.6	8.35	2.99	15.0	1.6	14.6	87.6
23/10/17	1,594.1	23,815.0	8.01	3.50	14.9	1.7	14.6	87.7
24/10/17	1,591.4	24,618.5	7.74	4.00	14.8	1.8	14.6	88.3
25/10/17	1,616.7	25,736.1	7.52	4.47	14.9	1.8	14.6	86.9
26/10/17	1,599.7	26,385.4	7.26	4.75	14.8	1.9	14.6	87.7
27/10/17	1,618.3	25,765.3	7.52	4.50	15.0	1.9	14.6	86.6
28/10/17	1,620.1	24,730.3	7.84	4.00	15.0	1.8	14.6	86.9
29/10/17	1,614.3	23,976.3	8.06	3.56	14.9	1.7	14.6	87.9
30/10/17	1,606.2	22,846.9	8.42	3.00	14.8	1.6	14.5	88.1
31/10/17	1,613.2	22,194.8	8.70	2.50	14.9	1.6	14.6	88.3

Table 4.9 Calculated results of hot oil furnace efficiency (Continued)

Date	Fuel gas flow rate (kNm^3/h)	Air flow rate (kg/h)	F/A (%)	Percent excess oxygen (%)	Released heat from fuel gas (kWatt)	Heat from inlet air (kWatt)	Absorbed heat from hot oil (kWatt)	Furnace efficiency (%)
1/11/17	1,608.9	21,621.6	8.91	2.05	14.9	1.5	14.6	89.0
2/11/17	1,613.6	20,749.6	9.31	1.32	14.9	1.5	14.6	89.0
4/11/17	1,588.3	20,629.8	9.22	1.31	14.6	1.5	14.6	91.0
9/11/17	1,614.4	21,640.1	8.93	2.00	15.0	1.5	14.7	88.5
10/11/17	1,612.2	21,538.4	8.96	2.00	15.0	1.5	14.7	88.5
11/11/17	1,602.9	22,158.2	8.66	2.46	14.9	1.6	14.7	88.9
12/11/17	1,598.4	22,408.2	8.54	2.50	14.8	1.6	14.6	89.2
13/11/17	1,603.9	22,966.8	8.36	2.92	14.9	1.6	14.7	88.4
14/11/17	1,616.7	23,108.1	8.38	3.00	15.1	1.7	14.7	87.6
15/11/17	1,611.1	22,310.7	8.65	2.50	15.1	1.6	14.7	88.0
16/11/17	1,576.0	22,161.7	8.52	2.50	14.7	1.6	14.6	89.3
17/11/17	1,590.3	21,524.1	8.85	2.00	14.9	1.5	14.6	88.5
18/11/17	1,603.9	21,611.0	8.89	2.00	15.0	1.5	14.5	88.1

Table 4.9 Calculated results of hot oil furnace efficiency (Continued)

Date	Fuel gas flow rate (kNm^3/h)	Air flow rate (kg/h)	F/A (%)	Percent excess oxygen (%)	Released heat from fuel gas (kWatt)	Heat from inlet air (kWatt)	Absorbed heat from hot oil (kWatt)	Furnace efficiency (%)
19/11/17	1,614.5	20,699.7	9.34	1.30	15.0	1.5	14.6	88.8
20/11/17	1,616.1	20,504.9	9.44	1.30	15.0	1.5	14.6	88.9
21/11/17	1,623.0	20,659.8	9.40	1.30	15.1	1.5	14.6	88.6
22/11/17	1,598.5	20,619.3	9.28	1.30	14.9	1.5	14.6	89.2
23/11/17	1,598.8	20,745.0	9.23	1.30	14.9	1.5	14.6	89.0

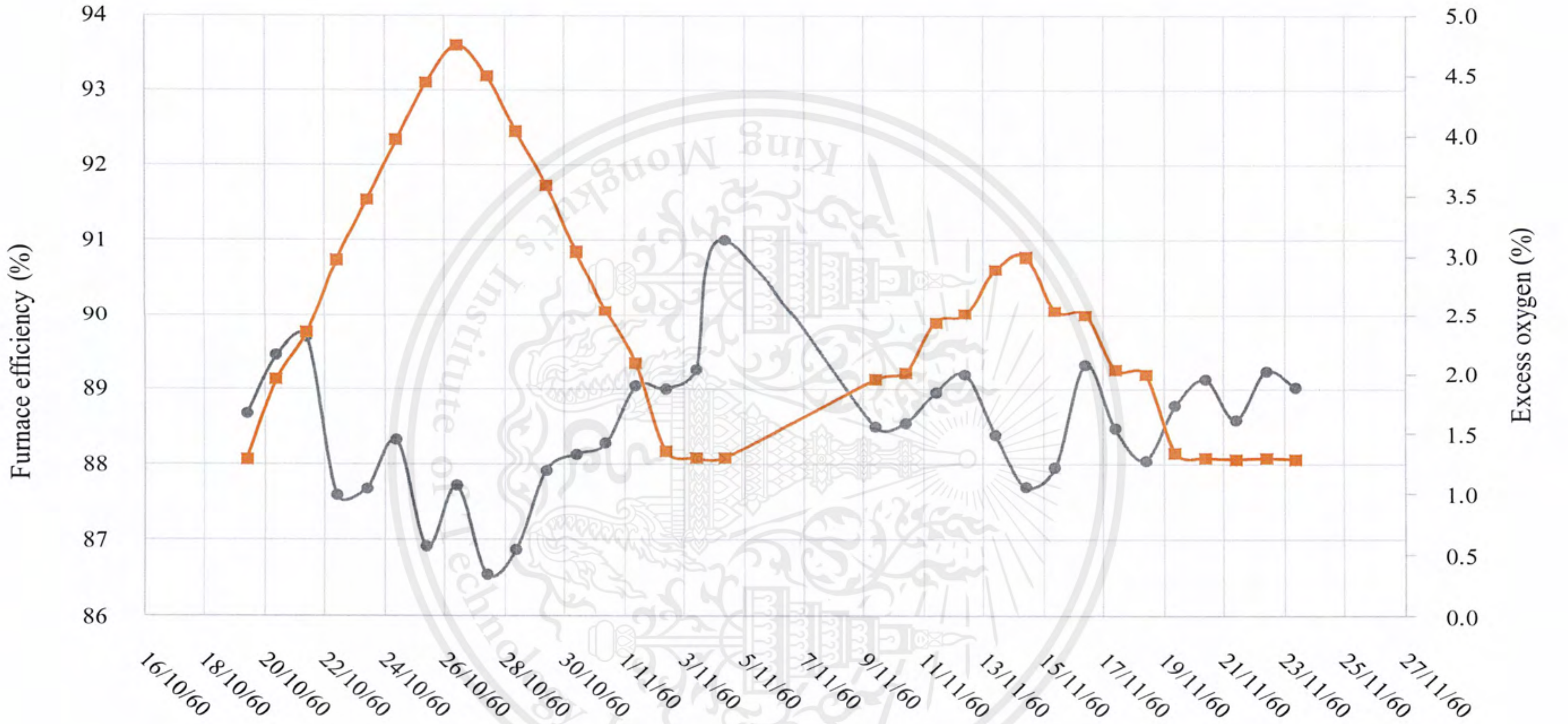


Figure 4.4 Relationship between hot oil furnace efficiency and excess oxygen

As shown in Figure 4.4, excess oxygen was increased by 0.5% in each day until 4.7% from 19 Oct. to 26 Oct. 2017 and then decreased to 1.3% that was normal operation. The excess oxygen could not be increased more than 4.7% because air compressor which supplied air to hot oil furnace had already been the highest capacity. The value of optimum excess oxygen could not be determined from 19 Oct. to 2 Nov. 2017 because the furnace efficiency fluctuated. Therefore, hot oil furnace was tested again. In the second test, excess oxygen was increased 0.5% in every two days until 3% and decreased to 1.3% in order to ensure the optimum excess oxygen. After excess oxygen was changed, the efficiency was difficult to determine the optimum excess oxygen. But, the average furnace efficiency in each excess oxygen values shown in Table 4.10.

Table 4.10 Average of furnace efficiency

Excess oxygen (%)	Average efficiency (%)
1.30	89.18
2.00	88.67
2.50	88.73
3.00	87.95
3.50	87.79
4.00	87.59
4.50	86.74

From Table 4.10, optimum excess oxygen was 1.3% which was the normal operation and average efficiency was 89.18 %. When excess oxygen increased, the average efficiency was gradually decreased and the least average efficiency was 86.74% at an excess oxygen of 4.5%.

When excess oxygen was increased more than 1.3%, furnace efficiency decreased because excess amount of air that exceed the air in the complete combustion carried heat loss to the atmosphere. When heat loss increased, the amount of fuel gas increases in order to keep the absorbed heat of process. Therefore, the optimum excess oxygen and furnace efficiency are same as the normal operation and then fuel gas consumption could not be reduced.

The errors of optimum excess oxygen from minitab program and test condition may come from two reasons. First, the heating value of fuel gas used in furnace efficiency calculation in minitab program used an average value at 900 BTU/SCF because the SMPC did not have the historical data of low heating value. The average value of lower heating value came from average value in test conditions. Second, the historical data did not have the hot oil flow rate same as the test conditions that equals to 620 ton/h which results in error of furnace efficiency equation from minitab program.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

Part I: Reduction steam loss from purified terephthalic acid production.

5.1 Conclusion

One part of steam loss in PTA production comes from opening of bypass valves of steam traps. In CTA and PTA units, steam traps of 7 equipment which are heat exchanger 102, dryer 304, heat exchanger 901, steam jacketed drum 509, heat exchanger 504, heater steam drum 1206, and dryer 404 are failure. These steam traps are opened bypass valves in order to discharge condensate for controlling the temperature of process stream. The possible causes and recommendations of the each steam traps were shown in Table 5.1 and Table 5.2.

Table 5.1 Possible causes and recommendations of the steam traps in CTA unit

Equipment	Problems	Possible causes	Recommendations
Heat exchanger 102	Cold failure	• High load of condensate • Unsuitable type of steam trap	Use mechanical type and larger capacity
Dryer 304	Cold failure	• Inability to discharge air • Trap body is filled with dirt.	• Check air venting • Clean and remove dirt at steam traps
Heat exchanger 901	Cold failure	• High backpressure • Inability to discharge air • Trap body is filled with dirt.	• Increase temperature control • Check air venting • Remove dirt and clean steam traps
Steam jacketed drum 509	Cold failure	• Low differential pressure • Unsuitable type of steam trap	Use mechanical type

Table 5.2 Possible causes and recommendations of the steam traps in PTA unit

Equipment	Problems	Possible causes	Recommendations
Heat exchanger 504	Cold failure	• Inability to discharge air • Trap body is filled with dirt.	• Check air venting • Remove dirt and clean steam traps
Heater steam drum 1206	Cold failure	• Low differential pressure • Unsuitable type of steam trap	Use mechanical type
Dryer 404	Leak (220 t/y)	• Internal of steam trap was damaged. • Dirty particles block the orifice that causes the steam leakage.	• Check internal of steam trap • Remove dirt and clean steam traps

5.2 Suggestions

5.2.1 Some parameters that affect to capacity of discharge condensate of seven steam traps such as backpressure should be measured in the real condition. The backpressure of steam trap or pressure of condensate return line should be installed the pressure indicator in order to receive the accurate data.

5.2.2 The other steam traps that are not seven problem steam traps should be checked the conditions. When other steam traps have problems, they should be solved the problems in order to reduce the steam loss and improve reliability of production process.

5.2.3 All steam traps in SMPC should be checked regularly in order to maintain the steam trap condition. Steam traps having problems should be inspected and solved the problems immediately. Operators should make a checklist for inspection the steam trap conditions.

Part II: Study the efficiency of hot oil furnace.

5.1 Conclusion

The optimum excess oxygen from test results is 1.3% which is same as normal operation and furnace efficiency is 89%. After the excess oxygen increased more than 1.3%, heat loss from flue gas increases which effects to decrease the furnace efficiency. From STAT program, the optimum excess oxygen is 3.0%, the errors of furnace efficiency which effect to the optimum excess oxygen between test and STAT results may come from two reasons. First, the heating value of fuel gas used in efficiency calculation was an average value at 900 BTU/SCF. Second, the historical data did not have the hot oil flow rate same as the test condition that equal to 620 ton/h.

5.2 Suggestions

5.2.1 Increasing of excess oxygen more than normal operation causes to produce more nitrogen oxide compounds. In test condition, the amount of nitrogen oxide compounds should be measured in order to ensure that it is still less than 45 ppm from Environmental Impact Assessment Report (EIA) of SMPC.

5.2.2 In test condition, excess oxygen should be decreased because the optimum excess oxygen which is highest furnace efficiency may be less than excess oxygen at normal operation. However, when excess oxygen was decreased, the smoke coming from unburned fuel may occur.

5.2.3 Study in detail should control some furnace parameters that effect the furnace efficiency calculation in test condition such as properties of hot oil, heating value of fuel gas, temperature of inlet air and temperature of inlet hot oil. If these parameters can be controlled to constant, the furnace efficiency in test condition will be more accuracy results.

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APPENDIX

APPENDIX A

STEAM TABLE

Table A.1 Steam table of saturated water—pressure table (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Pressure (MPa)	Sat. temp. (°C)	Specific volume (m^3/kg)		Internal energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kg.K)		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.0010	6.97	0.00100	129.18	29.3	2384.5	29.3	2484.4	2513.7	0.1059	8.8690	8.9749
0.0012	9.65	0.00100	108.67	40.6	2388.2	40.6	2478.0	2518.6	0.1460	8.7622	8.9082
0.0014	11.97	0.00100	93.90	50.3	2391.3	50.3	2472.5	2522.8	0.1802	8.6720	8.8522
0.0016	14.01	0.00100	82.74	58.8	2394.1	58.8	2467.7	2526.5	0.2100	8.5935	8.8035
0.0018	15.84	0.00100	74.01	66.5	2396.6	66.5	2463.4	2529.9	0.2366	8.5242	8.7608
0.0020	17.50	0.00100	66.99	73.4	2398.9	73.4	2459.5	2532.9	0.2606	8.4620	8.7226
0.0030	24.08	0.00100	45.65	101.0	2407.9	101.0	2443.8	2544.8	0.3543	8.2221	8.5764
0.0040	28.96	0.00100	34.79	121.4	2414.5	121.4	2432.3	2553.7	0.4224	8.0510	8.4734
0.0060	36.16	0.00101	23.73	151.5	2424.2	151.5	2415.1	2566.6	0.5208	7.8082	8.3290
0.0080	41.51	0.00101	18.10	173.8	2431.4	173.8	2402.4	2576.2	0.5925	7.6348	8.2273
0.010	45.81	0.00101	14.67	191.8	2437.2	191.8	2392.1	2583.9	0.6492	7.4996	8.1488
0.012	49.42	0.00101	12.36	206.9	2442.0	206.9	2383.4	2590.3	0.6963	7.3886	8.0849

Table A.1 Steam table of saturated water—pressure table (Continued) (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Pressure (MPa)	Sat. temp. (°C)	Specific volume (m^3/kg)		Internal energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kg.K)		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.014	52.55	0.00101	10.690	220.0	2446.1	220.0	2375.8	2595.8	0.7366	7.2945	8.0311
0.016	55.31	0.00102	9.431	231.6	2449.8	231.6	2369.0	2600.6	0.7720	7.2126	7.9846
0.018	57.80	0.00102	8.443	242.0	2453.0	242.0	2363.0	2605.0	0.8036	7.1401	7.9437
0.02	60.06	0.00102	7.648	251.4	2456.0	251.4	2357.5	2608.9	0.8320	7.0752	7.9072
0.03	69.10	0.00102	5.228	289.2	2467.7	289.3	2335.2	2624.5	0.9441	6.8234	7.7675
0.04	75.86	0.00103	3.993	317.6	2476.3	317.6	2318.5	2636.1	1.0261	6.6429	7.6690
0.06	85.93	0.00103	2.732	360.0	2489.0	359.9	2293.0	2652.9	1.1454	6.3857	7.5311
0.08	93.49	0.00104	2.087	391.6	2498.2	391.7	2273.5	2665.2	1.2330	6.2009	7.4339
0.1	99.61	0.00104	1.694	417.4	2505.6	417.5	2257.4	2674.9	1.3028	6.0560	7.3588
0.12	104.78	0.00105	1.428	439.2	2511.7	439.4	2243.7	2683.1	1.3609	5.9368	7.2977
0.14	109.29	0.00105	1.2366	458.3	2516.9	458.4	2231.6	2690.0	1.4110	5.8351	7.2461
0.16	113.30	0.00105	1.0914	475.2	2521.4	475.4	2220.6	2696.0	1.4551	5.7463	7.2014

Table A.1 Steam table of saturated water—pressure table (Continued) (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Pressure (MPa)	Sat. temp. (°C)	Specific volume (m^3/kg)		Internal energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kg.K)		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.18	116.91	0.00106	0.9775	490.5	2525.5	490.7	2210.7	2701.4	1.4945	5.6676	7.1621
0.20	120.21	0.00106	0.8857	504.5	2529.1	504.7	2201.5	2706.2	1.5302	5.5967	7.1269
0.30	133.52	0.00107	0.6058	561.1	2543.2	561.4	2163.5	2724.9	1.6717	5.3199	6.9916
0.40	143.61	0.00108	0.4624	604.2	2553.1	604.7	2133.4	2738.1	1.7765	5.1190	6.8955
0.60	158.83	0.00110	0.3156	669.7	2566.8	670.4	2085.7	2756.1	1.9308	4.8284	6.7592
0.80	170.41	0.00112	0.2403	720.0	2576.0	720.9	2047.4	2768.3	2.0457	4.6159	6.6616
1.00	179.88	0.00113	0.1944	761.4	2582.7	762.5	2014.6	2777.1	2.1381	4.4469	6.5850
1.20	187.96	0.00114	0.1633	797.0	2587.8	798.3	1985.4	2783.7	2.2159	4.3058	6.5217
1.40	195.04	0.00115	0.1408	828.4	2591.8	830.0	1958.8	2788.8	2.2835	4.184	6.4675
1.60	201.37	0.00116	0.1237	856.6	2594.8	858.5	1934.3	2792.8	2.3435	4.0764	6.4199
1.80	207.11	0.00117	0.1104	882.4	2597.2	884.5	1911.4	2795.9	2.3975	3.9800	6.3775
2.00	212.38	0.00118	0.0996	906.1	2599.1	908.5	1889.8	2798.3	2.4468	3.8922	6.3390
3.00	233.85	0.00122	0.0667	1004.7	2603.2	1008.3	1794.9	2803.2	2.6455	3.5401	6.1856
4.00	250.35	0.00125	0.0498	1082.5	2601.7	1087.5	1713.3	2800.8	2.7968	3.2728	6.0696

Table. A.1 Steam table of saturated water—pressure table (Continued) (Çengel, Yunus A. and Afshin J. Ghajar, 2011)

Pressure (MPa)	Sat. temp. (°C)	Specific volume (m^3/kg)		Internal energy (kJ/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kg.K)		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
6.00	275.58	0.00132	0.0325	1206.0	2589.9	1213.9	1570.7	2784.6	3.0278	2.8623	5.8901
8.00	295.01	0.00139	0.0235	1306.2	2570.5	1317.3	1441.4	2758.7	3.2081	2.5369	5.7450
10.00	311.00	0.00145	0.0180	1393.5	2545.2	1408.1	1317.4	2725.5	3.3606	2.2554	5.6160
12.00	324.68	0.00153	0.0143	1473.1	2514.3	1491.5	1193.9	2685.4	3.4967	1.9972	5.4939
14.00	336.67	0.00161	0.0115	1548.4	2477.1	1571.0	1066.9	2637.9	3.6232	1.7495	5.3727

APPENDIX B

RAW DATA

Table B.1 Results data from hot oil furnace in test condition

Date	Inlet hot oil temperature (°C)	Outlet hot oil temperature (°C)	Hot oil flow rate (kg/h)	Fuel gas flow rate (kNm^3/h)	Lower heating value (BTU/SCF)	Inlet air temperature (°C)	Air flow rate (kg/h)	Percent excess oxygen (%)
19/10/60	278.7	313.3	601.0	1,617.7	902.6	259.6	20,919.7	1.30
20/10/60	279.7	313.3	620.1	1,612.1	893.9	260.5	21,705.9	2.00
21/10/60	279.8	313.4	620.0	1,597.0	896.9	259.6	22,298.1	2.37
22/10/60	280.1	313.3	620.1	1,606.0	902.1	260.2	23,038.6	2.99
23/10/60	280.1	313.4	620.0	1,594.1	905.6	259.7	23,815.0	3.50
24/10/60	280.0	313.4	619.9	1,591.4	897.4	259.9	24,618.5	4.00
25/10/60	280.0	313.3	620.0	1,616.7	893.4	260.7	25,736.1	4.47
26/10/60	280.0	313.3	620.2	1,599.7	892.7	260.6	26,385.4	4.75
27/10/60	280.1	313.3	620.0	1,618.3	895.0	261.4	25,765.3	4.50
28/10/60	280.0	313.3	620.0	1,620.1	896.3	260.3	24,730.3	4.00
29/10/60	280.1	313.3	619.9	1,614.3	889.1	261.2	23,976.3	3.56
30/10/60	280.2	313.3	620.0	1,606.2	893.0	260.5	22,846.9	3.00
31/10/60	280.0	313.3	620.1	1,613.2	895.2	260.6	22,194.8	2.50

Table B.1 Results data from hot oil furnace in test condition (Continued)

Date	Inlet hot oil temperature (˚C)	Outlet hot oil temperature (˚C)	Hot oil flow rate (kg/h)	Fuel gas flow rate (kNm^3/h)	Lower heating value (BTU/SCF)	Inlet air temperature (˚C)	Air flow rate (kg/h)	Percent excess oxygen (%)
1/11/60	280.0	313.4	619.9	1,608.9	892.7	260.1	21,621.6	2.05
2/11/60	280.0	313.4	619.9	1,613.6	895.0	260.1	20,749.6	1.32
3/11/60	280.0	313.3	620.0	1,606.0	896.3	259.8	20,564.3	1.30
4/11/60	280.0	313.4	619.9	1,588.3	889.1	259.5	20,629.8	1.31
6/11/60	280.0	313.4	620.0	1,575.2	895.2	259.4	20,624.5	1.30
7/11/60	279.9	313.4	620.0	1,589.8	898.7	259.9	20,758.5	1.30
8/11/60	279.9	313.4	620.0	1,605.8	899.0	259.9	20,679.3	1.30
9/11/60	279.9	313.4	620.1	1,614.4	900.2	260.2	21,640.1	2.00
10/11/60	279.9	313.4	619.9	1,612.2	900.3	260.0	21,538.4	2.00
11/11/60	279.8	313.4	620.0	1,602.9	900.5	259.8	22,158.2	2.46
12/11/60	279.9	313.4	619.9	1,598.4	896.1	259.9	22,408.2	2.50
13/11/60	279.9	313.3	619.8	1,603.9	899.6	260.5	22,966.8	2.92

Table B.1 Results data from hot oil furnace in test condition (Continued)

Date	Inlet hot oil temperature (˚C)	Outlet hot oil temperature (˚C)	Hot oil flow rate (kg/h)	Fuel gas flow rate (kNm^3/h)	Lower heating value (BTU/SCF)	Inlet air temperature (˚C)	Air flow rate (kg/h)	Percent excess oxygen (%)
14/11/60	279.9	313.4	619.7	1,616.7	901.9	260.3	23,108.1	3.00
15/11/60	279.9	313.4	619.9	1,611.1	905.8	260.2	22,310.7	2.50
16/11/60	280.1	313.4	620.2	1,576.0	904.3	260.0	22,161.7	2.50
17/11/60	280.1	313.4	620.2	1,590.3	907.3	260.0	21,524.1	2.00
18/11/60	280.2	313.3	620.0	1,603.9	902.4	259.9	21,611.0	2.00
19/11/60	280.0	313.4	620.0	1,614.5	898.2	259.6	20,699.7	1.30
20/11/60	280.0	313.3	619.8	1,616.1	894.9	259.3	20,504.9	1.30
21/11/60	280.0	313.4	619.9	1,623.0	899.4	260.4	20,659.8	1.30
22/11/60	280.1	313.4	620.1	1,598.5	900.6	259.4	20,619.3	1.30
23/11/60	280.0	313.4	619.9	1,598.8	901.3	259.9	20,745.0	1.30

APPENDIX C

EXAMPLES OF CALCULATION

C.1 Example of condensate load calculation

The important thing that is used to select the steam trap is condensate load. Condensate will be formed from steam condensation. When steam released heat to process, steam will condense to liquid phase. Therefore, we need to determine the heat that is absorbed by process in order to calculate the condensate load. There are 7 steam traps that bypass valves of steam traps are opened. The heat exchanger 102 is one of equipment which bypass valve of the steam trap is opened. This condensate load calculation based on heat exchanger 102.

1. Data of process parameters and steam condition of heat exchanger 102

1. Process flow rate = 2,500 kg/h
2. Process inlet temperature = 40.9 ˚C
3. Process outlet temperature = 185.0 ˚C
4. Specific heat capacity = 3.003 kJ/kg*K
5. Steam pressure = 12 $\mathrm{kg/cm^2}$
6. Latent heat of steam at 12 $\mathrm{kg/cm^2}$ = 1,974.64 kJ/kg

2. Heat balance calculation

2.1 Overall heat balance of heat exchanger 102

$$\sum \dot{Q}_{in} = \sum \dot{Q}_{out} \tag{C.1}$$

$$\dot{Q}_{process,inlet} + \dot{Q}_{steam,inlet} = \dot{Q}_{process,outlet} + \dot{Q}_{steam,outlet}$$

When $\dot{Q}_{process,inlet}$ = The energy of inlet process

$\dot{Q}_{steam,inlet}$ = The energy of inlet steam

$\dot{Q}_{process,outlet}$ = The energy of outlet process

$\dot{Q}_{steam,outlet}$ = The energy of outlet steam

2.2 Energy calculation of process

$$\dot{Q}_{process,inlet} = \dot{m}_{process} c_{p,process} (T_{process,inlet} - T_{ref}) \tag{C.2}$$

$$\dot{Q}_{process,outlet} = \dot{m}_{process} c_{p,porcess} (T_{process,outlet} - T_{ref}) \tag{C.3}$$

2.3 Energy calculation of steam

The different value of energy of inlet and outlet steam is the latent heat of steam that is released to the process.

$$\Delta\dot{Q}_{steam} = \dot{Q}_{steam,inlet} - \dot{Q}_{steam,outlet} \tag{C.4}$$

$$\Delta\dot{Q}_{steam} = \dot{m}_{steam} h_{fg} \tag{C.5}$$

2.4 Condensate load calculation

From $$\sum \dot{Q}_{in} = \sum \dot{Q}_{out} \tag{C.6}$$

$$\dot{Q}_{process,inlet} + \dot{Q}_{steam,inlet} = \dot{Q}_{process,outlet} + \dot{Q}_{steam,outlet}$$

$$\dot{Q}_{steam,inlet} - \dot{Q}_{steam,outlet} = \dot{Q}_{process,outlet} - \dot{Q}_{process,inlet}$$

$$\dot{m}_{steam} h_{fg} = \dot{m}_{process} c_{p,process} (T_{process,outlet} - T_{ref}) - \dot{m}_{process} c_{p,process} (T_{process,inlet} - T_{ref})$$

$$\dot{m}_{steam} h_{fg} = \dot{m}_{process} c_{p} (T_{process,outlet} - T_{process,inlet})$$

$$\dot{m}_{steam} = \frac{\dot{m}_{process} c_{p} (T_{process,outlet} - T_{process,inlet})}{h_{fg}}$$

$$\dot{m}_{steam} = \frac{2{,}500 \dfrac{kg_{process}}{h} \times 3.003 \dfrac{kJ}{kg_{process} \times K} \times \left(185.0 - 40.9\right) K}{1{,}974.64 \dfrac{kJ}{kg_{steam}}}$$

$$\dot{m}_{steam} = 547.82 \quad kg$$

Table C.1 Heat exchanger conditions and condensate load calculation results

	Process flow rate (kg/h)	Inlet process temp. (˚C)	Outlet process temp. (˚C)	Specific heat capacity of process (kJ/kg*K)	Pressure of steam (kg/cm^2)	Latent heat (kJ/kg)	Condensate load (kg/h)
Heat Exchanger 102	2,500	40.9	185	3.00	12.0	1,974.6	547.82
Heat Excanger 901	155,022	35.6	90	1.04	3.0	2,134.5	4,108.82
Heat Excanger 504	6,300	99.1	170	5.44	10.4	1,996.4	1,217.13
Heater steam drum 1206	4,200	170.0	200	6.18	17.0	1,914.8	406.64

Note 1. Condensate loads of dryer 304 and dryer 404 are measured by flow indicator at local.

2. Condensate load of steam jacketed drum 509 comes from steam balance of PTA plant 2.

C.2 Example of furnace efficiency calculation on 21 Nov. 2017

The furnace efficiency can be calculated from energy balance. The absorbed heat of hot oil and released heat of fuel gas are the important values to calculate the furnace efficiency.

1. Data of hot oil furnace parameters

1. Hot oil flow rate = 620,000 kg/h
2. Inlet hot oil temperature = 280.0 ˚C
3. Outlet hot oil temperature = 313.4 ˚C
4. Specific heat capacity of hot oil = 2.5445 kJ/kg*K
5. Fuel gas flow rate = 1,612.84 m^3/h

6. Lower heating value = 33,508.66 kJ/m^3

7. Air flow rate = 20,675.20 kg/h

8. Air inlet temperature = 260.0 ˚C

9. Excess oxygen in flue gas = 1.3 %

10. Reference temperature = 15.0 ˚C

2. Absorbed heat of hot oil calculation

From
$$\dot{Q}_{hot\ oil,inlet} = \dot{m}_{hot\ oil} c_{p,hot\ oil} (T_{hot\ oil,inlet} - T_{ref}) \tag{C.7}$$

$$\dot{Q}_{hot\ oil,outlet} = \dot{m}_{hot\ oil} c_{p,hot\ oil} (T_{hot\ oil,outlet} - T_{ref}) \tag{C.8}$$

$$\Delta\dot{Q}_{hot\ oil} = \dot{Q}_{hot\ oil,outlet} - \dot{Q}_{hot\ oil,inlet}$$

$$\Delta\dot{Q}_{hot\ oil} = \dot{m}_{hot\ oil} c_{p,hot\ oil} (T_{hot\ oil,outlet} - T_{ref}) - \dot{m}_{hot\ oil} c_{p,hot\ oil} (T_{hot\ oil,inlet} - T_{ref})$$

$$\Delta\dot{Q}_{hot\ oil} = \dot{m}_{hot\ oil} c_{p,hot\ oil} (T_{hot\ oil,outlet} - T_{hot\ oil,inlet})$$

$$\Delta\dot{Q}_{hot\ oil} = 620{,}000 \frac{kg_{hot\ oil}}{h} \times 2.5445 \frac{kJ}{kg_{hot\ oil} \times K} \times (313.4 - 280.0)K$$

$$\Delta\dot{Q}_{hot\ oil} = 52{,}581{,}074 \quad kJ/h$$

$$\Delta\dot{Q}_{hot\ oil} = 14.61 \quad Mwatt$$

3. Released heat of fuel gas calculation

From
$$\dot{Q}_{fuel\ gas} = \dot{m}_{fuel\ gas} LHV \tag{C.9}$$

$$\dot{Q}_{fuel\ gas} = 1{,}612.84 \frac{m^3}{h} \times 33{,}508.66 \frac{kJ}{m^3}$$

$$\dot{Q}_{fuel\ gas} = 54{,}044{,}91.05 \quad kJ/h$$

$$\dot{Q}_{fuel\ gas} = 15.01 \quad Mwatt$$

4. Inlet heat of air calculation

From
$$\dot{Q}_{air,inlet} = \dot{m}_{air} c_{p,air} (T_{air} - T_{ref}) \tag{C.10}$$

$$\dot{Q}_{air,inlet} = 20{,}675.20 \frac{kg_{air}}{h} \times 1.05 \frac{kJ}{kg_{air} \times K} \times (260.0 - 15.0)K$$

$$\dot{Q}_{air,inlet} = 5{,}319{,}129.38 \quad kJ/h$$

$$\dot{Q}_{air,inlet} = 1.48 \quad Mwatt$$

5. Furnace efficiency calculation

From $$\text{Efficiency} = \frac{\text{Absorbed heat of process}}{\text{Inlet heat to furnace}} \times 100 \qquad \text{(C.11)}$$

$$\text{Efficiency} = \frac{\Delta\dot{Q}_{\text{Hot oil}}}{\dot{Q}_{\text{fuel gas}} + \dot{Q}_{\text{air}}} \times 100$$

$$\text{Efficiency} = \frac{14.61}{15.01+1.48} \times 100$$

$$\text{Efficiency} = 88.60\ \%$$

APPENDIX D

REGRESSION EQUATION FROM MINITAB PROGRAM

D.1 Find the correlation of furnace parameters

The furnace parameters that are used to determine the correlation of the furnace efficiency are mass flow rate of hot oil, inlet hot oil temperature and fuel gas per air ratio. The outlet hot oil temperature and lower heating value are constant. The inlet air temperature is not used to be independent variable in furnace efficiency equation because inlet air temperature is correlated with inlet hot oil temperature. Therefore, inlet air temperature can be eliminated in efficiency equation. Steps to determine the correlation between each parameters are shown in Figure D.1 to Figure D.10.

Step 1: Input data on work sheet and click stat -----> basic statistics -----> correlation.

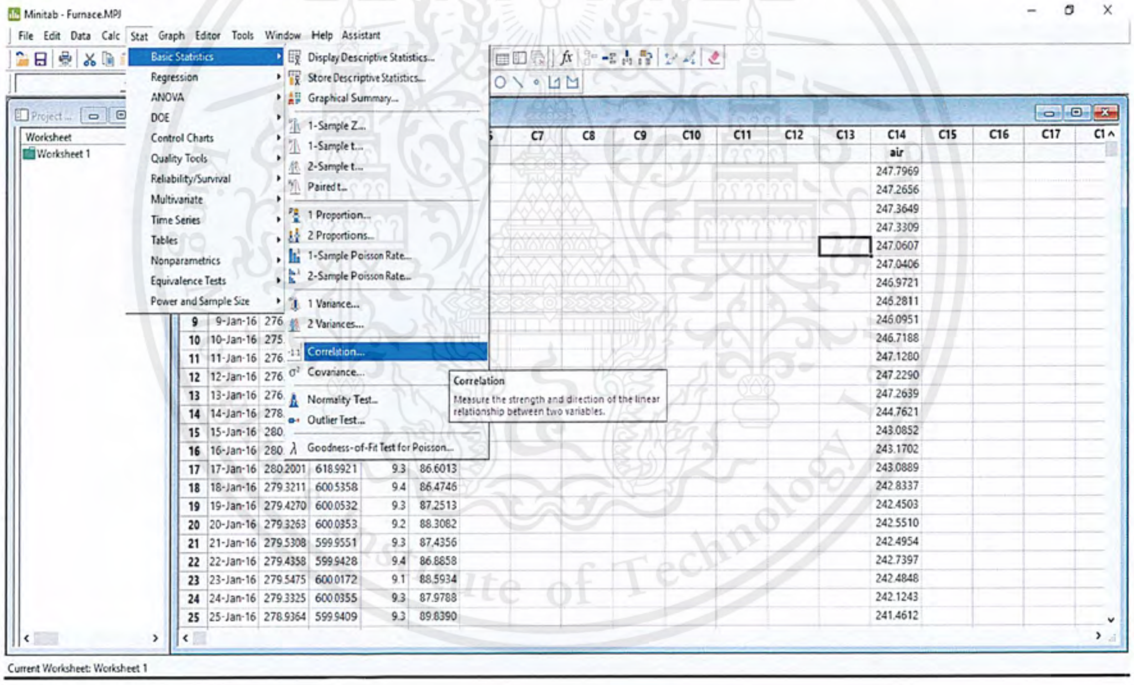
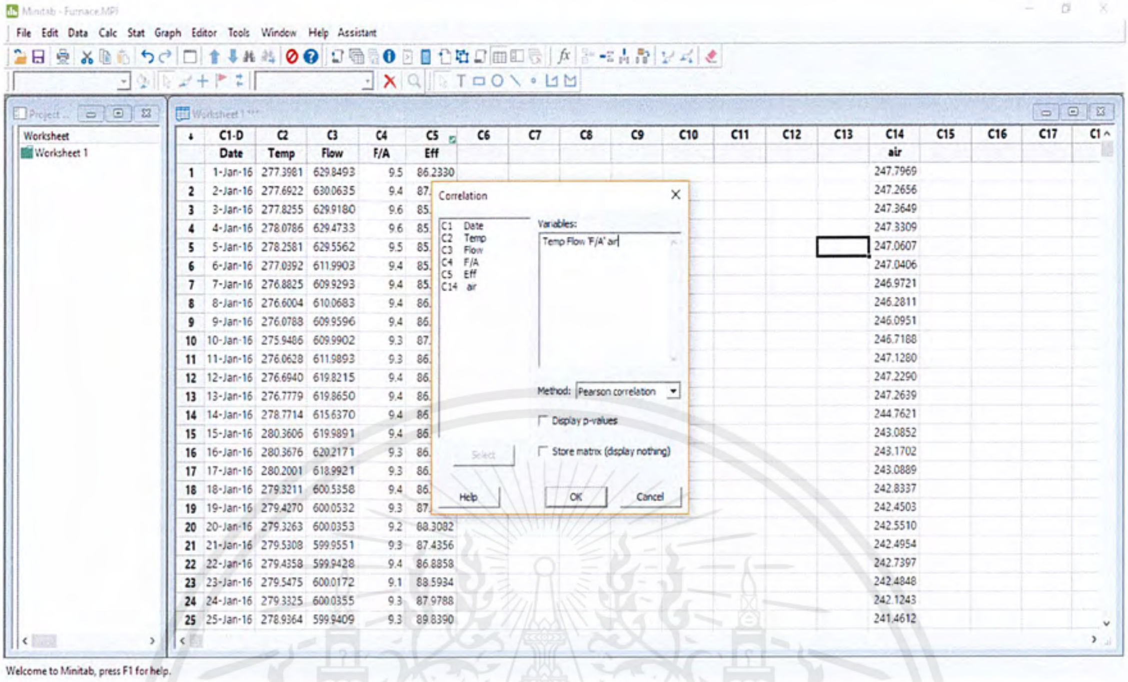


Figure D.1 Selection of correlation in minitab program

Step 2. In the correlation box, temp, flow, F/A and air are selected to be the variables and then click OK.



↓	C1-D Date	C2 Temp	C3 Flow	C4 F/A	C5 Eff	C14 air
1	1-Jan-16	277.3981	629.8493	9.5	86.2330	247.7969
2	2-Jan-16	277.6922	630.0635	9.4	87.	247.2656
3	3-Jan-16	277.8255	629.9180	9.6	85.	247.3649
4	4-Jan-16	278.0786	629.4733	9.6	85.	247.3309
5	5-Jan-16	278.2581	629.5562	9.5	85.	247.0607
6	6-Jan-16	277.0392	611.9903	9.4	85.	247.0406
7	7-Jan-16	276.8825	609.9293	9.4	85.	246.9721
8	8-Jan-16	276.6004	610.0683	9.4	86.	246.2811
9	9-Jan-16	276.0788	609.9596	9.4	86.	246.0951
10	10-Jan-16	275.9486	609.9902	9.3	87.	246.7188
11	11-Jan-16	276.0628	611.9893	9.3	86.	247.1280
12	12-Jan-16	276.6940	619.8215	9.4	86.	247.2290
13	13-Jan-16	276.7779	619.8650	9.4	86.	247.2639
14	14-Jan-16	278.7714	615.6370	9.4	86	244.7621
15	15-Jan-16	280.3606	619.9891	9.4	86.	243.0852
16	16-Jan-16	280.3676	620.2171	9.3	86.	243.1702
17	17-Jan-16	280.2001	618.9921	9.3	86.	243.0889
18	18-Jan-16	279.3211	600.5358	9.4	86.	242.8337
19	19-Jan-16	279.4270	600.0532	9.3	87.	242.4503
20	20-Jan-16	279.3263	600.0353	9.2	88.3082	242.5510
21	21-Jan-16	279.5308	599.9551	9.3	87.4356	242.4954
22	22-Jan-16	279.4358	599.9428	9.4	86.8858	242.7397
23	23-Jan-16	279.5475	600.0172	9.1	88.5934	242.4848
24	24-Jan-16	279.3325	600.0355	9.3	87.9788	242.1243
25	25-Jan-16	278.9364	599.9409	9.3	89.8390	241.4612

C1 Date
C2 Temp
C3 Flow
C4 F/A
C5 Eff
C14 air

Variables: Temp Flow 'F/A' air

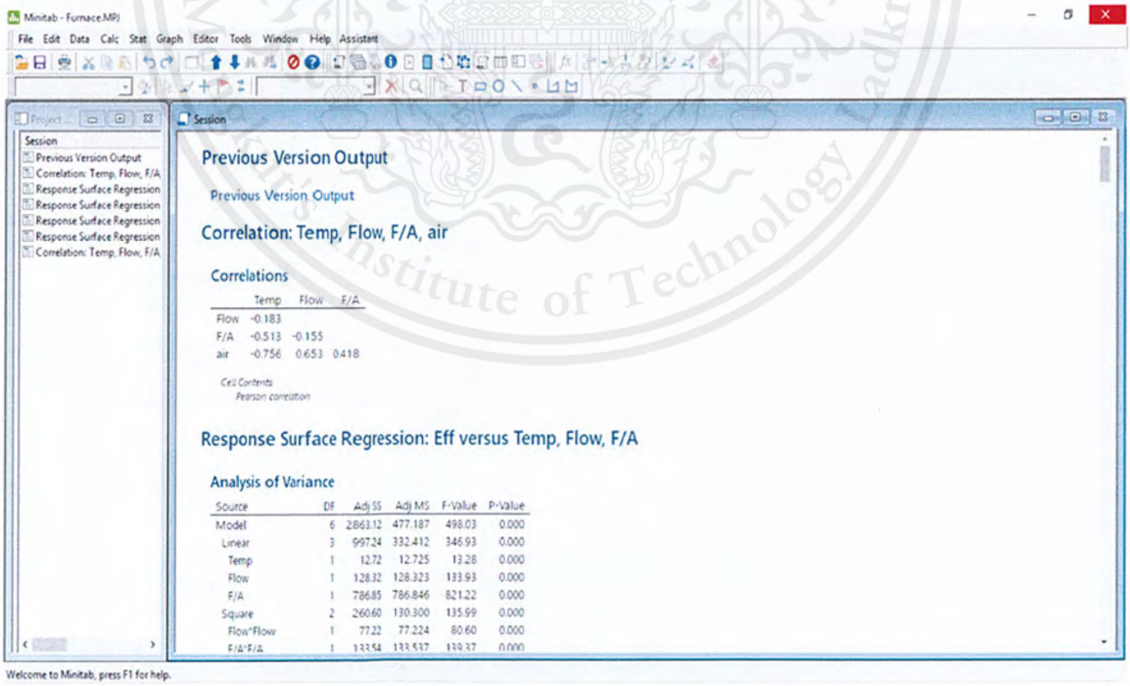
Method: Pearson correlation

☐ Display p-values

☐ Store matrix (display nothing)

Figure D.2 Selection the parameters to find the correlation

Step 3. Observe the results from session sheet.



```
Previous Version Output

  Previous Version Output

Correlation: Temp, Flow, F/A, air

  Correlations

          Temp    Flow    F/A
  Flow   -0.183
  F/A    -0.513  -0.155
  air    -0.756   0.653  0.418

    Cell Contents
      Pearson correlation

Response Surface Regression: Eff versus Temp, Flow, F/A

  Analysis of Variance

  Source          DF   Adj SS   Adj MS  F-Value  P-Value
  Model            6  2863.12  477.187   498.03    0.000
    Linear         3   997.24  332.412   346.93    0.000
      Temp         1    12.72   12.725    13.28    0.000
      Flow         1   128.32  128.323   133.93    0.000
      F/A          1   786.85  786.846   821.22    0.000
    Square         2   260.60  130.300   135.99    0.000
      Flow*Flow    1    77.22   77.224    80.60    0.000
      F/A*F/A      1   133.54  133.537   139.37    0.000
```

Figure D.3 Results of correlation from session sheet

Table D.1 Correlations of furnace parameters

	Temp	Flow	F/A
Flow	-0.183		
F/A	-0.513	-0.155	
air	-0.756	0.653	0.418

Where Temp = Temperature of inlet hot oil (°C)

Flow = Mass flow rate of inlet hot oil (ton/h)

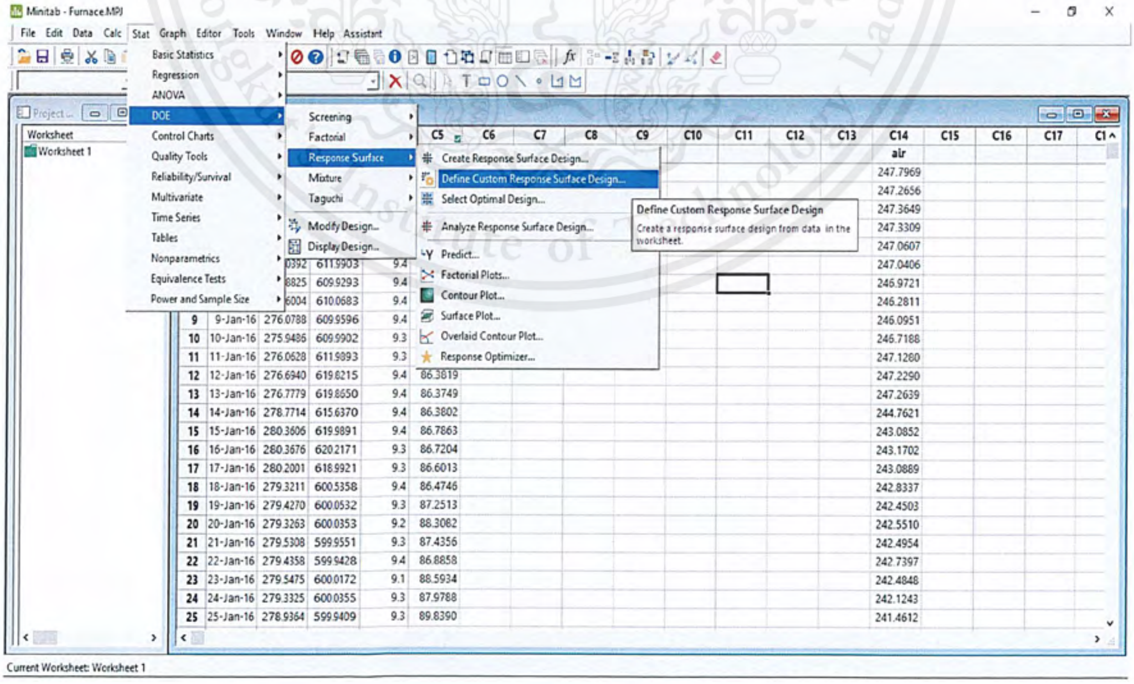
F/A = Fuel gas per air ratio

air = Temperature of inlet air (°C)

The correlation of F/A and Temp is more than 0.7. Therefore, air parameter can be eliminated and substituted by temp parameter.

D.2 Find the furnace efficiency equation from minitab program

Step 1. Open the minitab worksheet and click stat -----> DOE -----> response surface -----> define custom response surface design.



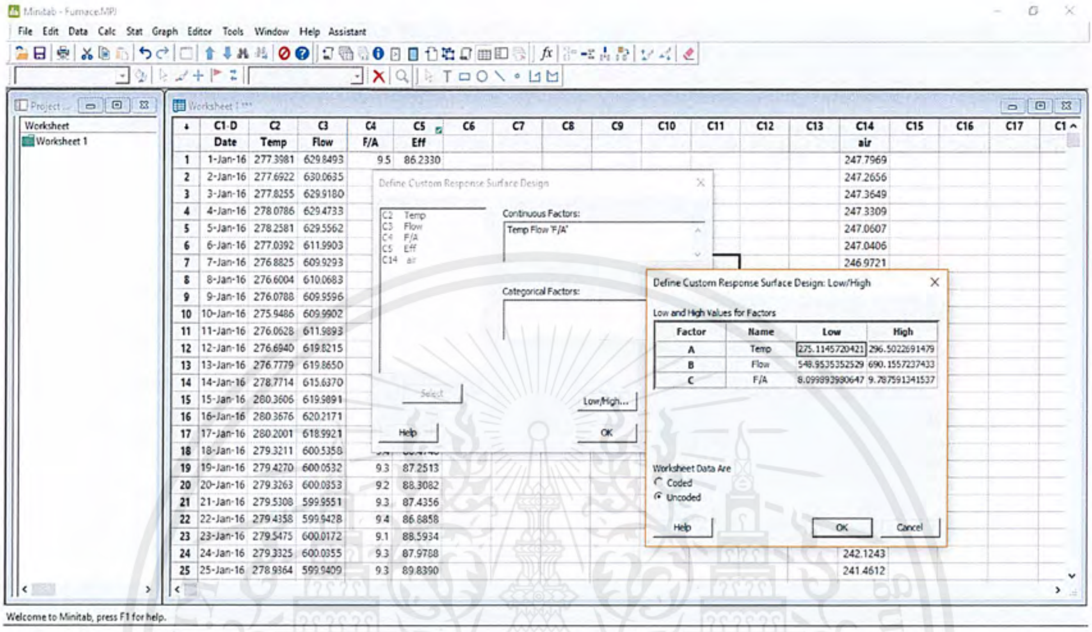
Define Custom Response Surface Design

Create a response surface design from data in the worksheet.

					C5	C14
						air
1						247.7969
2						247.2656
3						247.3649
4						247.3309
5						247.0607
6		0392	611.9903	9.4		247.0406
7		8825	609.9293	9.4		246.9721
8		6004	610.0683	9.4		246.2811
9	9-Jan-16	276.0788	609.9596	9.4		246.0951
10	10-Jan-16	275.9486	609.9902	9.3		246.7188
11	11-Jan-16	276.0628	611.9893	9.3		247.1280
12	12-Jan-16	276.6940	619.8215	9.4	86.3819	247.2290
13	13-Jan-16	276.7779	619.8650	9.4	86.3749	247.2639
14	14-Jan-16	278.7714	615.6370	9.4	86.3802	244.7621
15	15-Jan-16	280.3606	619.9891	9.4	86.7863	243.0852
16	16-Jan-16	280.3676	620.2171	9.3	86.7204	243.1702
17	17-Jan-16	280.2001	618.9921	9.3	86.6013	243.0889
18	18-Jan-16	279.3211	600.5358	9.4	86.4746	242.8337
19	19-Jan-16	279.4270	600.0532	9.3	87.2513	242.4503
20	20-Jan-16	279.3263	600.0353	9.2	88.3082	242.5510
21	21-Jan-16	279.5308	599.9551	9.3	87.4356	242.4954
22	22-Jan-16	279.4358	599.9428	9.4	86.8858	242.7397
23	23-Jan-16	279.5475	600.0172	9.1	88.5934	242.4848
24	24-Jan-16	279.3325	600.0355	9.3	87.9788	242.1243
25	25-Jan-16	278.9364	599.9409	9.3	89.8390	241.4612

Figure D.4 Define custom response surface design

Step 2. In the pop-up dialogue box, select the factors by double clicking and then click Low/High button, the low and high values of each factor are shown in the pop-up window. Then click OK back to previous dialogue box. Click OK again to finish defining custom factorial design.



Define Custom Response Surface Design

Continuous Factors: Temp Flow 'F/A'

Categorical Factors:

Define Custom Response Surface Design: Low/High

Low and High Values for Factors

Factor	Name	Low	High
A	Temp	275.1145720421	296.5022691479
B	Flow	548.9535352529	690.1557237433
C	F/A	8.099893980647	9.787591341537

Worksheet Data Are

○ Coded

● Uncoded

Figure D.5 Define custom response surface design: Low/High

Step 3. Click stat -----> DOE -----> response surface -----> analyze response surface design.

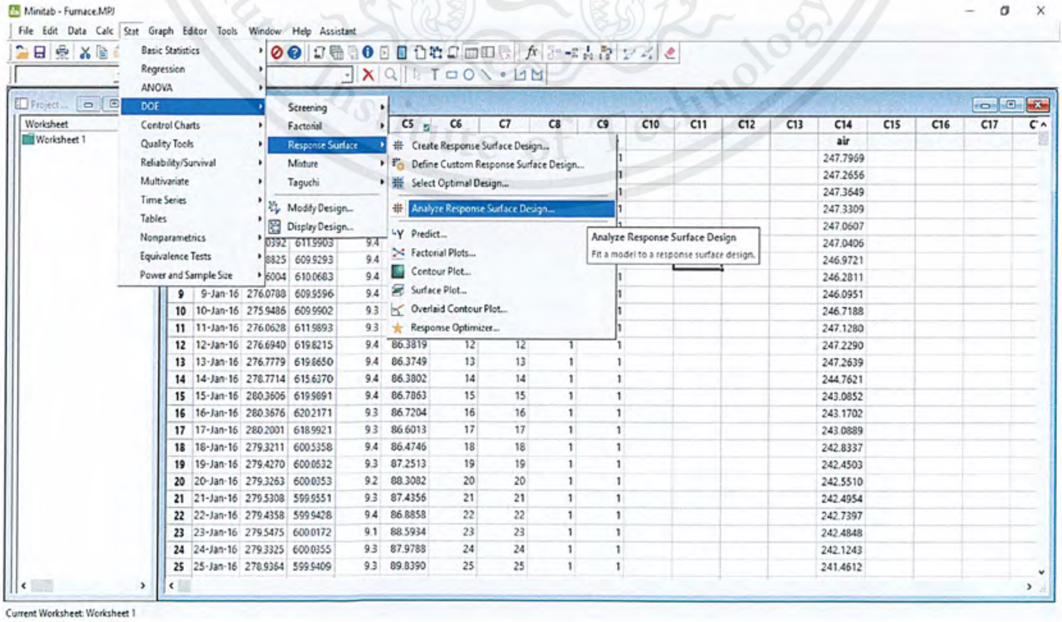
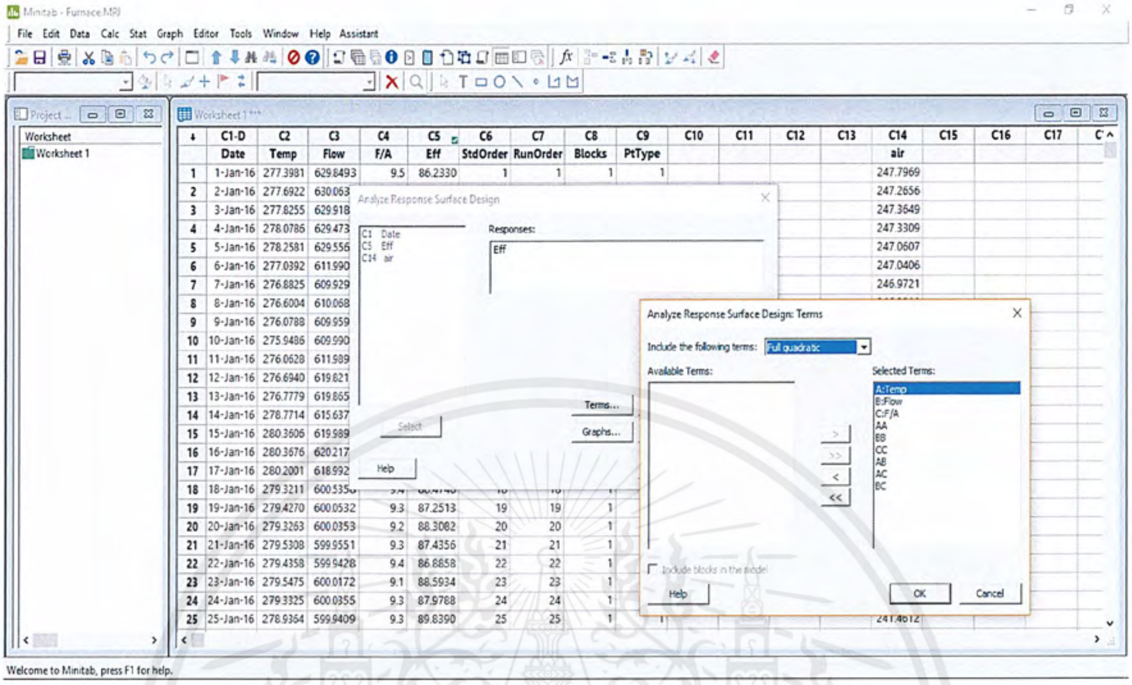


Figure D.6 Analyze response surface design

Step 4. In the analyze response surface design box, select the response variables and then click term and select full quadratic.



Analyze Response Surface Design

Responses: Eff

Analyze Response Surface Design: Terms

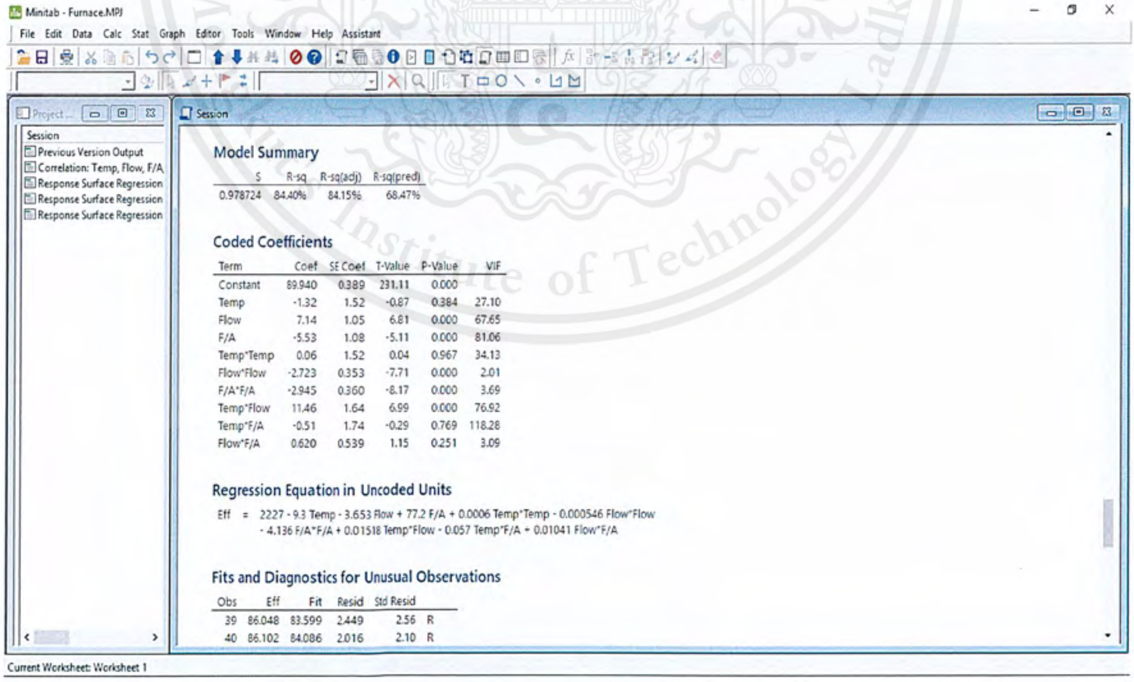
Include the following terms: Full quadratic

Selected Terms:
A:Temp
B:Flow
C:F/A
AA
BB
CC
AB
AC
BC

☐ Include blocks in the model

Figure D.7 Selection terms in analyze response surface design box

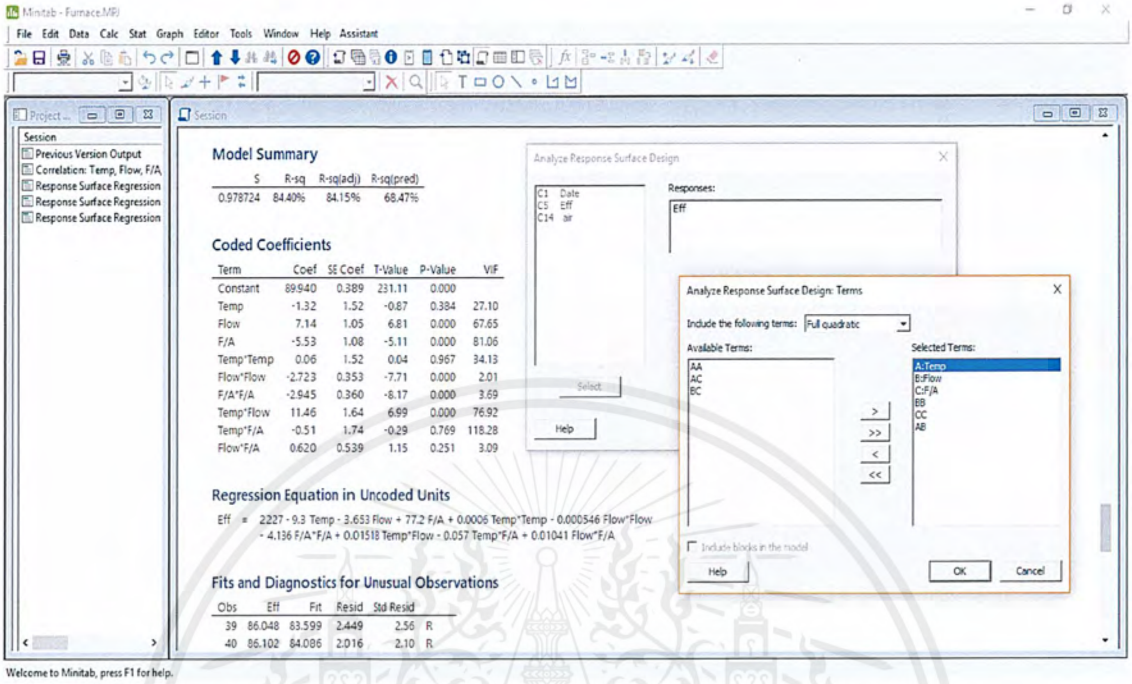
Step 5. Observe the P-value in the session sheet.



```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.978724  84.40%     84.15%      68.47%

Coded Coefficients

Term          Coef  SE Coef  T-Value  P-Value     VIF
Constant    89.940    0.389   231.11    0.000
Temp         -1.32     1.52    -0.87    0.384   27.10
Flow          7.14     1.05     6.81    0.000   67.65
F/A          -5.53     1.08    -5.11    0.000   81.06
Temp*Temp     0.06     1.52     0.04    0.967   34.13
Flow*Flow   -2.723    0.353    -7.71    0.000    2.01
F/A*F/A     -2.945    0.360    -8.17    0.000    3.69
Temp*Flow    11.46     1.64     6.99    0.000   76.92
Temp*F/A     -0.51     1.74    -0.29    0.769  118.28
Flow*F/A     0.620    0.539     1.15    0.251    3.09

Regression Equation in Uncoded Units

Eff  =  2227 - 9.3 Temp - 3.653 Flow + 77.2 F/A + 0.0006 Temp*Temp - 0.000546 Flow*Flow
        - 4.136 F/A*F/A + 0.01518 Temp*Flow - 0.057 Temp*F/A + 0.01041 Flow*F/A

Fits and Diagnostics for Unusual Observations

Obs     Eff     Fit  Resid  Std Resid
 39  86.048  83.599  2.449       2.56  R
 40  86.102  84.086  2.016       2.10  R
```

Figure D.8 Results of first regression equation from session sheet

Step 6. Click stat -----> DOE -----> response surface -----> analyze response surface design -----> term and then eliminate the term that P-value is less than 0.05.



```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.978724  84.40%     84.15%      68.47%

Coded Coefficients

Term          Coef  SE Coef  T-Value  P-Value     VIF
Constant    89.940    0.389   231.11    0.000
Temp         -1.32     1.52    -0.87    0.384   27.10
Flow          7.14     1.05     6.81    0.000   67.65
F/A          -5.53     1.08    -5.11    0.000   81.06
Temp*Temp     0.06     1.52     0.04    0.967   34.13
Flow*Flow   -2.723    0.353    -7.71    0.000    2.01
F/A*F/A     -2.945    0.360    -8.17    0.000    3.69
Temp*Flow    11.46     1.64     6.99    0.000   76.92
Temp*F/A     -0.51     1.74    -0.29    0.769  118.28
Flow*F/A     0.620    0.539     1.15    0.251    3.09

Regression Equation in Uncoded Units

Eff  =  2227 - 9.3 Temp - 3.653 Flow + 77.2 F/A + 0.0006 Temp*Temp - 0.000546 Flow*Flow
        - 4.136 F/A*F/A + 0.01518 Temp*Flow - 0.057 Temp*F/A + 0.01041 Flow*F/A

Fits and Diagnostics for Unusual Observations

Obs     Eff     Fit  Resid  Std Resid
 39  86.048  83.599  2.449       2.56  R
 40  86.102  84.086  2.016       2.10  R
```

Analyze Response Surface Design

C1 Date
C5 Eff
C14 air

Responses: Eff

Analyze Response Surface Design: Terms

Include the following terms: Full quadratic

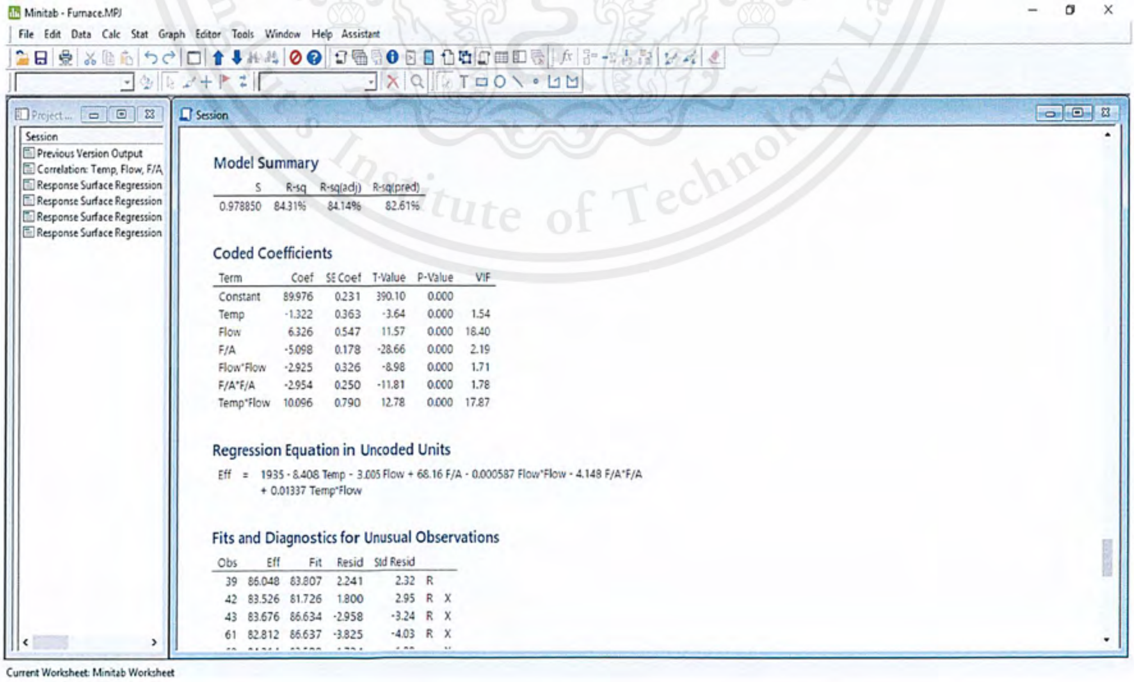
Available Terms: AA, AC, BC

Selected Terms: A:Temp, B:Flow, C:F/A, BB, CC, AB

☐ Include blocks in the model

Figure D.9 Elimination the term that P-value is less than 0.05

Step 7. Observe the results from session sheet. The regression equation of furnace efficiency can be used, when P-values of all terms are less than 0.05.



```
Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.978850  84.31%     84.14%      82.61%

Coded Coefficients

Term          Coef  SE Coef  T-Value  P-Value    VIF
Constant    89.976    0.231   390.10    0.000
Temp        -1.322    0.363    -3.64    0.000   1.54
Flow         6.326    0.547    11.57    0.000  18.40
F/A         -5.098    0.178   -28.66    0.000   2.19
Flow*Flow   -2.925    0.326    -8.98    0.000   1.71
F/A*F/A     -2.954    0.250   -11.81    0.000   1.78
Temp*Flow   10.096    0.790    12.78    0.000  17.87

Regression Equation in Uncoded Units

Eff  =  1935 - 8.408 Temp - 3.005 Flow + 68.16 F/A - 0.000587 Flow*Flow - 4.148 F/A*F/A
        + 0.01337 Temp*Flow

Fits and Diagnostics for Unusual Observations

Obs     Eff     Fit   Resid  Std Resid
 39  86.048  83.807   2.241       2.32  R
 42  83.526  81.726   1.800       2.95  R  X
 43  83.676  86.634  -2.958      -3.24  R  X
 61  82.812  86.637  -3.825      -4.03  R  X
```

Figure D.10 Results of regression equation from session sheet

Model summary

Table D.2 Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.9788	84.31%	84.14%	82.61%

Coded coefficients

Table D.3 Code coefficient

Term	Coef	SE Coef	T-Value	P-Value
Constant	89.976	0.231	390.10	0.000
Temp	-1.322	0.363	-3.64	0.000
Flow	6.326	0.547	11.57	0.000
F/A	-5.098	0.178	-28.66	0.000
Flow*Flow	-2.925	0.326	-8.98	0.000
F/A*F/A	-2.954	0.250	-11.81	0.000
Temp*Flow	10.096	0.790	12.78	0.000

Where Temp = Temperature of inlet hot oil (°C)

Flow = Mass flow rate of inlet hot oil (ton/h)

F/A = Fuel gas/air ratio

Regression equation

Eff = 1935 - 8.408 Temp - 3.005 Flow + 68.16 F/A - 0.000587 Flow*Flow - 4.148 F/A*F/A + 0.01337 Temp*Flow

Where Temp = Temperature of inlet hot oil (°C)

Flow = Mass flow rate of inlet hot oil (ton/h)

F/A = Fuel gas/ air ratio

BIOGRAHPY

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  Yothinburana School, Bangkok
- 2014 – 2017 : Bachelor of Petrochemical Engineering
  Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang

Working Experiences :

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  Project Based Internship Program 2017
- August 2016 – November 2016 : Siam Mitsui PTA Co.,Ltd.
  Co-operative Education 2017