สำนักหอสมุดกลาง พระจอมเกล้าลาดกระบัง

Report of Cooperative Education

Soot-Blowing Management



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Abstract

The cost of fouling is a reduction of heat transfer and loss of furnace efficiency. Soot blowing is always used to blow away the fouling, and schedule of soot blowing is a fixed schedule based on operation experience. The operation of soot blowing can increase efficiency. More frequent soot blowing times will be cause a waste steam, increase maintenance cost and tube erosion. In contrast, less soot blowing operation leads to soot accumulation and a decrease of thermal efficiency.

In the traditional ways, soot blowing operation are not optimal without a proper evaluation. Therefore, the assessment of fouling on heat transfer surface is needed. Fouling condition can be evaluated by on-line calculations and special instrumentations. The fundamental method is calculating the heat absorption on the convection bank by LMTD method. However, this method can be done only steady state operation. Dynamic behaviors of heat transfer surface are unable to be shown. The heat flux meters are well known as the instrument which can reflect the status of heat absorption bank. The status can be used to evaluate the fouling condition on the convection bank section. However, the equipment requires the installation and maintenance which are the investment cost

The method developed in this project can be used to monitor the fouling level of heat transfer without excessive cost. Based on the monitored, soft measure thermal parameters. The soot blowing operation and soot deposition behavior are demonstrated by the calculation of effectiveness. The optimization strategy can be developed for soot blowing operation. The key of optimization strategy is considering the heat loss due to the soot deposition of each operating

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conditions balanced with the energy consume by soot blowing operation, aiming at optimization soot blowing time per each operating condition. Then analysis the result for check the validation of results. The flow chart of soot blowing optimization is also given as the guideline for implementation. At last, the benefit calculation show the cost saving of the proposed method.

Keywords: Soot-blowing, Soot-blowing optimization, Gas-side fouling



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CHAPTER I
INTRODUCTION

1.1 Background

In the last years, concern about global warming and green house effect has tightened regulation of Refinery Plant, becoming a priority the improvement of efficiencies and the reduction of pollutant emission.

Fired heater is one of key equipment of heating process for every refinery plant. The problem of fired heater is the fouling deposition. Fouling deposition of heat transfer surface has always been the one of main opearation concerns in refinery plant. The effect of fouling deposition is a reduction of heat absorbtion resulting in a loss of thermal efficiency. On-load cleaning is usually carried out by blowing tube with pressureized steam. The consumption of steam penelizes the plant efficiency and increasing of heat losses. This should be balanced by increase of heat absorption in clean section. But assessment is never undertaken and blowing is often do under conservative schedules based on operation experiences.

Thai Oil Public Company Limited be aware of the important of energy saving and pollutant emission thus Efficiency Operation Support Combustion section (EOSC) initiated the **Soot Blowing Management Project**. This project is the optimization of steam consumption for cleaning purpose in convection bank of vacuum change heater. Online monitoring of performance of convection bank for indicating the performance of currently soot blowing schedule and providing optimization strategy to obtain the suitable soot blowing guideline in order to minimizing excessive loss of steam, maximizing the soot-blowing operation and improving the furnace efficiency.

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1.1 Objectives

1. To provide the monitoring tool for evaluation of the convection bank performance.

2. To provide the optimization strategy by using the monitoring tool.

3. To verify the current soot blowing guideline capacity.

4. To check the feasibility to develop the suitable soot blowing guideline.

1.2 Scopes of work

1. Study on the process and the theory fired equipment especially on the convection bank section.

2. Study on the energy absorbtion loss due to fouling deposition on the convection bank in different operating condition.

3. Study on the current soot blowing operation and soot blowing parameters (stream mass flow rate/soot blowing time).

4. Study on the soot blowing optimization

1.3 Expected outputs

1. Evaluation the convection bank performance by using the key parameter.

2. Opimization strategy which can be apply for all soot blowing operation of convection bank.

3. Minimizing the excessive loss of energy consumption of soot blowing operation by applying the soot blowing guideline.

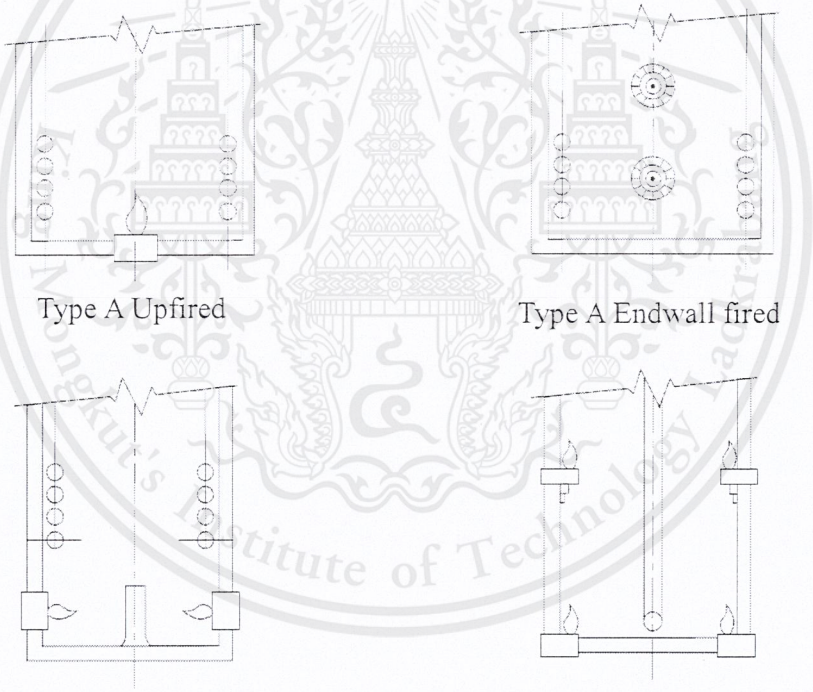
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CHAPTER II

LITERATURE REVIEW

2.1 Basic concept of fired heaters

A fired heater is an insulate enclosure that uses the heat created by the combustion of fuels to heat fluids contained in side coils. The type of heater is normally described by the structural configuration, the radiant tube coil configuration and burner arrangement. Some examples of structural configurations are cylindrical, box, cabin and multi-cell box. Examples of burner arrangement include upfired, down fired and wall fired. The wall fired arrangement can be further classified as sidewall, end wall and multi-level.



Type A Upfired

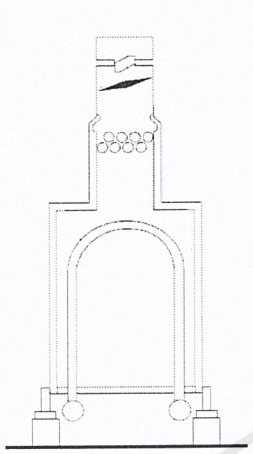
Type A Endwall fired

Type C Sidewall fired

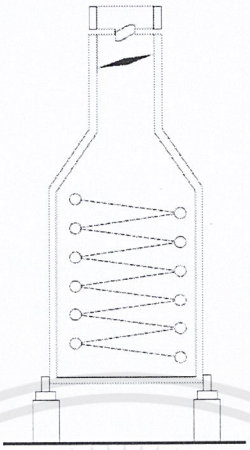
Type D Sidewall fired multi-level

Figure 2.1 Typical Burner Arrangements (Elevation View)

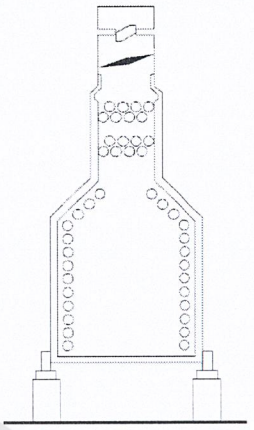
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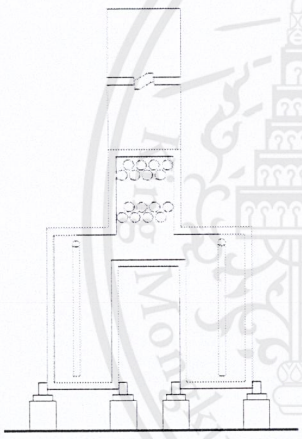
Type A Box heater with arbor coil



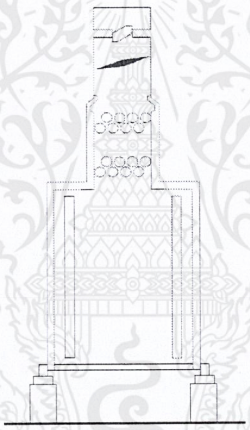
Type B Cylindrical heater with helical coil



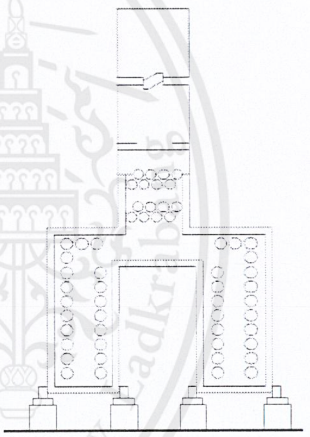
Type C Cabin heater with horizontal tube coil



Type D Box heater with vertical tube coil



Type E Cylindrical heater with vertical coil



Type F Box heater with horizontal tube coil

Figure 2.2 Typical heater types

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2.2 Fired heater equipment overview

A fired heater consists of three major components: heating coil, enclosure and combustion equipment. Figure 2.3 provides fired heater equipment overview. The heating coil consists of tube connected together in series that carry the fluid being heated. The enclosure concists a firebox. It is a steel structure lined with refractory material that holds the generated heat. Burners create the heat by combusting fuel, either oil or gas. The heating coil absorbs the heat mostly by radiation heat transfer in radiant cell and convection heat transfer from flue gases in convection bank. Then the flue gas is vented to the atmosphere through the stack. Burners are located on the flood or sidewalls. Combustion air is drawn from the atmosphere. For increase heat recovery, an air preheater is installed downstream of the convection section.

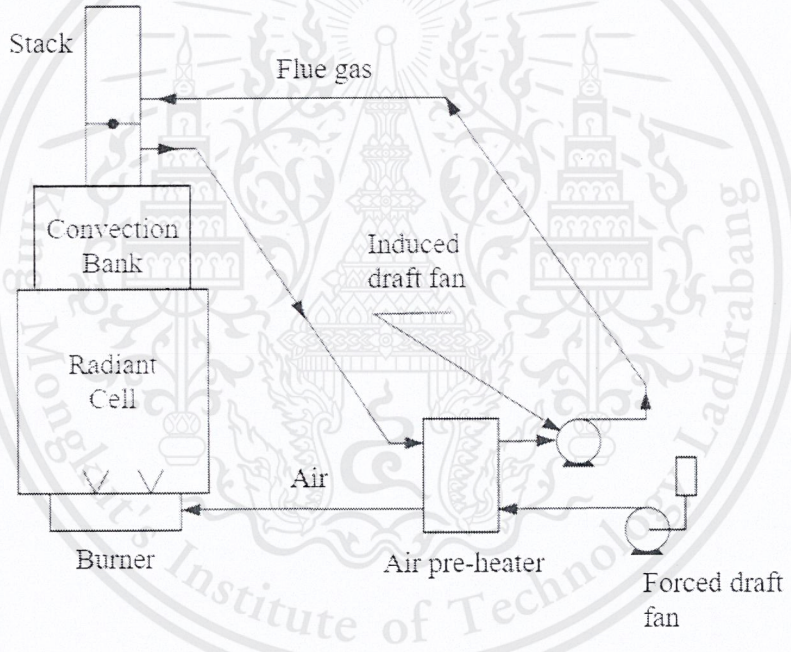


Figure 2.3 Fired heater equipment overview

2.2.1 Radiant cell

Radiant cell is an insulation box. It's propose is to contain the flame and heat up process stream. The dominant heat transfer mechanism is radiation. Radiant cell has one or more burners, walls being refractory lined and tubes containing process stream in vertical, horizontal, refractory backed and double fired.

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2.2.2 Convection bank

Convection bank propose is to recover heat from flue gas and heat up process stream, hence increase efficiency. The dominant heat transfer mechanism is convection except shock tubes. Convection bank consists of both bare tubes and extended surface tube arrange in staggered or in-line arrangement. Nomally flue gas and process strean flow counter current. In case of oil fouling on-line flue gas side cleaning required for removing fouling.

2.2.3 Air pre-heaters

Air pre-heaters propose is to recover heat from flue gas and heat up air to burner, hence increase efficiency. Since flue gas temperature is cooled in air pre-heater. Air pre-heater is susceptible to dew point corrosion during oil firing mainly. Air Pre-Pre-heater proposes is to prevent dew point corrosion in air pre-heater by heating air by an outside heat carrier example steam.

2.2.3 Burner

Burner is a device in which fuel and air are conditioned, mixed and heated so that continuous ignition, stable flame position, and complete combustion are obtained.

2.2.4 Force draft fan

Force draught fan propose is to provide and control air flow to burner for complete combustion reaction and over come air side pressure drop in burners and provide energy to mix fuel with air.

2.2.5 Induced draft fan

Induced draught fan propose is to remove flue gas inside furnace to outside always combined with stack. To ensure and control under pressure in radiant cell.

2.2.6 Stack

Stack propose is to control dispersion of flue gas in atmosphere and creation of draught. Stack height depends on local emission standards to ensure flue gas path should not hit working platforms and equipment and draught requirement of connected fired equipment. Stack draught should be sufficient to overcome the convection bank losses.

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2.2.7 Soot blower

Soot Blower is the operation for on-load cleaning the heat transfer surface on the convection bank section with a blowing medium of water or steam. The blowing flow through nozzle at the deposit resulting in the deposits are eroded away. The application of soot blowers varies widely based on the quality of fuel, and range of furnace operating conditions. Two distinct types of soot blower are used, the long retractable soot blowers and another type is rotary shoot blower.

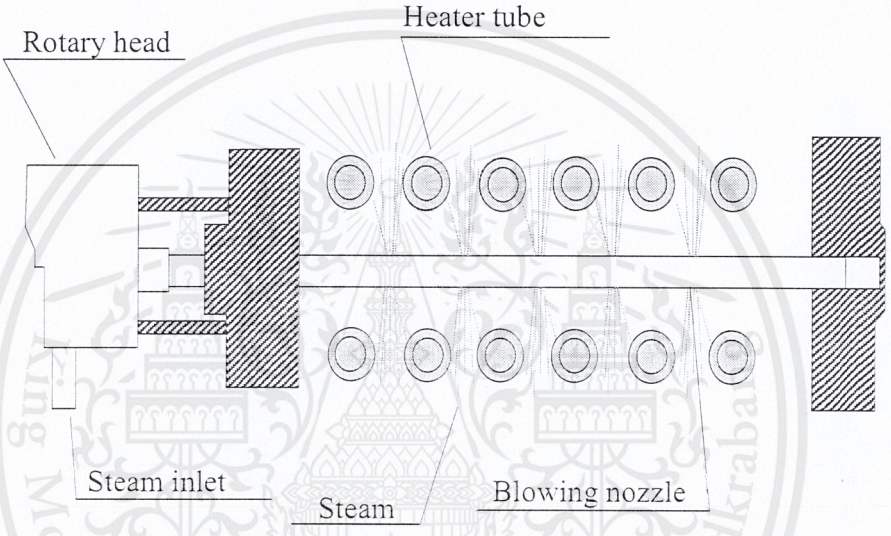


Figure 2.4 Rotary soot blower

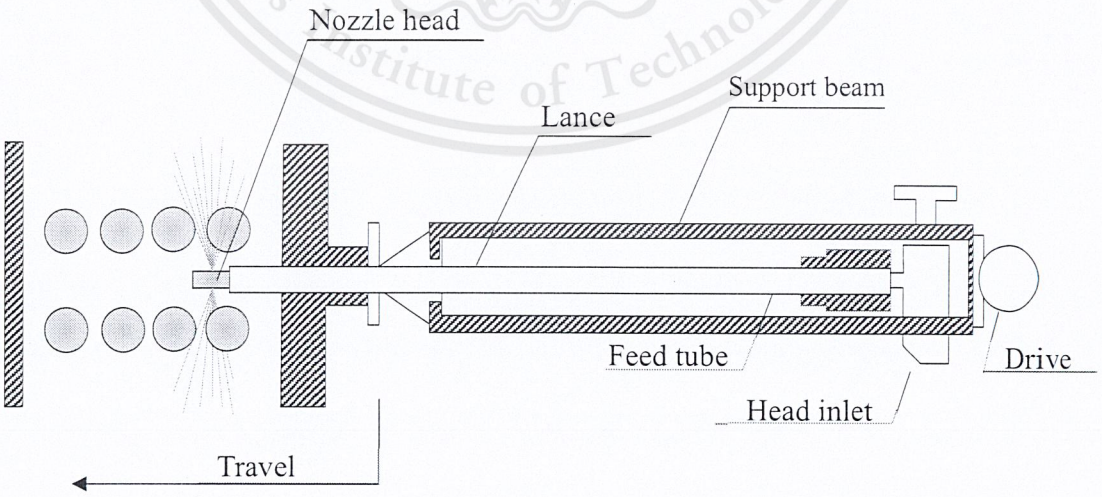


Figure 2.5 Long retractable soot blower

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2.3 Draft

Hot flue gases inside the firebox and stack are lighter than the cold ambient air. This results in a slightly negative pressure inside the furnace. Combustion air is drawn into the burners and hot gas flows out the stack due to this pressure differential. While passing through the convection section and stack, flue gases encounter friction resistance. Sufficient stack height is provided to overcome these losses and ensure that pressure is always negative inside the firebox. Figure 2.4 provides the furnace in different draft types.

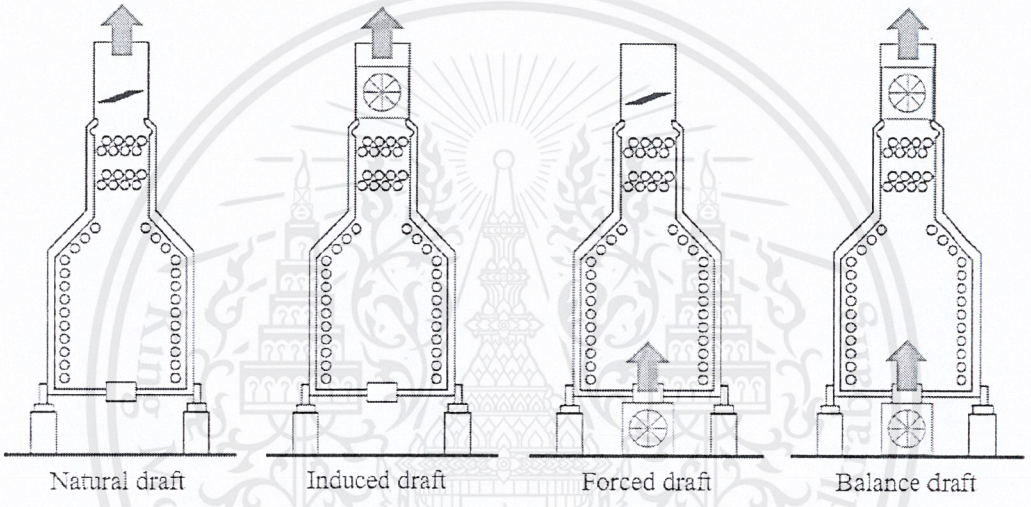


Figure 2.6 Types of draft control

2.3.1 Natural draft

Heater in which a stack effect induces the combustion air and removes the flue gases

2.3.2 Induced draft

Heater that uses a fan to remove flue gases and to maintain negative pressure in the heater to induce combustion air without a forced-draft fan

2.3.3 Forced draft

Heater for which combustion air is supplied by a fan or other mechanical means

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2.3.4 Balance draft

Heater that uses forced-draft fans to supply combustion air and uses induced draft fans to remove the flue gases

2.4 A brief overview of gas-side fouling

Combustion is an exothermic reaction resulting from rapid combination of oxygen with fuel. Normally the product of the combustion reaction is heat and flue gas which are mainly H_2O and CO_2. Since prefect mixing of fuel and air is not possible, excess air is needed to ensure complete fuel combustion. Incomplete combustion leads to produce undesired combustibies product example CO, unburned fuel and particulates called soot. After the the soot formation, soot transfers form radiant cell to the convection bank then deposits on it which is the mainly cause of gas-side fouling. The cost of fouling is the reduction of heat transfer between two fluids resulting in loss of furnace efficiency. Innormaly, fuel compostion is the one of criteria for on-line cleaning. When using gas fuel, gas combustion does not give rise to problem of fouling. In contrast when using oil fuel or mixture fuel (mix between gas and oil), the on-line cleaning is required for cleaning the convection bank to remove the fouling and increase furnace efficiency.

2.4.1 Definition of gas-side fouling

Fouling may be defined as the deposition of an insulating layer of material onto a heat-transfer surface. The effect of gas-side fouling on heat transfer are erosion (the wearing by the impact of a particular matter in the gas stream and corrosion (the destruction of a metal or alloy by means of a chemical with its environment).

2.4.2 Classification of gas-side fouling

Gas-side fouling can be classified in to 6 categories [4] by its mechanisms.

1) Preciptation Fouling

Precipitation of dissolved substances onto the heat transfer surface. Where the dissolved substances have inverse rather than normal solubility versus temperature characteristics, the precipitation occurs on superheated rather than subcooled surfaces and the process is often referred to as scaling.

2) Particulate Fouling

The accumulation of finely divided solids suspended in the process fluid onto the heat transfer surface. The process also called sedimentation fouling.

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3) Chemical Reaction Fouling

The deposition formed at the heat transfer surface by chemical reactions.

4) Corrosion Fouling

The heat transfer surface itself reacts to produce corrosion products which foul the surface and may promote the attachment of other foulants.

5) Biological Fouling

The attachment of macro-organisims (macro-fouling) or micro-organisms (micro-biofouling or microbial fouling) to a heat transfer surface, along with the adherent slimes often generated by the latter.

6) Solidification Fouling

Freezing of a liquid or some of its higher melting constituents onto a subcooled heat transfer surface.

All of six categories, but crystallization fouling can occur in gas-side fouling. Particulate fouling is most likely to be associated with gas-side fouling but chemical reaction fouling, corrosion fouling is also important due to the interaction of inorganic component in fuel. Preticipate fouling is known as permanent fouling, due to the temperature of flue gas is very high. The soot particle can be melted on the heat transfer surface resulting in the deposition which hard to remove.



Figure 2.7 Precipitation fouling of ash paticle on superheater tubes

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2.5 Heat exchanger

Heat exchangers are devices used to transfer heat between two or more fluid streams at different temperatures. In this section, the basic theory of heat exchangers and the aspects of heat exchanger analysis of this project are examined.

2.5.1 Heat exchanger analysis

The fundamental theory of heat transfer for a heat exchanger, according to the enthalpy balance on either fluid stream give:

$$\dot{Q}_c = (\dot{m}C_p)_c(T_{c2} - T_{c1})$$

and

$$\dot{Q}_h = (\dot{m}C_p)_h(T_{h1} - T_{h2})$$

From the energy conservation $Q_c = Q_h = Q$, and the heat transfer rate Q can be calculated by

$$\dot{Q} = UA\Delta T_m$$

where U is the overall heat transfer coefficient, ΔT_m mean temperature difference and A is total surface heat transfer area.

2.5.2 Overall heat transfer coefficient

Two fluids typically devided by a solid wall. Heat is transferred from hot by convection, through the wall by conduction and from the wall to the cold fluid by convection. The total thermall resistance can be defined as:

$$R = R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_o}$$

where A is the area of inner and outer surface of wall and h is the heat transfer coefficient of fluid inside and outside. The rate of heat transfer in heat exchanger is the sum of all thermall resistance in the path of heat flow. The rate of heat transfer between two fluids can be define as:

$$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T$$

Then the total thermall resistance can be written as:

$$R = \frac{1}{UA_s} = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_o}$$

Once the heat transfer coefficient and wall thermall resistance heve been determined, the overall heat transfer coefficient of the new heat exchanger can be obtained.

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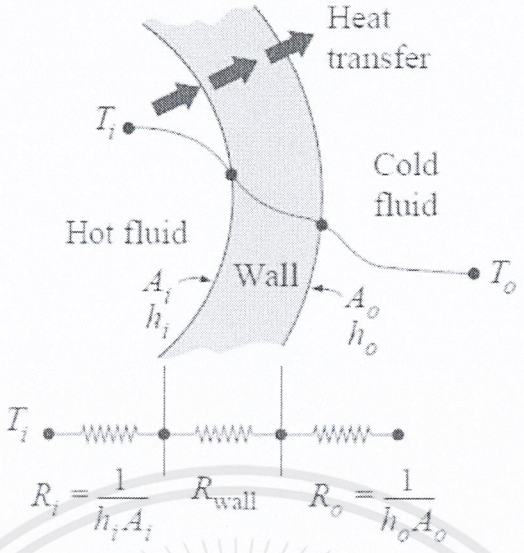


Figure 2.8 Thermal resistance network associated with heat transfer

Earlier, the concern about fouling is mentioned. The heat transfer of heat exchanger always deteriorates with time as result of fouling on heat transfer surface. The effect of fouling is represented by the fouling factor R_f which measure the thermall resistance by fouling. The fouling factor is zero for a new heat exchanger and increase with time. The evation of this parameter is very important in design, analysis and prediction the cleaning period of heat exchanger.

The overall heat transfer relation for claen surface needs to be adjusted to account for fouling on both inner and outer surface of tube can be defined as:

$$R = \frac{1}{UA_s} = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_o} + \frac{R_{f,o}}{A_o} + \frac{R_{f,i}}{A_i}$$

The overall heat transfer coefficient is the key parameter which can be use to evaluate the heat transfer of heat exchanger. The different quantity between overall heat transfer coefficient during the heat exchanger is clean and dirty condition can be use to determine the heat loss due to the fouling deposition which very useful for the optimization of on-load clean period of heat exchanger.

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2.5.2 LMTD

The log mean temperature difference (LMTD) is derived in all basic heat transfer texts. The LMTD has the from:

$$\Delta T_{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})}$$

where ΔT_1 and ΔT_2 is the temperature difference at each end for the heat exchanger and F is the correction factor. The LMTD method is applicable to cross flow arrangements when used correction factor. The correction factor depends on the geometry of heat exchanger, inlet and outlet temperatures of the the hot and cold fluids. The correction factor is less than unity for cross-flow and multipass shell-and-tube heat exchanger. The limiting value of $F = 1$ corresponds to counter-flow heat exchanger. Thus, the correction factor F is a measure of deviation of the ΔT_{LMTD} for the counter flow case. The correction factor F for common cross-flow heat exchanger is shown in Figure 2.6 versus two temperature ratios P and R defined as:

$$P = \frac{t_2 - t_1}{T_1 - t_1}$$

and

$$R = \frac{T_1 - T_2}{t_2 - t_1}$$

where the supscript 1 and 2 represent the inlet and outlet, respectively. T and t represent the path of fluids respectively, as shown in the correction factor chart. The value of P range from 0 to 1. The value of R, on the other hand, ranges from 0 to infinity, with R = 0 corresponding to phase change on one side. The correction factor is $F = 1$ for both of these limiting cases.

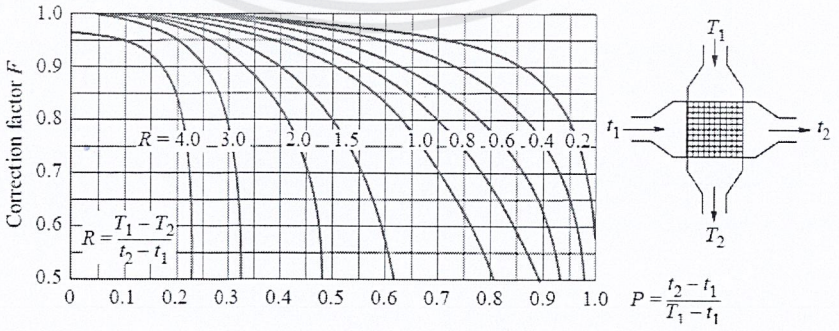


Figure 2.9 Correction factor chart for single pass cross-flow heat exchanger with both fluids unmixed

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2.5.3 $\in$ – NTU

The heat exchanger effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate if the heat transfer area is inifinite area. The actual heat transfer rate is can be calculated by energy balance of hot fluid or cold fluid:

$$\dot{Q} = \dot{Q}_h = \dot{Q}_c = C_h(T_{h,in} - T_{h,out}) = C_c(T_{c,in} - T_{c,out})$$

where $C = \dot{m}C_p$ is the heat capacity rate. Larger heat capacity rate require energy more for changing temperature. The fluid with the lower heat capacity rate will experience larger temperature change. The maximum temperature occurs when the hot fluid is cooled to inlet temperature of cool fluid or the cold fluid is heated to the inlet temperature of hot fluid. Therefore, the maximum possible heat transfer rate can be defined as:

$$\dot{Q}_{max} = C_{min}\Delta T_{max} = C_{min}(T_{h,in} - T_{c,in})$$

The effectiveness is defined as:

$$\in = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_h(T_{h,in} - T_{h,out})}{C_{min}(T_{h,in} - T_{c,in})}$$

or

$$\in = \frac{C_c(T_{c,in} - T_{c,out})}{C_{min}(T_{h,in} - T_{c,in})}$$

$$\in = \frac{(T_{c,in} - T_{c,out})}{(T_{h,in} - T_{c,in})}$$

where the C_{min} is the samller of $C_h = \dot{m}_h C_{ph}$ and $C_c = \dot{m}_c C_{pc}$ The effectiveness of heat exchanger depends on the geomethy of heat exchanger and the flow arrangement.

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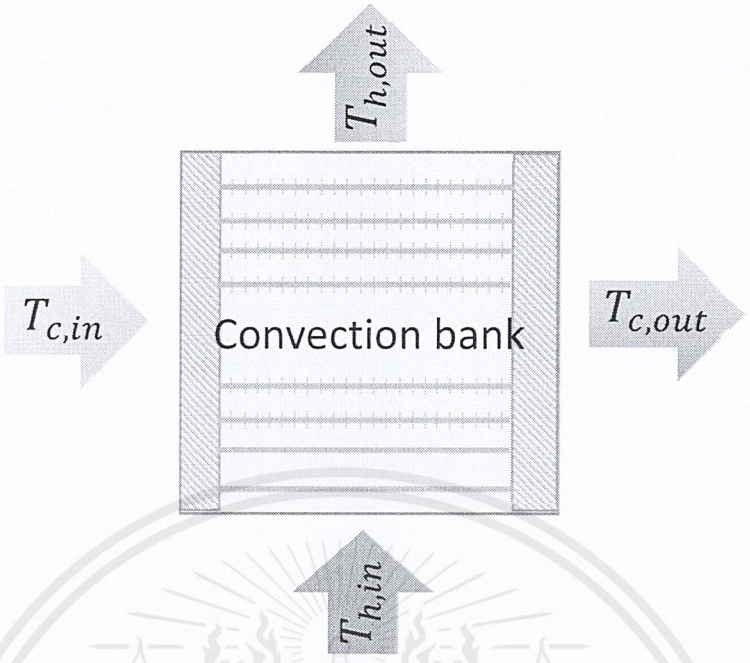


Figure 2.10 Convection bank parameters

therefore, different types of heat exchanger have different effectiveness relations. Effectiveness relations of heat exchangers normally invole the dimentionless group called the number of heat transfer units NTU and capacity ratio defined as:

$$NTU = \frac{UA_s}{C_{min}} = \frac{UA_s}{(\dot{m}C_p)_{min}}$$

and

$$c = \frac{C_{min}}{C_{max}}$$

Therefore, the effectiveness of heat exchanger is a function of the NTU and the capacity ratio depend on type of heat exchanger. Example of the cross-flow heat exchanger with C_{max} is unmixed (different flow path) and C_{min} is mixed (same flow path) defied as:

$$NTU = -\frac{\ln[c\ln(1-\epsilon) + 1]}{c}$$

Mass flow rate, heat capacity and temperature of both fluids are measured parameters. Once the quatities c and ϵ have been evaluated, the NTU can be determined from the effectiveness relation for the specific type of heat exchanger. Then the overall heat transfer rate and rate of heat transfer can be determined.

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2.6 The cost of fouling

In the earlier some of the factors that contribute to the cost of fouling were mentioned. It is the purpose of this chapter to give more detail in respect of these costs.

2.6.1 Increased capital investment

In order to make allowance for potential fouling the area for a given heat transfer is larger than for clean conditions that the required area for the given fouling conditions. Although the cost of heat exchangers is not strictly in relation to area it will be appreciated that for a large complex containing several heat exchangers additional capital cost for all the exchangers will represent a considerable sum of money.

In addition to the actual size of the heat exchanger other increased capital costs are likely. For instance, where it is anticipated that a particular heat exchanger is likely to suffer severe or difficult fouling, provision for off-line cleaning will be required. The location of the heat exchanger for easy access for cleaning may require additional pipe work and larger pumps compared with a similar heat exchanger operating with little or no fouling placed at a more convenient location.

Furthermore, if the problem of fouling is thought to be excessive it might be necessary to install a standby exchanger, with all the associated pipe work foundations and supports, so that one heat exchanger can be operated while the other is being cleaned and serviced. Under these circumstances the additional capital cost is likely to more than original cost.

Additional capital costs for injection equipment will also be involved if it is thought necessary to dose one or both streams with additives to reduce the fouling problem. Consideration of on-line cleaning that on-line cleaning can be very effective and that the additional capital cost can often be justified in terms of reduced operating costs.

2.6.2 Additional operating cost

The function of a heat exchanger is to transfer heat energy between streams. Reduced efficiency has to be compensated in some way in the process. If heat is not recovered. This will have to be made up by the consumption of more primary fuel.

The presence of deposits on the surface of heat exchangers restricts the flow area. As a consequence, for a given throughput the velocity of flow increases. Therefore, changing in velocity can represent substantial increases in pressure drop.

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Fouling deposits are usually rough in comparison with standard heat exchanger surfaces. The roughness increases the friction experienced by the fluid flowing across the surface so that for a given velocity pressure drop is greater than in the clean condition. The larger the pressure drop the higher the pumping energy required and hence a greater pumping cost.

2.6.3 Increased maintenance cost

The presence of fouling on the surface of heat exchangers may be the cause of additional maintenance costs. The more obvious result of course, is the need to clean the heat exchanger to return it to efficient operation. Not only labour costs but it may require large quantities of cleaning chemicals and there may be effluent problems to be overcome that add to the cost.

Additional maintenance costs may derive from the higher pressure drop across the exchanger due to the presence of the deposit. The higher inlet pressure may cause failure of joints and place a heavier load on the associated pump. It is possible that the presence of the deposit will accelerate corrosion of the heat exchanger resuting in lead to earlier replacement of the whole exchanger or failure of heat exchanger joints may lead to hazardous conditions due say to leaking flammable or toxic substances. The presence of a deposit of high temperature heat exchangers such as might be found in steam raising plant, may give rise to high metal temperatures that can increase corrosion or even loss of integrity of the metal with costly consequences.

2.6.4 Loss of production

The effects of fouling on the throughput of heat exchangers due to restrictions to flow and inefficient heat transfer, have already been mentioned. It need to restore flow and heat exchanger efficiency will necessitate cleaning. On a planned basis, the interruptions to production may be minimised but even so if the remainder of the plant is operating correctly then this will constitute a loss of output that, if the remainder of the equipment is running to capacity still represents a loss of profit and a reduced contribution to the overall costs of the particular site. The consequences of enforced shutdown due to the effects of fouling are of course much more expensive in terms of output. Much depends on a recognition of the potential fouling at the design stage so that a proper allowance is made to accommodate a satisfactory cleaning cycle.

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2.6.5 Concluding on the cost of fouling

A number of contributions to the cost of fouling have been identified, however some of the costs will remain hidden. Although the cost of cleaning and loss of production may be recognised and properly assessed, some of the associated costs may not be attributed directly to the fouling problem. For instance, the cost of additional maintenance of equipment such as pumps and pipework, will usually be lost in the overall maintenance charges. The additional energy used to accommodate the increased pressure drop or the loss in heat recovery that requires an additional energy input, are unlikely to be recognised.

Furthermore, because the fouling process is dynamic, i.e. the fouling effects generally increase with time, the effect on the associated services, e.g. hot and cold utilities may not be apparent for a considerable time.

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2.7 General model of fouling

Discussion on provided an idealised picture of the development of a deposit with time is demonstrated in this topic.

2.7.1 A simple general model

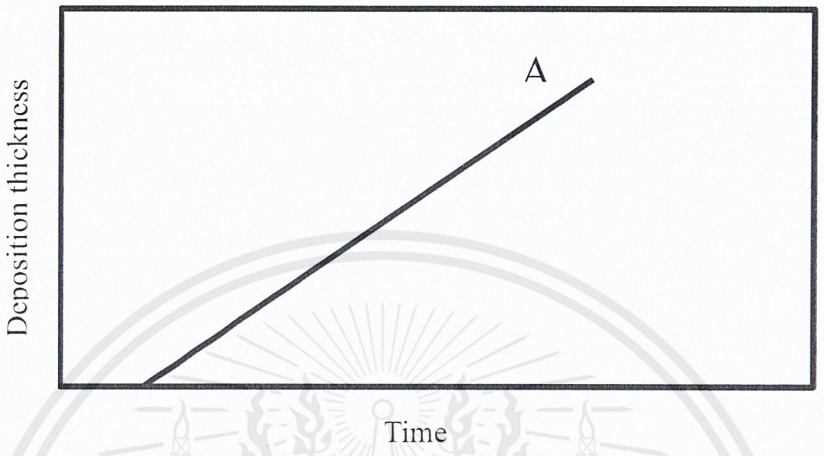


Figure 2.11 A Simple general model curve

The simplest model is the curve A in Fig X. The form of the model is:

$$X_f = \frac{dx_f}{dt}(t - t_i)$$

where x_f is the thickness of deposit at time t

The difficulty of course in using this model is that without the experimental work $\frac{dx_f}{dt}$ is unknown and the use fouling resistance to heat transfer surface is also a problem since the thermal conuctivity of foulant is not predictable. In term of fouling resistance would take this form:

$$R_f = \frac{dR_f}{dt}(t - t_i)$$

where R_f is the thickness of deposit at time t

Even in this form the model is difficult to use unless *dR/dt* is known from experimental determinations the conditions of which can also be applied to the fouling problem in hand

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2.7.2 Asymptotic fouling

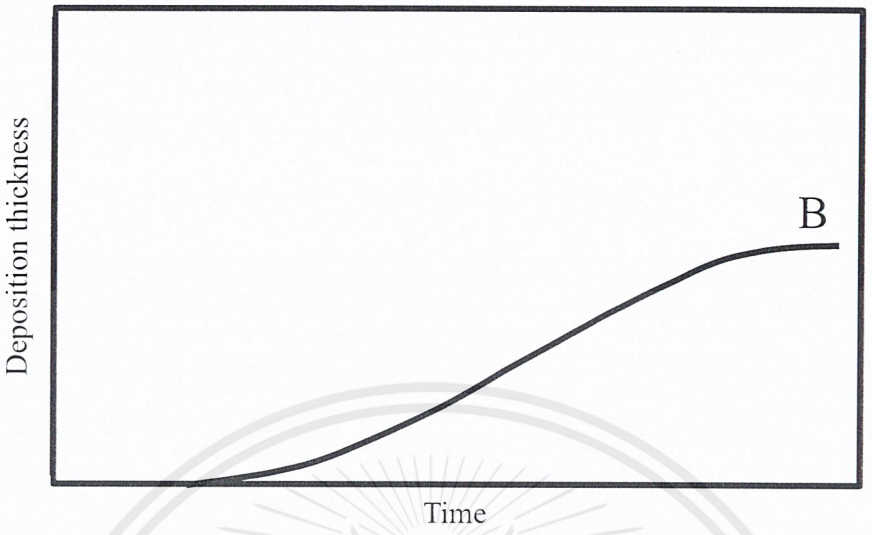


Figure 2.12 Asymptotic fouling model curve

$$R_{ft} = R_f(1 - e^{\beta t})$$

where R_{ft} is the thermal resistance at time t

R_f is the fouling resistance at infinite time – the asymptotic value

β is a constant dependent on the system properties

The model is essentially a mathermaticcal interpretation of asymptotic fouling curve. Curve B is an idealized model and does little for the designer of heat exchanger specific value of R_f and β are to hand. The actual values of these constants will depend upon the type of fouling and the operating condition.

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2.8.2 Falling rate fouling

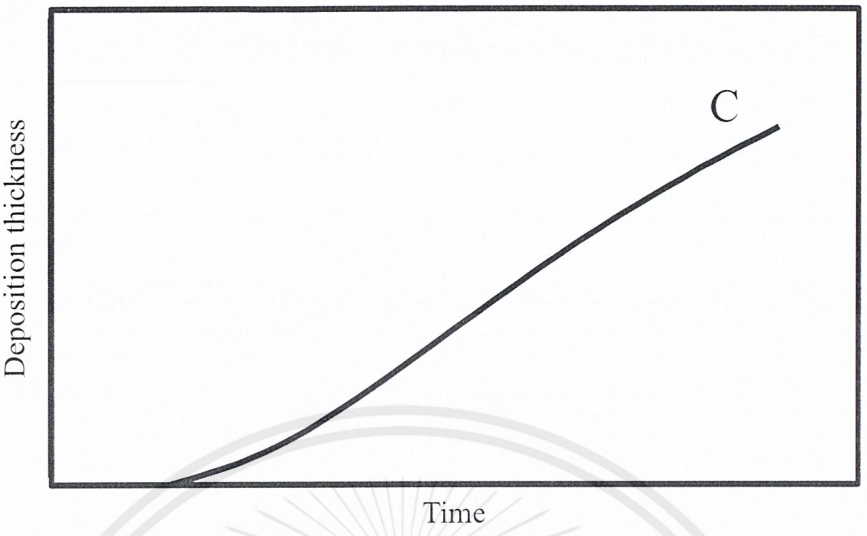


Figure 2.13 Falling rate model curve

A mathematical analysis of falling rate fouling as exemplified by Curve B on Fig. 4.1 as:

$$\frac{dR_f}{dt} \propto q^n$$

$$q = U_D \Delta T = \frac{\Delta T}{R_c + R_f}$$

$$R_c = \frac{1}{U_c}$$

$$\frac{dR_f}{dt} = \frac{K}{(R_c + R_f)^n}$$

$$\frac{1}{U_D^{n+1}} - \frac{1}{U_c^{n+1}} = Kt$$

where n is an exponent

q is the heat flux

U_D is the overall heat transfer coefficient for fouled conditions

R_c is the resistance to heat transfer for clean conditions

K is a constant

The values of K and n that will be necessary to allow an assessment of fouling to be made, will depend on the mechanism responsible for the fouling, e.g. whether or not the fouling is caused by chemical reaction or mass transfer of particles.

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CHAPTER III

RESEARCH METHODOLOGY

3.1 Steps of work

3.1.1 Gathering the information

1) Collect the temperature of flue gas and process fluid both inlet/outlet of the convection bank, data from 1/1/2013 - 31/12/2016.

2) Collect the heat transfer area of the convection bank of the furnace drawing data sheet.

3) Estimate heat capacity of flue gas from the reference temperature.

4) Simulate heat capacity of process fluid by using PRO2 simulation software.

3.1.2 Evaluation of convection bank effeciveness

1) Calculate effectiveness of the data from 1/1/2013 - 31/12/2016 by:

$$\epsilon = \frac{(T_{c,in} - T_{c,out})}{(T_{h,in} - T_{c,in})}$$

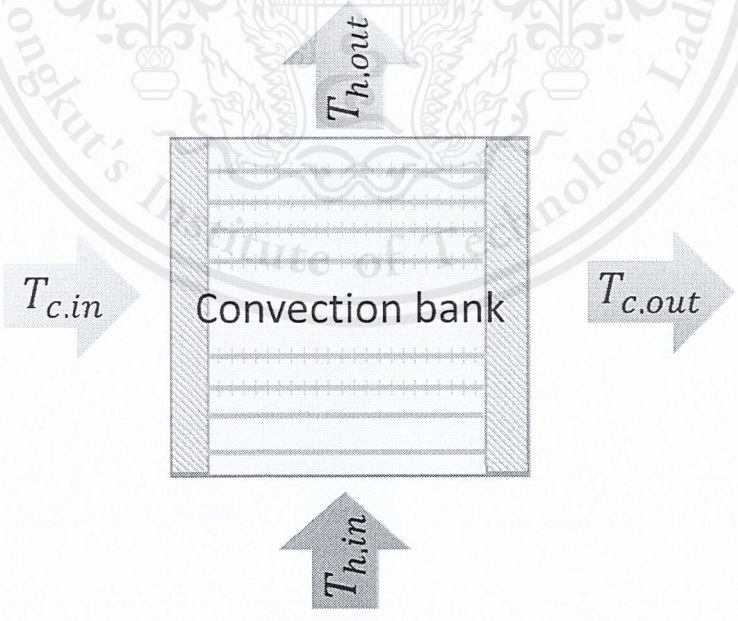


Figure 3.1 Calculation of effectiveness

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3.1.3 Selection and classification of data

1) Collect the effectiveness when using gas fuel as clean condition (no fouling deposition) per each operating condition.

2) Collect the effectiveness after soot blowing operation and rate of fouling deposition as dirty condition when using mixture fuel (oil and gas) per each operating condition.

2.1.1 For find the suitable range, check the criteria below:

1) Mass flow rate of flue gas and process fluid are stable

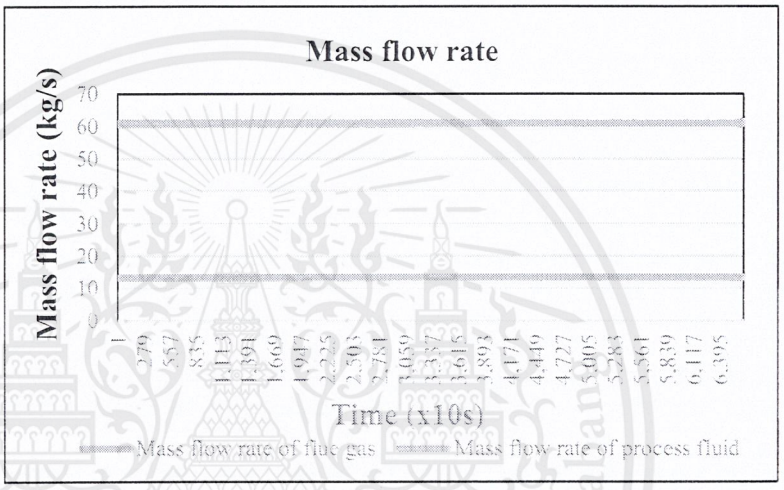


Figure 3.2 Example of effectiveness selection (Mass flow rate)

2) Fuel composition is stable

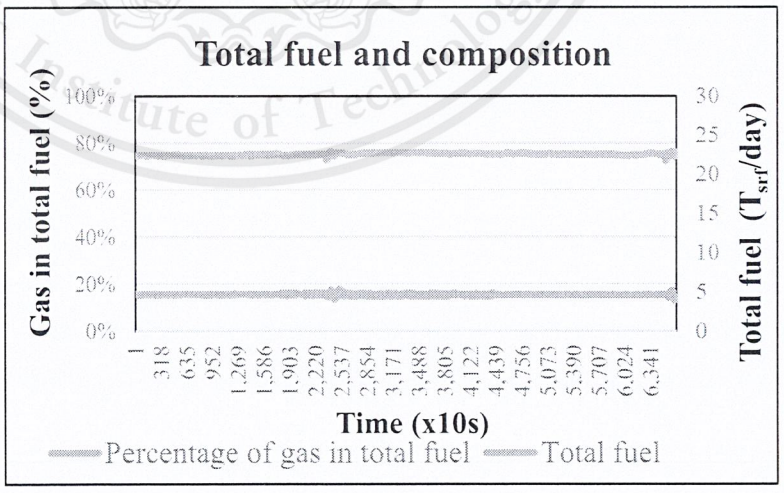


Figure 3.3 Example of effectiveness selection (Fuel)

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3) Temperature of process fluid inlet/outlet are stable

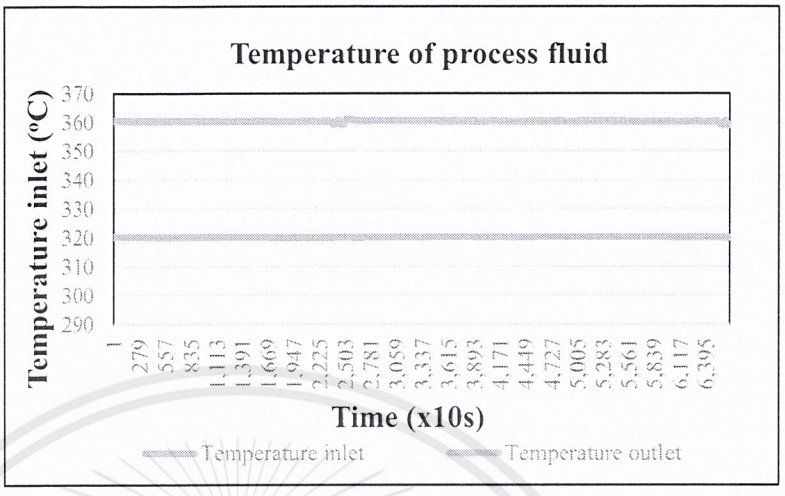


Figure 3.4 Example of effectiveness selection

(Temperature of process fluid)

4) Flue gas inlet temperature is stable but outlet temperature increases

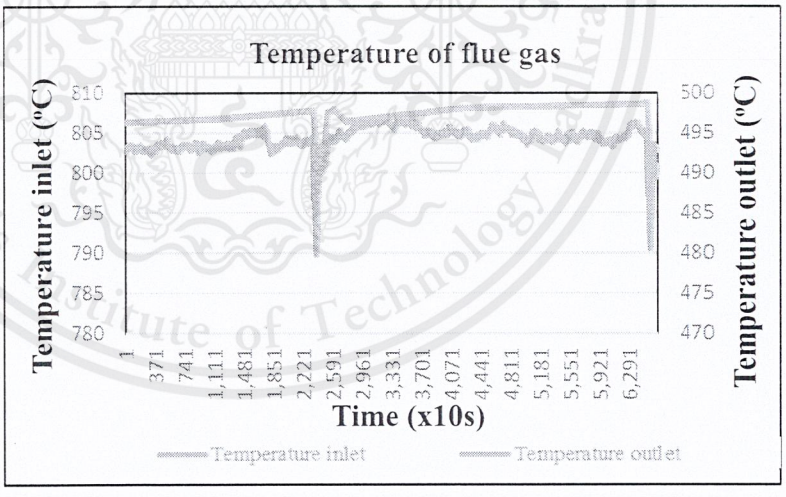


Figure 3.5 Example of effectiveness selection

(Temperature of flue gas)

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3.1.4 Calculation on the optimum soot blowing time

1) Assume after soot blowing operation, the effectiveness always returns to the clean condition.

2) Calcualte heat loss due to fouling deposition by calculate heat transfer rate different between clean and dirty conditions from the effectiveness by using NTU-relation and LMTD method.

3) Calculate energy consume by soot blowing operation.

4) Balance the energy consume by soot blowing operation and the heat loss due to fouling deposition to obtain the optimum soot blwing time.

5) Do the same method for every case of operating condition to obtain the soot blowing guideline.

3.1.5 Analysis of the results

1) Collect the data deviation of effectiveness, mass flow rate and temperature.

2) Investigate the effect of data deviation to the optimum soot blowing time by sensitivities analysis.

3) Adjust the soot blowing guideline.

3.1.6 Implementation of soot blowing guideline

1) Provide recomendation and limitation for apply the soot blowing guideline.

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CHAPTER IV

RESULTS AND DISCUSSION

4.1 Evaluation of convection bank effectiveness

In this part, the convection bank effectivness is measured which can be calculated by the temperature of flue gas and process fluid. Since the reduction of effectiveness by fouling deposition is demonstrated. The evaluation of fouling condition of convection bank and soot blowing performance is feasible.

Gas and oil are the fuel for the furnace. Using gas or oil depend on the cost of the fuel. Fuel is injected thought the nozzle of burner then it is consumed by the combustion reaction. Combustion reaction produces the heat which transfer to process fluid by the radiation and convection. Combustion-generated particles are called soot. Fuels that have a higher carbon-to-hydrogen mass ratio tend to produce more soot than fuels with a lower ratio. For example, gas fuel (C1-C3) is more likely to produce soot than oil fuel (C4+) which has a C:H mass ratio. For clean burning fuels like natural gas, it is more difficult to produce sooty flames compared to other fuels, such as oil.

4.1.1 Effectiveness of convection bank when using gas fuel

The inlet and outlet temperature of process fluid are measured by the thermocouples at the inlet and outlet of the convection bank. Effectiveness can be calculated by the temperature. There are two range, first in 7/2013 – 12/2013 and 4/2015 – 7/2015 which are collected the effectiveness.

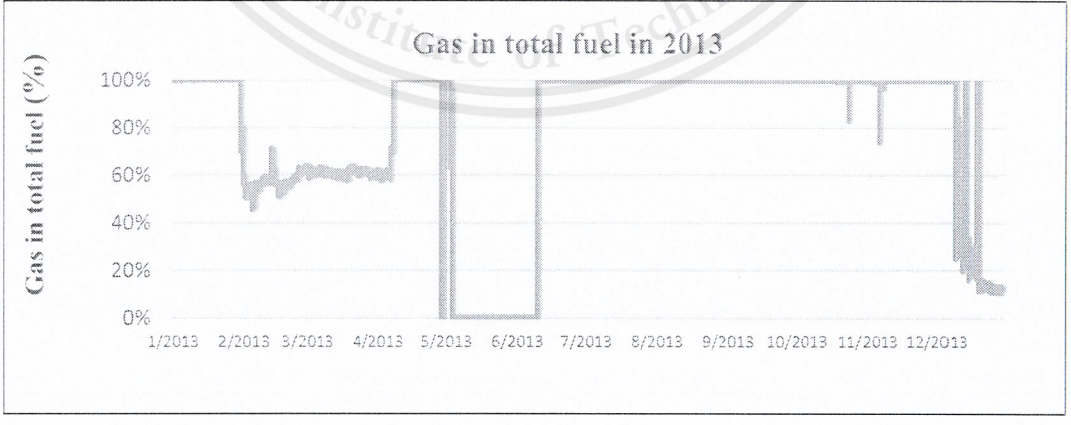


Table 4.1 Percentage of gas in total fuel in 2013

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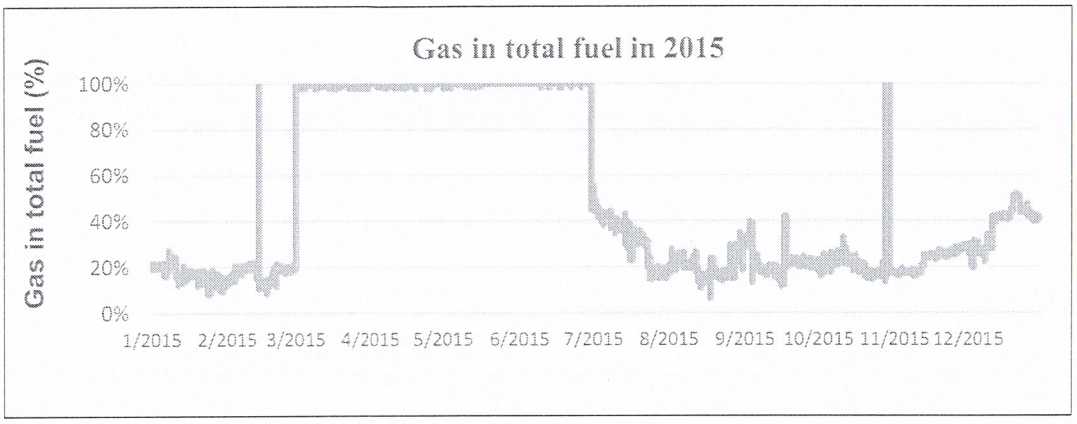


Table 4.2 Percentage of gas in total fuel in 2015



Table 4.3 Effectiveness of the convection bank at the specific total fuel, 100% gas fuel

From the table 4.3, the effectiveness is stable at the specific heat load. Because of the soot is not produced during gas firing. Therefore, the convection bank is not attached by the soot particle. The heat transfer by the convection bank is stable at the specific fuel inlet. The soot blowing operation is not required for gas firing

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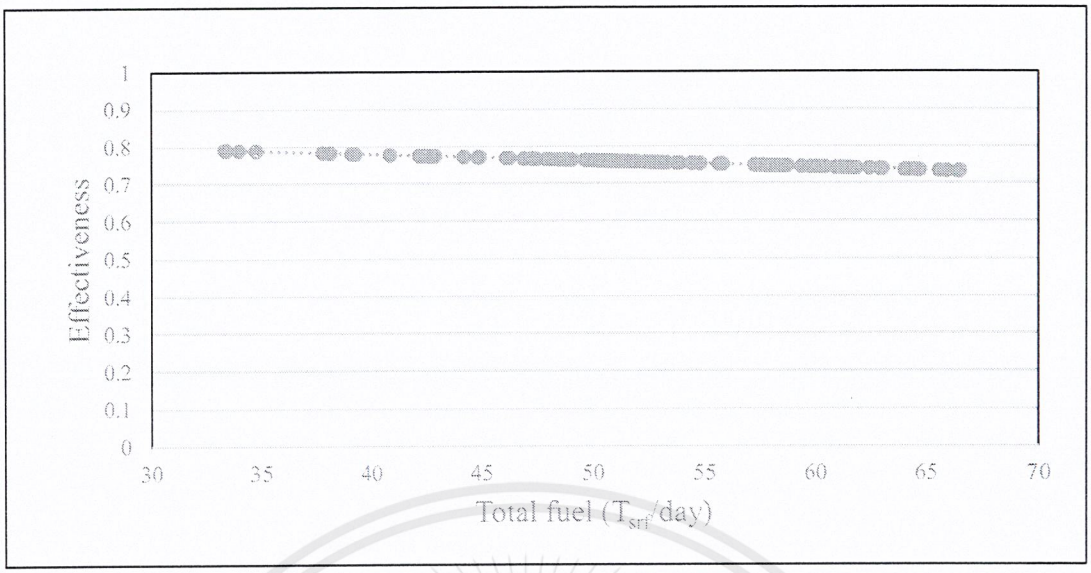


Table 4.4 Effectiveness of the convection bank of the different in the operating condition

Effectiveness is collected for all operating condition (total fuel). The graph is shown. The effectiveness is about 0.7-0.8 for all operating condition of the convection bank. In this project the effectiveness of gas firing can be used as the clean condition (no fouling deposition on the convection bank.

4.1.2 Effectiveness of convection bank when using mixture fuel

Effectiveness is collected by the same method of effectiveness of gas firing. The graph below show the effectiveness during mixture fuel firing.

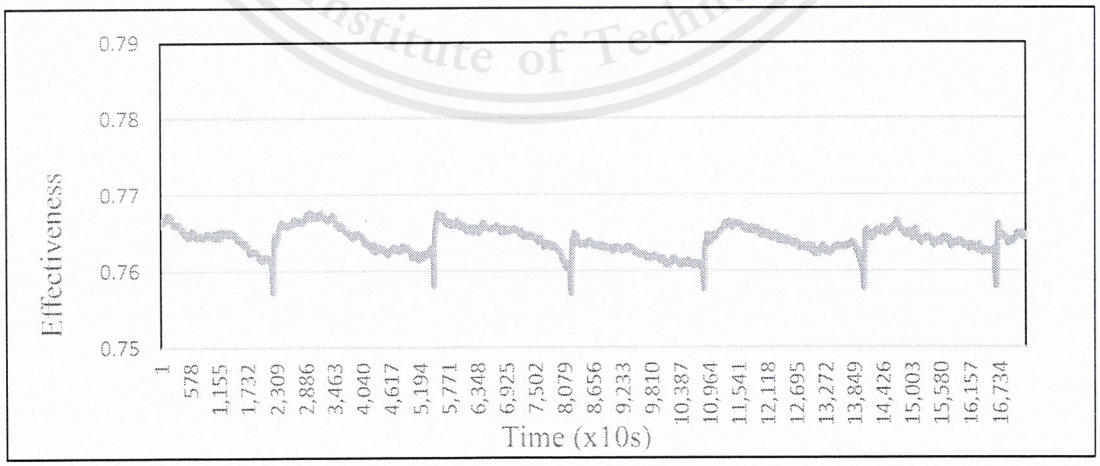


Table 4.5 Effectiveness of the convection bank at specific amount of total fuel and fuel composition

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The table 4.5 shows the example of the effectiveness at the specific amount of fuel and its compositon. During mixture of gas and oil firing the soot is produced by the combustion reaction then deposits on the convection bank resulting in loss of heat transfer of the convection bank and reduction of the effectiveness. Until the soot blowing is activated. The stream is injected inside the convection bank. The convection bank is cleaned. Therefore, the deposition is removed, the heat transfer increases resulting in increasing of the effectiveness. The cycle repeats. Untill the process shutdown. Another thing is demonstrated by this graph is the effectiveness after the convection bank is cleaned. If the soot blowing can perfectly clean the convection bank, the effectiveness after soot blowing always returns to the clean condition. Unfortunately, after soot blowing is activated. There might be soot left on the convection bank. The heat transfer does not return to the clean condition resulting the effectiveness deviation from the clean condition. From the results, the effectiveness show the behavior of soot deposition and the soot blowing performance. Soot deposition of gas firing can be neligible. Therefore. the gas firing effectiveness is stable. There is the clean condition per each operating condition. In contrast, the effectiveness of mixture fuel firing reduces when soot depositon and increases during the soot blowing operation. It's the dirty condition. These two conditions are very important for finding the optimization strategy.

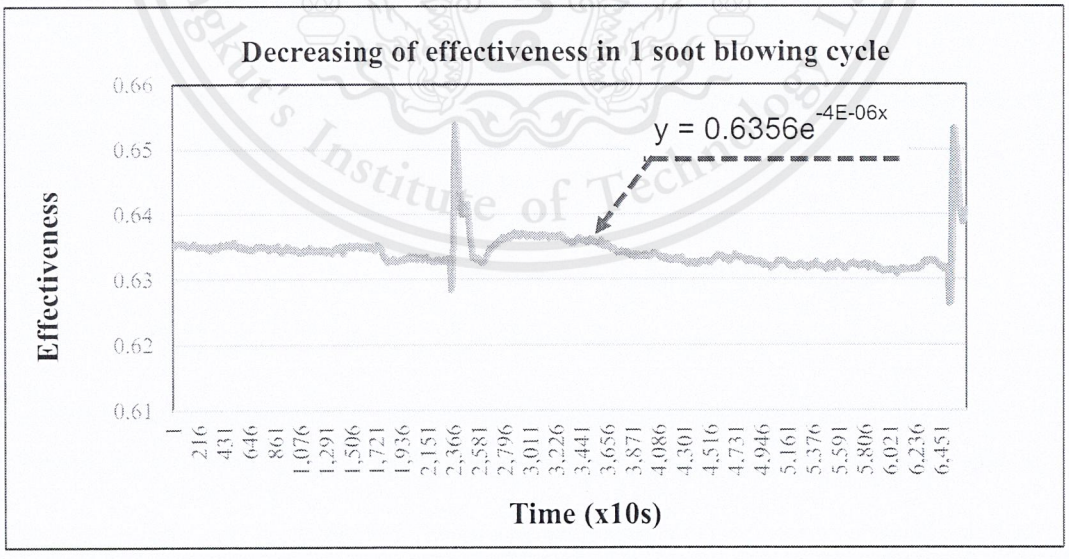


Table 4.6 Effectiveness of the convection bank as exponential relationship

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For easy to calculate the optimum soot blowing time and analyze. The effectiveness is estimated as the exponential relationship which can be approximate as:

$$E(t) = E_o e^{-kt}$$

E_o = Effectiveness after soot blowing
k = Soot deposition rate
t = Time

Table 4 shows the soot deposition constant of each cases which collected from the data during 2014 – 2016. The results were classified by the operating condition which are total fuel and fuel composition. The table show effectiveness of cases which using lower percentage of gas in total fuel and low fuel comsumption, effectiveness reduces faster or high soot formation. In contrast, for cases which using higher percentage of gas in total fuel and high fuel consumption, effectiveness reduces lower or low soot formation.

Soot deposition rate (k)			
Gas in total fuel (%) \ Total fuel (T_{srf} day)	34-47	47-60	60-73
15-30	-6.00E-06 -5.00E-06 -6.00E-06 -4.00E-06 -4.00E-06 -5.00E-06 -5.00E-06 -6.00E-06 -6.00E-06 -6.00E-06 -4.00E-06	-4.00E-06 -5.00E-06 -4.00E-06 -4.00E-06 -4.00E-06 -5.00E-06 -4.00E-06 -5.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -5.00E-06 -5.00E-06 -3.00E-06 -4.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -5.00E-06 -3.00E-06 -5.00E-06 -3.00E-06 -3.00E-06 -4.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -4.00E-06 -4.00E-06 -4.00E-06 -3.00E-06 -4.00E-06 -4.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -3.00E-06 -4.00E-06 -3.00E-06 -3.00E-06	-2.00E-06 -3.00E-06 -2.00E-06 -3.00E-06 -2.00E-06 -2.00E-06 -1.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -3.00E-06 -3.00E-06 -1.00E-06 -2.00E-06
30-50	-3.00E-06 -5.00E-06 -5.00E-06 -3.00E-06 -4.00E-06 -4.00E-06 -3.00E-06	-3.00E-06 -4.00E-06 -3.00E-06 -3.00E-06 -2.00E-06 -3.00E-06 -2.00E-06 -3.00E-06 -3.00E-06 -2.00E-06 -5.00E-06	-2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -3.00E-06 -2.00E-06 -1.00E-06 -3.00E-06
50-65	-2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06 -2.00E-06	-2.00E-06 -2.00E-06	-2.00E-06 -1.00E-06 -2.00E-06

Figure 4.7 Soot deposition constant of each operating condition in 2013 - 2016

This topic show different in operating condition which are the total fuel and fuel composition, different in the soot formation and reduction of effectiveness. Therefore, the condition of soot blowing should be different for every operating condition for the

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optimum benefit of soot blowing operation and eliminating the excessive loss cost for the cleaning.

4.2 Optimization strategy and optimum soot blowing time

After the evaluation of the convection bank performance is undertaken. The behevior of soot deposition and soot blowing operation is demonstared. Based on the energy balance, assume the soot blowing operation can perfectly clean convection bank (no soot deposition) and the effectiveness is return to the clean condtion (effectiveness from using gas fuel). This concept allows us to optimize the soot blowing time per each operating condition to obtain the optimum soot blowing guideline by balance between energy loss due to soot deposition and energy loss due to soot blowing operation.

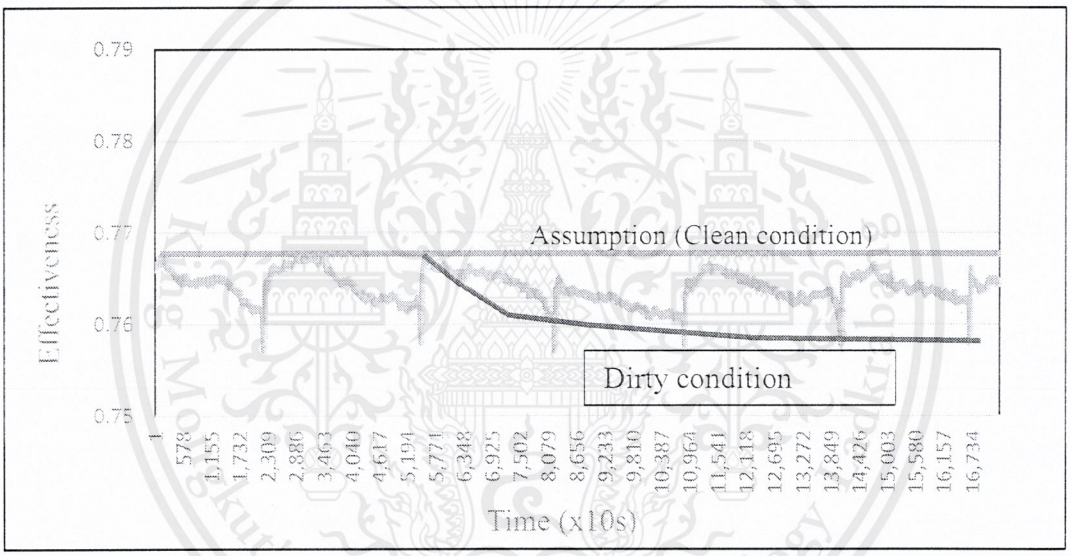


Figure 4.8 Assumption of the effectiveness for optimization strategy

The energy loss due to the soot deposition is calculated by the energy absoption different between clean and dirty condition. Clean condition is the assumption comdition (effectiveness from using gas fuel). The effectiveness of this condition is stable due to no soot deposition. Dirty condition is the condition when soot deposite on the convection bank, the effectiveness decreases until reach the convection bank limit. The energy consum by soot blowing operation is calculated by the energy consume to produce the stream of boiler. Afterr these two things are obtained. The optimum soot blowing time can be provided.

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To convert effectiveness to the term of energy, convert effectiveness to term of overall heat transfer coefficient by using NTU-method. Then overall heat transfer coefficient can be convert to energy by LMTD method. After the energy loss, due to soot deposition is calculated. The optimum soot blowing time is intersection point between energy consume by soot blowing operation and enery loss due to soot deposition.

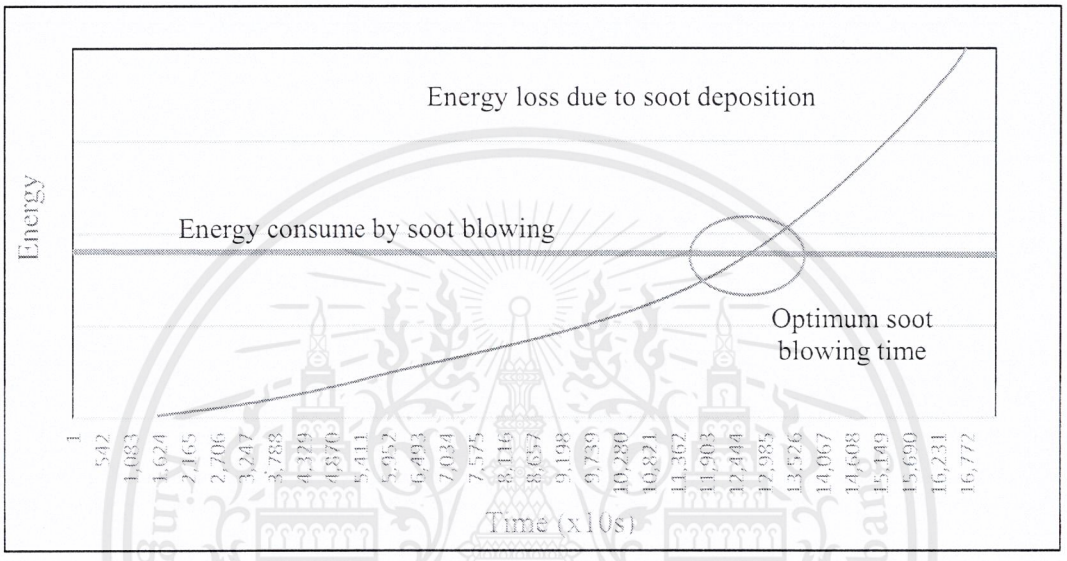


Figure 4.9 Determining of the optimum soot blowing time

From the proposed concept, the effectiveness is collected from the process book. The optimum soot blowing time is calculated as shown in the table below.

Soot blowing time (hr.)			
Gas in total fuel (%) \ Total fuel (T_{srf}/day)	Min.	Med.	Max.
Min.	20	25	34
Med.	23	27	34
Max.	33	34	37

Table 4.1 The optimum soot blowing time per each operating condition

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4.3 Effect of effectiveness on the optimum soot blowing time

From the data selection step, the effectiveness after soot blowing operation is deviate from the clean condition (assumption). Table 4.11 shows the effectiveness deviation from the clean condition. The maximum possible effectiveness deviation is -0.05 and 0.04. To find out its effect to the optimum soot blowing time. The sensitivity analysis of the effectiveness after is created.

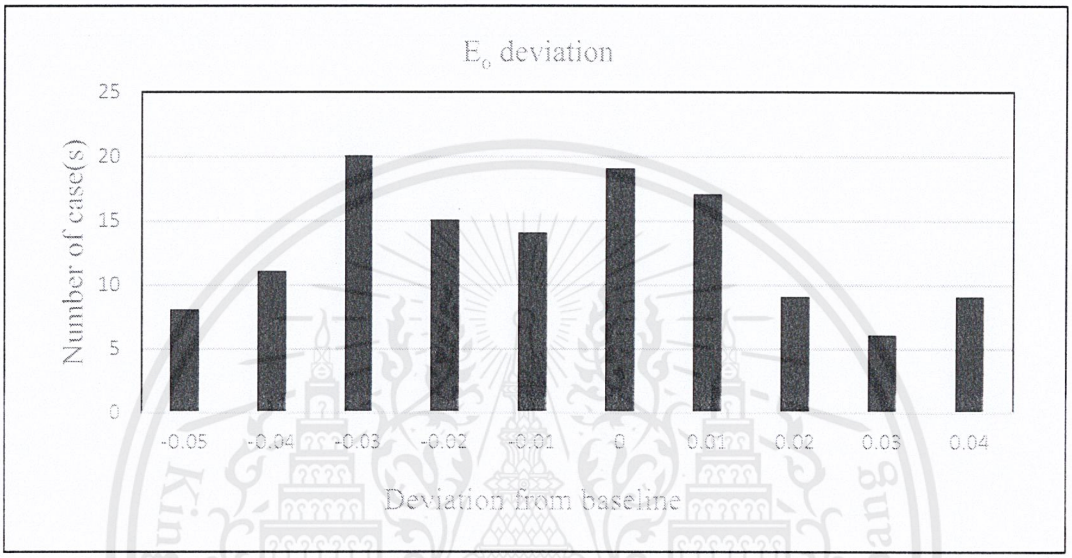


Figure 4.10 The effectiveness deviation from the clean condition (assumption)

Table 4.12 shows the results from the sensitivity analysis. When the effectiveness deviate to upper from clean condition, it will decrease the optimum soot blowing time and might be excessive loss of steam. Eventhrough, the maximum benefit of soot blowing operation can not be taken but the convection bank is clean. In contrast, when the effectiveness deviate to the lower from clean condition. In this case, it will increase the optimum soot blowing time, longer the optimum soot blowing time means loss is more due to the soot deposition and soot might accumulate on the convection over the convection bank limit resulting in damaging to equipment. Therefore, to eliminate this situation. The maximum possible deviation is -0.06 effects to the optimum soot blowing time about 20% for all cases. Savety marging 20% should be added to the guideline for safety reason.

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E_o deviation	No. of cases	Optimum time deviation		
		Low Load	Medium Load	High Load
0.04	9	13%	12%	11%
0.03	6	10%	9%	9%
0.02	9	7%	6%	6%
0.01	17	4%	3%	3%
0	19	0%	0%	0%
-0.01	14	-4%	-3%	-3%
-0.02	15	-7%	-6%	-6%
-0.03	20	-10%	-8%	-8%
-0.04	11	-14%	-12%	-11%
-0.06	8	-20%	-19%	-17%

Table 4.2 Sensitivities analysis of effect of effectiveness deviation to the optimum soot blowing time

Soot blowing time (hr.)			
Gas in total fuel (%) \ Total fuel (T_{srf}/day)	Min.	Med.	Max.
Min.	16	20	27
Med.	18	22	28
Max.	16	27	30

Table 4.3 The Adjusted soot blowing guideline

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4.4 Guideline implementation

To implement the guideline in the real process, the cooperation between soot blowing guideline and effectiveness monitoring is nescessary. The figure 4.1 shows the implementation flow chart.

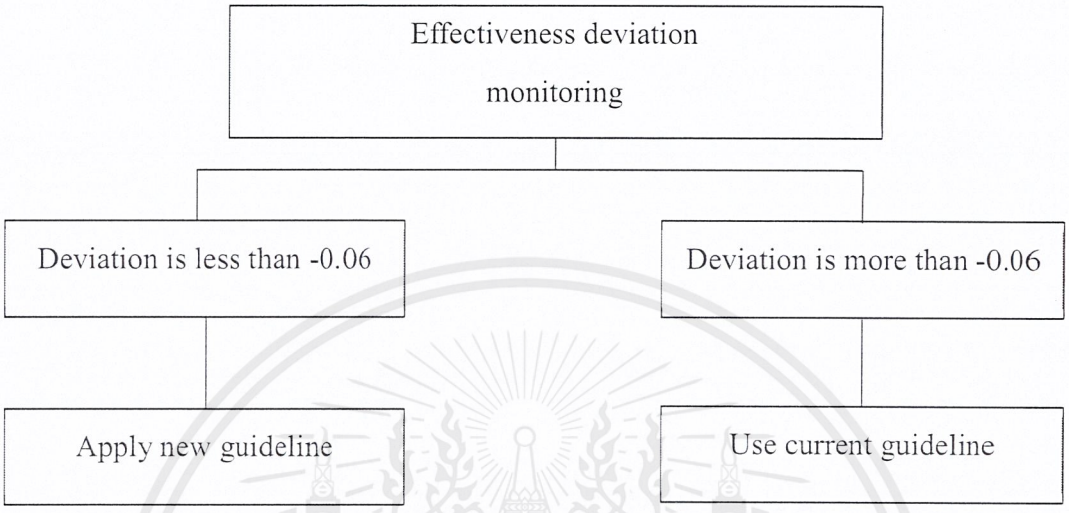


Figure 4.11 Implementation guideline

From the figure 4.1, when the effectiveness deviation is less than -0.06. The guideline is recommended in order to minimize the excessive loss of steam. But the guideline still have the limitation which is when the effectiveness deviation is larger than -0.06. The deviation -0.06 has been proved that the effectiveness can be returned to the clean condition. The operaation during the effectiveness deviation larger than -0.06 might be risk of the undesired situation like permanent fouling or the model is not valid which makes the optimum point is not optimum any more.

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CHAPTER V

CONCUSIONS AND RECOMMENDATIONS

5.1 Concusions

5.1.1 Online monitoring tools for evaluation the convection bank performance

From the perposed method, the effectiveness is the key parameter in this project which can be use for evaluation of the convection bank and use to determine the optimum soot blowing time.

5.1.2 Developing the new soot blowing guideline

Current soot blowing guideline based on the operation experience is fixed schedule for every operating condition. Three time per day will be cause of waste stream, increase maintenace cost and tube erosion. The new soot blowing guideline based on the operating condition is now obtained:

Soot blowing time (hr.)			
Gas in total fuel (%) \ Total fuel (T_{srf}/day)	Min.	Med.	Max.
Min.	16	20	27
Med.	18	22	28
Max.	16	27	30

Table 5.1 Optimized soot blowing guideline

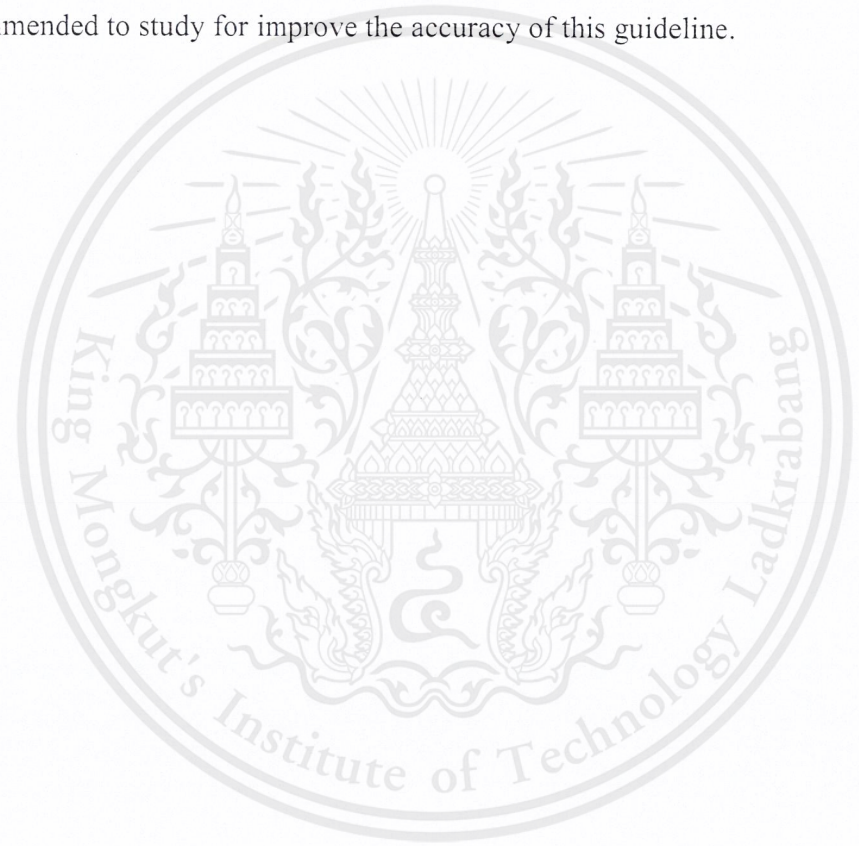
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5.2 Recommendations

5.2.1 For current operating condition, recommended to apply new soot blowing guideline in order to minimize the excessive loss of stream and monitor the effectiveness to prevent the invalidation of model and permanent fouling.

5.2.2 The excessive energy loss from flue gas is going to air preheater unit where energy loss will be recovered. Recommended to investigate heat recovery in the air preheater unit to improve accuracy of guideline.

5.2.3 The steam soot blowing condition example amount of steam and time per one soot blowing cycle is not studied yet. Due to the limitation of proposed method. Recommended to study for improve the accuracy of this guideline.



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APPENDIX

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APPENDIX A

Selected data of the effectiveness of dirty and clean condition in 2013 – 2016

In the table below, shows the data that using for calculation the optimum soot blowing time. All cases of operating codition is collected from the historical data during 2013 – 2016 for providing the optimum soot blowing time of each cases and combination the optimum soot blowing time to obtain the soot blowing guideline

Table 1.1 data of the effectiveness of dirty and clean condition in 2013 – 2016

Total fuel (T_{srf}/day)	Gas in fuel percentage (%)	Mass flow rate of flue gas (kg/s)	Mass flow rate of process fluid (kg/s)	Clean condition effectivness	Soot deposition constant
33	32%	7	39	0.79	-3E-06
33	12%	9	58	0.79	-3E-06
34	66%	7	14	0.79	-2E-06
34	66%	7	14	0.79	-2E-06
35	42%	9	41	0.79	-4E-06
38	23%	9	58	0.78	-2E-06
38	23%	9	58	0.78	-4E-06
38	18%	9	58	0.78	-3E-06
39	23%	9	60	0.78	-4E-06
39	18%	10	60	0.78	-3E-06
41	20%	10	58	0.78	-4E-06
42	20%	10	58	0.78	-5E-06
42	20%	10	58	0.77	-2E-06
43	19%	10	58	0.77	-3E-06
43	18%	10	55	0.77	-4E-06
43	22%	9	55	0.77	-6E-06
44	18%	10	55	0.77	-8E-06
45	18%	10	56	0.77	-6E-06
45	18%	10	57	0.77	-1E-06
46	25%	9	52	0.77	-6E-06
46	22%	9	64	0.77	-5E-06
47	40%	10	49	0.77	-3E-06
47	32%	8	57	0.77	-2E-06
47	32%	8	57	0.77	-3E-06
47	31%	8	57	0.77	-4E-06

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Total fuel (T_{srf}/day)	Gas in fuel percentage (%)	Mass flow rate of flue gas (kg/s)	Mass flow rate of process fluid (kg/s)	Clean condition effectivness	Soot deposition constant
49	27%	8	53	0.76	-2E-06
50	27%	8	53	0.76	-3E-06
50	24%	8	53	0.76	-1E-06
50	26%	8	53	0.76	-4E-06
50	26%	8	53	0.76	-3E-06
50	26%	8	53	0.76	-3E-06
50	26%	8	53	0.76	-3E-06
50	24%	8	53	0.76	-3E-06
50	23%	8	53	0.76	-3E-06
50	22%	10	65	0.76	-3E-06
50	22%	10	65	0.76	-4E-06
50	22%	10	65	0.76	-4E-06
51	34%	8	41	0.76	-3E-06
51	23%	10	60	0.76	-3E-06
51	23%	10	60	0.76	-3E-06
51	23%	11	64	0.76	-3E-06
51	24%	11	64	0.76	-4E-06
51	22%	10	64	0.76	-3E-06
51	23%	10	60	0.76	-5E-06
51	45%	12	62	0.76	-3E-06
51	45%	12	62	0.76	-2E-06
51	19%	11	60	0.76	-3E-06
51	22%	10	64	0.76	-5E-06
51	22%	10	64	0.76	-4E-06
52	19%	11	60	0.76	-4E-06
52	33%	12	69	0.76	-2E-06
52	34%	12	69	0.76	-3E-06
52	24%	11	65	0.76	-3E-06
52	24%	11	65	0.76	-2E-06
52	25%	11	65	0.76	-2E-06
52	20%	12	61	0.76	-8E-06
52	36%	13	69	0.76	-1E-06
53	37%	13	69	0.76	-3E-06
53	37%	13	69	0.76	-3E-06
53	20%	11	60	0.76	-1E-06
53	20%	11	60	0.76	-3E-06
53	20%	11	60	0.76	-3E-06

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Total fuel (T_{srf}/day)	Gas in fuel percentage (%)	Mass flow rate of flue gas (kg/s)	Mass flow rate of process fluid (kg/s)	Clean condition effectivness	Soot deposition constant
53	20%	11	56	0.76	-7E-06
53	30%	10	51	0.76	-3E-06
54	24%	10	51	0.75	-4E-06
54	26%	10	53	0.75	-3E-06
54	26%	10	53	0.75	-3E-06
54	30%	12	58	0.75	-2E-06
54	30%	12	58	0.75	-2E-06
54	30%	12	58	0.75	-2E-06
55	27%	12	58	0.75	-5E-06
56	27%	12	58	0.75	-1E-06
56	25%	12	58	0.75	-3E-06
56	26%	12	58	0.75	-2E-06
56	26%	12	58	0.75	-2E-06
57	26%	12	58	0.75	-2E-06
58	25%	12	58	0.75	-2E-06
58	25%	12	58	0.75	-2E-06
58	26%	12	58	0.75	-2E-06
58	33%	12	60	0.75	-2E-06
58	24%	13	62	0.75	-2E-06
58	23%	13	62	0.75	-1E-06
58	24%	11	59	0.75	-1E-06
59	25%	12	59	0.75	-2E-06
59	27%	12	59	0.75	-1E-06
59	28%	11	59	0.75	-2E-06
60	16%	10	66	0.74	-3E-06
60	16%	10	66	0.74	-4E-06
60	18%	8	54	0.74	-4E-06
60	18%	8	54	0.74	-5E-06
60	16%	9	60	0.74	-4E-06
61	16%	9	60	0.74	-6E-06
61	16%	9	62	0.74	-6E-06
61	19%	8	58	0.74	-6E-06
61	22%	8	57	0.74	-2E-06
61	23%	8	57	0.74	-5E-06
61	59%	7	57	0.74	-3E-06
61	58%	7	57	0.74	-2E-06
62	52%	6	45	0.74	-2E-06

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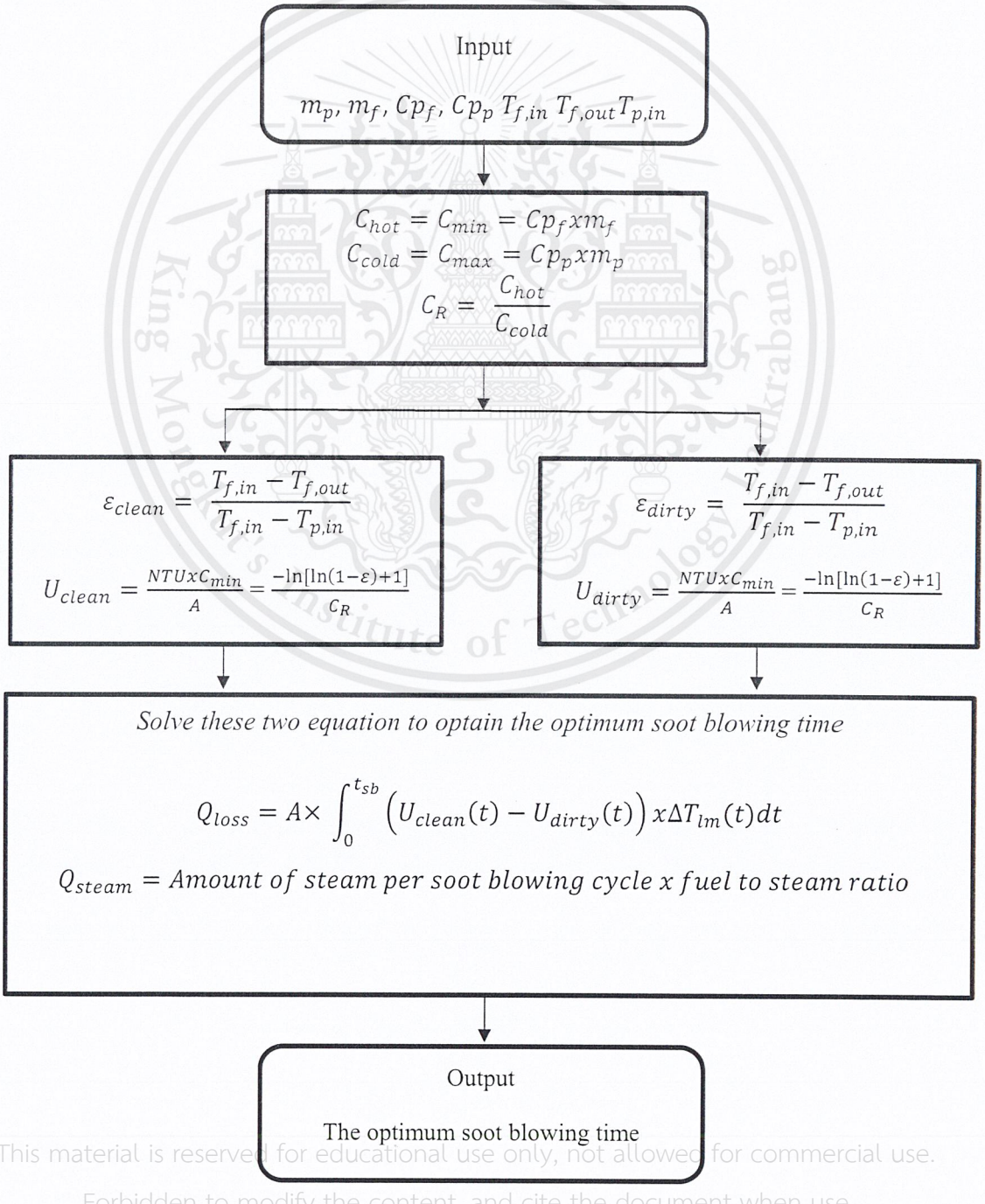
Total fuel (T_{srf}/day)	Gas in fuel percentage (%)	Mass flow rate of flue gas (kg/s)	Mass flow rate of process fluid (kg/s)	Clean condition effectivness	Soot deposition constant
62	53%	6	45	0.74	-2E-06
62	53%	6	45	0.74	-2E-06
62	54%	6	45	0.74	-2E-06
63	68%	12	74	0.74	-2E-06
63	68%	12	74	0.74	-1E-06
63	23%	11	65	0.74	-6E-06
63	23%	11	65	0.74	-5E-06
64	22%	10	58	0.74	-5E-06
64	22%	10	58	0.74	-3E-06
64	22%	10	58	0.74	-3E-06
64	24%	10	60	0.74	-3E-06
65	19%	9	60	0.74	-7E-06
65	69%	12	74	0.74	-2E-06
66	26%	7	46	0.73	-5E-06
66	26%	7	46	0.73	-6E-06
66	18%	10	60	0.73	-3E-06
66	18%	10	60	0.73	-3E-06

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APPENDIX B

Calculation of the optimum soot blowing time methodology

The optimum soot blowing time is calculate follow the flow chart below. The process data from the appendix A which are the mass flow rate of flue gas, mass flow rate of process fluid, and temperature inlet/outlet of flue gas and process fluid can be use to calculate the energy absorption loss by using NTU-relation and LMTD method then balance the energy loss due to soot deposition with the energy of steam consumption by soot blowing operation to obtain the optimum soot blowing time.



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APPENDIX C

Results of the sensitivies analysis of effect of effectiveness deviation to the optimum soot blowing time

In the chapter 4, the discussion on the effect of the efectiveness deviaiton on the optimum sooy blowing time is demonstrated. The sensitivity of different convection bank load (fuel inlet) is constructed to confirm the results of 3 cases which are when the convection bank operate in low load medium load and high load

Table 1.1 Input of sensitivity analysis No.1 (Low load case)

Convection bank load	15	Mw
Percentage of gas in fuel	53	%
Mass flow rate of flue gas	6.22	kg/s
Mass flow rate of process fluid	45.12	kg/s
Soot deposition rate (K)	-2.00E-06	
Heat capacity of flue gas	1250	J/kg-DegC
Heat capacity of process fluid	2850	J/kg-DegC
Effectiveness at clean condition	0.790	

Table 1.2 Results of sensitivity analysis No.1

Effectiveness deviation	Effectiveness at clean condition	Optimum soot blowing time (hr)	Optimum soot blowing time deviation
-0.06	0.73	41.98	20%
-0.04	0.75	39.67	13%
-0.02	0.77	37.34	7%
0	0.79	35.00	0%
+0.02	0.81	32.61	-7%
+0.04	0.83	30.17	-14%
+0.06	0.85	27.64	-21%
+0.08	0.87	24.99	-29%

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Table 2.1 Input of sensitivity analysis No.2 (Medium load case)

Convection bank load	24.18	Mw
Percentage of gas in fuel	26	%
Mass flow rate of flue gas	8.36	kg/s
Mass flow rate of process fluid	53.22	kg/s
Soot deposition rate (K)	-3.00E-06	
Heat capacity of flue gas	1250	J/kg-DegC
Heat capacity of process fluid	2850	J/kg-DegC
Effectiveness at clean condition	0.680	

Table 2.2 Results of sensitivity analysis No.2

Effectiveness deviation	Effectiveness at clean condition	Optimum soot blowing time (hr)	Optimum soot blowing time deviation
-0.06	0.7	30.66	18%
-0.04	0.72	29.08	12%
-0.02	0.74	27.50	6%
0	0.76	25.99	0%
+0.02	0.78	24.32	-6%
+0.04	0.8	22.70	-13%
+0.06	0.82	21.04	-19%
+0.08	0.84	19.34	-26%

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Table 3.1 Input of sensitivity analysis No.3 (High load case)

Convection bank load	30.76	Mw
Percentage of gas in fuel	33	%
Mass flow rate of flue gas	11.87	kg/s
Mass flow rate of process fluid	60.17	kg/s
Soot deposition rate (K)	-2.00E-06	
Heat capacity of flue gas	1250	J/kg-DegC
Heat capacity of process fluid	2850	J/kg-DegC
Effectiveness at clean condition	0.690	

Table 3.2 Results of sensitivity analysis No.3

Effectiveness deviation	Effectiveness at clean condition	Optimum soot blowing time (hr)	Optimum soot blowing time deviation
-0.06	0.67	40.55	17%
-0.04	0.69	38.54	12%
-0.02	0.71	36.55	6%
0	0.73	34.56	0%
+0.02	0.75	32.57	-6%
+0.04	0.77	30.56	-12%
+0.06	0.79	28.53	-17%
+0.08	0.81	26.46	-23%

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2014	President of the 20th class of chemical engineering during 2014-2017

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