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Design of the Optimum Heat Pipe Heat Exchanger to Recover Heat From Flue Gas of Boiler in case of Chiang Mai Orchid Hotel, Thailand

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ABSTRACT

This study aims to design the optimum heat pipe heat exchanger (HPHE) to recover heat from flue gas of boiler for increasing the temperature of feed water. The optimum thermosyphon heat exchanger sizing was simulated on the basis of thermo-economical method and simulation program was construct by using the MATLAB 2021b. The program was simulated by input physical parameters of the thermosyphon and heat exchanger and the thermoeconomic parameters. It was found that R134a was chosen as the working fluid of this study. In addition, the optimum of number of tubes, heat transfer rate and the optimized effectiveness of HPHE were 87 tubes, 4,873 W and 0.237, respectively. Moreover, the net saving and payback period of this HPHE were 14,865 USD and 310 days, respectively.

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1. Introduction

The Department of Alternative Energy Development and Efficiency, Ministry of Energy reported the Thailand's energy situation in 2021 (January – October). It was found that Thailand's final energy consumption was 58,920 thousand tons of crude oil equivalent (toe), divided into 52 million toe or 88.3 % of commercial energy. The consumption of natural gas was 4.24 million toe (7.2%), increasing of 3.7%. In the same time, the Renewable and Alternative Energy Development Plan (AEDP 2018), Ministry of Energy: AEDP 2018 aims to increase the ratio of renewable and alternative energy to final energy consumption of 30% in 2037. They found that there is only 14.54% of the renewable energy performance in Thailand, during 2018 to 2021. While the Energy Efficiency Plan 2018-2037 (EEP 2018) aims to reduce energy intensity (EI) of 30% in 2037, but it was found that Thailand's energy conservation performance from 2011 - 2020 was only 11.8% [1]. Meanwhile, according to IPCC (The Intergovernmental Panel on Climate Change) report, the global temperature tends to rise by 1.5 °C between 2030-2052 due to greenhouse gas emissions. This greatly affected on climate change, sea level continued to rise, and global natural disasters occurred frequently and dangerously. According to the 2006 IPCC Guidelines said that Thailand got, the greenhouse gas emissions ranked 19th in the world at 286,680.53 GgCO_2eq. The highest greenhouse gas emissions, accounting for 69.06% for energy sector. However, Sustainable (Net Zero CO_2) could stop global warming. Thailand has a plan to emit zero greenhouse gases in 2065 (Net Zero Greenhouse Gas Emission) bases on Thailand's Net Zero Road Map 2065. Energy conservation is one of the measures to reduce greenhouse gas emissions in Thailand. Chiang Mai Orchid Hotel is a commercial service building. The total heat consumption (LPG gas) of medium-sized hotels is 169,995 kilograms, equivalent to 3,719,496 baht, equivalent to 1,174,193 kgCO_2eq. Most energy is mainly used for generating steam and hot water in boilers and laundry system as shown in Fig.1 and it was found that the high temperature of flue gas is released to surrounding as shown in Fig. 2. Thus, the Chiang Mai Orchid Hotel aims to reduce energy consumption and greenhouse gas emissions by recovering heat from flue gas of boiler to pre-heat feed water by using heat pipe heat exchanger (HPHE). Therefore, this study aims to design the optimum HPHE by using the basis of thermo-economical method.

Figure 1. *Boiler for producing hot water and steam*

Figure 2. *Flue gas of boiler is released to surrounding*

2. Methodology

2.1. Thermosyphon principle

Main structure of the thermosyphon is a closed-end tube, which is evacuated and partially filled with working fluid. It can be separated into 3 parts. The evaporator section is the heat input section, the adiabatic section is the section without heat exchange between thermosyphon and the environment and the condenser section are the heat output section as shown in Fig.3. When the evaporator section receives heat, the working fluid vaporizes by latent heat of evaporation and flows to the condenser section where its temperature decreases. In the condenser section, the vapor condenses into liquid condensate and releases the heat by latent heat of condensation. The condensate returns to the evaporator section by gravitational force. The thermosyphon can only operate when the evaporator section is positioned below the condenser section because it requires gravitational force for returning the condensate to the evaporator section [2]

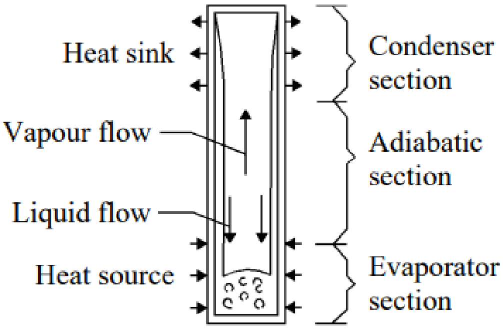

Figure 3. *The thermosyphon principle [2]*

2.2. The heat recovery by HEHE

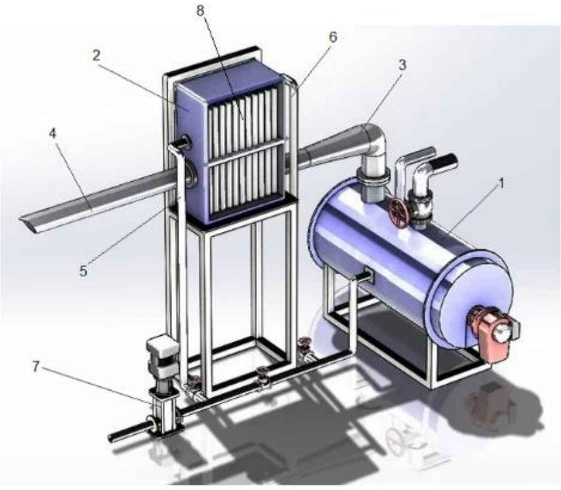

Figure 4. *The heat recovery by HPHE*

Referring to Fig.4, flue gas from boiler about 200 ^{O}C is discharged at the stack 3. Then, the flue gas flows through the HPHE 2 on the evaporator section of thermosyphon bank and exit at the stack 4. While feed water from water pipe 5, temperature about 40 ^{O}C counter flows through the condenser section of the thermosyphon bank, then exits at the water pipe 6. As the working principle of the thermosyphon, it receives heat from the flue gas (at the bottom of the HPHE) and transfer heat to the top of the HPHE, then exchange with the feed water. Therefore, the outlet temperature of water at water pipe 6 is rises and flows to the boiler 1. Due to the temperature rise, the amount of liquefied petroleum gas consumption to the boiler can be saved.

2.3. Thermo-economical method

The HPHE will be designed firstly by applying thermo-economical method. This method, is widely used to determine the optimum sizing of the heat exchanger to recover heat. Original results are presented by Soylemez [3]-[5]. The net savings function for waste heat recovery from the HPHE can be written by (1) and (2).

$$S = P_1 C_E H \dot{Q}_{THE} - P_2 First\ cost \tag{1}$$

$$S = P_1 C_E H \varepsilon_c C_{\min}(T_{h,i} - T_{c,i}) - P_2 C_A \frac{C_c ln\frac{1-\varepsilon_c C^*}{1-\varepsilon_c}}{(1-C^*)U} \tag{2}$$

Where;

S	savings gained from waste heat recovery (USD)
P1	ratio of life cycle energy cost saving to first year energy cost saving
P2	ratio of life cycle expenditures incurred because of additional capital investment to initial investment
C_E	cost of energy recovered by HPHE (baht/W/hr)
H	annual time of operation (hr/yr)
$\dot{Q}_{THE}$	heat recovered by HPHE (W)
C_A	area dependent first cost of HPHE (baht /m^2)
ε	effectiveness
C_{min}	the smaller of heat capacity rate (W/°C)
$T_{h,i}$	temperature of inlet heating fluid (°C)
$T_{c,i}$	temperature of inlet cold fluid (°C)
C^*	ratio between C_c to C_h
U	overall heat transfer coefficient (W/m^2 K)

The performance of HPHE can be calculated by (3) and (4).

$$\dot{Q}_{THE} = \frac{\Delta T}{Z_{total}} \tag{3}$$

$$\varepsilon = \frac{\dot{Q}_{thermo}}{\dot{Q}_{max}} \tag{4}$$

Where;

$\dot{Q}_{THE}$	heat transfer rate of HPHE (W)
ΔT	the effective temperature difference between the heat source and the heat sink of HPHE (°C)
Z_{total}	overall thermal resistance of HPHE (K/W)
$\dot{Q}_{max}$	maximum possible heat transfer rate (W)

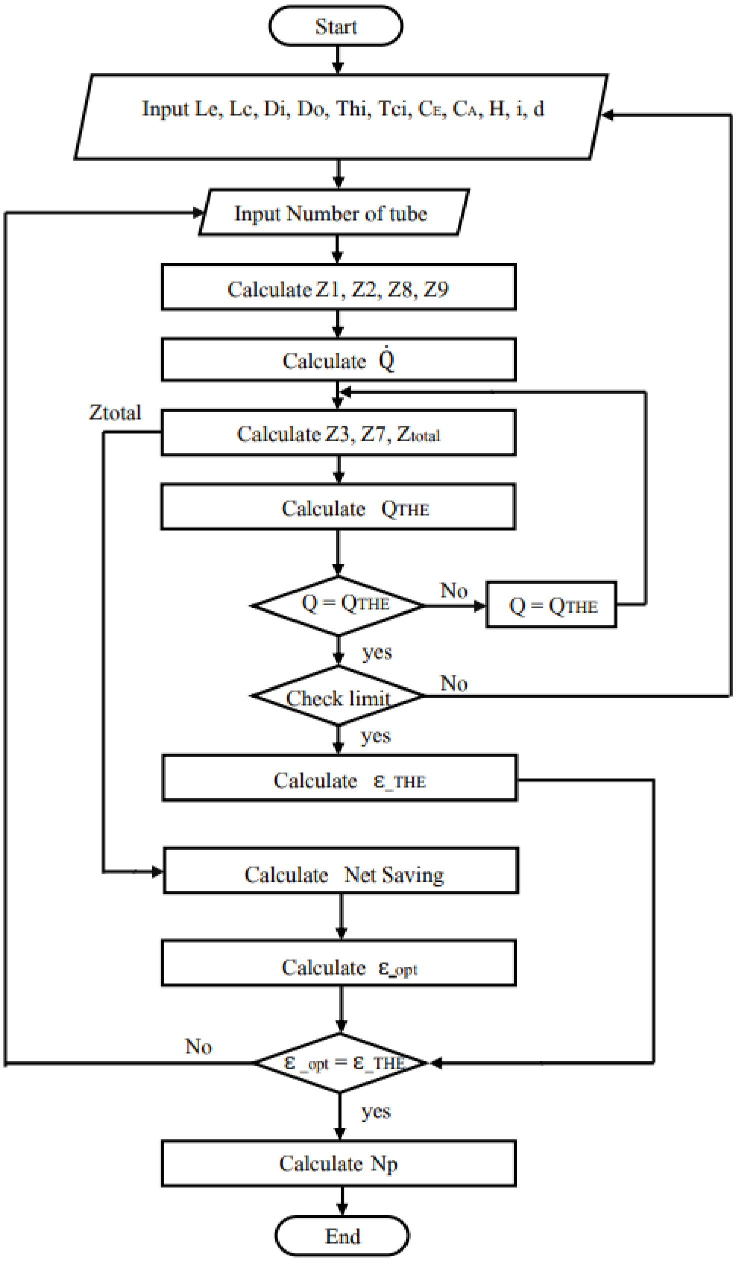

Figure 5. *The HPHE simulation program [5]*

Procedure of the simulation program is applied as shown in Fig. 5 [6]. The program is coded into computer by using the MATLAB 2022b and all parameters were inputted to the program as shown in Table 1.

Table 1. *Input parameters of the simulation program*

Input parameters	
- maximum number of tubes (N)	480
- length of evaporator section (Le)	0.4 m
- length of condenser section (Lc)	0.4 m
- inside diameter (Di)	0.01905 m
- outside diameter (Do)	0.01921 m
- pipe alignment (Staggered/Aligned)	Staggered
- number of columns	60
- heating medium (water/flue gas)	flue gas
- cooling medium (water/air)	water
- temperature of inlet heating fluid ($T_{h,i}$)	473 K
- temperature of inlet cold fluid ($Tc_{,i}$)	303 K
- flow rate of heating fluid ($\dot{m}_h$)	576 m^3/hr.
- flow rate of cooling fluid ($\dot{m}_c$)	0.33 m^3/hr.
- transverse pitch (S_T)	0.04 m
- longitudinal pitch (S_L)	0.04 m
- tube materials (steel/copper/aluminum)	copper
- Working fluid (water/R134a)	water/R134a
- fill ratio of Working fluid	0.5
- incline angle	1.57
- operation day per year	360 day/yr.
- operation year	20 yrs
- working hour per day	10 hrs/day
- energy price rate (i)	0.04
- market discount rate (d)	0.016
- ration of annual maintenance (Ms)	0.06
- ration of resale value into first original cost	0.1
- LPG cost	22 baht/kg
- area dependent first cost of HPHE (C_A)	3,000 baht/m^2

Referring Fig. 5, the simulation program is started by inputting the first value of the Le , Lc, Di, Do, Thi, Tci, C_E, C_A, H, i, d , N and the working fluids (WF). Then, the thermal resistance of thermosyphon (Z1, Z2, Z8, Z9) are calculated by using the performance of thermosyphon calculation [7], [8]. Next, the program calculated rate of heat transfer ($\dot{Q}$), Z3, Z7 and Ztotal, respectively. The $\dot{Q}_{THE}$ will be determined and compared with $\dot{Q}$, if it is not equal, the $\dot{Q}$ will be instead of by $\dot{Q}_{THE}$ and Z3, Z7, Ztotal will be recalculated. The limitations to heat transport in a heat pipe will be checked and then ε, net saving and Np will be determined, respectively.

3. Results and Discussion

Procedure of flow chart for the HPHE simulation is to predict sizing of the thermosyphon, working fluid, $\dot{Q}_{thermo}$, ε and Np at the maximum net saving by using thermo-economical method as shown in Fig.5 and the parameters will be inputted as shown in Table 1. The results can be explained with water and R134a as working fluid.

3.1. Effect of effectiveness on the net savings with water as working fluid

Referring to Fig.6, in the first period, as the effectiveness was increased from 0 to 0.2, the saving was strongly increased and then a trend was slightly increased up to the maximum point at 0.237. This period, the saving was increased due to the cost of energy recovered by HPHE in the first term of (1) and (2) was higher than the first cost of HPHE. While the second period, the effectiveness was higher than 0.237, a large of HPHE area caused the first cost in the second term of (1) and (2) HPHE was rapid increased. It can be seen that the results of this study was agreed with previous researches [3]-[6]. Therefore, the saving was strongly decreased. It was found that the maximum of net saving was 14,865 USD baht and tube number was 87 tubes. While, heat transfer rate was 4,873 Watt and optimized effectiveness of HPHE was 0.237. In addition, payback periods of the HPHE was 310 days.

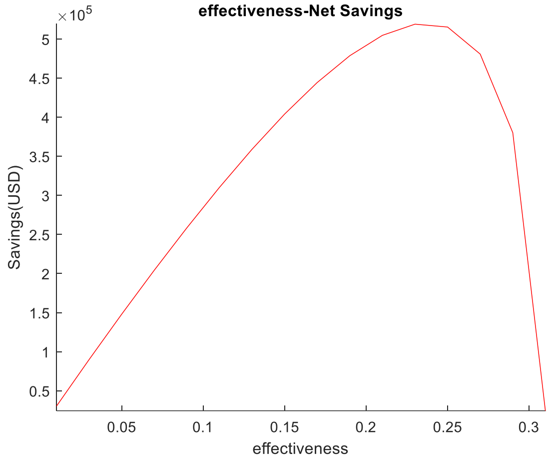

Figure 6. *The effect of effectiveness on the net savings with water as working fluid*

3.2. Effect of effectiveness on the net savings with R134a as working fluid

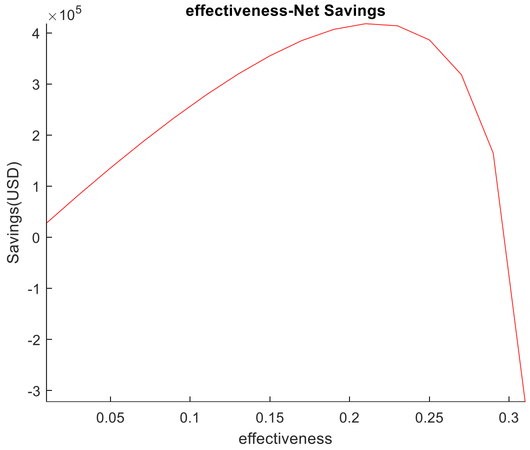

Figure 7. *The effect of effectiveness on the net savings with R134a as working fluid*

The effect of effectiveness on the net savings with R134a as working fluid is shown in the Fig. 7. The trend was similar to the Fig.6. It was found that the maximum of net saving and tube number were 11,957 USD and 103 tubes, respectively. While, heat transfer rate, optimized effectiveness and payback periods of the HPHE were 4,435 Watt, 0.215 and 401 days, respectively. Moreover, it can be seen that the net saving of HPHE with 134a as working fluid was lower than the net saving of HPHE with water as working fluid, this result was agreed with the study by Yeunyongkul (2012) [5]. In addition, the temperature of flue gas is very high therefore it is not suitable in case of R134a as working fluid for this study.

4. Conclusions

This research presented the optimum design of HPHE to recover heat from flue gas of boiler to pre-heated feed water in case Chiang Mai orchid hotel. The results showed that the optimum of the working fluid in this study was water. Moreover, the number of tubes, the heat transfer rate and the optimized effectiveness were 87 Tubes, 4,873 W, 0.237, respectively. In addition, the saving and the payback period of the HPHE were 520,290 baht and 310 days, respectively. For the future study, the HPHE will be constructed under the optimum condition as shown in Fig.8 and located at the hotel. Then, the experimental and simulation results will be compared.

Figure 8. *The 80 tubes of HPHE*

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