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Experimental Investigation of a Thermosyphon Economizer to Recover Waste Heat in the Electronics Industry

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Abstract

A case study was conducted to design, construct and test a themosyphon economizer for increasing the temperature of feed water by using waste hot water. The simulation of the themosyphon economizer (heat exchanger) for the establishment of the optimum size was performed using the thermo-economical method. The thermosyphon was made of a total of 80 copper tubes (outside diam. 19.05 mm) with evaporative, adiabatic and condensation lengths of 300, 10 and 300 mm, respectively. The working fluid was R-134a, filling ratio was 50 % by evaporative volume, and the thermosyphon was arranged in a staggered form. In testing performance, flow rate of the inlet hot water was set at 10 L/min and the controlled inlet temperature of cold water at 25° C. The average flow rate of the cold water was set at 5, 7 and 10 L/min, respectively. Results showed that the maximum of rate of heat transfer from the condenser section occurred at the flow rate of the cold water of 10 L/min. When test the inlet temperature of hot water of 45, 55 and 65° C were used at the inlet volume flow rate of cold water of 10 L/min maximum heat transfer rates from the condenser 4,626, 8260 and 8,790 W were achieved. Moreover, the outlet temperature of the cold water which was initially 25° C changed to 31.1, 34 and 37° C, respectively. Therefore, increasing the outlet feed water temperature reduced energy consumption. The effectiveness of the thermosyphon economizer with the inlet temperatures of hot water of 45, 55 and 65° C was 0.47, 0.48 and 0.49, respectively.

Keywords: Thermosyphon; Economizer ; Electronics Industry ; Working Fluid

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1. Introduction

Energy is critical for life because many human activities involve some reliance on energy. Demand for energy is increasing in most if not all countries around the world. The most common types of energy come from fossil sources such as fuel oil, natural gas, and coal which are used in industrial, agricultural and residential sectors to increase productivity and human comfort. The main energy consumption in transportation and industry requires fuel oil. However, the amount of fuel oil available globally is declining and its cost is unpredictable. Many countries must import fuel oil from other countries and maintain some reserves. While the price of fuel oil affects economies, there are increasing concerns regarding the environmental impacts that result from the use of fuel oils. The cost of energy and the related environmental concerns can impact strongly on the economies in developing countries, it is necessary to decrease energy consumption wherever possible and to explore options for the supply of other types of energy. In Thailand, a lot of heat is produced from many industrial sources, such as from the industries that produce electronic devices. This energy is often lost but when it is in the form of waste heat, it may be able to be recovered for use in various applications with direct environmental and economic benefits. Equipment is available, that is low in capital cost and simple to maintain, has the ability to recover and reutilize waste heat. One such example is the thermosyphon economizer or thermosyphon heat exchanger. This study aimed to evaluate the effectiveness of such a device in recovering heat for reutilization in an industrial context.

2. Research Methodology

2.1 Theory and formula

2.1.1 Thermosyphon

The heat pipe first described by Perkins in 1831. Later in 1892, Perkins and Buck developed and patented at two phase heat pipe [1]. Subsequently, the heat pipe has been continuously developed and used in a number of engineering applications. The basic heat pipe can be divided in to two types. The first type has an internal wick structure and is called a “conventional heat pipe”. The other type is termed a “thermosyphon” which is a heat pipe without a wick structure that use gravity in order to circulate the working fluids inside a tube (**Fig. 1**). 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 above the condenser section because it requires gravitational force for returning the condensate to the evaporator section [2-4].

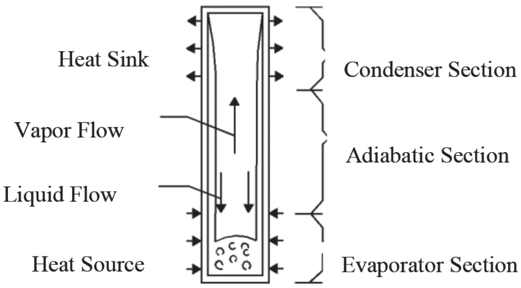

Fig. 1 A diagram of a basic thermosyphon comprising a evaporator, adiabatic and an evaporator section [4].

2.1.2 Heat transfer rate of thermosyphon

The closed two-phase thermosyphon is an effective heat transfer device. The working principle can be easily explained as receiving the heat from the evaporator section by means of the evaporating mechanism, and then releasing the heat out of the condenser section by means of the condensing phenomena. Because the latent heat of vaporization of the working fluid is relatively high, a large amount of heat can be transported through the thermosyphon as shown in equation (1).

$$\dot{Q} = \frac{\Delta T}{Z_{total}} \qquad (1)$$

Where:

$\dot{Q}$ = Heat transfer rate of the thermosyphon (W)

ΔT = Temperature difference between the heat source and the heat sink (°C)

Z_{total} = Overall thermal resistance of the thermosyphon (°C/W)

2.1.3 Heat transfer rate of the thermosyphon heat exchanger

There are many factors that influence the performance of the thermosyphon heat exchanger, including: size, type, geometry, construction material, inclination of the thermosyphon, working fluid, heat flux and container. The heat lost from the high–temperature stream can be calculated from the equation (2). Similarly, the gained heat by the low–temperature stream can be calculated as shown in equation (3)

$$\dot{Q}_h = \dot{m}_h Cp_h \left(T_{h,i} - T_{h,o}\right) \qquad (2)$$

$$\dot{Q}_c = \dot{m}_c Cp_c \left(T_{c,o} - T_{c,i}\right) \qquad (3)$$

Where:

$\dot{Q}_h$ = Heat lost from the high temperature stream (W)

$\dot{Q}_c$ = Heat gained from the low–temperature stream (W)

$\dot{m}_h$ = Mass flow rate of high–temperature fluid stream (kg/s)

$\dot{m}_c$ = Mass flow rate of low–temperature fluid stream (kg/s)

Cp_h = Specific heat of the high–temperature fluid stream (J/kg•°C)

Cp_c = Specific heat of the low temperature fluid stream (J/kg•°C)
$T_{h,i}$ = Inlet temperature of the high temperature fluid stream (°C)
$T_{h,o}$ = Outlet temperature of the high temperature fluid stream (°C)
$T_{c,i}$ = Inlet temperature of the low temperature fluid stream (°C)
$T_{c,o}$ = Outlet temperature of the low temperature fluid stream (°C)

2.1.4 Effectiveness – number of transfer units (ε-NTU)

The ε - NTU method, which is used to measure the heat exchanger effectiveness, is defined as the ratio of actual heat transfer in a heat exchanger to the heat transfer that would occur in a heat exchanger with infinite surface area. With infinite surface area, the exit temperature of the low temperature fluid would equal the inlet temperature of the high temperature fluid. Therefore, the effectiveness can be given as:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{C_h\left(T_{h,i} - T_{h,o}\right)}{C_{\min}\left(T_{h,i} - T_{c,i}\right)} = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{\min}\left(T_{h,i} - T_{c,i}\right)} \quad (4)$$

Where:
ε = Heat exchanger effectiveness
$\dot{Q}_{\max}$ = Heat transfer that would occur in a heat exchanger with infinite surface area (W)
$C_{\min}$ = Minimum heat capacity (W/°C)

The number of transfer units, NTU, is a non-dimensional expression of the "heat transfer size" of the exchanger,

$$NTU = \frac{U_t A_t}{C_{\min}} \quad (5)$$

Where:
NTU = Number of transfer units
U_t = Overall heat transfer coefficient of the thermosyphon heat exchanger (W/m^2•°C)
A_t = Total heat transfer surface area of the thermosyphon heat exchanger (m^2)

2.1.5 Thermosyphon heat exchanger design

A thermosyphon heat exchanger is designed by applying the thermo-economical method. This method is widely used to determine the optimum sizing the heat exchanger that are designed to recover heat. Original results are presented by Soylemez [8, 9]. The net savings function for waste heat recovery from the thermosyphon heat exchanger can be written as

$$S = P_1 C_E H \dot{Q}_{th} - P_2 C_{HX} \quad (6)$$

where:
S = Savings gained from waste heat recovery (Baht)

P_1 = ratio of life cycle energy cost saving to first year energy cost saving

P_2 = ratio of life cycle expenditures incurred because of additional capital investment to initial investment

C_E = Cost of energy recovered by thermosyphon heat exchanger (Baht/W•hr)

H = Annual time of operation (hr/yr)

$\dot{Q}_{th}$ = Heat recovered by thermosyphon heat exchanger (W)

2.2 Experimental setup

2.2.1 Design conditions

The thermosyphon heat exchanger was designed on the basis of the optimization technique by using thermoeconomical method. The optimum size of the system with R134a as the working fluid, were determined to be: 0.3 m evaporator section length (Le), 0.3 m condenser section length (Lc), 19.05 mm inner diameter of tubes (Di), and 80 tubes (N).

2.2.2 The setup

The experimental setup consisted of 12 major components (**Fig. 2**). The thermosyphon economizer had total outside cross section area of 350 x 450 mm and was 590 mm high. The thermosyphon was made of copper tube with an outside diameter of 19.05 mm and 0.8 mm wall thickness. There was a total of 80 tubes with evaporative length, adiabatic and condensation lengths of 300, 10 and 300 mm, respectively.

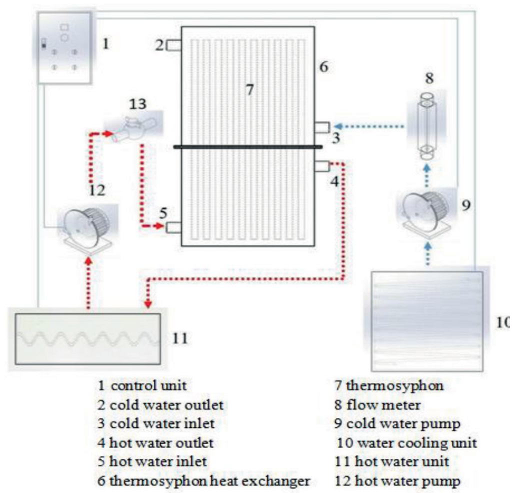

Fig. 2 Design of the experimental thermosy-phon showing schematic layout (upper), actual test unit (middle) and thermosyphon heat exchanger (lower)

The working fluid was R-134a, filling ratio was 50% by evaporative volume, and the thermosyphon tubes were arranged in a staggered array of 10 rows with 8 tubes per row. The hot water passed through the evaporator face cross section area of 350 × 320 mm and the feed water passed through the condenser which had a face cross section area of 350 × 470 mm. The experiments was tested at three inlet temperature of 45, 55 and 65 °C. At each of these temperatures, three flow rates of 5, 7 and 10 L/min, were evaluated. All data were recorded under a steady state conditions.

3. Results and Discussion

All input temperatures when the inlet flow rate of cold water was increased, the heat transfer rate was increased; the trends at each temperature are similar (**Fig. 3**). Moreover, it was found that when the inlet temperature of hot water was increased, the heat transfer rate was increased with the same inlet flow rate of cold water. Referring to equation (3), the heat transfer rate was calculated as having a maximum of 8,790 W with an inlet temperature of hot water of 65 °C and an inlet volume flow rate of cold water of 10 L/min.

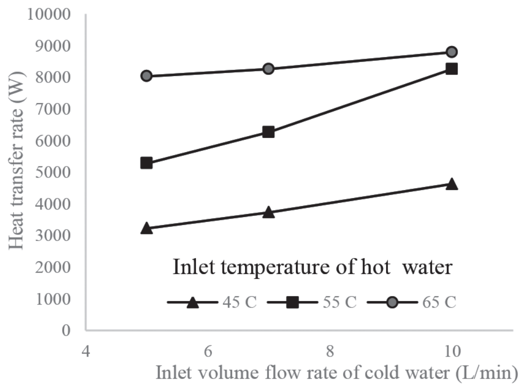

Fig. 3 Effect of the inlet water volume flow rate of cold water on the heat transfer rate at three different inlet temperatures of hot water.

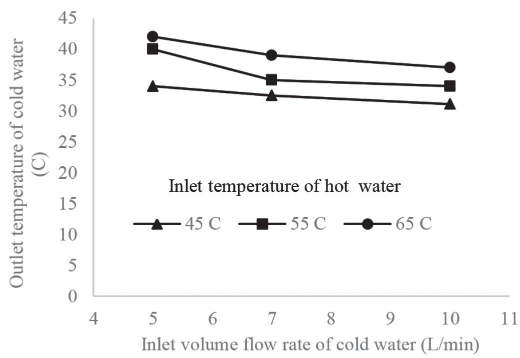

Fig. 4 Effect of the water volume flow rate of cold water on the outlet temperature of the cold water

Fig. 4 shows the effect of the water volume flow rate of cold water on the outlet temperature of the cold water from the condenser section when the inlet temperature of cold water was fixed at 25 °C. The outlet temperature of cold water increased, as expected, when the inlet temperature of hot water was increased and the inlet volume flow rate of cold water was decreased. Further, the outlet temperature of cold water was maximum, at 42 °C with the inlet temperature of hot water of 65 °C and the inlet water flow rate cold water of 5 , 10 L/min. The outlet temperature of the cold water which recovers heat from the condenser section of the thermosyphon economizer, was increased showing the possibility of recovering heat for future utilization.

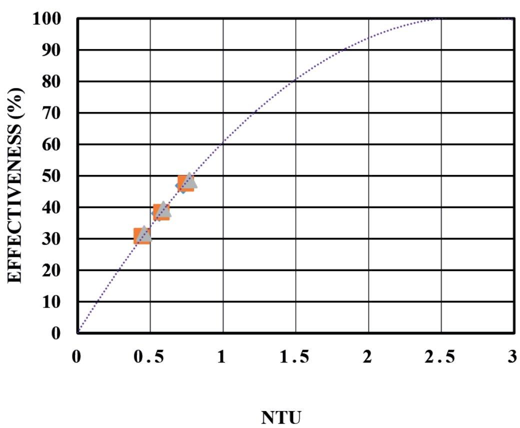

Fig. 5 Effect of NTU on the effectiveness of the thermosyphon heat exchanger. The data represent three test temperatures for the input water and three flow rates

The effect of the NTU on the effectiveness of the thermosyphon heat exchanger is shown in **Fig. 5.** In these tests, the value of Cr was fixed, thus the effectiveness of the thermosyphon heat exchanger was obtained using equation 4. As NTU increasd, the effectiveness of the thermosyphon heat exchanger was increased. The effectiveness with the inlet temperatures of hot water of 45, 55 and 65 °C was 0.47, 0.48 and 0.49, respectively.

4. Conclusion

4.1 The heat transfer rate was maximum, with a value of 8,690 W with an inlet temperature of hot of 65 °C and an inlet volume flow rate of water of 10 L/min.

4.2 The outlet temperature of cold water was a maximum of 42 °C with an inlet temperature of hot of 65 °C and an inlet volume flow rate of water of 5, 10 L/min.

4.3 The effectiveness with the thermosyphon heat exchanger with the inlet temperatures of hot water of 45, 55 and 65 °C was 0.47, 0.48 and 0.49, respectively.

4.4 The outlet temperature of the cold water which recovers heat from the condenser section of the thermosyphon economizer, was increased showing the possibility of recovering heat for future utilization.

5. Acknowledgement

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