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Experimental performance comparison of shell-side heat transfer for shell-and-heat pipe heat exchanger with and without baffle

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ABSTRACT

Thermal performance of shell-and-heat-pipe heat exchanger (S-HPHE) and shell-and baffled heat-pipe heat exchanger (S-BHPHE) have been experimentally investigated. Methanol (CH_3OH) has been used as working fluid of heat pipe. The mass flow rate of water on the shell side was varied from 30 lph to 60 lph, while on the condenser side it has been varied from 10 lph to 60 lph for all mass flow rate of hot water on the shell side of the heat pipe heat exchanger with baffles and without baffles. Heat input to the heat exchanger has been varied by varying the power input in the range of 1kW to 4kW. The results showed that, based on the shell-side flow rate and temperature of hot water, the effectiveness of heat-pipe heat exchanger with rectangular baffles is higher than that of the heat exchanger without baffles. The performance of heat-pipe heat exchanger with rectangular baffles with 1:1 ratio of mass flow rate of hot and cold water has shown minimum effectiveness. The shell and baffled heat-pipe heat exchanger (S-BHPHE) with 1:0.5 ratio of mass flow of hot and cold water shows the best performance.

Nomenclature

A	-	total heat transfer area, m^2
C	-	heat capacity rate, kW/K
q	-	heat input, kW
c	-	specific heat of the water, kJ/ kg K
D	-	diameter, m
L	-	length of tube, m
L_s	-	length of shell, m
$\dot{m}$	-	mass flow rate, lph
N	-	total number of heat pipes
NTU	-	number of heat transfer units
n	-	total number of baffles ,
p	-	pitch, m
T	-	temperature, ^oC
Q	-	heat transfer, W
U	-	Overall heat transfer coefficient, kW/m^2K
S-HPHE	-	shell and heat-pipe heat exchanger
S-BHPHE	-	shell and baffled heat - pipe heat exchanger
ΔT	-	difference in temperature, ^oC or K
l	-	length of baffle plate, m
t	-	thickness of baffle plate, m
h	-	height of baffle plate, m

Subscripts

c	-	cold water
h	-	hot water
i	-	inner
o	-	outer
in	-	inlet
out	-	outlet
act	-	actual
max	-	maximum
min	-	minimum

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s	-	shell
lm	-	logarithmic mean
Greek Letters		
$\in$	-	effectiveness
ψ	-	inclination angle

Introduction

Heat exchanger with heat-pipes have been considered as promising means for effective heat transfer in energy transport and storage system operating in a medium and high temperature range such as concentrated solar thermal energy system. Faghri [1] investigated the medium – temperature range for a heat-pipe is normally between 500 K and 700 K based on the operating temperature. Dunn and Reay [2] reported that the heat-pipes have made them more attractive for use as heat-pipe heat exchanger due to their special advantages, such as no moving parts, compactness, perfect separation between hot and cold fluid, light weight and high reliability. Shimura et al. [3] investigated the heat pipe thermal resistance with different working fluids at various inclination angles in gravity-assisted condition. The medium temperature range working fluids for heat pipes such as Dowtherm-A was reported by Reay and Kew. [4]. This study focused on the use of a heat-pipe using methanol as working fluid to investigate the thermal performance of shell-and-heat-pipe heat exchanger.

Kral et al. [5] discussed the performance of heat exchangers with helical baffles based on test results of various baffles geometries. A comparison between the test data of shell-side heat transfer coefficient versus shell-side pressure drop was provided for five helical baffles and one segmental baffle measured from a water-water heat exchanger.

Air-to-air thermosyphon heat exchanger using water as the working fluid with 12 kW of input heat into the evaporator section, operating below 300^0C was investigated by Dube et al. [6]. Analysis of hydrodynamic and heat transfer characteristics of a heat exchanger with single-helical baffles, experimentally and numerically using CFD model and comparing the performance of heat exchanger with single-segmental baffles was reported by Gang Lei et al.[7] The importance of baffle spacing in the thermodynamic analysis of shell and tube heat exchanger design was reported by Eryener [8]. The investigation of heat transfer enhancement for a shell and tube heat exchanger by providing sealers in the shell side which blocks the gap between the baffle plate and shell was reported by Wang et al. [9].

From the above brief review, it has been proposed to conduct comparative study on a shell-and-heat-pipe heat exchanger using methanol as working fluid with and without baffles in shell-side of heat exchanger. S-BHPHE having nine numbers of rectangular baffles which were arranged inside the shell of heat exchanger. The effect of various parameters such as heat input (q), mass flow rate of hot water $(\dot{m}_{h\,in})$ and inlet temperature of water to shell-side $(T_{h\,in})$ were being considered in both heat exchangers.

An experimental setup has been developed with baffles and without baffles in the shell side of the heat exchanger, in order to investigate the performance of heat exchanger. The $\in$-NTU method has been used to predict the performance of S-HPHE and S-BHPHE.

Shell-And-Baffled Heat-Pipe Heat Exchanger

Both S-HPHE and S-BHPHE consists of three number of heat-pipes. For this experimental study, shell-and-heat-pipe heat exchanger and shell-and-baffled heat-pipe heat exchanger were designed and constructed. Methanol (CH_3OH) had been used as the working fluid in the heat pipes. The schematic and operational procedure of a heat-pipe is shown in figure.1.

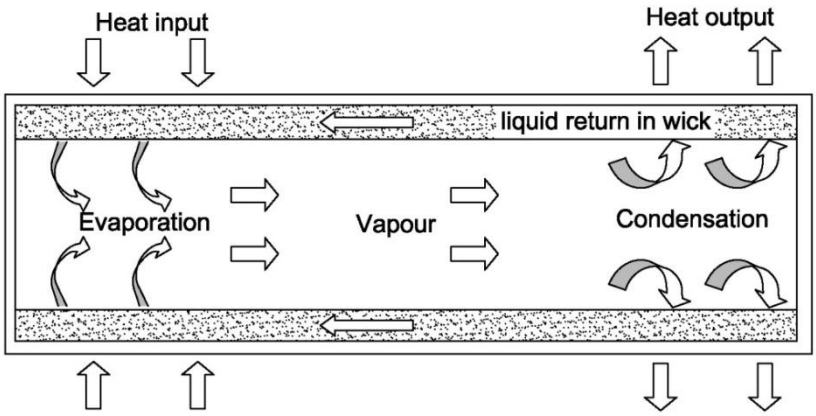

Figure 1. Schematic diagram of heat pipe operation

Both heat exchangers consisted of three heat pipes made up of copper that were 1000 mm long, had a 17 mm inside diameter and a 19mm outside diameter. In S-BHPHE, nine number of rectangular baffles were attached inner surface of the shell. Each baffle plates were 150 mm long, had a 40 mm height and 10 mm thick. Three heat-pipes were arranged in two rows, co-axially in both the heat exchangers. The heat-pipes consists of three section namely evaporator section which is of length 700 mm, condenser section of length 150 mm, and its central adiabatic section of 150 mm. The evaporator section of each heat-pipe was located inside the shell of length 1000 mm and diameter of 102 mm. In order to restrict the flow of hot water inside the shell, nine numbers of baffle plates were

attached in the inner surface of the shell. Three of them were attached nearer to the inlet of shell, three of them were attached closer to the outlet of shell and remaining three were attached at the middle of the shell. The constructed shell of heat exchanger without, with baffles and heat pipes arrangements are shown in Figure.2 and Figure.3. The detailed specification of heat pipe were listed in Table.1 and physical parameters of shell and baffles were given in Table.2.

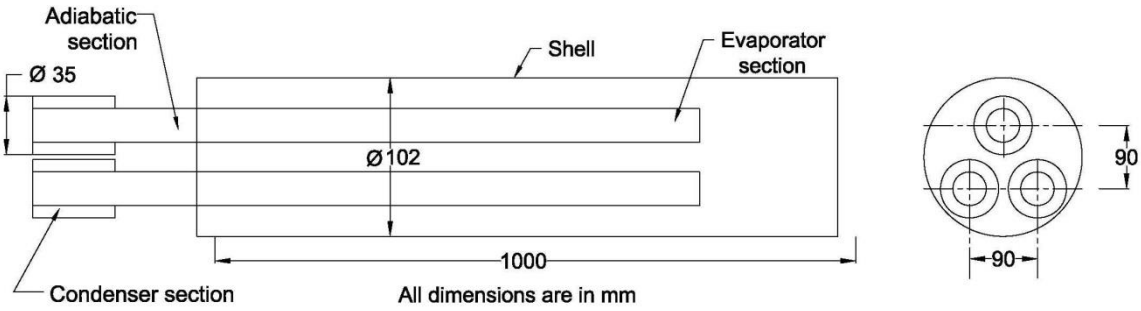

Figure 2. Schematic of the shell without baffle and arrangement of heat pipes

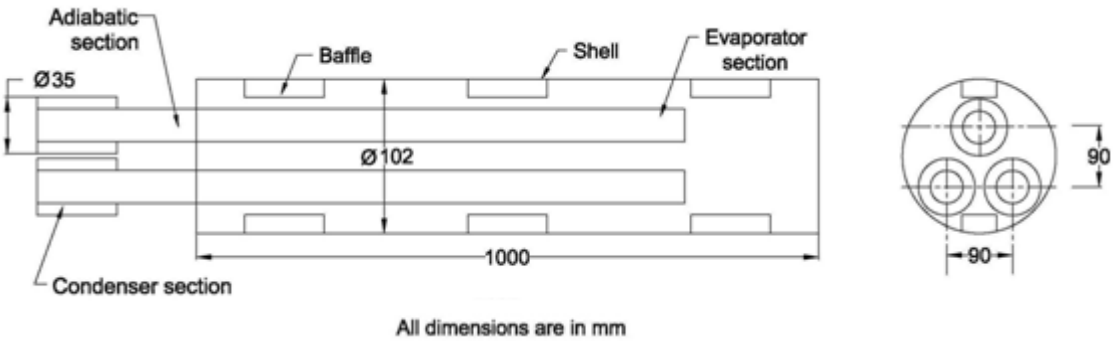

Figure 3. Schematic of the shell with baffles

Table 1. Specifications of heat-pipe

Material	Copper
Diameter, mm	D_o : 19, D_i : 17
Number of heat-pipes (N)	3
Heat-pipe pitch (p), mm	90
Wick	Stainless Steel, 2 layer of mesh number : 2000
Working fluid	Methanol (CH_3OH)
Length, mm	Evaporator : 700 Adiabatic section : 150 Condenser: 150

Table 2. Physical Parameters of shell and baffle

Shell diameter (D), mm	102
Shell Length (L_s), mm	1000
Total number of baffle plates (n)	9
Physical dimensions of baffle (l x h x t), mm	150x40x10
Baffle plate material	Mild Steel
Heat input to electrical heater	1kW, 2kW, 3kW, 4kW
Inclination angle (ψ)	0°

Experimental Setup

To investigate the thermal performance of S-HPHE and S-BHPHE, an experimental setup was fabricated and the Figure 4 shows a schematic diagram of the experimental setup of S-HPHE with baffles used for this investigation. It consisted of a shell, three heat-pipes, electrical heater (with total capacity of 4 kW), six thermocouple and temperature indicator. Rotameter have been used to measure and control the flow rate of hot and cold water to the heat exchanger. In order to measure the relative temperature of both water a digital temperature indicator is used. Six number of Copper Constantan thermocouples were provided to measure the temperature of hot and cold water. Two thermocouples for hot water and four thermocouples for cold water temperature measurement.

A vacuum pump was used to remove the non condensable gases from each heat pipes. The heat-pipes were charged with methanol (CH_3OH) which is used as working fluid in both S-HPHE and S-BHPHE.

Initially the effect of mass flow rate of water on the thermal performance of both S-HPHE and S-BHPHE with constant inlet temperature of hot water was investigated. It was followed by a set of experiments to investigate the influence of inlet temperature of hot water with constant mass flow rate. Experiments were carried out by varying the heat input to the electrical heater from 1 kW to 4 kW during both investigations.

Effectiveness Calculation

In both S-HPHE and S-BHPHE, the heat capacity rate of evaporator section of heat-pipe is C_h and condenser section is C_c.

Heat capacity rate is defined as the product of mass flow rate and specific heat of fluid. Therefore,

$$C_h = \dot{m}_h c_h \quad (1)$$

and

$$C_c = \dot{m}_c c_c \quad (2)$$

Energy balance equation has been applied to determine the heat transfer from hot water to cold water. Therefore,

$$Q = \dot{m}_h c_h (\Delta T)_h = \dot{m}_c c_c (\Delta T)_c \quad (3)$$

The overall heat transfer coefficient (U) has been obtained from the heat transfer (Q), total area of heat exchanger (A) and log mean temperature difference of heat exchanger $(\Delta T)_{lm}$ as given below,

$$U = \frac{Q}{A.(\Delta T)_{lm}} \quad (4)$$

The effectiveness of heat exchanger is defined as the ratio of actual heat transfer of heat exchanger to the maximum possible heat transfer between the water streams, considering the heat loss from the heat exchanger to the surroundings is negligible. Therefore,

$$\in = \frac{Q_{act}}{Q_{\max}} \quad (5)$$

Actual heat transfer of S-HPHE and S-BHPHE depend on the maximum possible heat transfer, i.e.

$$Q_{\max} = C_{\min} (\Delta T)_{\max} \quad (6)$$

Number of transfer unit (NTU) can be obtained from the product of total area of heat exchanger and overall heat transfer coefficient to minimum heat capacity rate. Therefore,

$$NTU = \frac{UA}{C_{\min}} \quad (7)$$

Appropriate empirical expression has been used to estimate the effectiveness using the minimum heat capacity fluid.

Result and discussion

The result reported in this paper has been obtained on both S-HPHE and S-BHPHE having some fixed and variable parameters. The fixed parameters were such as working fluid, diameter of shell, diameter of heat pipe, size of baffle, material of heat pipe and material of wick structure. The variable parameters were inlet mass flow rate of hot water, inlet mass flow rate cold water, inlet temperature of water to the evaporator section and heat input to the electrical heater.

In order to investigate the thermal performance of shell and heat-pipe heat exchanger with and without baffles, numbers of tests were conducted. In every test, the mass flow rate of hot water at the inlet of evaporator section was fixed and varying the mass flow rate of cold water in the ratio of 1:1, 1:0.7, 1:0.5, 1:0.4, and 1:0.3. Figure 5 to 8 show the comparative effect of heat capacity ratio C_h / C_n on overall effectiveness for different mass flow rate of water to the shell-side of both S-HPHE and S-BHPHE. The heat input to electrical heater varied between 1kW and 4 kW. It has been found that the effectiveness increased with increasing the mass flow rate of water to the shell side of heat exchangers. It is found that the effectiveness of S-BHPHE is higher than S-HPHE for all mass flow rate of water and heat input.

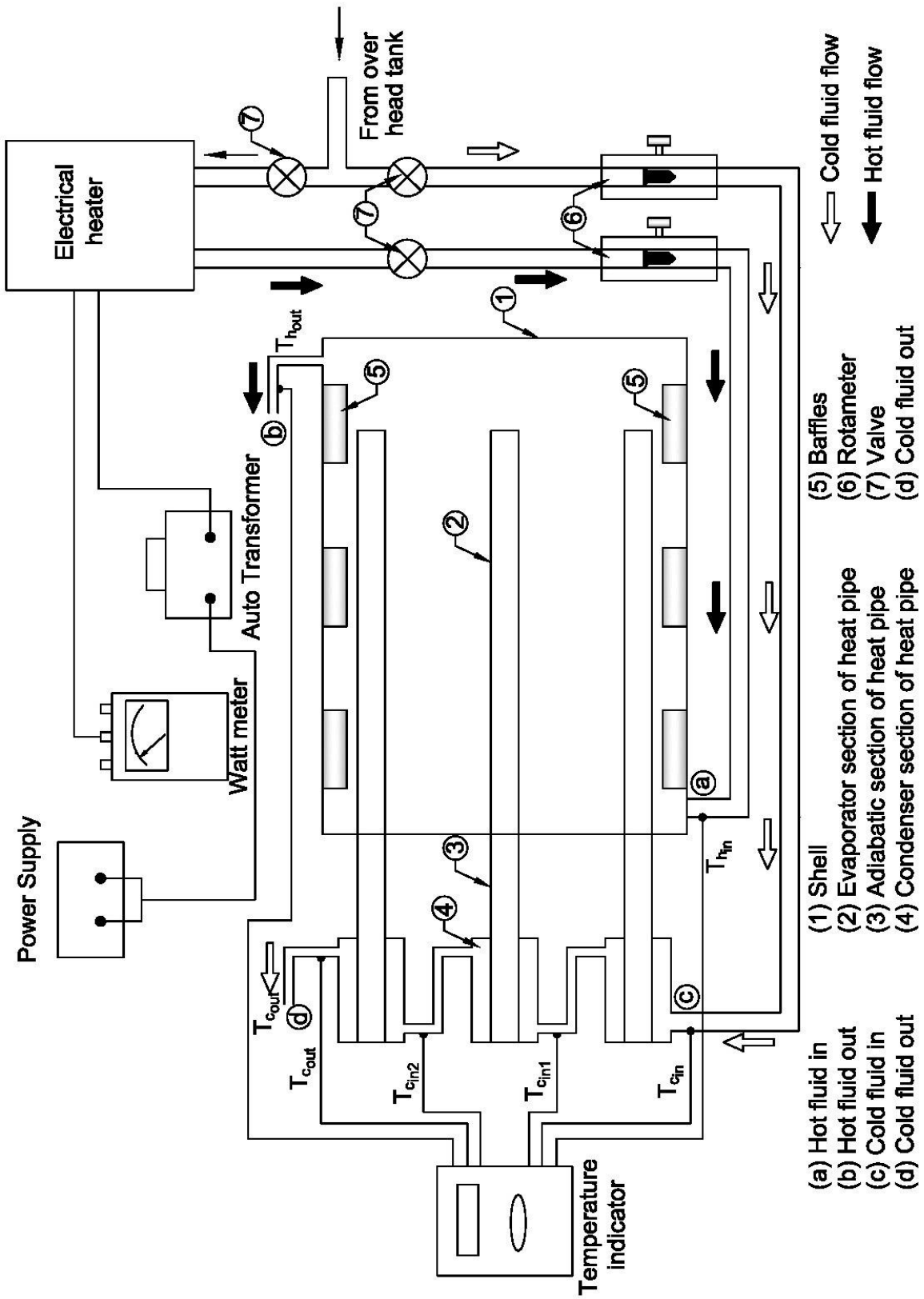

Figure 4. Schematic arrangement of experimental setup of S-BHPHE

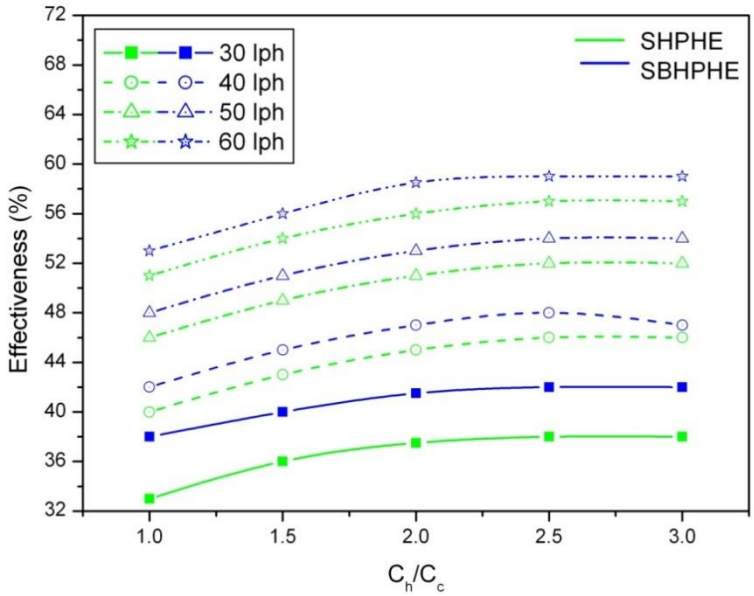

Figure 5. Effect of overall effectiveness on C_h/C_c at q = 1 kW

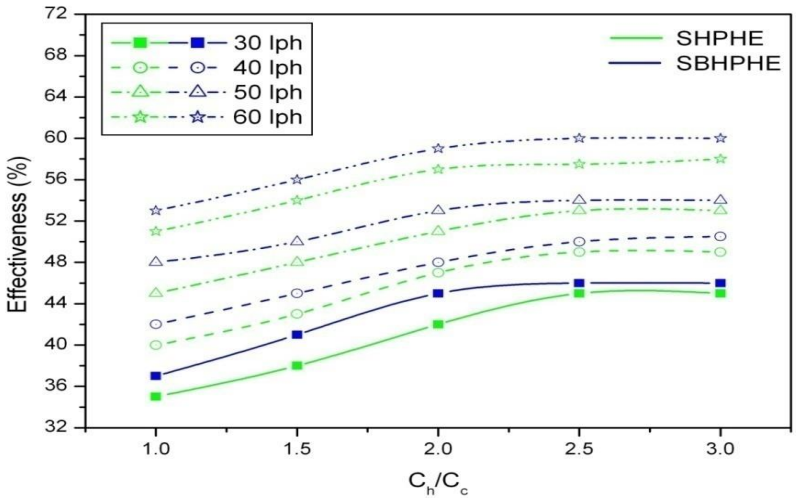

Figure 6. Effect of overall effectiveness on C_h/C_c at q = 2 kW

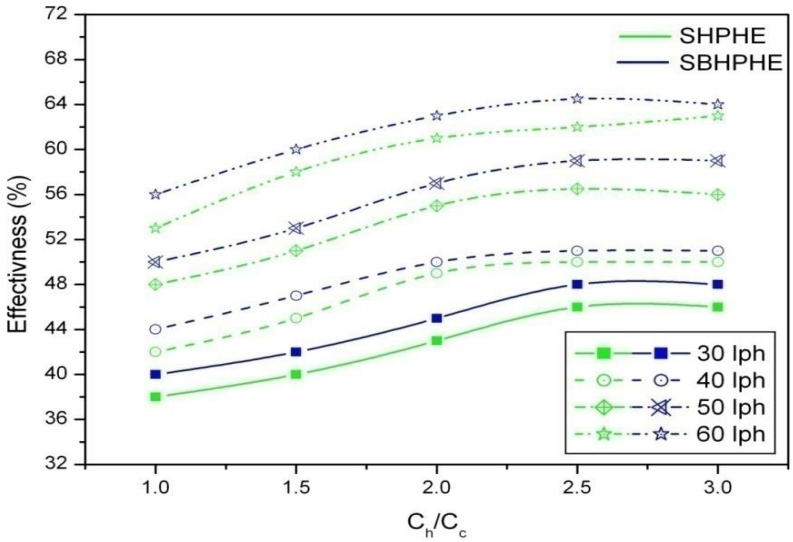

Figure 7. Effect of overall effectiveness on C_h/C_c at q = 3 kW

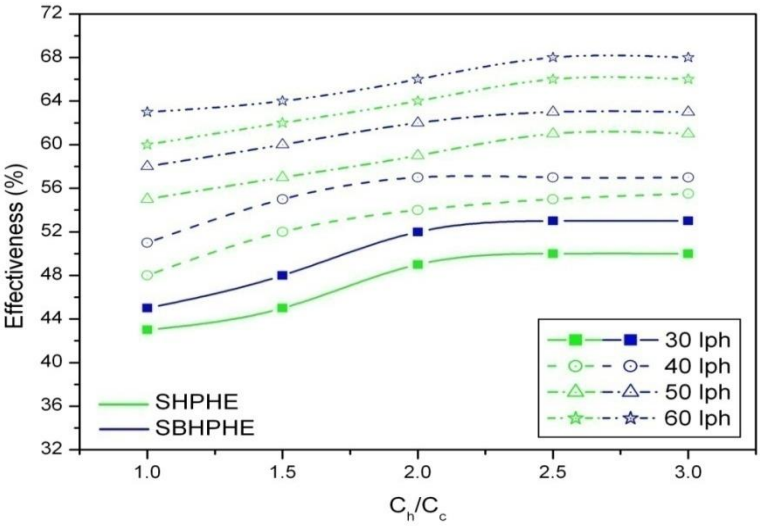

Figure 8. Effect of overall effectiveness on C_h/C_c at q = 4 kW

In both heat exchanger minimum value of effectiveness is obtained at $m_h=m_c$. Hence to get better performance of shell and heat-pipe heat exchanger with baffles, it is clearly observed that equal flow rate of water should be avoided in the condenser and evaporator section.

The experimental investigation showed that the maximum thermal performance of S-BHPHE has been achieved upto 68% but for S-HPHE effectiveness has been achieved upto 62% with increasing the mass flow rate of water in the shell side of heat exchangers.

The effectiveness of the S-HPHE and S-BHPHE, with respect to inlet temperature of water to the shell side of heat exchanger for constant mass flow rate of water to shell side of heat exchanger is shown in figure 9. The experimental investigation showed that the effectiveness of S-BHPHE has been increased upto 68% with increasing the mass flow rate of hot water and temperature of hot water at the inlet of heat exchanger.

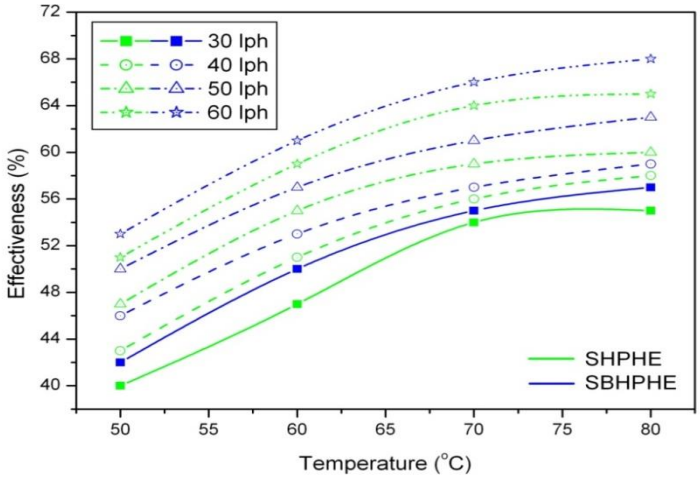

Figure 9. Effect of overall effectiveness Vs Inlet temperature of water to the evaporator section

The variation of overall heat transfer coefficient (U) and inlet temperature of hot water to the shell side of both S-HPHE and S-BHPHE has been represented in the figure.10. It is observed that overall heat transfer coefficient increases with increasing the inlet temperature and mass flow rate of water to the shell side of both heat exchangers.

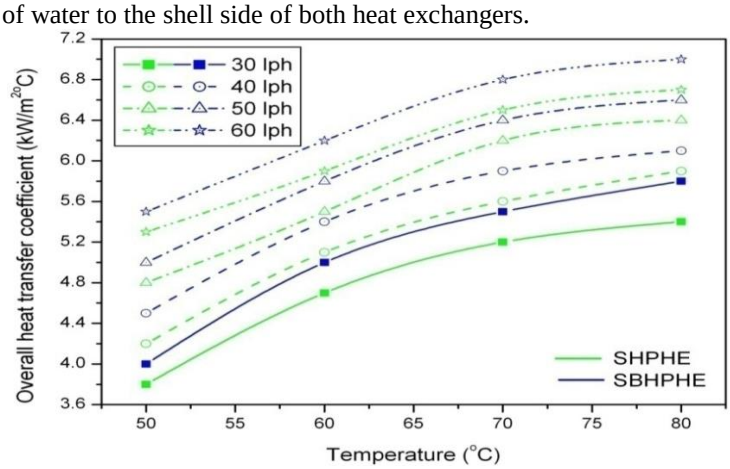

Figure 10. Effect of overall heat transfer coefficient Vs Inlet temperature of water to the evaporator section

Conclusion

In this paper the effect of mass flow rate of water, inlet temperature of water for various heat input on heat transfer characteristics of a S-HPHE and S-BHPHE have been analyzed experimentally and compared the thermal performance of both heat exchanger.

Based on the results in both heat exchangers, the following conclusions were obtained. In all opening condition, the experimental results showed that the minimum effectiveness for both S-HPHE and S-BHPHE took place at $m_h = m_c$. Therefore equal mass flow rate of water in the evaporator and condenser should be avoided. It is noticed that the S-BHPHE has nearly 5% of effectiveness higher than S-HPHE.For all values of C_h / C_c, it is found that the optimum effectiveness of S-HPHE and S-BHPHE is obtained when . . Therefore half the amount of cold water in the condenser section than hot water in the shell side of heat exchanger $m_h = 2m_c$ should be preferred in both heat exchangers.

The overall effectiveness of the shell and baffled heat-pipe heat exchanger was over 40% for each of the conditions of all experiments and reaches up to 68% with increasing of hot water flow rate to the evaporator section but for shell and heat-pipe heat exchanger it is only 35% for each of the conditions of all experiment and reaches up to 62% with increasing of hot water flow rate to the evaporator section.

From the experimental result it is found that the shell and baffled heat-pipe heat exchanger, the optimum effectiveness ranges from 61% to 68% for heat input from 1kW to 4kW. It is obvious that shell and heat-pipe heat exchanger with baffles having high thermal performance than shell and heat-pipe heat exchanger without baffles. In order to achieve high effectiveness and better thermal performance, it is better to provide more number of baffles inside the shell to restrict the flow of hot water in the shell side of the heat exchangers which in turn increases the overall performance of heat exchangers.

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