OPTIMIZING MECHANICAL EFFICIENCY OF CONICAL COIL HEAT EXCHANGER USING THERMOELECTRIC GENERATION

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ABSTRACT

Coiled tubes are designed to improve heat transfer performance and minimize pressure drops in compact heat exchangers. Heat loss is most common in heat exchangers and this heat is not often used. Waste heat recovery is an important pathway to more efficient technologies. In the present study, the heat energy that would normally be wasted in a heat exchanger is allowed to run through a thermoelectric generator prior to being introduced in the heat exchanger. This design allows the waste heat energy to be recovered by the thermoelectric generator, and the power generated is measured. A conical coil heat exchanger is built and the test setup is used to conduct experimental analysis at varying temperatures and flow rates. The obtained results are validated by comparing them to experimental results of a previous study. It is observed that with increase in flow rates, heat transfer coefficient increases and maximum effectiveness is obtained at lower flow rates. As the difference in fluid temperature increases, the thermoelectric generator produces more power.

KEY WORDS: Heat Exchanger, Conical Coil, Shell and Tube, Thermoelectric Generator

1. INTRODUCTION

The push for energy efficiency is growing due to climate change initiatives and worries about increasing utility cost. Global investment in energy efficient technologies grew 6% in 2015¹ and it has critical influence in academic research. One target of energy efficient technologies is to turn energy that would traditionally be wasted into useful work. There are several studies that influence the use thermoelectric generation technologies to turn waste heat into electric energy.

Heat exchangers are used in many applications across various industries including chemical, energy generation, and automotive. Shell and tube heat exchangers allow one fluid to flow through a tube while another fluid flows around the tube, transferring energy across the boundary of the tube. Research evidence shows that coiled heat exchangers are much more advantageous to straight tube heat exchanger. This is generally due to the phenomenon known as secondary flows created by centrifugal force of the fluid flow. Recent studies have been performed to evaluate the performances of helical and spiral tube heat exchangers, but few have been performed to evaluate conical tube heat exchangers. The conical shape seems to be advantageous because it has stronger secondary flows than a spiral tube heat exchanger, and less pressure drop than a helical tube heat exchanger. These secondary's allow the fluid to mix more evenly, so that the fluids retain a higher temperature gradient and therefore have a higher rate of heat transfer. The conical shape is advantageous because it requires less power input due to a lower friction factor than a vertical helix design, yet when the curvature becomes more severe at the top, the increase in secondary's promotes more effective heat transfer than a spiral coil design². This equates to a heat exchanger that has a heat transfer coefficient close to a similar sized helical tube heat exchanger, but with less power input necessary.

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Thermoelectric generators (TEGs) are another device that have been the subject of recent studies. TEGs use an energy gradient from temperature difference to generate an electrical current. TEGs have been studied recently as a way to use the technology to harness electricity from what would generally be waste heat. This technique of energy generation from waste heat can be implemented in many applications that uses fluids with a temperature gradient. This technology could be of use in industries similar to heat exchangers that have high temperature gradients.

2. LITERATURE REVIEW

Li et. Al\textsuperscript{[2]} explored the thermal performance of heat exchangers for thermoelectric generation applications. In their work they used a 3D turbulent flow model to show the effectiveness of two different heat exchanger types as they were used to keep a temperature gradient for the thermoelectric generator. Their research showed that both fin heat exchangers and tube heat exchangers outperformed the existing correlations, with fin heat exchangers showing a greater thermal performance than the tube heat exchanger, due to its compactness.

Purandare, Lele, and Gupta\textsuperscript{[3]} studied how heat transfer coefficient varied with a change in the cone angle of a coiled tube for a shell and tube heat exchanger. Their findings for each cone angle illustrated an increase in the Nusselt number and the friction factor with an increase in the tube side flow rate. In contrary, the parameters decreased with an increase in the shell-side tube flow rate. The experiment also showed that the effectiveness of the heat exchanger decreased with increased cone angle, which implies that as the tube coil transitioned from vertical helix to spiral, the effectiveness dropped. It is important to distinguish that effectiveness refers only to the heat transfer capability of the system, and not the efficiency.

Naphon and Wongwises\textsuperscript{[4]} studied the heat transfer of a compact spiral heat exchanger. They found that in the spiral heat exchanger, an increase in shell side flow rate would result in a decrease in temperature change for the shell side flow. They also found that as the shell side flow rate increased, the enthalpy effectiveness decreased, and the tube surface temperature increased.

Andhare and Kriplani\textsuperscript{[5]} studied the heat transfer coefficients of helical shell and tube heat exchangers with varying pitches. They used flow rates, temperatures, and pressures of the fluids to determine the overall heat transfer coefficient of the systems. They found that the lower the pitch angle resulted in an increase in the overall heat transfer, maximizing at a helical shape, and minimizing at a spiral shape.

Shinde and Dange\textsuperscript{[6]} studied a conical tube shell and tube heat exchanger and related the overall heat transfer coefficient to the flow rates ranging between 60-280 lph. They found that the heat transfer coefficient increased as the flow rate increased, and the effectiveness decreased as the flow rates increased. They compared the results of the conical tube shell and tube heat exchanger with a helical tube shell and tube heat exchanger and found that the conical tube was shown to possess higher effectiveness and lower overall heat transfer coefficient than the helical tube.

Saikhedkar and Dewangan\textsuperscript{[7]} used a TEG to generate power from the exhaust gases of an internal combustion engine. The power generated from the TEG is used to increase the efficiency of the engine with respect to power output and power input. The experiment showed that a TEG could potentially be used to turn waste heat into useful energy, not only for combustion engines, but for a multitude of other applications as well.

Liu, Chen, and Li\textsuperscript{[8]} developed a TEG for the purposes of harvesting low temperature geothermal resources. The experiment showed that at a small temperature difference, the TEG was able to generate over 160W of power. They also showed a TEG efficiency of 4.5% at low temperature differences. Their analysis showed that taking the capacity factor into account, the cost per kilowatt of energy produced was actually lowest for the thermoelectric power generation as compared to wind and photovoltaic power generation.
3. METHODS

In this experiment, hot water was allowed to flow through the inside of a conically coiled tube, and cold water was allowed to flow through an outer shell made of cold galvanized 1020 Steel. The heat exchanger in this experiment was built using common materials. The copper tubing was coiled into a conical shape and attached to two through-wall brass fittings. The dimensions of the coiled tube are shown in Table 1. The shell was made from 1/8” thick 1020 Steel and welded in three parts, the flat bottom, the rolled cylinder, and the upper flange. The service lid was then sealed with waterproof caulk and bolted to the flange. The external portion of the shell is insulated to prevent heat loss to the surroundings. The solid model of the assembly is shown in Figure 2 and the experimental set-up is shown in Figure 1.

Table 1. Coil Dimensions

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (in)</th>
<th>Max Radius (in)</th>
<th>Min Radius (in)</th>
<th>Height (in)</th>
<th>Number of Coils</th>
<th>Helix Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type L Copper</td>
<td>300</td>
<td>8.5</td>
<td>2</td>
<td>14</td>
<td>12</td>
<td>65.1</td>
</tr>
</tbody>
</table>
The working fluid of this experiment is water. The design of the experiment is shown in Figure 3.

**Fig 3 Experimental Set-up and Flow Diagram**

**4. EXPERIMENTAL ANALYSIS**

For this experiment, the flow rate and inlet temperatures were controlled, and the overall heat transfer coefficient was measured. The conductive heat transfer through the coil wall and the heat loss to the environment were considered to be negligible. The experiment was conducted at inlet temperatures of 55, 60, 65, 70, 75, and 80°C. The flow rates were varied at 2 lpm, 4 lpm, 6 lpm (Re ≥ 5000) for the tube side fluid, and 2 lpm and 3 lpm for the shell side fluid, due to pressure limitations of the fittings.

The experiment was analyzed using the Log Mean Temperature Difference method (LMTD) and the equation is indicated below. In equation 1, the difference in temperature is evaluated according to the type of heat exchanger where $T_{h,in}$ and $T_{h,out}$ are the inlet and outlet temperature of hot water. $T_{c,in}$ and $T_{c,out}$ are the inlet and outlet temperatures of the cold water. The type of heat exchanger used in the present study is a parallel flow shell and tube heat exchanger.

$$LMTD = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,out})}{\ln \left(\frac{T_{h,in} - T_{c,in}}{T_{h,out} - T_{c,out}}\right)}$$

Then the heat transfer of the water was analyzed using equation 2, where $(\dot{Q})$ represents the heat transfer rate, $(\dot{m})$ is the mass flow rate of shell side water, $(c_{p,water})$ is the specific heat of water at 20°C, $(T_{in})$ is the inlet temperature of the shell side, and $(T_{out})$ is the outlet temperature of the shell side. This method was repeated for both shell and tube side of the heat exchanger.

$$\dot{Q} = \dot{m}c_{p,water}(T_{out} - T_{in})$$  (2)
The heat transfer rate was averaged between the two to find the overall heat transfer of the heat exchanger. This value was used to determine the overall heat transfer coefficient by equation 3, where \( U_{\text{exp}} \) is the experimental overall heat transfer coefficient, \( Q_{\text{avg}} \) is the average heat transfer rate, \( A_s \) is surface area, and \( \text{LMTD} \) is the LMTD of the system.

\[
U_{\text{exp}} = \frac{Q_{\text{avg}}}{A_s \times \text{LMTD}}
\]

Effectiveness of the heat exchanger (\( \varepsilon \)) analyzes the performance of the heat exchanger by comparing the experimental rate of heat transfer (\( \dot{Q}_{\text{actual}} \)) of the heat exchanger with the maximum possible rate of heat transfer of the heat exchanger (\( \dot{Q}_{\text{max}} \)). The maximum heat transfer is shown in equation 4. Equation 5 represents the effectiveness as the ratio of the actual heat transfer to the maximum heat transfer of the system.

\[
\dot{Q}_{\text{max}} = \dot{m}c_p,\text{min}(T_{\text{out}} - T_{\text{in}})_{\text{max}}
\]

\[
\varepsilon = \frac{\dot{Q}_{\text{actual}}}{\dot{Q}_{\text{max}}}
\]

Power generated from the thermoelectric generator was determined using the internal resistance of the generator and the electric potential measured across the generator at different temperatures. Equation 6 indicates the correlation of power with voltage and resistance

\[
P = \frac{V^2}{R}
\]

5. RESULTS AND ANALYSIS

The results of this experiment showed that the heat exchanger corroborates an increase in the rate of heat transfer. The system showed that as the inlet temperature increased the overall heat transfer coefficient increased. In addition, an increase in flow rate of water in the tube side resulted in an increase in overall heat transfer coefficient. The results are in agreement with the fundamental concepts of Nusselt Number. Rise in temperature increases the Nusselt Number, as the diameter and thermal conductivity are constant. This further enhances the convection heat transfer coefficient leading to increase in overall heat transfer coefficient. Figure 4 shows the data with respect to a constant cold flow rate.

Table 2 Experimental data for 55 degree trials

<table>
<thead>
<tr>
<th>Cold Flow Rate (lpm)</th>
<th>Hot Flow Rate (lpm)</th>
<th>Hot Temp In (°C)</th>
<th>Hot Temp Out (°C)</th>
<th>Cold Temp In (°C)</th>
<th>Cold Temp Out (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>55</td>
<td>32.2</td>
<td>25</td>
<td>25.9</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>55</td>
<td>37.8</td>
<td>25</td>
<td>29.1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>55</td>
<td>41.1</td>
<td>25</td>
<td>30.2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>55</td>
<td>35.6</td>
<td>25</td>
<td>29.1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>55</td>
<td>38.4</td>
<td>25</td>
<td>30.4</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>55</td>
<td>40.7</td>
<td>25</td>
<td>31.8</td>
</tr>
</tbody>
</table>

The above data indicates a sample of the raw data collected for 55°C hot inlet temperature. The cold flow rates were kept constant and hot flow rates were varied at 55°C hot water inlet temperatures. Similar data was collected for temperatures ranging between 55°C to 80°C at varying flow rates.
Figure 5 shows the effectiveness of the heat exchanger compared to the flow rate of the tube side fluid with respect to change in tube side inlet temperature. The figure represents a decrease in the effectiveness as the flow rate increases. The system also yielded an increase in effectiveness as the inlet temperature of the hot fluid was increased. These results are in good agreement with the fundamental concepts of heat transfer, where increase in flow rate decreases the heat transfer. Similar results were extrapolated for overall heat transfer coefficient and effectiveness for 3lpm and 4lpm flow rates at the cold-water inlet.
The TEG generated an increase in power as the temperature difference increased between the shell and tube side. Figure 6 displays the power generated from the TEG with change in temperature gradient. A prior research on TEG suggested that waste heat could be converted to useful energy for different applications apart from combustion engines [7]. This study substantiates the need for increase in use of TEG in industrial heat exchangers where large temperature differences are involved.

6. CONCLUSIONS

The conical coil heat exchanger has started to gather attention in research due to its superior efficiency compared to spiral coil shell and tube heat exchanger. The conical coil shell and tube heat exchanger in this experiment showed that with an increase in fluid flow rate, the overall heat transfer coefficient of the heat exchanger also increased. The effectiveness of the heat exchanger was maximum at the lowest flow for each fluid, and minimum at the highest flow, showing a trend of decrease in the results as flow increases. In addition, the Thermoelectric Generator in the system is used to generate power from the waste heat of the system. It showed an increase in power generation as the temperature gradient increased, showing that a thermoelectric generator has a viable application in a heat exchanger scenario in order to recoup some of the waste heat from the temperature gradient. This could lead to more energy efficient heat exchanger operations, on a much larger scale. These results obtained from the study are very close to the results from a previous study on conical coil heat exchangers conducted by Shinde[6]. The results from that study showed that the overall heat transfer coefficient decreased with increase in flow rates. Although, they have used more number of coils in the tube side and lower flow rates in liters per hour. The current work expands on these findings for increasing flow rates in liters per minute and decrease in number of coils. Further, the current study provides the effectiveness and illustrates that the thermoelectric generator could be used to create useful power out of what would otherwise be waste energy.
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REFERENCES


