Incorporating Aluminum Honeycomb to Increase Efficiency of U-tube Removable Heat Exchanger

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This report contains the results of attempting to improve on the results of Scott R. Sawyer and Alan M. L’Esperance research paper “Investigation of Paraffin Wax as an Energy Storage Medium Within a Shell-and-Tube Heat Exchanger.” The overall goal of the paper mentioned was to investigate the usefulness of wax as an energy storage medium. Scott R. Sawyer and Alan M. L’Esperance determined that “the amount of energy that can be released by the paraffin wax back to the airflow reaches a plateau, despite an increase in heating times.” They suggested that by surrounding the airflow tubes of a heat exchanger with metal foam that heat conduction would occur throughout the wax via the metal foam and increase the energy output from the wax. Unfortunately there was not enough money in the budget to implement metal foam to the heat exchanger and instead an aluminum honeycomb sheet was used. A difference to point out from Scott R. Sawyer and Alan M. L’Esperance experiment is this experiment uses a removable heat exchanger instead of a fixed tube heat exchanger and aluminum honeycomb was wrapped around the inflow tubes.

The heat exchanger was filled with three pounds of paraffin wax. A heater heated the inflow air temperature that passed through the heat exchanger, which could be turned on or off. Thermocouples were used to measure the inflow air temperature and the outflow air temperature. A flow meter was used to measure and a valve controlled the volumetric flow rate. The experiment consisted of two tests. The first test consisted of heating the airflow into the heat exchanger for three hours and a heater off phase that lasted three hours. The second experiment was the same except that aluminum honeycomb was used to surround the inflow tubes. The findings of the experiment were similar to Scott and Alan’s, despite surrounding the inflow tubes with aluminum honeycomb there was no increase in efficiency. For both runs the amount of energy extracted from the hot wax to the cold air was only 34%. A likely reason for this is the presence of solid and liquid wax within the heat exchanger. Originally it was believed that the deposits of wax in the honeycomb would increase heat conduction, but the wax deposits in the honeycomb closest to the cold airflow tubes solidified and thus did not allow energy transfer from the hot wax to cold air because the wax deposits closest to the tube acted as an insulator.

Nomenclature

\begin{align*}
E &= \text{efficiency}, \frac{Q_{\text{wax}}}{Q_{\text{heater}}} \\
H &= \text{enthalpy, kJ} \\
\dot{Q} &= \text{heat flow rate, kJ/min} \\
T &= \text{temperature, } ^\circ\text{C, } ^\circ\text{F} \\
V &= \text{volumetric flow rate, liters/min} \\
\dot{h}_H &= \text{specific enthalpy of hot tube airflow, kJ/kg} \\
\dot{h}_H &= \text{specific enthalpy of cold tube flow, kJ/kg} \\
\dot{m} &= \text{mass flow rate, kg/min} \\
t &= \text{time, minutes} \\
\rho &= \text{density, kg/m}^3
\end{align*}

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I. Introduction

There are wide ranges of industries that use phase change material for thermal management. It can be found in everything from aeronautics to building applications. A phase change material is a substance that can absorb a large amount of heat energy while melting from solid to liquid and once the material solidifies it then releases the energy. One industry where it is beginning to be used heavily is in electric vehicles. Thermal management of Li-ion batteries is critical for high power applications. Electric vehicles that use lithium batteries are susceptible to thermal runaway, which is an uncontrollable release of energy that causes a chain reaction in which the temperature increases causing further increases in temperature. Typically for high-energy dense battery packs, cooling systems are used, but recently phase change material has been implemented. During thermal runaway the problem occurs when a single cell explodes and then it spreads to neighboring cells and spreads quickly through the entire pack. A thermal management system can quickly move away heat from the problematic cell and absorb it to prevent a chain reaction. A system such as this is great because systems that use fans or pumps add cost, weight, and space. A thermal management system that uses paraffin wax would only occupy the space between cells. As can be seen in Figure 1 below the temperature remains constant over time when the wax is melted this is because by melting a material the user is able to gain a large increase in energy storage with a very small rise in temperature. A much larger amount of energy can be stored when the paraffin wax goes through a phase change as can be seen in Figure 2. Paraffin wax is used in many applications because of its high melting point of 60°C which positions it perfectly in the temperature range of many thermal management applications.

In order to determine the total energy absorbed or released by the wax, thermodynamic and flow properties across the heat exchanger can be used. The equations discussed below can be used to calculate the energy from the hot airflow to the wax (heater on phase) as well as the energy released by the hot wax to the cold airflow (heater off phase). The total energy absorbed or released by the wax can be calculated with

\[ \dot{Q} = \dot{m} (h_H - h_c) \]  

(1)

Subscripts

\[
\begin{align*}
C & = \text{cold} \\
H & = \text{hot}
\end{align*}
\]
where $h_H$ and $h_c$ are the specific enthalpy of the inlet and outlet respectively during the heater on phase and $\dot{m}$ is the mass flow rate of the airflow which is found using Eq. 2, where $\rho$ is the airflow density. The density $\rho$ of the airflow was calculated by using a standard conditions MATLAB code whose inputs were temperature, humidity, and pressure, and $V$ was the measured volumetric flow rate recorded with the Omega Flow Meter shown in Figure 6.

\[
\dot{m} = V \rho
\]  

(2)

For the heater off phase the equation is reversed $h_H$ and $h_c$ now become the specific enthalpy at the outlet and inlet respectively. If Eq. 1 is now integrated over the total time $T$ the total energy transferred during the heater on or heather off phase is found with

\[
Q = \int_0^T \dot{m}(h_H - h_c)dt
\]

(3)

In order to determine the efficiency of the heat exchanger Eq. 4 was used. $Q_{wax}$ is the amount of energy transferred from hot wax to the cool air during the heater off phase and $Q_{Heating}$ is the amount of energy that was stored in the wax during the heating on phase. The ratio of these energies was taken to get the efficiency in terms of a percentage.

\[
E = \frac{Q_{wax}}{Q_{Heating}}
\]

(4)

II. Experimental Apparatus

Three pounds of wax filled the shell of the heat exchanger and air passed through the U-tube in the heat exchanger as shown in Figure 3. A schematic of the experiment set up is shown in FIGURE 4.

**Figure 3. Removable Heat Exchanger:** This particular type of heat exchanger uses U-tubes for the in and out flow of air. The wax used in the experiment was poured in through a plug on the top of the heat exchanger.

**Figure 4. Schematic of Experiment:** All the components used to run and acquire data for each of the experiments are labeled.
A Norgren Excelon pressure regulator (model R74G-4AK-RMG) shown in Figure 5 was used to insure the system received a steady pressure. The pressure regular has \( \frac{1}{2} \) inch PTF threaded inlet and outlet ports as well as two outlet pressure measurement ports. It has an outlet pressure range of 5 to 150 psig and can utilize up to a 300 psig supply pressure. From previous experiments it was noted that the delivery pressure could fluctuate by as much as 14 psig however with the pressure regulator it damped out most of the fluctuations in pressure. The actual pressure was not recorded because it was unimportant as long as the delivery pressure was large enough to overcome system pressure losses. A valve located downstream of the pressure regulator was placed as can be seen from the figure above. The purpose of the valve was to create a variable pressure drop sink, hot flow eventually exhausts to ambient and as the pressure downstream of the gate valve decreases so will the flow rate. This valve insures that the flow rate recorded with the Omega FMA 1700 flow meter shown in Figure 6 is the desired volumetric flow rate. The flow meter is capable of measuring flow rates up to 1000 liters per minute ±2.5%. The flow meter standardizes the flow rate to 14.7 psia and 70°F which results in a final output of standard liters per minute.

![Pressure Regulator](image1.png)

**Figure 5. Pressure Regulator:** Used to ensure that the system received a constant stream of pressure.

![Flow Meter](image2.png)

**Figure 6. Flow Meter:** Used to visually adjust to the desired volumetric flow rate for each experiment.

To heat the airflow before entering the heat exchanger an Omega AHF-10120 air heater was used. This heater is capable to heat up to 5,700 liter per minute and can heat up to 316°C. The reason why such a capable heater was used was to retain a small flow velocity and minimize pressure losses caused by the heater. The heater is shown in Figure 7.
Two Omega thermocouples (SAI-K) were used to measure the inlet and outlet temperatures of the heat exchanger. A copper pipe was connected in line with the heated inflow air to the heat exchanger and a second copper pipe was placed at the outlet of the heat exchanger to draw the airflow away from the lab setup. Small holes were drilled in the copper pipes to allow the thermocouple leads to measure temperature, which were placed in the middle of the pipe. One thermocouple lead was placed about 1 inch before the entrance to heat exchanger and the other lead was placed about 1 inch after the outflow side of the heat exchanger. Each thermocouple was then attached to an Omega temperature converter (SMCJ-K), which has a significant reading of 1°F. Below is a picture of the thermocouple and converter.

To ensure as much a closed system as possible and prevent any amount of heat from leaking out to the surrounding environment the heat exchanger was covered with insulation as shown in Figure 9. As can be seen in the image below the heat exchanger was equipped with a pressure gage rated for pressures up to 160 psi. This pressure gage was mounted for safety reasons to ensure that during the experiment the pressure in the heat exchanger did not reach its maximum rated value.
Figure 9. Heater Exchanger: The heat exchanger was covered in insulation to prevent any leaks of hot air to the environment.

To test the effectiveness of adding honeycomb sheets to the heat exchanger, a removable heat exchanger was used because it allowed easy access to the U-tube as can be seen in Figure 10. The honeycomb metal sheets used in the experiment can be seen in Figure 11. Initially the honeycomb sheet was going to be wrapped around the U-tube, but this would create a heat transfer between the cold and hot flow, which was undesired in the experiment. The inflow tubes were located on the bottom of the heat exchanger as can be seen in Figure 3. Initially it was planned to wrap the bottom half of the U-tube with a honeycomb sheet, but there was not enough space to house both the honeycomb and U-tubes inside the shell of the heat exchanger. So to make the tubes and honeycombs fit inside the shell the honeycomb sheet was placed in-between the spacing of the inflow tubes as can be seen in Figure 12.

Figure 10. Removable Heat Exchanger: The goal of this experiment was to see the effects of insert honeycomb sheets to the heat exchanger and this can only be done with a removable heat exchanger.

Figure 11. Honeycomb Aluminum Sheet: These aluminum sheets were inserted in the spacing between the u tubing that was used for hot flow of air.

Figure 12. U-tubes with honeycomb: From a plug on the top of the heat exchanger when can see honeycombs in-between the tubes.
III. Procedure

Airflow was allowed to run for one hour before the heater on phase to ensure a steady flow rate. It was found that if the airflow was not allowed to run for at least one hour before turning on the heater variations of volumetric flow rates up to 40 liters per minute would be present. Because of this the airflow was allowed to run for an hour before starting the actual experiment to keep flow rate as steady as possible.

Once the flow rate appeared to remain at its constant value of 620 liters per minute the Omega heater was plugged in and was left on for three hours. Data was recorded using Labview code in the laboratory computer, which recorded the inlet temperature, the outlet temperature, and the volumetric flow rate. After the three-hour heater on phase the heater was turned off and the airflow was left running for three hours. If the flow rate dropped significantly the valve was opened to increase the flow rate to the desired value.

Data was taken every three seconds. Every three seconds 1000 data points were collected for the temperature in, temperature out, and the flow rate. An average of the 1000 data points was taken for each of the three measurements. The test data was then exported as a DAT file and was analyzed in MATLAB.

The second experiment had the exact same procedure; the only difference was that now the aluminum honeycomb sheets were surrounding the inlet tubes of the heat exchanger as mentioned in Figure 12.

IV. Results and Discussion

After performing the two different experiments the ideal result was to see an increase in energy given back to the air by the wax, but no real change was seen. Figure 13 and Figure 14 show the temperatures for each of the experiments. When the heater is turned on the inflow air rises in temperature rapidly while the outflow takes more time to rise in temperature. After three hours of heating, the heater was disconnected and the inflow temperature dropped almost instantly and now the wax begins to release its energy making the outflow temperature hotter than the inflow temperature and it remained this way until both temperatures became the same. Each experiment showed this trend as can be seen below. For the second experiment the assumption was that the outflow temperature would remain hotter for a longer period of time. In other words it was predicted that the amount of energy released with the honeycomb would increase, but there is almost no change to the results with the addition of the honeycomb.

![Graph showing Inflow and Outflow Air Temperatures](image)

**Figure 13. Inflow and Outflow Temperatures (Wax Only):** The recorded temperatures can be seen for the first experiment with just the addition of paraffin wax.
Figure 14. Inflow and Outflow Temperatures (Wax and Honeycomb): The recorded temperatures can be seen for the second experiment when the honeycomb was placed inside of the heat exchanger as well as the wax.

The energy absorbed by the wax during the heater on phase and the amount of energy released during the heater off phase are shown in Figure 15 and Figure 16. The plots from each experiment had the same trend. The x-axis in Figure 15 and Figure 16 correspond to the “heater on phase” as well as the “heater off phase.” For example if examining the red curve the x-axis will correspond to the three-hour heating phase and the y-axis would correspond to the amount of energy being absorbed during those three hours. If the blue curve is being examined the x-axis will correspond to the three-hour cooling phase and the y-axis would correspond to the amount of energy being released by the wax to the cold airflow. The energy put into the system (red curve) continues to increase with time, but the energy that is release by the wax (blue curve) reaches a plateau. This means that heating the wax after a certain amount of time will be useless, because at that point the wax will not be able to release any more energy.
Figure 15. Energy Absorbed and Released by Wax: The energy into the system keeps increasing while the energy out of the system plateaus after a certain amount of time.

Figure 16. Energy Absorbed and Released by Wax and Honeycomb: The energy into the system keeps increasing while the energy out of the system plateaus after a certain amount of time.

Table 1 below shows the energy put into the wax during the heating phase, the energy released by the wax during the cooling phase, and the efficiency. The efficiency was calculated by dividing the energy released from the wax by the amount energy put into the system.
Table 1. Energy and Efficiency for Each Experiment: This table shows the energy into the system, energy out of the system and the efficiency.

<table>
<thead>
<tr>
<th></th>
<th>Wax Only</th>
<th>Wax and Honeycomb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Input (kJ)</td>
<td>2038.5</td>
<td>2672.2</td>
</tr>
<tr>
<td>Energy Output (kJ)</td>
<td>724.8</td>
<td>929.4</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>34.8</td>
<td>34.8</td>
</tr>
</tbody>
</table>

There was more energy put into the system and more energy released for the wax and honeycomb run, but the system efficiency stayed the same. The reason why more energy was put into the system was a much better job was done of insulating the heat exchanger for the second run. The same efficiency indicates that the addition of the honeycomb did nothing to help the amount of energy released by the wax during the cooling time of the experiment.

V. Conclusions

In this experiment a U-tube removable heat exchanger was compared to aluminum honeycomb sheets inserted in-between the inlet U-tubes of the heat exchanger in an attempt to increase the efficiency of the energy released from the hot wax to the cold airflow. It turned out that the honeycomb sheets did not increase the efficiency. One reason is that the wax still solidified even with the addition of aluminum honeycomb. Figure 17 shows a top view of the heat exchanger along with what is happening inside the heat exchanger during cooling process. The wax deposits in the honeycomb closest to the cold airflow tubes solidified and thus did not allow energy transfer from the hot wax to cold air because the wax deposits closest to the tube acted as an insulator.

Figure 17. Heat Exchanger Cut Away View: This picture shows the top view of the heat exchanger if the top part was removed showing how the honeycombs were placed in-between the tubes. Also this image points out some of the interactions that may be occurring during the cooling process.

The honeycomb was inserted around the incoming flow in an attempt to increase the energy transfer from the hot wax to the cold air, but because the solid wax has a specific capacity of 2140 J/kgK it takes a lot of energy to melt and the rate at which the wax adjacent to the cold tubes (solid wax) was releasing heat to the cold airflow and the rate at which the solid wax was absorbing energy from the aluminum was not large enough to create a phase change. When a material undergoes a phase change the material is able to gain a large increase in energy storage, but the wax was solid at the tube walls and because of this the amount of energy transferred from the wax to the cold airflow plateau.

VI. References
