MEEG346 Thermal Laboratory

5. Heat Transfer in a Double Pipe Heat Exchanger

Objective

For our double pipe heat exchanger, hot fluid flows in the inner tube and cold fluid in the outer annular gap. Heat is transferred from the hot to the cold fluid. Our objective is to examine this process in detail. Specifically:

- Study heat transfer in a double pipe heat exchanger under conditions of parallel flow and counter flow.
- Determine heat fluxes from inner tube to the outer fluid and estimate heat losses/gains.
- Experimentally determine the value of the overall heat transfer coefficient based on the inner tube surface $U_i$.
- Compare the experimental value of $U_i$ with the empirical value provided by the Dittus-Boelter correlation for forced convection heat transfer in a tube.

Theoretical Considerations

As heat flows from the hot fluid to the cold fluid, it has to overcome three thermal resistances associated with (i) convective heat transfer from the hot fluid to the inner wall of the inner tube ($R_1$), (ii) conduction across the thickness of the inner tube ($R_2$), and (iii) convective heat transfer from the outer wall of the inner tube to the outer fluid ($R_3$).

We can represent the total heat transfer $Q$ as follows:

$$ Q = \frac{T_A - T_B}{R_{\text{total}}} $$

where $T_A$ and $T_B$ are the hot and cold fluid temperatures, and

$$ R_{\text{total}} = R_1(\text{convection}) + R_2(\text{conduction}) + R_3(\text{convection}) $$

Using results derived in class, we can further write:

$$ Q = \frac{T_A - T_B}{\frac{1}{h_i A_i} + \frac{\ln r_i/r_o}{2 \pi k L} + \frac{1}{h_o A_o}} $$

where $A_i = 2\pi r_i L$ and $A_o = 2\pi r_o L$. $k$ is the thermal conductivity of the inner wall material, $L$ is the length of the heat exchanger, and $h_i$ and $h_o$ are the heat transfer coefficients at the inner and outer walls respectively.

An overall heat transfer coefficient $U$ which represents the heat transfer from hot fluid to cold fluid can be defined as

$$ Q = \frac{\Delta T_m}{U_i A_i} = \frac{\Delta T_m}{U_o A_o} $$

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where $U_i$ (based on the inner surface of the tube) and $U_o$ (based on the outer surface of the tube) are

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{A_i}{2\pi k L} \frac{\ln \frac{r_o}{r_i}}{r_i} + \frac{A_i}{A_o} \frac{1}{h_o} + \frac{F_i}{A_o} F_o}$$

and

$$U_o = \frac{1}{\frac{A_o}{A_i} \frac{1}{h_i} + \frac{A_o}{2\pi k L} \frac{\ln \frac{r_o}{r_i}}{r_i} + \frac{1}{h_o} + \frac{A_o}{A_i} F_i + F_o}$$

where $F_i$ and $F_o$ are fouling factors for the inner and outer tubes. Fouling factors account for accumulations of deposits (mineral or biological) on heat transfer surfaces which increase the overall thermal resistance. $\Delta T_m$ above is the logarithmic mean temperature differential (LMTD) given by:

$$\Delta T_m = \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln[(T_{h2} - T_{c2})/(T_{h1} - T_{c1})]}$$

Figure 1: Schematic of parallel and counter flow heat exchangers

The LMTD defined above is equally applicable to parallel flow and counter flow heat exchangers (Figure 1). Finally, energy balance yields:

$$Q = U A \Delta T_m = \dot{m}_h C_p h (T_{h1} - T_{h2}) = \dot{m}_c C_p c (T_{c2} - T_{c1})$$

Procedure

The experimental set-up consists of two double-pipe heat exchangers in series as shown in Figure 2. The inlet, mid-point, and outlet temperatures of the hot and cold fluids can be measured with thermocouples. To minimize energy losses and radiation effects, the hot fluid should always be directed through the inner tube. Study Figure 2 carefully to understand the possible flow configurations.
Figure 2: Schematic of double-pipe heat exchanger

The flow rate is regulated with gate valves located at the exits of each line (valves 13 and 14). All other valves should be fully closed or fully open according to the chart provided alongside the experimental set-up.

- **Parallel Flow**

  1. Adjust the flow rate of cold water $Q_c = 1.0$ cfm and then direct this flow out of the flow meter.

  2. Adjust the flow rate of hot water to $Q_h = 1.0$ cfm and then direct this flow through the inner tube.

  3. Allow sufficient time for steady state conditions to be reached and record temperatures $T_1 \cdots T_6$.

  4. Repeat steps 2 and 3, but use $Q_c = 1.0$ cfm and $Q_h = 0.8$ cfm.

- **Counter Flow**

  Repeat steps 1 – 4 for the counter flow arrangement. For the first run, use $Q_c = 0.8$ cfm, and $Q_h = 1.0$ cfm; for the second run, use $Q_c = Q_h = 0.8$ cfm.

**Heat-Exchanger Specifications**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tube: $D_i$</td>
<td>1.27 cm</td>
</tr>
<tr>
<td>Outer Tube: $D_i$</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Length</td>
<td>99.6 cm</td>
</tr>
<tr>
<td>Tube material</td>
<td>Copper</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Tube: $D_o$</td>
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<tr>
<td>Outer Tube: $D_o$</td>
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<td>Length</td>
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<tr>
<td>Tube material</td>
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</tr>
</tbody>
</table>
Analysis

1. Plot the temperatures of both fluids as a function of length of the heat exchanger (from inlet of heat exchanger 1 to outlet of heat exchanger 2). Take the inlet of exchanger 1 to be the reference and the outlet of exchanger 1/inlet of exchanger 2 to be length $L$. Take the outlet of exchanger 2 to be length $2L$.

2. Using energy balance, determine the heat flux from the from the inner tube to the outer tube (summing the heat transfer from both heat exchangers). The difference between the heat lost by the hot fluid and the heat gained by the cold fluid is the heat lost to/gained from the surroundings. Discuss your result.

3. Calculate the four experimental values (two each for parallel flow and counter flow) for $U_i$ based on the inner surface area $A_i$ of the heat exchanger. Note that in calculating $\Delta T_m$ for counter flow, subscripts 1 and 2 refer to the reference planes as shown in Figure 1(b).

4. Calculate the heat transfer coefficients at the inner $h_i$ and outer $h_o$ surfaces of the inner tube using the empirical Dittus-Boelter correlation for turbulent forced convection in a tube.

$$Nu_{D_H} = 0.023 \, Re_{D_H}^{0.8} \, Pr^n$$

Here, Reynolds number is defined as $\rho V D_H / \mu$. The hydraulic diameter $D_H$ is the $4A_c / P$, where $A_c$ is the cross-sectional area available for the flow and $P$ is the perimeter. For the inner tube, $D_H = D$ (show this), but for the outer tube, the cross-sectional area is an annulus, and the perimeter is the sum of the outer perimeter of the inner tube and inner perimeter of the outer tube. In order to determine fluid properties use the bulk fluid temperature (i.e. the arithmetic mean of temperatures at Planes 1 and 2). $n = 0.3$ for cooling and 0.4 for heating.

From the Nusselt numbers, determine the respective heat transfer coefficients ($Nu_{D_H} = hD_H / k_f$).

Use $h$ to determine $U_i$ for each of the four cases. Fouling factors can be found in your textbook. For our case, use $F_i = F_o = 0.0002$ Km$^2$/W. Also, determine $U_i$ neglecting the fouling factors. Which one better matches your experimental value for $U_i$?

Error Analysis

1. What is the error in the heat ($Q$) gained (lost) by the cold (hot) fluid? Contributing sources are the error in flow rate, and the uncertainty in the entry and endpoint temperatures. (You will have noticed that the hot fluid temperature tends to fluctuate a bit.)

2. Determine the error in $\Delta T_m$.

3. Use the above two values to determine the error in the experimental value of $U_i$. 

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