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Heat Exchanger Analysis

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Overview

Source: Alexander S Rattner and Christopher J Greer; Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA

Heat exchangers transfer thermal energy between two fluid streams, and are ubiquitous in energy systems. Common applications include car radiators (heat transfer from hot engine coolant to surrounding air), refrigerator evaporators (air inside refrigerator compartment to evaporating refrigerant), and cooling towers in power plants (condensing steam to evaporating water and ambient air). The objective of this experiment is to introduce experimental measurement (*rating*) and modeling procedures for heat exchangers.

In this experiment, a water-to-water tube-in-tube heat exchanger will be constructed, and evaluated. Temperature and flow rate measurements will be employed to determine the heat transfer rate (*Q*) and overall conductance (UA). The measured heat exchanger UA will be compared with predicted values for the geometry and operating conditions.

Principles

In a heat exchanger (HX), thermal energy is transferred from a hot (*H*) fluid stream to a cold (*C*) fluid stream. Each stream may have a different mass flow rate ($\dot{m}_H,\ \dot{m}_C$) and specific heat ($c_{p,H},\ c_{p,C}$). As the streams pass through a HX, the temperature of the hot flow decreases, and the temperature of the cold stream increases. During steady operation, if heat leakage to the surroundings is negligible, then the energy changes of the two streams from inlets to outlets must balance. This energy change is the heat exchanger heat transfer rate *Q*.

$$Q = \dot{m}_H c_{p,H}\left(T_{H,\text{in}} - T_{H,\text{out}}\right) = \dot{m}_C c_{p,C}\left(T_{C,\text{out}} - T_{C,\text{in}}\right) \quad (1)$$

In this experiment, heat transfer performance is analyzed for a counter-flow tube-in-tube heat exchanger. Here hot fluid flows in one direction through an inner tube. Cold fluid flows in the opposite direction through the annular space between the inner tube and an outer tube. The average temperature difference that drives heat transfer between the two streams is the log-mean temperature difference (LMTD, Fig. 1), defined in Eqn. 2 for the counter-flow HX configuration. If the temperature differences at both ends of the heat exchanger match within measurement precision ($\left(T_{H,\text{in}} - T_{C,\text{out}}\right) = \left(T_{H,\text{out}} - T_{C,\text{in}}\right)$), a simpler LMTD formula should be used.

$$\text{LMTD} = \begin{cases} \dfrac{\left(T_{H,\text{in}}-T_{C,\text{out}}\right)-\left(T_{H,\text{out}}-T_{C,\text{in}}\right)}{\ln\left(\frac{T_{H,\text{in}}-T_{C,\text{out}}}{T_{H,\text{out}}-T_{C,\text{in}}}\right)} & \left(T_{H,\text{in}} - T_{C,\text{out}}\right) \neq \left(T_{H,\text{out}} - T_{C,\text{in}}\right) \\ \dfrac{\left(T_{H,\text{in}}-T_{C,\text{out}}\right)+\left(T_{H,\text{out}}-T_{C,\text{in}}\right)}{2} & \left(T_{H,\text{in}} - T_{C,\text{out}}\right) = \left(T_{H,\text{out}} - T_{C,\text{in}}\right) \end{cases} \quad (2)$$

The heat transfer capacity of a heat exchanger is measured in terms of the overall conductance (UA). This quantity has units of W K^{-1} (heat transfer rate per temperature difference). The UA can be evaluated from measured heat transfer rates and fluid temperatures:

$$\text{UA} = Q/\text{LMTD} \quad (3)$$

The tube-in-tube HX geometry is defined by the length of the tubes (*L*), the inner tube inner and outer diameters (ID_i, OD_i), and outer tube diameters (ID_o, OD_o). Using these parameters and material properties, the heat exchanger UA can be predicted by accounting for the thermal resistances between the two streams. For fully developed laminar flow in the inner tube, the thermal resistance from the inner stream to the inner tube inner wall is: $R_{\text{conv,i}} = (4.36 k\pi L)^{-1}$ where *k* is the fluid thermal conductivity (0.61 W m^{-1} K^{-1} for water). The thermal resistance for conduction through the inner tube wall, is: $R_{\text{cond}} = \ln(\text{OD}_i/\text{ID}_o)/(2\pi L k_{\text{tube}})$ (k_{tube} = 160 W m^{-1} K^{-1} for aluminum). Finally, for fully developed laminar flow in a narrow annulus, the convection resistance from the outside of the inner tube to the outer stream is: $R_{\text{conv,o}} = (\text{ID}_o - \text{OD}_i)/(5.48 k\pi \text{OD}_i L)$. Under these conditions, the predicted HX UA is:

$$\text{UA} = \left(R_{\text{conv,i}} + R_{\text{cond}} + R_{\text{conv,o}}\right)^{-1} = \left(\frac{1}{4.36 k\pi L} + \frac{\ln(\text{OD}_i/\text{ID}_o)}{2\pi L\, k_{\text{tube}}} + \frac{\text{ID}_o - \text{OD}_i}{5.48 k\pi \text{OD}_i L}\right)^{-1} \quad (4)$$

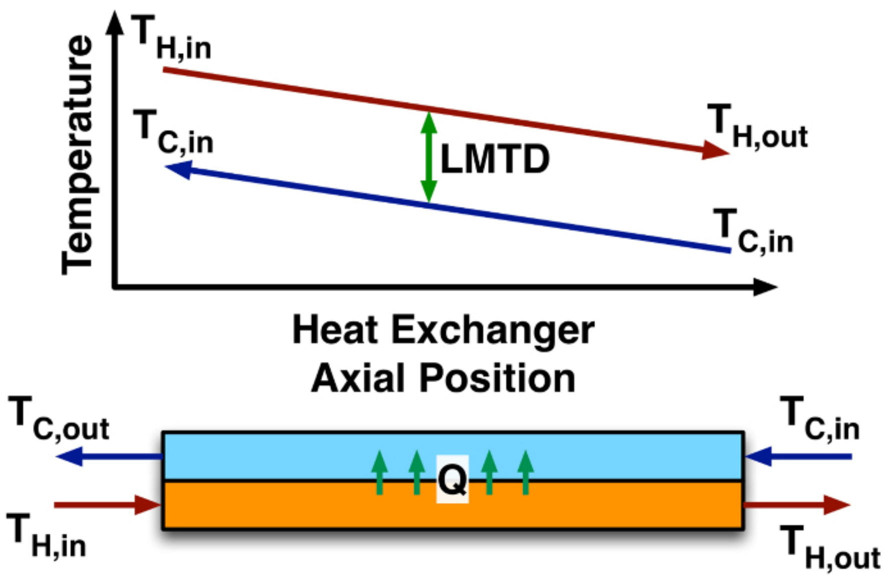

Figure 1: Cold and hot stream temperature profiles and log-mean temperature difference in a counter-flow heat exchanger.

Procedure

1. Fabrication of heat exchanger system (see schematic and photograph, Fig. 2)

1. Affix two plastic water reservoirs (~1 liter each) to a work surface (~0.6 m apart). If these are covered containers, drill holes in the lid for the inlet and outlet water lines and pump power cable. These will serve as the hot and cold water reservoirs.
2. Mount one small submersible pump in each reservoir.
3. Vertically mount two water flow meters (rotameters), one near each reservoir. Use soft PVC tubing to connect the flow meter inlets to the pump discharge ports.
4. Install the heat exchanger (HX) outer tube (~0.3 m long, outer diameter OD = 12.7 mm, inner diameter ID = 9.5 mm) into two compression pipe tee fittings (see Fig. 2). Connect a flexible PVC tube (OD = 12.7 mm, ID = 6.2 mm) from the side port on one tee fitting to the hot flow meter outlet.
5. Cut an aluminium tube (OD = 7.9 mm, ID = 6.2 mm) to the length of the heat exchanger, including the tee fittings on the end (~0.38 m long), and insert it into the heat exchanger assembly. The aluminium tube should slide snugly into the soft connecting PVC tube (OD = 12.7 mm, ID = 6.2 mm) at the end of the compression fitting.
6. Connect a soft PVC tube from the compression fitting at the other end of the HX assembly to the hot water reservoir. Tighten the compression fittings to seal the soft plastic tubing around the aluminium tube. This will separate the hot flow through the inner aluminium tube from the outer cold flow.
7. Connect a flexible PVC tube from the side port on one tee fitting to the cold flow meter outlet. Connect a PVC tube from the side port on the other tee fitting to the cold water reservoir (return flow). The hot and cold stream inlets to the HX should be on opposite ends.
8. Drill small holes (~1.6 mm diameter) through one side of the soft plastic tubes near each heat exchanger inlet and outlet port (4 total). Gently insert a thermocouple probe into each port so that the probe tip is approximately in the center of the tube. Connect the thermocouple probes to a thermocouple reader
9. Using epoxy or similar adhesive to seal the small gap in the tubes around the thermocouple probes so that no water leaks out.

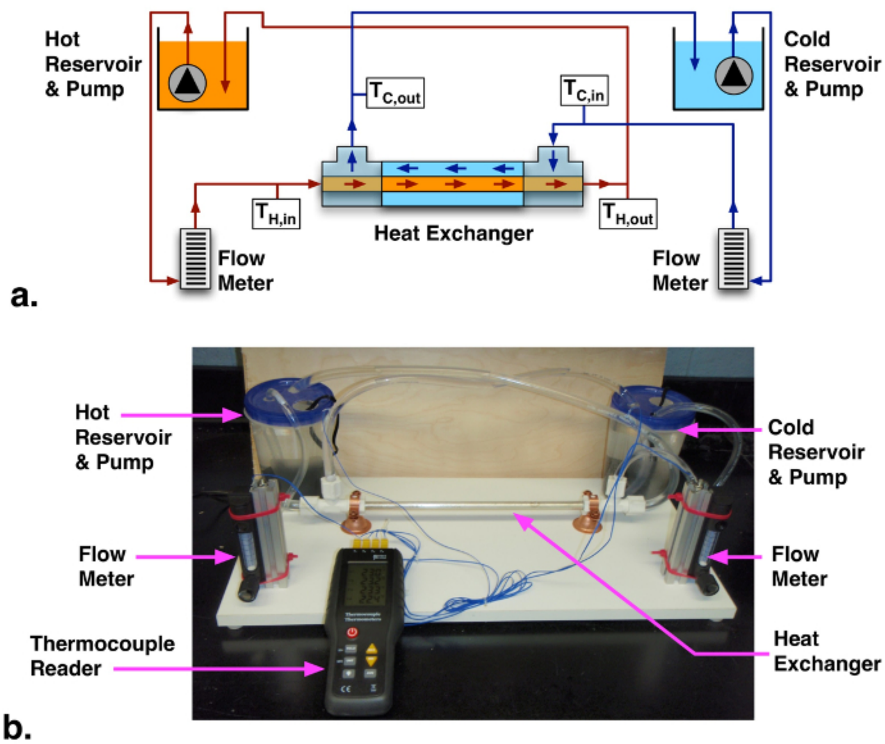

Figure 2: (a) Schematic and (b) labelled photograph of heat exchanger rating experimental system

2. Operation

1. Fill the cold reservoir with room temperature tap water, and the hot reservoir with warm water.
2. Turn on the two water pumps, and use the flow meter needle valves to adjust the flow rates to desired values (*e.g.*, 0.1 l min^{-1}). It may be necessary to circulate water at a higher flow rate initially to clear out trapped air bubbles.
3. Allow the system to stabilize for a couple minutes, and then record the four thermocouple measurements representing the inlet and outlet temperatures. Record a few sets of readings for each flow condition. If available, the *hold* function on the thermocouple reader can freeze readings to help recording.
4. Collect temperature measurements at a few sets of hot and cold water flow rates. Periodically refill the reservoirs with fresh hot and cold water to maintain sufficient average temperature differences (~5 - 10°C).

3. Analysis

1. For each condition, compare the hot- and cold-stream energy change rates ($\dot{m}_H c_{p,H}(T_{H,\text{in}} - T_{H,\text{out}})$, $\dot{m}_C c_{p,C}(T_{C,\text{out}} - T_{C,\text{in}})$). For water, c_p = 4.2 kJ kg^{-1} K^{-1}. and the volume flow rate can be multiplied by density (ρ_{water} = 997 kg m^{-3}) to find the mass flow rate. Do the energy change rates (Q) match, as assumed in Eqn. 1?
2. Evaluate the LMTD for each condition following Eqn. 2 using *Q* from Step 3.1. Evaluate the heat exchanger UA (defined in Eqn. 3). Is this quantity approximately constant for considered conditions?
3. Evaluate the theoretical UA for fully developed laminar flow in this HX (Eqn. 4) using the mean heat transfer rate ($(Q_C+Q_H)/2$). How does this theoretical value compare to the measured value?

Results

Table 1 - Measurements and derived LMTD and UA values for heat exchanger at hot and cold flow rates of 0.20 and 0.15 l min^{-1}.

Hot and cold flow rates (l min^{-1})	$T_{H,in}$ (°C, ±0.25°C)	$T_{C,out}$ (°C, ±0.25°C)	$T_{H,out}$ (°C, ±0.25°C)	$T_{C,in}$ (°C, ±0.25°C)	Q_C (W)	Q_H (W)	LMTD (°C, ±0.25°C)	UA (W K^{-1})
0.126 ± 0.006	31.2	25.7	28.7	23.1	22.8 ± 3.3	21.9 ± 3.3	5.55	4.0 ± 0.5
0.126 ± 0.006	31.2	25.8	28.7	23.1	23.7 ± 3.3	21.9 ± 3.3	5.50	4.1 ± 0.5
0.126 ± 0.006	31.1	25.9	28.6	23.4	21.9 ± 3.3	21.9 ± 3.3	5.20	4.2 ± 0.5
0.094 ± 0.006	30.8	26.2	28.1	23.7	16.4 ± 2.6	17.7 ± 2.6	4.50	3.8 ± 0.5
0.094 ± 0.006	30.7	26.2	27.7	23.8	15.8 ± 2.6	19.7 ± 2.7	4.19	4.2 ± 0.5
0.094 ± 0.006	30.6	26.2	27.7	23.9	15.1 ± 2.5	19.1 ± 2.7	4.09	4.2 ± 0.6

Representative measured temperatures and flow rates and resulting LMTD and UA values are presented in Table 1 for hot and cold fluid flow rates of 0.20 and 0.15 l min^{-1} (3 measurements each). Uncertainty propagation analysis was performed to determine uncertainties for derived quantities (Q_C, Q_H, LMTD, UA). The UA was evaluated using the mean heat transfer rate of the two streams. At the higher flow rate conditions close agreement for hot and cold flow rates is observed. At lower flow rates, agreement is just within experimental uncertainty.

The average overall heat transfer rate is relatively constant over the considered range of conditions (UA ~ 4.0 ± 0.5 W K^{-1}). This is higher than the predicted value for laminar steady fully developed flow (Eqn. 4): UA = 2.7 W K^{-1}. The measured value is lower than the result assuming developing flow in both channels beginning at the inlets: 4.8 W K^{-1} (using developing flow correction factors from [1]). In actuality, the hot inner channel flow partially develops in the plumbing before reaching the HX inlet. This may explain the intermediate measured UA value.

Applications and Summary

In this experiment, a tube-in-tube counter-flow heat exchanger was fabricated, and its heat transfer capacity (UA) was experimentally measured (*rated*). The resulting performance was compared with results from a theoretical model. Modern heat exchangers often employ more sophisticated designs, with finned and enhanced surfaces to increase heat transfer intensity and optimized arrangements of fluid cross- and counter-flow. However, the basic concepts and parameters introduced here (UA, LMTD) apply to all heat exchangers.

Heat exchanger *rating* experiments, as demonstrated here are critical for determining whether manufactured heat exchangers meet desired capacities (UA values) to ensure acceptable energy system performance. Similarly, heat exchanger performance models (*e.g.*, Eqn. 4) must be developed and validated to guide heat exchanger design. This experiment provides a hands-on introduction to these heat exchanger rating and modeling processes.

Heat exchangers are employed in numerous energy intensive technologies and familiar household appliances. In many power generation plants, steam generator heat exchangers transfer heat from high temperature gas to produce high-pressure steam to drive turbines. Downstream from these turbines, condenser heat exchangers reject heat from the low-pressure steam, liquefying the fluid, and allowing the cycle to operate continuously. In many industrial processes, recuperative heat exchangers can transfer low-temperature heat from an exhaust stream to preheat intake fluid, reducing energy consumption. In refrigerators and air conditioning systems, evaporator heat exchangers absorb thermal energy from air in a conditioned space to maintain desired temperatures.

References

1. G. Nellis, S.A. Klein, Heat Transfer, Cambridge University Press, New York, NY, 2009.