Compact and Low-Cost Heat Exchangers for an Undergraduate Laboratory

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Abstract: The construction and operation of low-cost concentric double-tube heat exchangers is presented. These exchangers occupy little laboratory space due to their compact and portable design. Water taken from the laboratory mains is used as cooling fluid and flows in the shell side of exchanger. Hot fluid, which circulates in the tube side, is water supplied by a domestic electric heater. Flow rates are measured with flow meters and temperatures with thermocouples connected to a computer. Second-year undergraduate students of chemistry have been satisfactorily working with these exchangers for two years. Experimental data and calculated results from students are shown. Overall and film heat-transfer coefficients are determined. The main goal of the experimentat described is to examine the heat transfer between incompressible fluids in the steady state.

Introduction

The transfer of heat from one hot fluid to another cold one is a common unit operation encountered in chemical industry. The equipment used to accomplish this energy transfer is called a heat exchanger. These can have several geometries and configurations, although the double-tube heat exchanger represents the basis for the study of principles of heat transfer between fluids. Commercial equipment for teaching chemical engineering is usually expensive and sometimes it takes up too much space. As the maximum profit must be achieved from both the teaching budget and the available laboratory space, design and construction of simple and low-cost equipment is a common task in undergraduate laboratories. The experimental setup presented in this paper describes three low-cost concentric double-tube heat exchangers with a compact and portable design. The laboratory experiment suits first-year chemical engineering students, and it affords them a better understanding of the fundamentals of heat exchange between fluids. Although a complete theoretical background is available elsewhere [1–4], the main equations controlling the heat flux in a double-tube heat exchanger are described next (see the nomenclature table at the end of the paper).

The overall heat balances for both streams (without phase change) are

$$q_h = G_h\, C_{p,h}\, (T_{h1} - T_{h2}) \tag{1a}$$

and

$$q_c = G_c\, C_{p,c}\, (T_{c2} - T_{c1}) \tag{1b}$$

with q the heat flux, G the mass rate, and C_p the specific heat at constant pressure. Subscripts h and c refer to hot and cold streams, while 1 and 2 refer to the inlet and outlet, respectively.

The rate of heat loss from the hot line in the steady state must be equal to the rate of heat gain to the cold line, assuming no other sources or sinks of heat, so

$$q_h = q_c = q \tag{2}$$

Furthermore, the design equation for a concentric double-tube heat exchanger is

$$q = U_o\, A_o\, \Delta T_{lm} \tag{3a}$$

or

$$q = U_i\, A_i\, \Delta T_{lm} \tag{3b}$$

where U is the overall heat transfer coefficient, A the area for heat transfer, and with subscripts o and i referring to the outside and inside heat transfer area, respectively. Thus, for an exchanger with a useful length L, the heat transfer area is expressed as

$$A_o = \pi D_o L \tag{4a}$$

or

$$A_i = \pi D_i L \tag{4b}$$

with D as the diameter of the inner tube of the exchanger (where heat transfer occurs).

Although the value of the overall heat transfer coefficient is different depending on which area it is based on, U_o and U_i are simply related by

$$U_o D_o = U_i D_i \tag{5}$$

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The term ΔT_{lm} in eq 3 is the logarithmic mean temperature difference whose value depends on the arrangement of the streams within the exchanger, and it is defined as

$$\Delta T_{1m} = \frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln \frac{(T_{h1} - T_{c2})}{(T_{h2} - T_{c1})}} \text{ for countercurrent arrangement} \tag{6a}$$

or

$$\Delta T_{1m} = \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{\ln \frac{(T_{h1} - T_{c1})}{(T_{h2} - T_{c2})}} \text{ for cocurrent (or parallel) arrangement} \tag{6b}$$

Equations 1 to 3 assume the following: (i) the operation is in steady state, (ii) the heat losses are negligible, (iii) the specific heat is constant over the temperature range for both streams, and (iv) the overall heat-transfer coefficient is constant over the exchanger length. That last is the most debatable supposition, although the error made is acceptable whenever the temperature interval is moderate.

Neglecting fouling and wall thermal resistances, the overall and film transfer coefficients are related by

$$\frac{1}{U_\text{o}} = \frac{1}{h_\text{o}} + \frac{D_\text{o}}{D_\text{i} h_\text{i}} \tag{7a}$$

$$\frac{1}{U_\text{i}} = \frac{1}{h_\text{i}} + \frac{D_\text{i}}{D_\text{o} h_\text{o}} \tag{7b}$$

where h is the film heat-transfer coefficient.

The film heat-transfer coefficients are estimated by well-known dimensionless equations, as a function of Nusselt ($Nu = hD/k$), Reynolds ($Re = Du\rho/\mu$) and Prandtl ($Pr = C_\text{p}\mu/k$) numbers. The parameters k, ρ, and μ are the thermal conductivity, density, and viscosity of the fluid, respectively. In the working conditions, eqs 8a and b were used for water flowing inside the tubes (inside stream).

$$Nu = 1.86\left(RePr\frac{D_i}{L}\right)^{0.33}\left(\frac{\mu}{\mu_\text{w}}\right)^{0.14} \text{ for } Re < 2100 \tag{8a}$$

or

$$Nu = 0.116\left(Re^{0.67} - 125\right)Pr^{0.33}\left[1 + \left(\frac{D_i}{L}\right)\right]^{0.67}\left(\frac{\mu}{\mu_\text{w}}\right)^{0.14}$$

$$\text{for } 2100 < Re < 10^4 \tag{8b}$$

and eq 9 for the annular section (outside stream).

$$Nu = 1.01Re^{0.50}Pr^{0.55}\left(\frac{D_\text{a} - D_o}{L}\right)^{0.45}\left(\frac{D_a}{Do}\right)^{0.80}\left(\frac{\mu}{\mu_\text{w}}\right)^{0.14}$$

$$\text{for } Re < 2100 \tag{9}$$

where μ_w is the viscosity of the fluid at the wall temperature and D_a the outer diameter of the annulus (i.e. the inner diameter of the outer tube of the exchanger). Notice that D_o is the inner diameter of the annulus and also the outer diameter of the inner tube.

Design and Construction

The main dimensions for each heat exchanger were chosen as follows: the outside diameters for the inner and outer tubes are 10 and 16 mm, respectively; thickness is 1 mm for both tubes; and the useful length is 0.82 m. Copper-tubing connections are made with reducing T-connectors (16 × 10 mm). Cold water is the outside stream and hot water the inside stream. A water flow meter (Cole-Parmer 32461-42, range 200-3000 mL/min) measures each stream flow. Stream temperatures are measured with thermocouple probes, K type (Cole-Parmer 8515-01) previously calibrated in an insulated ice-water bath. Each probe is placed in the center of the stream by a reducing T-connector (10 × 4 mm). A piece of 4-mm nylon tubing keeps the end of each probe away from any metal compounds, and a bit of sealing paste avoids fluid leaks. Exchanger and flow meter connections are made of polyamide tubing (10-mm outside diameter). A partial scheme for the constructed heat exchangers is shown in Figure 1.

The cold stream is taken directly from the laboratory water facility. Hot water is supplied by a domestic electric heater (power 1.8 kW, capacity 75 L, and maximum outlet temperature 70 °C) already available in the laboratory. As maximum operational temperature for these flow meters is 65°C, flows are measured after hot streams have been cooled. Water pressure is displayed by both pressure gauges (0 to 1000 kPa). A three-way divider permits us to distribute both main water streams into three independent flows (one for each exchanger). The countercurrent or cocurrent layout is easily achievable by inverting the cold line connections (this is preferable for protecting flow meters from higher temperatures). Each exchanger is inserted into a PVC tube (40-mm OD) and the resulting annular space is filled with polyurethane expanding foam for insulation. Exchangers and flow meters are fixed to two aluminum 2-mm sheets, both held on a portable frame-rod support. The hot water line is also insulated with expanded rubber tubing. The processed streams are finally piped to drainage.

A surplus 8-channel data acquisition board (Omega OMD-5508TC), supported by a discarded computer, allows recording of the temperature data. Six input channels were used for registering outlet-stream temperatures, and the two remaining channels were for cold and hot inlet temperatures (both are just measured in the middle exchanger and assumed to be equal for the other two). The cost of a new DAQ board is $650, and the software required can be downloaded free from http://www.omega.com.

Its complete assembly (see Figure 2) takes about ten hours, and it can be dismantled for storing in less than an hour. A break (about 30 to 60 min) is usually necessary during the experiment because hot-water temperature is dropping in the electric heater through time. Students spend about 2 to 3 hours performing the experiment (break included). The system takes up little space, excluding monitor and computer: 1.04-m

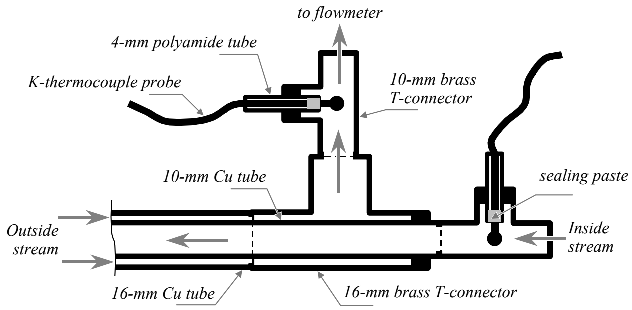

Figure 1. Schematic drawing of the inlet/outlet ends (countercurrent layout) for the heat exchangers constructed.

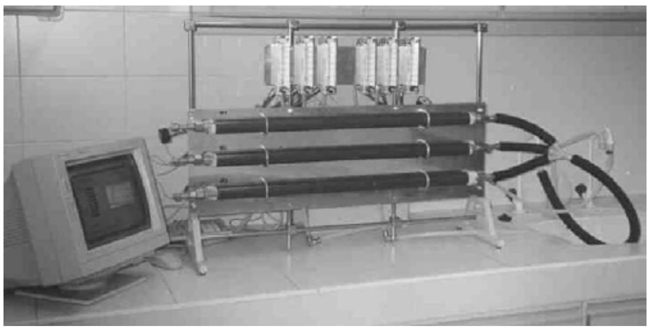

Figure 2. Photograph of the three compact double-tube heat exchangers. The computer is located behind the framework (on a 0.3-m high wooden support), and the electric heater is just below.

length, 0.68-m height, and 0.15-m width (just 0.30 m at the base). All minor components (copper and plastic tubing, rod support, aluminum sheets, insulating and sealing materials, pressure gauges, brass fittings and mounting pieces) were purchased from local hardware stores. The total cost is less than $950 (heater, computer, and DAQ board not included), which is quite affordable for the results obtained.

Operation and Results

System operation is quite simple: (1) check that the flow meter valves are fully open before turning on the water taps; (2) fix the cold and hot flow rates using the valves; (3) register the water flow rates and stream temperatures when a steady state is reached; (4) repeat for different flow-rate sets, covering all of the range proposed by the instructor. Water flow rates were tested between 200 and 2000 mL/min through all the experiments. The cold inlet temperature cannot be manipulated and is nearly constant. The hot inlet temperature can be varied between 45 and 65 °C by regulating the heater thermostat. Temperature versus time experimental data is displayed on the PC monitor as a moving time window in such a way that setting its width to 200 or 300 seconds is enough to determine the steady state satisfactorily. As an example of experimental data, Figure 3 plots temperature versus time curves (compressed in the time axis) measured in an exchanger with a countercurrent layout. Several pseudo-steady-states are observed after 20 minutes, each of them from a different set of flow rates. Temperatures are software averaged for use in further calculations.

As inlet and outlet temperatures are measured, the logarithmic mean temperature difference is calculated and mean values of transport properties for each stream can be estimated from literature data. Mass flow rates are calculated with the corresponding volumetric flows measured and the previously estimated densities. The heat balances, and therefore the heat flux, are already determined by eq 1. The heat-transfer area is easily calculated by eq 4 because equipment dimensions are known. Next, the *experimental* overall heat-transfer coefficient is obtained with eq 3. Furthermore, the film heat-transfer coefficients can be calculated from eqs 8 and 9, and then the *calculated* overall heat-transfer coefficient with eq 7.

Students are requested to hand in a written report, including: (i) the fundamentals of heat exchange between fluids in the steady state; (ii) a description of their work in the laboratory and the experimental data obtained; (iii) the estimation of all transport properties of the fluids (ρ, μ, k, and C_p) needed to predict heat-transfer coefficients; (iv) a verification of the overall heat balance (eq 2); (v) the calculated film heat-transfer coefficients, comparing them with other ones reported; (vi) a comparison between the experimental and calculated values of the overall heat-transfer coefficients; (vii) a verification (whenever possible) of all assumptions made to obtain eqs 1 through 3; and finally, (viii) a discussion of the effect of the experimental variables on these coefficients.

In Figure 4 about eighty experimental values of U (from five pairs of students) are compared to the values calculated using eqs 7 tthrough 9. The mean relative error is about 11%, and the results are in good agreement. The maximum error due to the viscosity correction term was less than 3% for all the experiments, so $(\mu/\mu_w)^{0.14}$ is neglected to simplify the calculations.

Significant differences were observed in the verification of the overall heat balance, eqs 1 and 2, with about 20% of the experimental data showing absolute relative errors above 20%. The majority of students attributed this deviation to: (i) experimental errors, (ii) an incomplete insulation in the ends of the exchangers (an additional insulation will be provided from next year on), and (iii) their impatience in waiting to reach the steady state.

Conclusions

The construction of these compact and low-cost double-tube heat exchangers is a useful proposal for those with low budgets or full teaching laboratories. First-year chemical engineering students have satisfactorily tested the equipment. Its application familiarizes students with the principles of heat transfer between fluids.

Remarks

Several thermometers will be necessary when a DAQ board is not available. Glass thermometers are not recommended if the experimental setup is to remain portable because of the risk of breakage. An economic alternative consists of having only one thermometer for all the exchangers (inexpensive four-channel thermometers are available) connected to a simple switch for a sequential reading of the different probes. Calibration of temperature probes is necessary in any case, and the offset values must be provided to the students.

Because raising the water temperature from 20 to 65 °C can take up to two hours in a typical domestic heater, attention must be given to the hot-water consumption. Low flows can increase the autonomy of operation, but an intermediate break

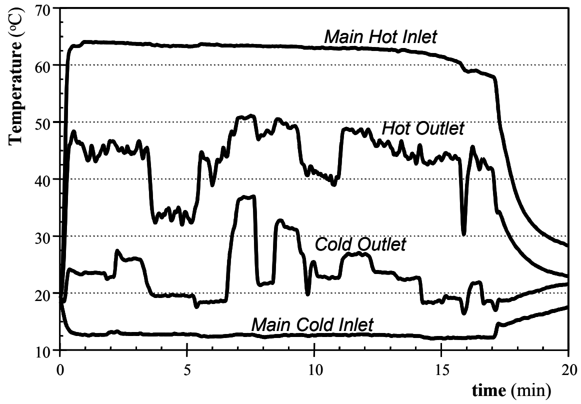

Figure 3. Example of students' raw temperature data.

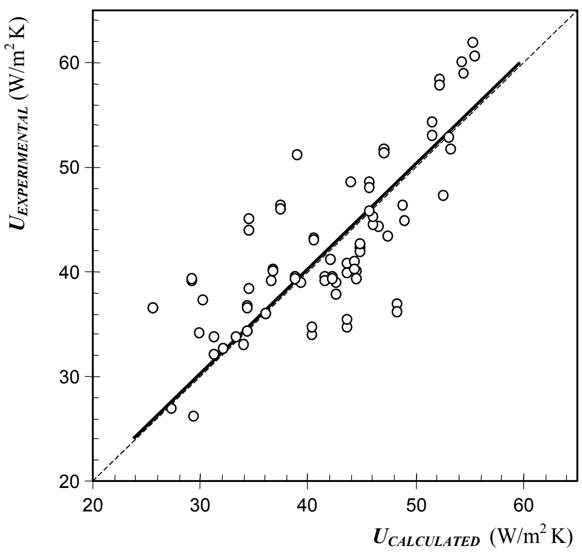

Figure 4. Plot of the experimental overall heat-transfer coefficients versus those calculated from eqs 7 to 9. The solid line was obtained by linear regression.

should be programmed for maintaining the temperature level. Installing a gas heater (or a bigger electric one) can also be considered. Where compressed air is available, it could be interesting to use air as the hot fluid (instead of water). In such cases, an electrical resistance can be easily used for heating the air flow and a potentiometer for regulating the inlet temperature.

Air bubbles inside the exchangers can affect the efficiency of heat exchange and also the stability of flow rate readings. Passing a high water flow through the system for a short time is usually a good solution, but this is not recommended for the hot-stream line if an electric heater is used. In this case, a purge valve could be installed in the upper unit, buty momentarily lifting the frame support by the hot-stream outlet end is usually enough.

Although fluctuations in the water supply rate are certainly unavoidable, they can be minimized by keeping water consumption closely constant during the experimental session (i.e. do not close or open the other water taps suddenly). For instance, we have installed several equalization tanks for supplying water to the rest of the experiments carried out in our laboratory. Each tank is located about 3 m above the floor and open to the atmosphere. Because the flow of fresh incoming water is slightly larger than that used by the two experiments connected to each tank, the level and flow of the water stays constant. The excess is drained to a priming tank where it is mixed with outlet water streams from all other experiments. Only one small centrifugal pump is enough to provide water from this priming tank to the four equalization ones.

Besides the application of eq 2, the verification of the overall heat balance can be accomplished by measuring the temperature at various locations outside the exchanger to estimate overall heat loss.

Because mercury thermometers have been avoided, there is no chemical hazard. Safety issues are limited to water-drainage splashing, so the computer (and any nearby electric components) must be protected. Special care must be taken if air is used as the hot fluid because achievable temperatures can be much higher than those that a water heater provides. Then, risk of skin burns could exist if insulation is inadequate. We had no problems throughout the first year of use.

Nomenclature

A	heat-transfer area (m^2)
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D	diameter (m)
D_a	outer diameter of the annulus or inner diameter of the outer tube (m)
h	film heat-transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	useful length of the heat exchanger (m)
G	mass rate of fluid (kg s^{-1})
Nu	Nusselt number (h D k^{-1}, dimensionless)
Pr	Prandtl number (C_p μ k^{-1}, dimensionless)
q	heat flux (W)
Re	Reynolds number (D u ρ μ^{-1}, dimensionless)
T	temperature (K)
ΔT_{lm}	logarithmic mean temperature difference (K)
U	overall heat-transfer coefficient (W m^{-2} K^{-1})
u	velocity (m s^{-1})

Greek symbols

μ	viscosity (kg m^{-1} s^{-1})
μ_w	viscosity of fluid at wall temperature (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

1	inlet
2	outlet
c	cold fluid
h	hot fluid
i	refers to inside heat-transfer area
o	refers to outside heat-transfer area

Suporting Materials. Two supporting files are available. Instructors notes (http://dx.doi.org/ 10.1007/s00897020543b) and Student notes (http://dx.doi.org/10.1007/ s00897020543c).

References and Notes

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