CAMBRIDGE UNIVERSITY ENGINEERING DEPARTMENT
PART IIA - DESIGN PROJECT

SHELL AND TUBE HEAT EXCHANGER

Heat Exchanger Project GA3 2022

1. Introduction

In this project you will design, assemble and test a small shell and tube heat exchanger. The device should maximize the heat transferred between a stream of cold water at about 20 °C and a stream of hot water at about 60 °C in a test rig in the Hopkinson Laboratory. Your design should conform to the following constraints:

(a) the total mass must not exceed 1.1 kg;
(b) the total length must not exceed 0.35 m;
(c) no more than 3.5 m of copper tube;
(d) only the supplied materials can be used.

A description of shell and tube heat exchangers is given in Section 2, equations needed for calculations in Section 3, the design procedure is summarized in Section 4, and administrative information is in Section 5.

2. Shell and tube heat exchangers

The most common type of heat exchanger (HX) is the *shell and tube* (S&T). One fluid flows inside a bank of *tubes* while the other fluid passes over this bank inside a *shell*. The S&T heat exchanger is very common for liquids and can withstand high pressures.

The simplest configuration would be a single tube surrounded by a concentric pipe but this would have poor performance. In practice there are several tubes, which are collectively called the *tube bundle*. Four configurations are shown in Fig. 1, in which the tube bundles are shown as a single line. The simplest has one shell pass and one tube pass, which approaches pure counter flow. The most common is the one shell / two tube arrangement, which enables higher velocities inside the tubes and hence better heat transfer. Multiple tube passes and multiple shell passes are sometimes used. Some terminology and standardized S&T HX parts are shown in Figs 2 & 3.

The tubes are arranged in a square or triangular *pitch* and both ends are held by the *tube plates*. The fluid starts in a *header*, which is enclosed by an *end plate*. The tube flow is reversed either with U-shaped tubes or in a *fixed* or a *floating head*. The latter design accommodates differential expansion of the shell and tubes. You will use a fixed head in this project.

The shell flow passes around a series of *baffles* in order to increase the heat transfer rate and to avoid by-passing. The *segmental baffle* (Fig. 4c) is the most common. Conventional baffle spacing (*baffle pitch*) is between 1/5 and 1 shell diameter and an excessive number of baffles introduces a significant pressure drop.

You will design, provide drawings for, and assemble (i) the shell, (ii) the tube bundle, (iii) the tube plates, (iv) the baffles, (v) the header, (vi) the end plates, and (vii) the inlet and outlet nozzles.

3. Theory

3.1 Thermal design

The thermal design determines the *heat transfer area* required for a given heat exchange. It uses basic principles of heat transfer and empirical laws for the heat transfer coefficients.

A. Basic equations

There are three expressions for the rate of heat transfer, Q, in Watts:

$$Q = m_1 c_{p,1} (T_{1,\text{out}} - T_{1,\text{in}}) = m_2 c_{p,2} (T_{2,\text{in}} - T_{2,\text{out}}) = U A F \Delta T_{\text{lm}} \quad (1)$$

where m is the mass flow rate (kg s^{-1}), c_p is the specific heat capacity (J $kg^{-1}K^{-1}$), T is the temperature (K), U is the overall heat transfer coefficient ($Wm^{-2}K^{-1}$), A is the total transfer area (m^2), ΔT_{lm} is the log mean temperature difference (K), subscript 1 refers to the cold stream and subscript 2 refers to the hot stream. The log mean temperature difference (LMTD) for counterflow, which is the most usual arrangement, is given by:

$$\Delta T_{\text{lm}} = [(T_{2,\text{in}} - T_{1,\text{out}}) - (T_{2,\text{out}} - T_{1,\text{in}})] / \ln[(T_{2,\text{in}} - T_{1,\text{out}}) / (T_{2,\text{out}} - T_{1,\text{in}})] \quad (2)$$

More complicated configurations require a correction factor F (Fig. 5). Remember to take this into account if you are designing multi-pass configurations.

B. Overall heat transfer coefficient

The overall heat transfer coefficient based on the inside tube area is given by:

$$1 / U = 1/h_i + A_i \ln (r_o/r_i) / (2\pi kL) + A_i/(A_o h_o) \quad (3)$$

where L is the total length of the tubes (m), k is the thermal conductivity ($Wm^{-1}K^{-1}$), r_i and r_o are the inner and outer tube radii, A_i and A_o are the tube surface areas (m^2) and h_i and h_o are the tube film heat transfer coefficients ($Wm^{-2}K^{-1}$). After years of operation, deposits or corrosion of the tubes may increase resistance to heat transfer and degrade the performance. This is represented by a *fouling factor* R_f, which is added to the r.h.s. of Eq. (3). A typical range of U for *large* water-water heat exchangers is 850-1700 $Wm^{-2}K^{-1}$. The fouling factor R_f is around $2x10^{-4}$ m^2KW^{-1} for boiler feedwater but $2x10^{-3}$ m^2KW^{-1} for seawater [1].

C. Heat transfer coefficient

The inner Nusselt number based on the inner tube diameter can be calculated using the following relationship, valid for *turbulent* pipe flow.

$$Nu_i = 0.023\, Re^{0.8}\, Pr^{0.3} \quad (4)$$

The outer heat transfer coefficient depends on the actual configuration of the tube bundle and the baffles [2]. For the purposes of this project, the following may be used:

$$Nu_o = c\, Re^{0.6}\, Pr^{0.3} \quad (5)$$

The constant c is 0.2 for triangular tube pitch and 0.15 for square tube pitch. In (5), the Reynolds number is based on the outer tube diameter d_o and on a bulk velocity V_{sh}. This is calculated from

$$V_{sh} = m_1/(\rho_1 A_{sh}) ,$$

with the area A_{sh} given by:

$$A_{sh} = D_{sh} (Y - d_o) B / Y \quad (6)$$

where D_{sh} is the inner diameter of the shell, Y the tube pitch, and B the baffle spacing. Equation (6) applies only to tube bundles at least ten rows deep and so it gives only a rough indication of the value of the velocity flowing above the tube bundle, and hence of h_o, for small heat exchangers.

D. Effectiveness

The effectiveness is defined as the ratio of the actual heat transfer to the maximum possible heat transfer, q_{max}. The quantity q_{max} would be attained if one of the fluids were to undergo a temperature change equal to the maximum possible temperature difference present in the exchanger, which is the difference between the entering temperatures of the hot and the cold streams. The stream for which that could happen is the one having the minimum value of mc_p, because ΔT would be largest for this stream. This fluid is called the *minimum fluid* and its mc_p is denoted as $(mc_p)_{min}$. The q_{max} then becomes

$$q_{max} = (mc_p)_{min} (T_{2,in} - T_{1,in})$$

and the effectiveness

$$\varepsilon = \Delta T_{min\ fluid} / (T_{2,in} - T_{1,in}) \quad (7)$$

For example, if the minimum fluid is the cold fluid, $\Delta T_{min\ fluid} = (T_{1,out} - T_{1,in})$. The effectiveness is usually expressed as a percentage. It is also used in the "effectiveness-NTU" method for designing heat exchangers [1], which does not use the LMTD concept. We will use the LMTD approach in this handout because the calculations are more transparent. However, each group should use both methods to assess the best design of heat exchanger.

3.2 Hydraulic design

The pressure drop across the heat exchanger can be very influential. In the test rig the mass flow rates of both streams are functions of the pressure drop (Fig. 6). This relationship is changed every year by changing the pump or by introducing a constriction into the pipe. The pressure drop introduced by the heat exchanger changes the potential for maximizing the heat transfer rate.

The pressure drop along the tubes can be calculated easily from the Moody diagram (the classical chart of C_f as a function of Re). There is an additional pressure drop associated with the flows into and out of the tube bundle. This may be estimated as

$$\Delta P_{in+out} = 0.5\ \rho\ V_t^2 (K_c + K_e) \quad (8)$$

where V_t is the velocity in the tube and K_c and K_e are given in Fig. 7 as a function of σ, the ratio of free area (i.e. number of tubes times tube area) over the total area (i.e. area of the tube plate). *Be careful how you use* (8) *in multi-pass arrangements.* The pressure drop associated with the flows from the inlet and into the outlet nozzles may be estimated as a total of two velocity heads, based on nozzle velocity.

The shell side pressure drop is more complex and the available empirical correlations are of dubious validity. The following can give an indicative value:

$$\Delta P_{sh} = 4\ a\ Re^{-0.15}\ N\ \rho\ V_{sh}^2 \quad (9)$$

where a = 0.2 for triangular pitch and 0.34 for square pitch, N is the number of tubes in the flow direction per shell pass and V_{sh} is the velocity across the tube bundle (6). A further two velocity heads (based on the nozzle velocity) should be added for the inlet and exit losses of the shell fluid. The pressure drop induced by the baffles is harder to calculate. The volumetric flowrates and baffle configurations through the shells of previous years' heat exchangers will be supplied.

4. Design procedure and project progress

4.1 Specifications

Your aim is to maximize the heat exchange between a cold stream at 20 °C and a hot stream at 60 °C by making a heat exchanger out of the following materials:

(i) 3.5 m of 8 mm OD, 6 mm ID copper tube (~0.20 kg/m each batch changes so check),
(ii) 500 mm of 70 mm OD, 64 mm ID acrylic pipe for the shell (0.650 kg/m),
(iii) four 3-D printed nozzles, with bore 20 mm, will be supplied (0.025 kg each),
(iv) 4.5 mm thick plastic sheet for the tube plates and end plates (6.375 kg/m^2),
(v) 1.5 mm thick plastic sheet for the baffles (2.39 kg/m^2).

The constraints are that:

(i) the total mass should not exceed 1.1 kg;
(ii) the total length should be less than 0.35 m;
(iii) the copper tubes must be straight and total length of tubes not to exceed 3.5 m;
(iv) the mass flow rates through the HX depend on the pressure drop across it (Fig. 6).

Component templates (Creo4.0) are available from the IIA GA3 Moodle site.

4.2 Procedure

A. Design

Each pair should generate one software design tool that uses the LMTD method and one that uses the Effectiveness-NTU method. Each student's interim report should contain a detailed description of at least one of the tools and a section that compares the LMTD tool with the Effectiveness-NTU tool. Equations (1) to (9) can be solved by iteration either with Matlab, Python or …. One technique is to start with a design (e.g. one-shell/two-tube), estimate a set of mass flow rates, find the temperatures and the pressure drop, and then iterate (since the pressure drop will affect the mass flow rate.)

Each pair should then iterate their heat exchanger design until an optimum is found. In most years, the pair with the best iteration procedure designs the heat exchanger with the best performance. Half way through the second week, pairs will be paired up to make groups of four students. Each group of four will select one heat exchanger to manufacture. The interim report should describe the reasons for this choice.

It is important that your designs are simple to manufacture. The copper tubes will be cut to the correct length but cannot have any additional machining. In your tube length calculation, allow the extra length needed for attaching a tube to a tube plate. Be careful how the end plates, tube plates and any splitter plates in the header sections are joined to the shell and to each other. Note that the acrylic pipe used for the shell cannot have grooves cut in it. You should either consider the effect of the baffles slipping during operation or how to prevent them from slipping.

B. Drawings

Detailed manufacturing drawings should be produced by CAD and uploaded to Moodle **(but must be submitted to the machine shop in paper form once approved by Dr Longley)**. You should discuss your final drawing and designs with the workshop to make sure that they can make them and that they are happy that the drawings include all key measurements. The work shop staff will be asked at the end of the project which design drawings they found most clear and which design was the most elegant. The machine shop has instructions to make whatever is drawn, be it right or wrong.

C. Build and test
You will assemble the components in the Dyson Centre, where you will be shown how to use the tools. The copper tube *must* be tightly sealed to prevent leaks. This is done with a swage tool, which creates a ridge in the copper pipe, and should be backed up with epoxy resin or sealant applied to the outer side of the tube plate. It is recommended that you do a trial swage on a short length of copper tube which will be provided. On test day the heat exchangers will be weighed and then tested for leaks. The thermal performance test involves measurement of temperatures, flow rates and pressure drops.

5. Project management and reports

<u>5.1 Project management and deadlines</u>
This project is particularly intensive in the first two weeks but eases off in weeks three and four. You and your partners should work together at all stages of the project and must both be present at the start of each timetabled session. The following set of milestones for monitoring your own progress is recommended:

(i) Friday week 1 – You should be able to calculate the heat exchange in a given heat exchanger and be able to estimate where the major uncertainties lie. You will have started to develop a software design tool.
(ii) Tuesday week 1 – You will have completed a literature search of heat exchanger design and resolved the major uncertainties. The first version of your software design tool will be completed. Each group will give a 5 minute presentation of its software design tool.
(iii) Friday week 2 – You will have completed the software design tool and have finalized your pair's heat exchanger configuration ready for the down selection in groups of four.
(iv) Tuesday week 2 – Each group's final drawings should be near completion.

The project deadlines are:

(i) Wednesday 25th May, 4pm: **Interim report** and **final drawings**
(upload two distinct ".pdf" files to Moodle).
(ii) Wednesday 1st June, 4pm: **Performance predictions** (including "blind" testcase)
(upload ".pdf" file to Moodle).
(iii) Wednesday 8th June, 4pm: **Final report**
(upload ".pdf" file to Moodle).

Report cover sheets and allowance forms can be downloaded from:
http://teaching.eng.cam.ac.uk/information/projects/part-iia/content

<u>5.2 Reports</u>
Each individual will submit online *three reports* and each group of four will upload *one set of technical drawings (all drawings in a single pdf)*. **The *combined* page limit for the three reports is 15 pages, single-sided, 12 point font, 2 cm margins. The mark split between the interim report, performance report and final report is 27:13:10 so an appropriate page split is 8:4:3.** This 15 page limit covers *everything* except the engineering drawings.

(i) The most significant report is the ***interim report***. Remember to write for the audience, i.e. me. I don't want to read through a copied out version of the notes that I provided you with 24 times. When you're writing any report you must think about the following points:

- What are you trying to do? (Articulate with no jargon).
- What is normal practice for the reader and how is it limited?
- What is new about your approach and why do you think it will be beneficial?
- What difference has your analysis made?

Use simple language and write exactly what you mean. The report should contain an executive summary. The report should include the principles of the iteration process that you have used. Again think about how the basic structure of your iteration process from the perspective of the points listed above (i.e. don't list lines of code and don't just repeat the iteration structure in the notes). The report should compare the LMTD technique with the ENTU technique, describe the design that you came to in your pair, the reasons for this design, a brief description of the design that you chose in your four and the reasons that this design was chosen. It does not require a conclusion because this will be in the final report. This report will be handed back to you after marking and you will hand it back in with the final report in week 4.

(ii) The ***technical drawings*** will be uploaded (all drawings in a single pdf but separate from the interim report) with the interim report. They will be used by the workshop for the manufacture of the shell, nozzles, tube plate, baffles and tubes. **Each team is responsible for making sure the workshop has a full set of paper drawings once they have been approved by Dr Longley.** Discuss your designs with the workshop.

(iii) The ***performance report*** (including your "blind" testcase prediction), which is done individually, should examine the sensitivity of your heat exchanger to changes in the inputs. This term is deliberately vague because I would like you to think through the factors that will affect performance. You should also use your software packages to predict the performances of the other groups' heat exchangers and to comment on their designs. Think about how best to present the results because there is a very tight page limit. (Additional data will be made available for you to further calibrate your analysis software to enable upper and lower limits.)

(iv) The ***final report*** consists of your test results, a discussion, recommendations and conclusions . This report should be brief.

Marks will be awarded for the design principles, thermal and hydraulic calculations, the optimization method, initiative, originality, ease and quality of assembly and performance.

	Marks	Page limit
Interim report (with technical drawings)	27	8 (excluding drawings)
Performance report (including blind test case prediction)	13	4
Final report	10	3
Project / technical skills (including initiative)	20	
Performance of your heat exchanger	10	

You will benefit greatly by sharing ideas between groups.

References

1. Holman, J. P. "Heat Transfer". 8th Edition, MacGraw Hill.
2. Kakac, S., Bergles, A. & Malyinger, F. "Heat Exchangers: Thermo-Hydraulic Fundamentals and Design". MacGraw Hill.
3. Miller, D.S. "Internal Flow Systems", BHRA (TA379)

J.P. Longley May 2020 (based on E. Mastorakos, M Juniper, R Miller).

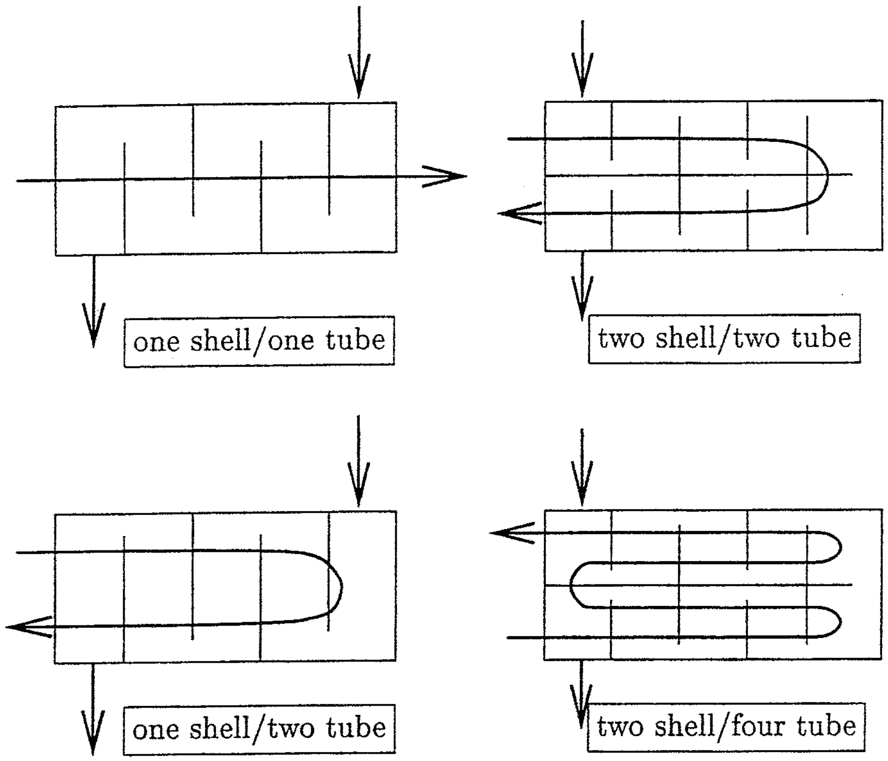
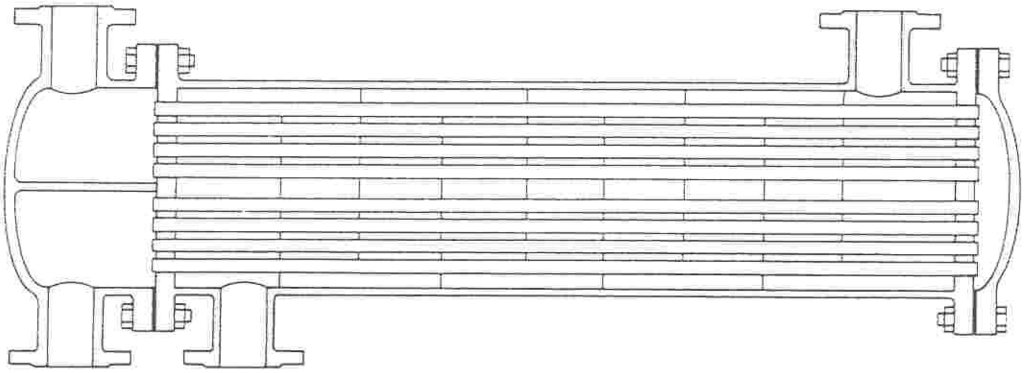


Figure 1. Flow arrangements in shell and tube heat exchangers



(b)

Figure 8.2 (*a*) Simple tube-within-a-tube counterflow heat exchanger. (*b*) Shell-and-tube heat exchanger with segmental baffles: two tube passes, one shell pass.

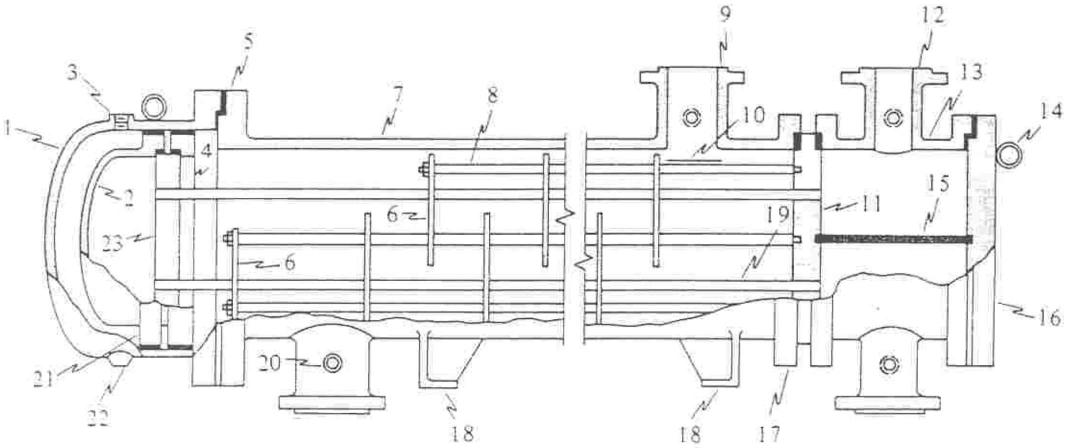


Figure 8.6 Shell-and-tube heat exchanger with floating head. (Courtesy of the Tubular Exchange Manufacturers Association.)

Key:

1. Shell cover
2. Floating head
3. Vent connection
4. Floating-head backing device
5. Shell cover—end flange
6. Transverse baffles or support plates
7. Shell
8. Tie rods and spacers
9. Shell nozzle
10. Impingement baffle
11. Stationary tube sheet
12. Channel nozzle
13. Channel
14. Lifting ring
15. Pass partition
16. Channel cover
17. Shell channel—end flange
18. Support saddles
19. Heat transfer tube
20. Test connection
21. Floating-head flange
22. Drain connection
23. Floating tube sheet

Figure 2. Some S&T heat exchangers

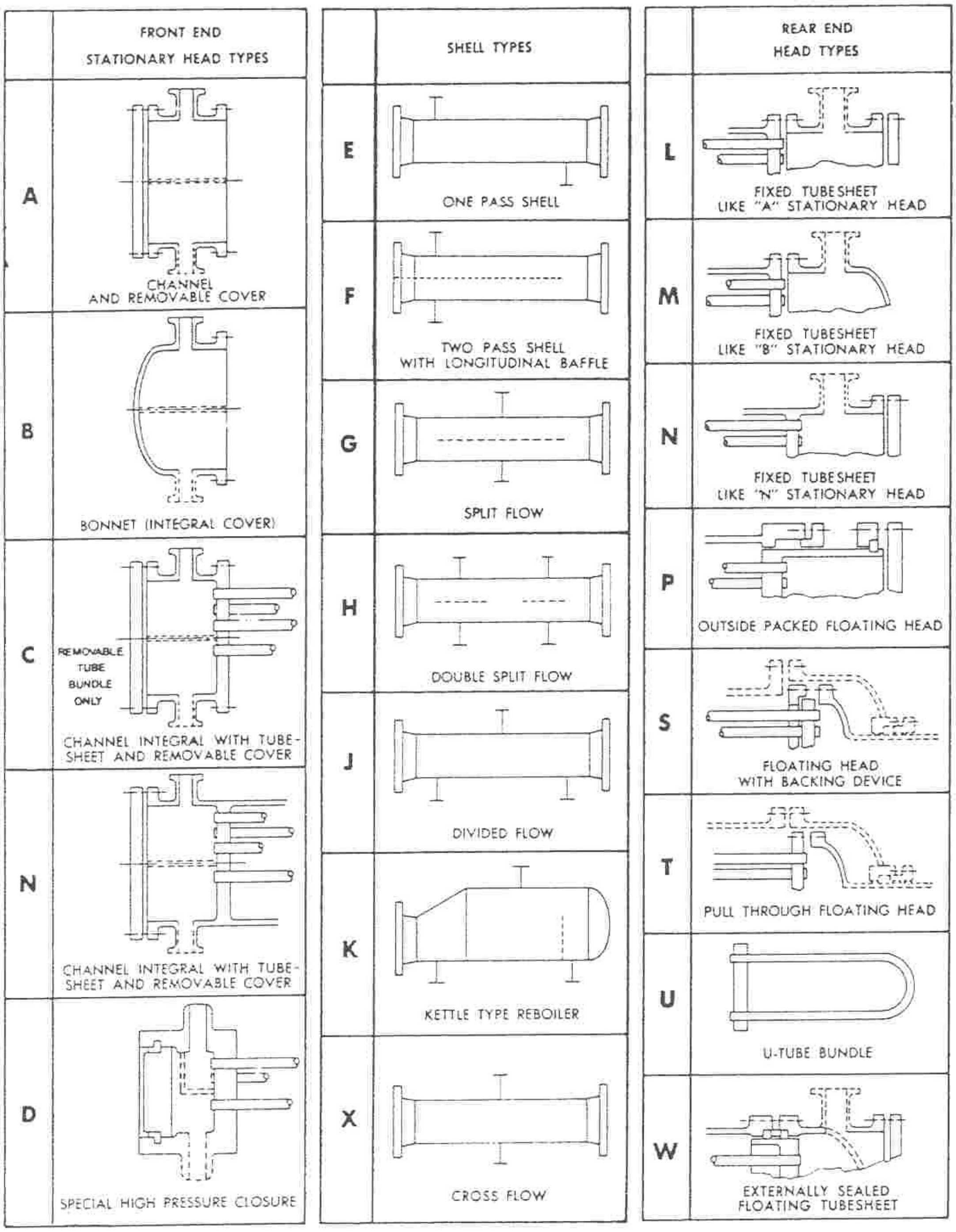


Figure 3. Shell and tube heat exchanger standard designation (TEMA)

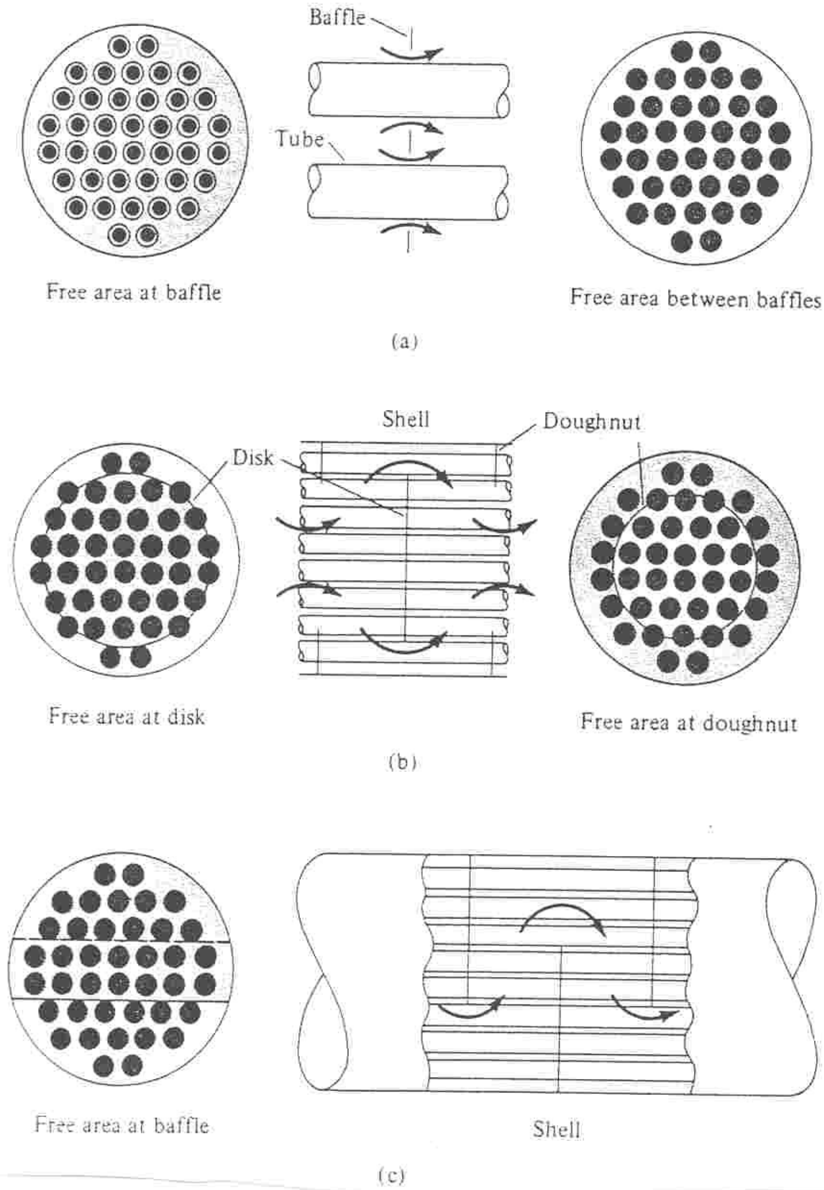


Figure 4. Various baffle shapes

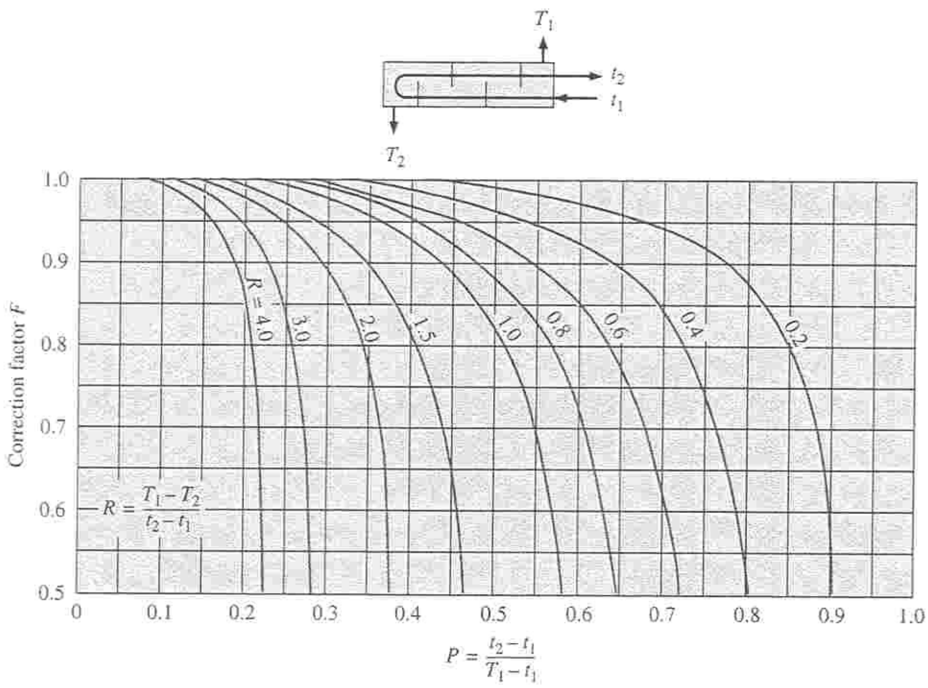


FIG. 10-8
Correction-factor plot for exchanger with one shell pass and two, four, or any multiple of tube passes.

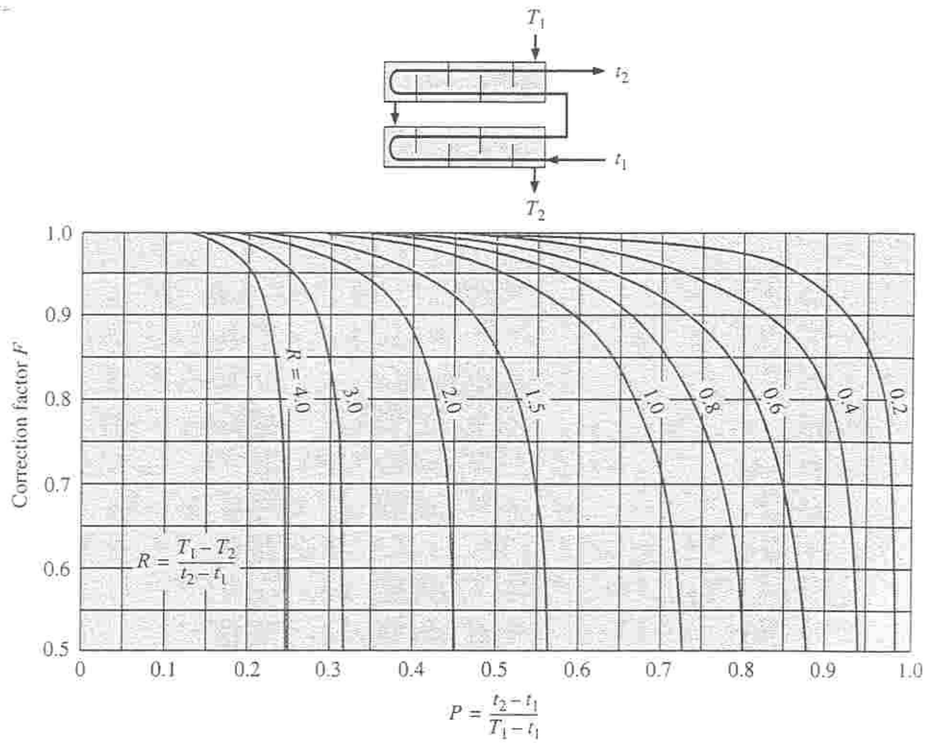


FIG. 10-9
Correction-factor plot for exchanger with two shell passes and four, eight, or any multiple of tube passes.

Figure 5. Correction factor for multi-pass configurations (from Ref. [1]).

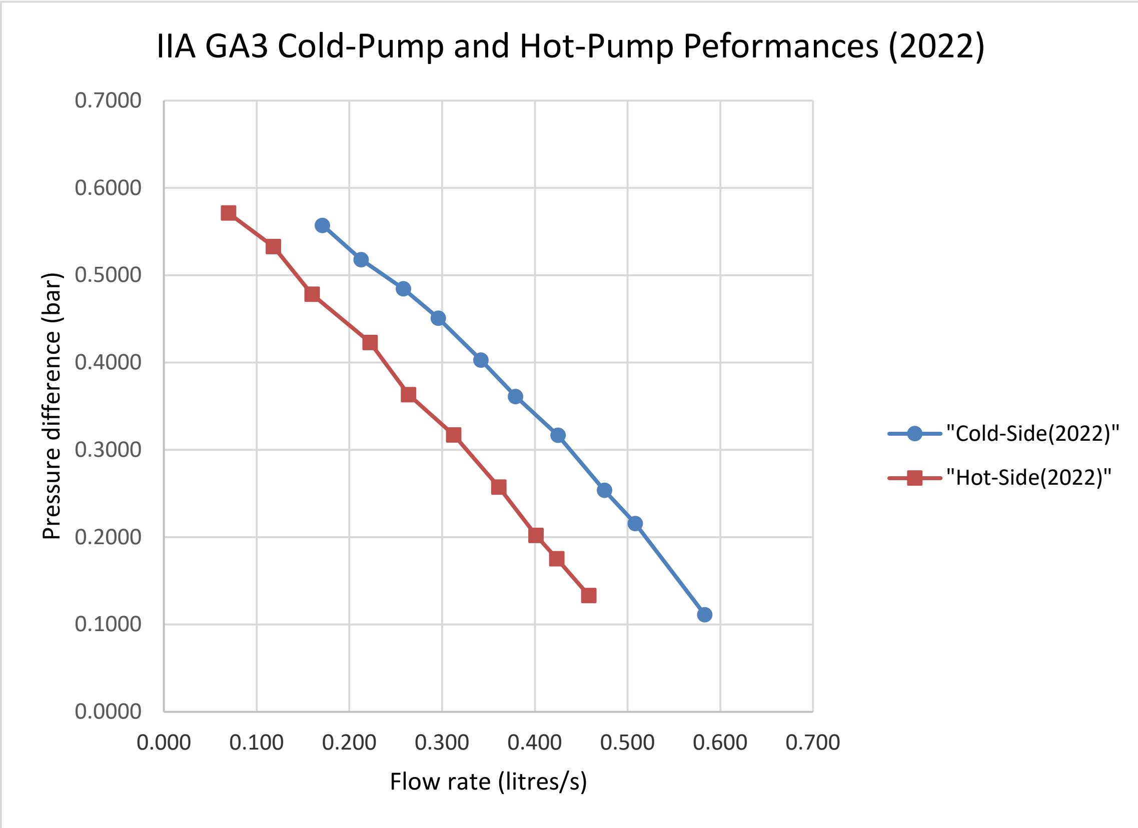


Figure 6. Characteristics of the cold and hot circuit of the 2022 CUED test rig. (File “nnnn_calibration.txt” contains the associated data for year “nnnn”.)

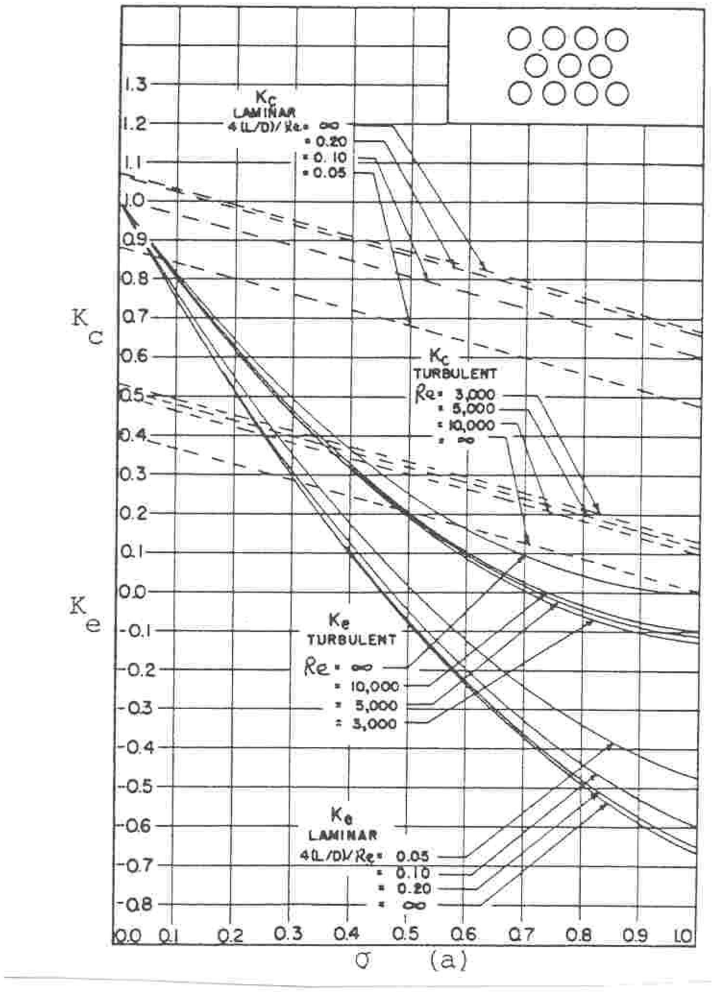
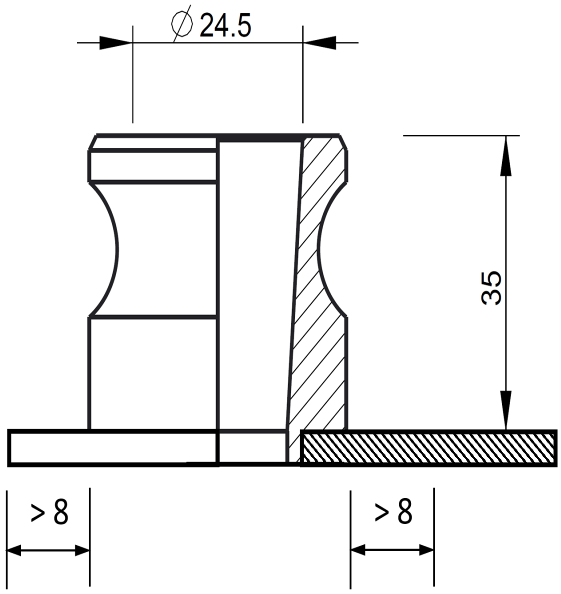


Figure 7. Pressure drop factors for tube entrance and exit effects (from Ref.[2]).

Figure 8. Diagrams and dimensions of heat exchanger components.



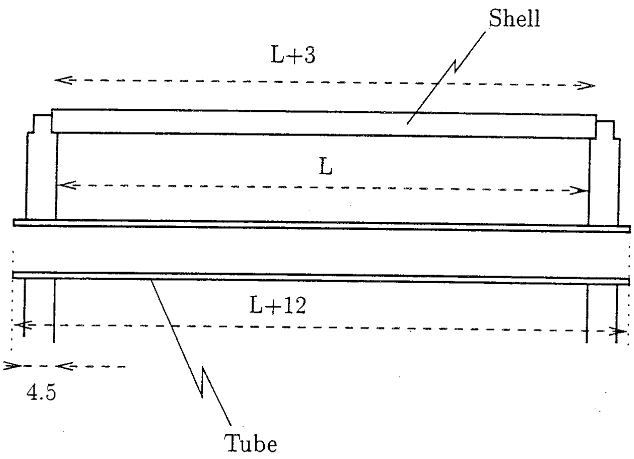


Figure 8a.

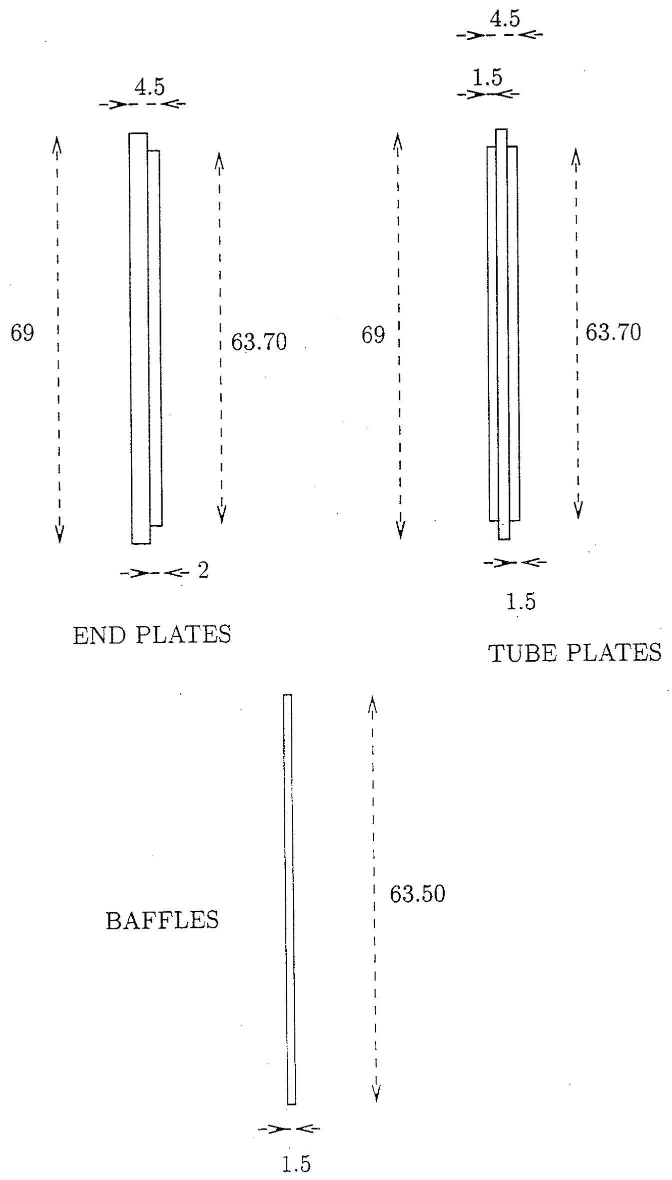

4.5
69
63.70
2
END PLATES
4.5
1.5
69
63.70
1.5
TUBE PLATES
BAFFLES
63.50
1.5

Figure 8b.