PROCESS HEAT EXCHANGE

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INTRODUCTION

Industry uses 3,500 billion kWh equivalents of energy, or nearly 40% of the total consumed in this country, according to a recent Annual Survey of Manufacturers[1]. Over 80% of industry's share is employed in the chemical process industries (CPI).

It takes only a quick calculaton to show that even a small percentage improvement in energy efficiency holds vast potential for reducing fuel consumption and cutting operating costs. And the price of energy is not going down; in the future the savings will be even greater.

In the CPI, heat is the predominant form of energy used. So, in order for engineers to help meet energy goals, they must have a thorough understanding of heat exchange and its associated equipment in CPI processes.

This necessity was underscored in a recent Department of Energy document[2], which included recommendations for energy conservation measures. Some of these are: improvements in process heaters, boilers, steam systems and waste heat recovery systems; the application of heat exchangers, air coolers and insulation; and housekeeping measures.

In this book, we have presented a range of useful information on the transfer of heat in the CPI. The opening section focuses on heat exchange equipment, with shell-and-tube exchangers in the spotlight. That section then weaves through other heat exchanger designs (such as plate and spiral exchangers) and materials of construction for heat exchangers. Proper operation and regular maintenance of equipment is a must for peak performance; Section II presents a series of articles on that subject.

Sections III and IV outline heat transfer considerations in reaction units and piping systems, respectively. The design and optimization of fired heaters for process fluids in the CPI are thoroughly covered next, in Section V. Steam, which is by and large the most important heat transfer medium, is discussed in Section VI, which includes articles on boiler design and improvement as well as methods to reduce steam losses in transmission lines. Cooling towers are discussed in Section VII. This is followed by a section on heat transfer calculations, and one on water and other media used as cooling or heating agents. Finally, methods of waste-heat recovery are outlined in Section X.

This book was designed to be helpful to engineers in many sectors of industry. For the design engineer, it will be a useful guide for the proper design and specification of heat exchange systems and equipment. For the plant operations engineer, it provides timely tips on saving energy and lowering operating costs through design modifications and correct operating procedures. The plant process engineer will find it a handy troubleshooting guide for tackling operating problems. For the plant maintenance engineer, practical details on programmed and crises maintenance are presented.

All in all, this book provides a combination of theoretical and practical information on process heat exchange that is virtually unavailable elsewhere.

August 1979

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1. 1975 Bureau of Census survey
2. Industrial Energy Efficiency Improvement Program, Annual Report Support Document, Vol. II, June 1978, Dept. of Energy, Asst. Secretary for Conservation and Solar Applications, Div. of Industrial Convervation.

CONTENTS

Section I

HEAT EXCHANGER DESIGN AND SPECIFICATION (A., B., C.)

(A) Shell-and-Tube Heat Exchangers

How to select the optimum shell-and-tube heat exchanger

Developing an optimum unit can be a complex process because of the many interdependent parameters involved. An experienced engineer is required—either to design the exchanger himself or to evaluate offers from vendors based on his specifications.

John P. Fanaritis and James W. Bevevino, Struthers Wells Corp.

Because a shell-and-tube heat exchanger has no moving parts and exchanges heat between two fluids, an engineer could develop the mistaken impression that the design of this equipment is simple and straightforward. Although this type of exchanger is not usually a sophisticated piece of equipment, many considerations are involved in obtaining the optimum design for a given service.

This article does not provide design formulas or special methods for determining the optimum design, because these vary from process to process. Instead, the parameters involved and the complexities that surround the design are presented.

Included are charts and drawings—taken from the Tubular Exchanger Manufacturers Assn. (TEMA)—that pertain to the construction features of common heat exchangers, as well as to the nomenclature involved in describing them.

Also included are curves and data that provide approximate present-day prices for the several types of heat exchangers. In addition, a curve is provided to estimate the expected surface area for a given shell size, based on alternate tube-lengths. These graphs and charts can be used as guides in determining the approximate size and today's prices for the common variety of shell-and-tube heat exchangers.

Designing such an exchanger is based on the designer's knowledge and experience in heat transfer, mechanical design, utility, maintenance and cost. Inasmuch as the considerations that enter into the selection of the optimum heat exchanger are very difficult to evaluate quantitatively, a designer's experience is of the utmost importance.

Every designer's goal should be to provide a heat exchanger that will meet the specified performance requirements and provide long-term, trouble-free service at a minimum cost to the user. Due to the complexity in the design, and the interrelation between variables, each exchanger application will have as many different designs offered as there are designers or bidders. Under these circumstances, the ultimate choice rests with the purchaser.

Although each vendor or bidder warrants that his proposed design will meet the specified performance requirements, many questions require answers from the user in selecting the design. For example:

- Has the shell side of the heat exchanger been properly evaluated for maximum efficiency in heat-transfer rate, corresponding to the pressure drop?
- Are fluid velocities within reasonable limits, to avoid erosion of components or mechanical failure due to flow-induced vibrations?
- Have vents and drains been included where needed?
- Has differential expansion between the shell and tubes been considered?
- What type of tube-to-tubesheet joint is best?
- Are the specified metals compatible for good mechanical design and weldability?

Questions like the above must be answered to make a

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reasonable assessment of a heat-exchanger design.

Usually, the repair costs connected with correcting a deficiency in a heat exchanger are only a small part of the penalty paid for poor design; the resulting loss in plant production for one day will often cost many times the purchase price of the heat exchanger.

Some exchangers are used in critical services involving extremely high pressures and/or temperatures, and handle hazardous fluids such as hydrogen. The purchaser must evaluate whether a particular vendor has the experience to provide the design integrity and the quality in fabricating for such special services.

Performance data specified by user

Selecting a heat-exchanger design must not be done casually; a considerable amount of time may easily be spent in heat-transfer and mechanical-design calculations. A purchaser should establish firm requirements for his heat exchanger at the time he asks for bids. The practice of imposing on a vendor the design and pricing of alternative selections is wasteful and in many cases costly.

To provide an optimum heat-exchanger design, the manufacturer or designer should be furnished by the user with the following minimum service information: (1) total heat load, Btu/h; (2) fluid quantities entering and leaving the exchanger, lb/h; (3) specific heat, thermal conductivity, viscosity, molecular weight or specific gravity of the fluids in appropriate units; (4) heat-exchanger ingoing and outgoing temperatures, °F; (5) operating pressures, psia; (6) allowable pressure drops, psi; (7) fouling factors; (8) design pressures and temperatures, psia and °F; (9) heat-exchanger type; (10) materials of construction; (11) tube-wall thickness for corrosion considerations, in; (12) corrosion allowance; (13) specifications, codes and standards; (14) size or space limitations; and (15) horizontal or vertical installation.

Process conditions

Since the size and resulting cost of a heat exchanger depend greatly on the log-mean-temperature difference (LMTD), a process designer should consider the effect of the operating temperature levels in the early stages of process design.

A high LMTD generally results in a smaller heat exchanger. Therefore, when considering operating temperature levels, a larger LMTD can be achieved by increasing the temperature level of the cooling medium. Close temperature approaches, where small differentials exist between the inlet of one fluid stream and the outlet of the other, will result in very low LMTDs.

There are no specific rules for determining the optimum operating temperatures. These should be selected based on the service and utility of the heat exchanger. Inefficient design and poor heat-exchanger performance can result when the LMTD is too high or too low. For a good design that is to cover many services, the lesser temperature difference between the shellside and the tubeside fluids should be greater than 10°F; the greater temperature difference should exceed 40°F.

Flow quantities—Fluid flowrates (lb/h) on both the shell and tube sides can affect the size and design of an exchanger. A designer may be forced to resort to multiple shells in series when the LMTD and flow quantities are low, and when a large temperature difference exists between the shellside and the tubeside fluids. Under these conditions, a countercurrent flow pattern must be maintained.

Under low-flow conditions, the designer may resort to multiple shells in series, to achieve reasonable fluid velocities and heat-transfer rates. When flowrates are extremely high for the surface requirement, multiple shells in parallel may be needed to achieve reasonable velocities, pressure drops, and an efficient heat-exchanger design.

Fouling factors—Dirt, scale or other deposits formed on the tube—inside and/or outside—which results in resistance to the flow of heat is called "fouling." The size and cost of a heat exchanger are related to specified fouling resistance; haphazard guessing of fouling can be costly.

Inasmuch as fouling factors are difficult to determine, they should be based on experience. Therefore, the user of the heat exchanger has the responsibility of providing the designer with the fouling factors peculiar to his operation. There are very limited data available for accurate assessment of the degree of fouling that should be applied for given service conditions. Fouling varies and depends on the material of construction of the tubes, the types of fluids involved, temperatures, velocities and other operating conditions. Thus, the selection of fouling factors is arbitrary. Many complaints in heat-exchanger operation that cannot be traced to errors in thermal design are generally traced to fouling.

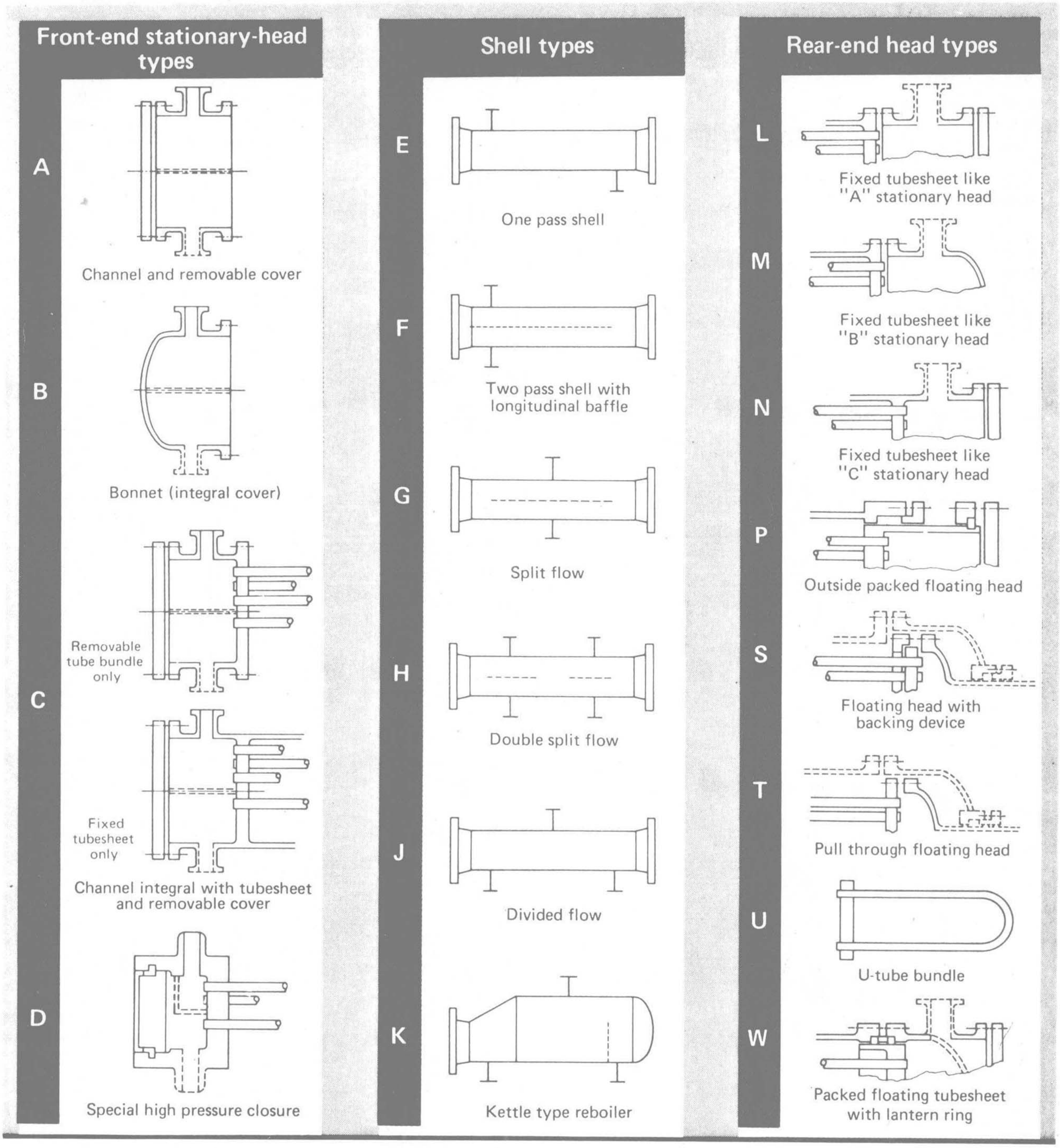
If heavy fouling is anticipated for a particular service, the user should make provisions for periodic chemical or mechanical cleaning of the exchanger. If heavy tubeside fouling is foreseen, a straight-tube heat exchanger with larger-diameter tubes (1-in O.D. at least) should be specified. But when heavy shellside fouling is anticipated, the purchaser should specify a removable-bundle design, with tubes on a square pitch for mechanical cleaning of the bundle.

Allowable pressure drop—Selecting the optimum allowable pressure drop involves consideration of the overall process. However, high pressure drops may result in a smaller size (less costly) heat exchanger for other than isothermal-service requirements. The savings in the initial cost of a heat exchanger must be evaluated against a possible increase in operating costs.

For reasonable designs, the allowable pressure drops should be 5 psi, or higher for operating pressures in excess of 10 psig. In some instances, it is not practical to use all of the available pressure drop, because the resulting high fluid velocities could cause erosion or vibration damage to heat-exchanger components.

Heat-exchanger type and maintenance

Since there are many shell-and-tube heat-exchanger types to choose from, the preferred heat exchanger should be based on desired characteristics for utility and maintenance. The various types and construction features are shown in the "Standards of Tubular Exchanger Manufacturers Assn." (TEMA), and reproduced in this article for convenience (Fig. 1 and 2).



Shell types, and front- and rear-end head types, as defined by TEMA, for shell-and-tube heat exchangers **Fig. 1**

Courtesy of Tubular Exchanger Manufacturers Assn.

Comparative costs between the common types of heat exchangers can be derived from the graphs. Supplemental information is included further on in this article.

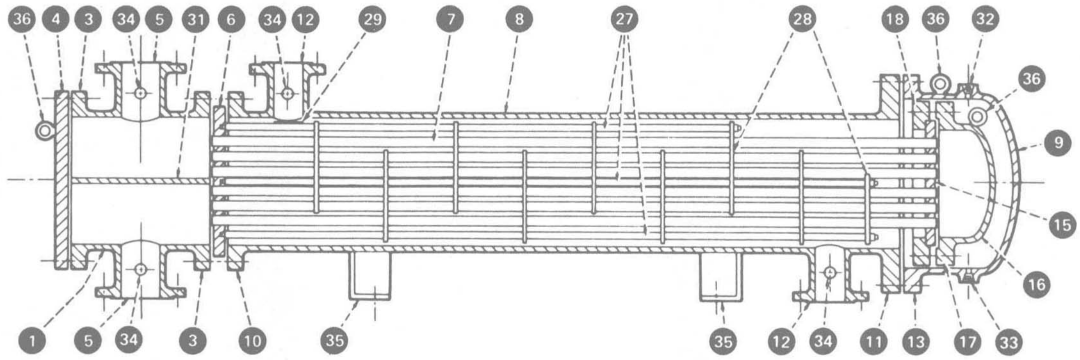
Users or purchasers are responsible for specifying design conditions and materials of construction, because these factors, plus the corrosion allowance and specified tube-wall thickness, are relevant to the service life of the equipment. Materials of construction are generally selected based on pressure-temperature requirements; corrosion resistance to the operating fluid streams; and economics, based on anticipated service life versus initial cost.

Careful consideration should be given to the selection of tube material and tube-wall thickness, because heat is transferred through the wall of a tube. There-

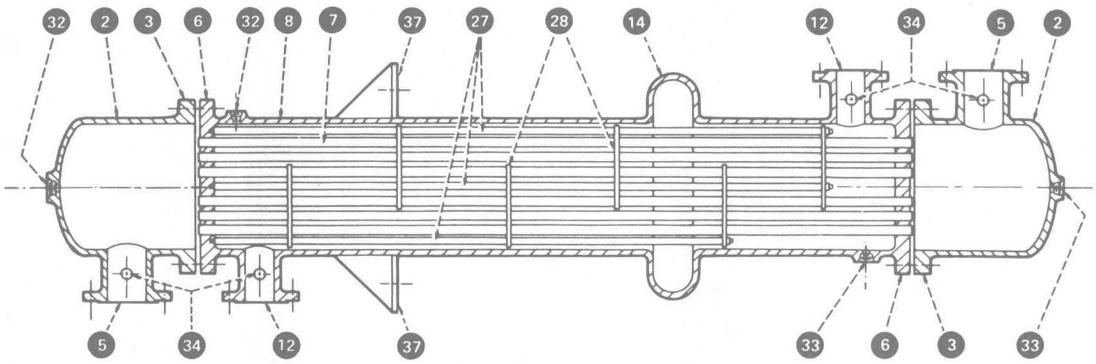
Nomenclature of heat-exchanger components

1. Stationary head—channel
2. Stationary head—bonnet
3. Stationary-head flange—channel or bonnet
4. Channel cover
5. Stationary-head nozzle
6. Stationary tubesheet
7. Tubes
8. Shell
9. Shell cover
10. Shell flange—stationary-head end
11. Shell flange—rear-head end
12. Shell nozzle
13. Shell-cover flange
14. Expansion joint
15. Floating tubesheet
16. Floating-head cover
17. Floating-head flange
18. Floating-head backing device
19. Split shear-ring
20. Slip-on backing flange
21. Floating-head cover—external
22. Floating-tubesheet skirt
23. Packing-box flange
24. Packing
25. Packing follower ring
26. Lantern ring
27. Tie rods and spacers
28. Transverse baffles or support plates
29. Impingement baffle
30. Longitudinal baffle
31. Pass partition
32. Vent connection
33. Drain connection
34. Instrument connection
35. Support saddle
36. Lifting lug
37. Support bracket
38. Weir
39. Liquid-level connection

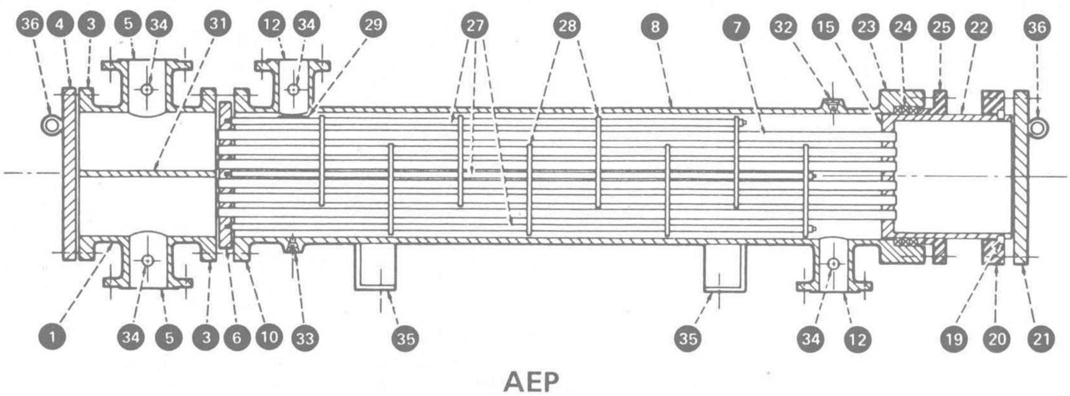
Construction types



AES

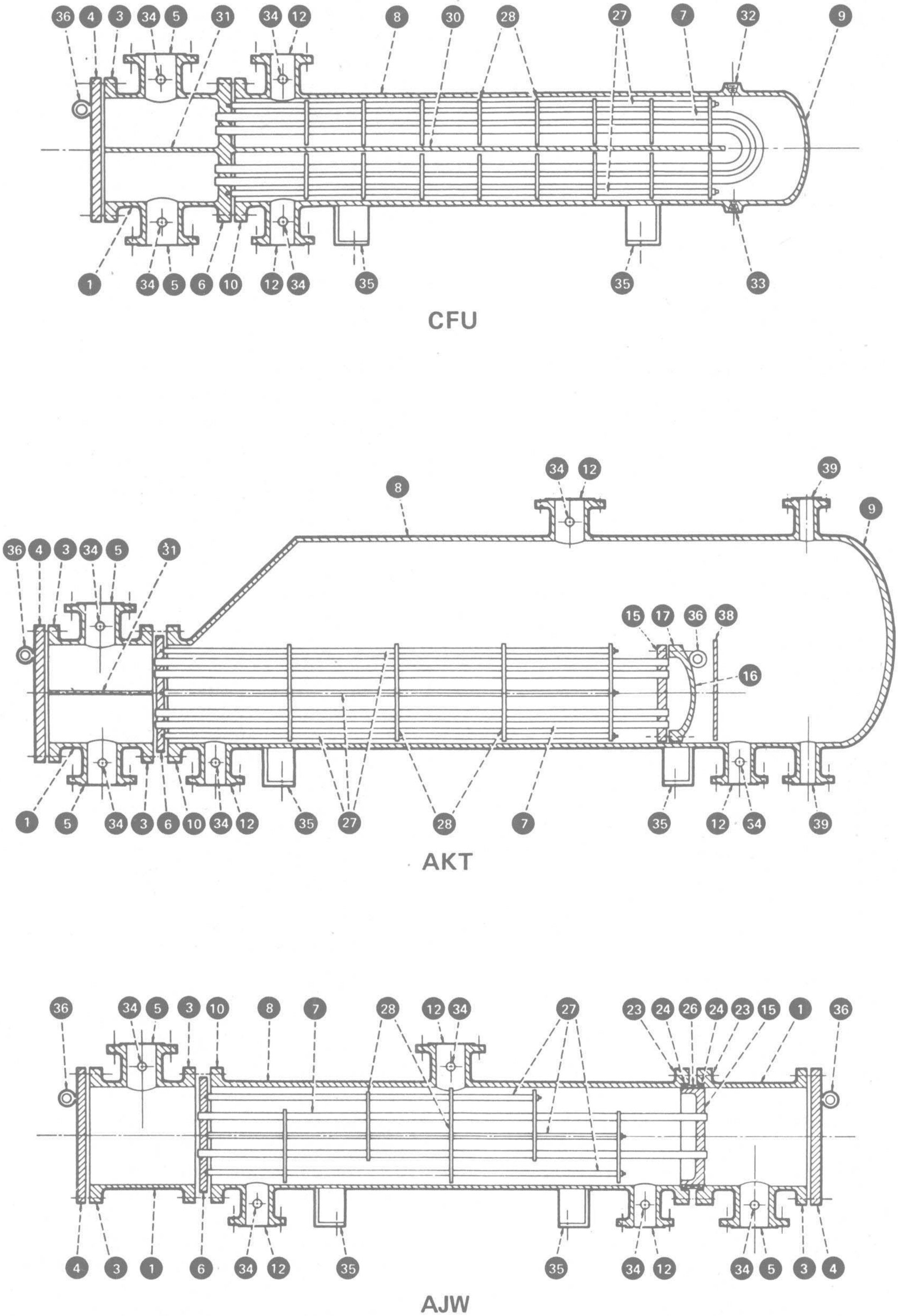


BEM



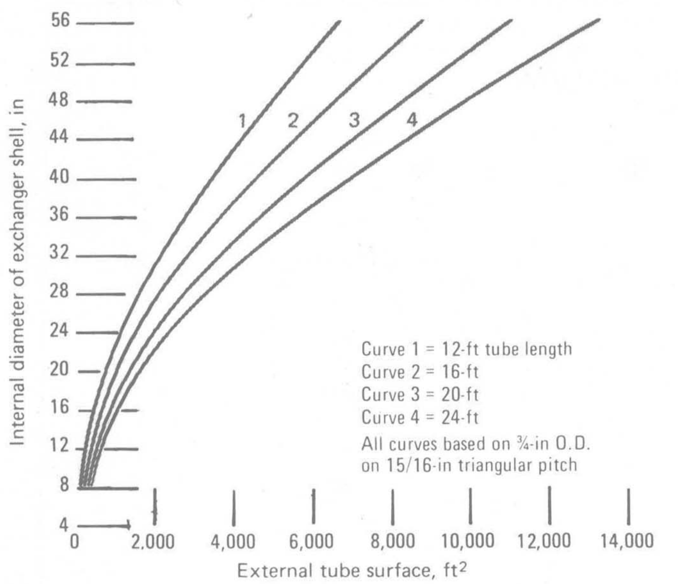
AEP

Construction types (cont'd)



Heat-exchanger construction types, showing their components and standard terminology — Fig. 2

Courtesy of Tubular Exchanger Manufacturers Assn.



Struthers Wells Corp.

Diameter of shell versus total tube surface **Fig. 3**

fore, desirable characteristics should include material with high thermal conductivity and a thin wall.

Fluid allocation

Physical-property data should be as accurate as possible. Data for specific heat, density and/or molecular weight, thermal conductivity and viscosity should be provided to the designer.

To determine which fluid should be in the shell and which one in the tube, consider the following factors:

Corrosion—Fewer costly alloy components are needed if the corrosive fluid is inside the tubes.

Fouling—Placing the fouling liquid in the tubes allows better velocity control; increased velocities tend to reduce fouling. Straight tubes allow mechanical cleaning without removing the tube bundle.

Temperature—For high-temperature services requiring special or expensive alloy materials, fewer alloy components are needed when the hot fluid is placed within the tubes.

Pressure—Placing a high-pressure stream in the tubes will require fewer high-pressure components.

Pressure drop—For the same pressure drop, higher heat-transfer coefficients are obtained on the tubeside. A fluid with a low allowable pressure drop should generally be placed inside the tubes.

Viscosity—Higher heat-transfer rates are ordinarily obtained by placing a viscous fluid on the shell side.

Flowrate—Placing the fluid with the lower flowrate on the shellside usually results in a more economical design. Turbulence exists on the shellside at much lower velocities than within the tubes.

Considerations by the designer

A heat-exchanger designer should be informed at the start regarding any size or space limitations for installation of the exchanger. Limited space can exist when the heat exchanger is to be installed in a building or within a structure with other equipment.

Restrictions on the size of a heat exchanger may affect the initial cost, because the designer may not be able to optimize the design. This is particularly true when restrictions are imposed on tube lengths.

In addition to being a specialist in heat transfer, a designer should have a firm grasp of mechanical design, fabrication, and costs of the equipment involved.

He must evaluate the many variables in establishing the following characteristics of the heat exchanger: (1) tube O.D. and length; (2) tube pitch; (3) number of tube passes; (4) number of shell passes; (5) number of baffles and baffle type; (6) number of shells; (7) fluid velocities; (8) actual pressure drops; (9) shell size; (10) fluid distribution at the inlet and outlet of the shell; (11) tube-to-tubesheet attachment; (12) ease of maintenance; and (13) vibration, operating differential-expansion between shell and tubes, and other potential problem areas.

Tube size and length

Heat-exchanger designs with small-diameter tubes (⅝-in to 1-in O.D.) generally are more economical than designs with larger tubes, because the smaller tubes provide for a more compact unit. However, the use of such small tubes may be prohibited by an extremely low allowable tubeside-pressure-drop. Normally, ⅝-in-O.D. tubes are the smallest considered for process heat exchangers, but there are some applications where smaller tubes may be better. Larger-diameter tubes are used when heavy fouling is expected, and when the inside of the tubes is to be cleaned mechanically.

Because tubes in the ⅝–1-in-O.D. range are normally common for shell-and-tube exchangers, tubes in these sizes are more readily available in various materials of construction. Under equal-velocity conditions, smaller tube diameters increase the heat-transfer coefficient, as well as the pressure drop.

Ordinarily, the investment per unit area of heat-transfer surface is less for longer heat exchangers. Therefore, the purchaser should avoid restrictions on length wherever possible. In addition to potential savings in construction through the use of longer tubes, higher heat-transfer rates (less surface) are possible in sensible-heat-transfer service.

Tube pitch or arrangement

In shell-and-tube heat exchangers, tubes are generally arranged on a triangular, square or rotated-square pitch. Although the tube pitch can vary for a given tube size, the designer should limit the center-to-center spacing to the minimum, as outlined in the TEMA Standards, for good mechanical design.

Triangular-tube patterns provide better shellside heat-transfer coefficients in sensible-heat exchange, and provide more surface area for a given shell diameter. Square-pitch tube patterns are generally used when mechanical cleaning of the outside of the tubes is necessary or expected. However, square- and rotated-square-tube patterns provide lower pressure drops, and, therefore, correspondingly lower heat-transfer coefficients in most cases involving sensible heat.