DESIGN AND APPLICATION OF TWISTED-TUBE EXCHANGERS

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Conventional baffled shell-and-tube exchangers, while having an excellent record of acceptance and functionality, have some notable limitations. In particular, the shell-side flow path is wasteful on pressure drop, limits maximum thermal effectiveness and encourages dead spots where fouling or corrosion may occur. This paper describes an advanced shell-and-tube design, known as the *twisted-tube exchanger*, which is inherently able to overcome these limitations in addition to providing the further advantages of tube-side enhancement and good tube support to reduce susceptibility to vibration. The paper compares the twisted-tube exchanger with conventional designs and with other advanced designs.

INTRODUCTION

The shell-and-tube heat exchanger is the most widely used single type with a market share of over 85 per cent for new exchangers supplied to the oil-refining, chemical, petrochemical, and power companies in leading European countries (1). They are flexible and robust units which can handle shell-side pressures up to 300 bar, tube-side pressures up to 650 bar and temperatures from -125 to +600°C. These ranges can be extended with special designs or materials.

Nevertheless, other heat exchanger types are taking market share from the shell-and-tube because of real and perceived advantages of these. This is especially so for pressures below 16 bar and temperatures below 200°C where many other types are available. Widely-used alternatives are gasketed plate-and-frame, plate-fin and spiral. The operating envelope of plate-type designs is being extended by developments in gasketing the introduction of welded construction. A leading plate manufacturer has estimated that the world market for compact (non-tubular) heat exchangers is increasing by 5 per cent per annum, that for plate-type by 10 per cent while the market for all types is only increasing by 1 per cent.

Given the flexibility of the shell-and-tube exchanger, there is considerable scope for advanced developments which overcome the known shortcomings in their conventional configuration. Such advanced developments give attractive alternatives to both conventional shell-and-tube and plate exchangers. The important new design, featured in this paper, is the *twisted-tube exchanger*. Before describing this, the shortcomings in the conventional shell and tube are discussed. Other methods for improving the basic shell-and-tube design have been developed and these are also briefly reviewed to give a complete picture of the relative benefits the twisted-tube exchanger.

SHORTCOMINGS IN THE CONVENTIONAL SHELL-AND-TUBE DESIGN

In the conventional TEMA-type (2) shell-and-tube exchanger, baffles are provided on the shell-side which both support the tubes and direct the shell side stream to flow across the tubes rather than along the tubes. This zigzag flow gives a relatively high pressure drop per unit of heat transfer because pressure drop is wasted in reversing the flow instead of enhancing the heat transfer. The high turnaround pressure drop as the flow passes around a baffle will tend to make more fluid than necessary leak through the tube-to-baffle and shell-to-baffle clearances thus giving lower crossflow and hence lower coefficients. Furthermore, the shell-to-baffle leakage tends to evade the bundle and hence takes no part in the heat transfer until it can re-mix with the crossflow at some point downstream. Baffles also tend to create dead spots or recirculation zones in the flow which give poor heat transfer and can promote fouling and corrosion.

The mean temperature difference (MTD) or thermal effectiveness (ε) in a shell-and-tube exchanger is almost invariable calculated assuming the ideal of perfect radial mixing of the shell side stream but no axial mixing. In practice, however, there is considerable axial mixing within a baffle compartment and, furthermore, the stream is in crossflow for part of the time rather than axial flow. These effects are complicated by the shell-to-baffle leakage stream and by the bundle-bypass stream which do not take full part in the heat transfer. The overall effect of this is that the true MTD and ε are lower than the ideal values and lower than the values obtained by other exchanger types which do not suffer from these problems. It is unusual, therefore to use shell-and-tube units when an effectiveness greater than 90 per cent is required. Typically, they are used in the range 60 - 80 per cent. A plate can readily achieve over 90 per cent while plate-fin exchangers are often designed for an effectiveness of 98 per cent in combination with temperature differences of 1 K.

THE TWISTED TUBE EXCHANGER

Far from being a new design, twisted tube exchangers have been available in Sweden since 1984 from Allards of Falun. Successful applications of the exchanger by Allards have included single phase and condensing duties in the power, chemical and paper industries. Since 1994 the twisted tube exchanger has been manufactured and marketed outside Scandinavia by the Brown Fintube Company who found a good synergy between this design and their technology of tube-side, twisted-tape turbulators.

Construction

The twisted-tube exchanger eliminates the baffles entirely by arranging for the tubes to support themselves. The tubes are formed into an oval cross section with a superimposed twist as illustrated in figure 1. It is stressed that this is done in a special, single-step process which ensures that the wall thickness remains constant and that the yield point is not exceeded. Good mechanical integrity of the tubes is therefore retained. Hydraulic tests have been carried out at pressures up to 1340 bar to obtain ASME code approval. The tubes are left round at the ends for conventional fixing into the tube sheet. They can be manufactured from a full range of materials including carbon steels, stainless steels, titanium and copper and nickel alloys.

The tube bundle is assembled a row at a time, turning the tubes to ensure that the twists are all aligned at every plane along the bundle length. This is illustrated in figure 1. As shown, this gives contact between adjacent tubes at many points along the tube. The bundle is strapped firmly by metal belts to give a very rigid construction. Figure 2 shows an assembled bundle and figure 3 a part-assembled bundle. These can be built with lengths up to 11 m and with shells up to 1.5 m diameter (corresponding to 3000 tubes), or even larger if necessary.

The shell-side flow follows a complex meandering path which is predominantly axial. Typically, the shell side flow area is approximately equal to the tube side flow area. The bundle is often shrouded to avoid bypass flows. Paths are available to allow the fluid to flow into and out of the bundle at the ends. When high inlet and outlet velocities must be avoided, "vapour belts" may be used as with conventional designs. The design imparts swirling flow to the tube side fluid. In order to increase design flexibility, twisted tubes and plain tubes may be mixed in the same bundle but this is only done when high thermal effectiveness is not required.

Advantages

Higher Thermal-Hydraulic Performance. Replacement of the zigzag flow with more uni-directional flow on the shell side gives a much higher heat transfer coefficient per unit of pressure drop. Typically heat transfer coefficients are 40 per cent higher for the same pressure drop or, conversely, pressure drops are halved for the same heat transfer coefficient. Furthermore, the swirl on the tube side enhances the coefficients by an amount similar to that of twisted tape inserts in a plain tube. The overall effect of this is a substantial reduction of heat transfer area for a twisted tube exchanger compared with a conventional exchanger for the same duty. Alternatively, significant improvements in the performance of an existing exchanger can be achieved by replacing a conventional bundle with a twisted-tube bundle.

Higher Thermal Effectiveness. The closer approach to pure plug flow on the shell side means that designs achieving higher thermal effectiveness, more typical of plate exchangers, are possible with twisted-tube exchangers.

Lower Fouling and Cleanability. The elimination of dead spots on the shell side and the increased turbulence induced, both on the shell side and the tube side, reduces fouling. Particulate fouling is reduced by the scouring action. Other types of fouling, like scaling and chemical-reaction, are prevented by the removal of hot spots. Fouling characteristics are, therefore, more akin to plate exchangers than shell-and-tube. The lower shell-side pressure drop for a given flow means that higher velocities are possible thereby reducing clogging with fibrous materials. Practical evidence of lower fouling comes from the pulp and paper industry where a conventional exchanger had to be cleaned every three or four weeks whereas the replacement twisted-tube exchanger only has to be cleaned with hot condensate. Should fouling occur, the twist alignment in the twisted-tube exchanger provides cleaning lanes even though a triangular pitch is used. Hence the cleanability of a conventional square layout is combined with heat-transfer-area density of a triangular layout.

Vibration Avoidance. Flow induced vibration can be occur in conventional exchangers although special designs, like "no tubes in the window" are available to overcome the problem by giving more tube support. The most damaging vibration arises from fluid-elastic instability which can lead to damage within a few hours of operation. The possibility if such vibration in twisted-tube exchangers is almost completely eliminated by going to axial flow and because the tubes are supported every 80mm or so. Clearly, there is some crossflow at inlet and outlet but the good tube support ameliorates this and the use of shrouds within a slightly larger shell provides additional inlet flow area before having to go to the expense of "vapour belts". Furthermore, the "cleaning lanes" mentioned above provide smooth paths for the flow entering and escaping the bundle.

Example Applications

The twisted-tube exchanger meets the requirements of TEMA, API 660 and all other major design codes. It can therefore be used in most of the applications for which a conventional shell-and-tube is specified. It also has many performance features hitherto only available from plate exchanger and can therefore be considered as an alternative to these.

Over 400 twisted-tube exchangers have been manufactured and sold since 1984 which includes nearly 60 produced by Brown Fintube in the last 12 months. The range of industries and applications to date is given in Table 1. Figure 4 shows an enstalled exchanger used as a power condenser. Table 2 compares twisted-tube with conventional shell-and-tube exchangers for actual applications. This shows heat-transfer-area savings of 20 - 50 per cent and cost savings of 20 - 30 per cent. All cases shown are for carbon steel exchangers.

TABLE 1. Applications of the twisted-tube exchanger

Industry	Application
Chemical	• Sulphuric acid cooling
	• Ammonia preheating
	• Hydrogen peroxide cooling/heating
Petroleum	• High pressure gas heating/cooling
	• Oil heating
	• Bitumen heating
	• LNG heating
Pulp & paper	• Black liquor heating/cooling
	• White water cooling
	• Oil heating/cooling
	• Effluent cooling
Power	• Turbine steam condensing
	• Boiler feedwater heating
	• Lube oil cooling
Steel	• Quench oil cooling
	• Lube oil cooling
	• Compressed gas cooling
Mining & mineral processing	• Liquor cooling
	• Effluent cooling
District heating	• Closed loop water heating
	• Steam heaters

TABLE 2. Examples of savings obtained by using twisted-tube exchangers

	Feed/bottoms exchanger	Lean/rich DEA	Crude oil cooler	MVGO product cooler
Shell side				
Fluid	Stripped water	Lean DEA	Crude oil	MVGO prod.
Temp. in/out (°C)	121/59	118/57	50/36	127/82
Operating press. (bar)	1.0	0.7	69	9.7
Tube side				
Fluid	Sour water	Rich DEA	Sour water	Water
Temp. in/out (°C)	38/94	36/93	18/23	52/79
Operating press. (bar)	5.5	5.2	5.5	5.0
Twisted tube				
Surface area (m^2)	441	71	512	102
Approx. cost ($k)	90	25	170	30
Conventional S&T				
Surface area (m^2)	893	107	833	201
Approx. cost ($k)	130	35	215	40

OTHER ADVANCED DESIGNS

Grid Tube Supports

An alternative way to achieve axial shell-side flow is to replace the segmental baffles with some form of grid support. The Phillips RODbaffle is the best known and most widely used system of grid supports (3 - 6). The system was developed in the 1960s to overcome vibration problems. The axial shell-side flow was also found to give the advantages already noted for twisted-tube exchangers; namely good heat transfer per unit pressure drop, good fouling avoidance and the ability to achieve high thermal effectiveness. They have to be made with a square tube layout thus providing cleaning lanes but also giving a lower heat transfer area density. Despite the extra turbulence generated by the RODbaffles, they do have a relatively low shell-side heat transfer coefficient. They can, however, be made with low-fin tubes to overcome this (4). Inserts are necessary if tube-side enhancement is required.

Baffles Giving Helical Flow

Helical shell-side flow has been seen for many years as an improvement over the conventional zigzag flow for providing a better conversion of pressure drop into heat transfer. A number of patented designs for specialist applications have been developed. Some of these designs involve continuous helical baffles. They tend to be limited to small exchangers with, say, maximum shell diameters of 140 mm and tube lengths of 1.2 m. These types are reviewed elsewhere (7, 8).

Breakthroughs in producing full-scale industrial exchangers with helical shell-side flow were made independently in Norway (9, 10) and what was Czechoslovakia (now the Czech Republic) (11, 12). Both groups hit on the idea of using quadrant baffles set at an angle. The Czech design was marketed for many years in Eastern Europe under the name *Helixchanger* by the research institute VUCHZ in Brno. It is now marketed by ABB Lummus Heat Transfer BV who have a paper on the helixchanger in this conference. The Norwegian design was marketed by Norsk Hydro AS under the name *Spiral Flow Heat Exchanger*.

These helical flow designs gave the expected improved conversion of pressure drop into heat transfer in addition to reducing dead spots and therefore fouling. The helixchanger involves conventional tube layouts and can therefore be made with square layouts to give cleaning lanes. A double helix arrangement is available to provide extra tube support to overcome possible vibration problems.

Detailed measurements by Næss et al (10) on the spiral flow heat exchanger showed that significant radial temperature variations can arise as a result of radial variations in flow, heat-transfer coefficient and heat-transfer area. They have therefore worked on special tube layouts which reduce this problem. The occurrence of such temperature variations would make this design unsuitable for duties requiring high thermal effectiveness. No precautions are taken with the helixchanger to mitigate this problem.

Summary Comparison

Table 3 summarises the qualities of the different heat exchanger types discussed in this paper.

TABLE 3. Summary comparison of the qualities of various shell-and-tube designs

	Twisted tube	Segmental baffle	Helical baffle	ROD baffle
Good heat transfer per unit pressure drop	Yes	No	Yes	Yes
Good fouling avoidance	Yes	No	Yes	Yes
Cleaning lanes with close triangular pitch	Yes	No	No	Not available
Tube-side enhancement	Yes	With inserts	With inserts	With inserts
Can give high thermal effectiveness	Yes	No	Only with special designs	Yes
Good for vibration avoidance	Yes	Only with special designs	With double helix	Yes

CONCLUSION

The construction, thermal characteristics and use of the twisted tube exchanger has been reviewed. It has been shown that this exchanger type has a number of advantages over the conventional shell-and-tube exchanger with segmental baffles, along with some advantages over other advanced shell-and-tube designs. It has also been shown that the twisted tube exchanger has some valuable characteristics previously only available from plate exchangers. It is therefore recommended that this type should be considered whenever specifying a shell-and-tube, plate or welded-plate exchanger.

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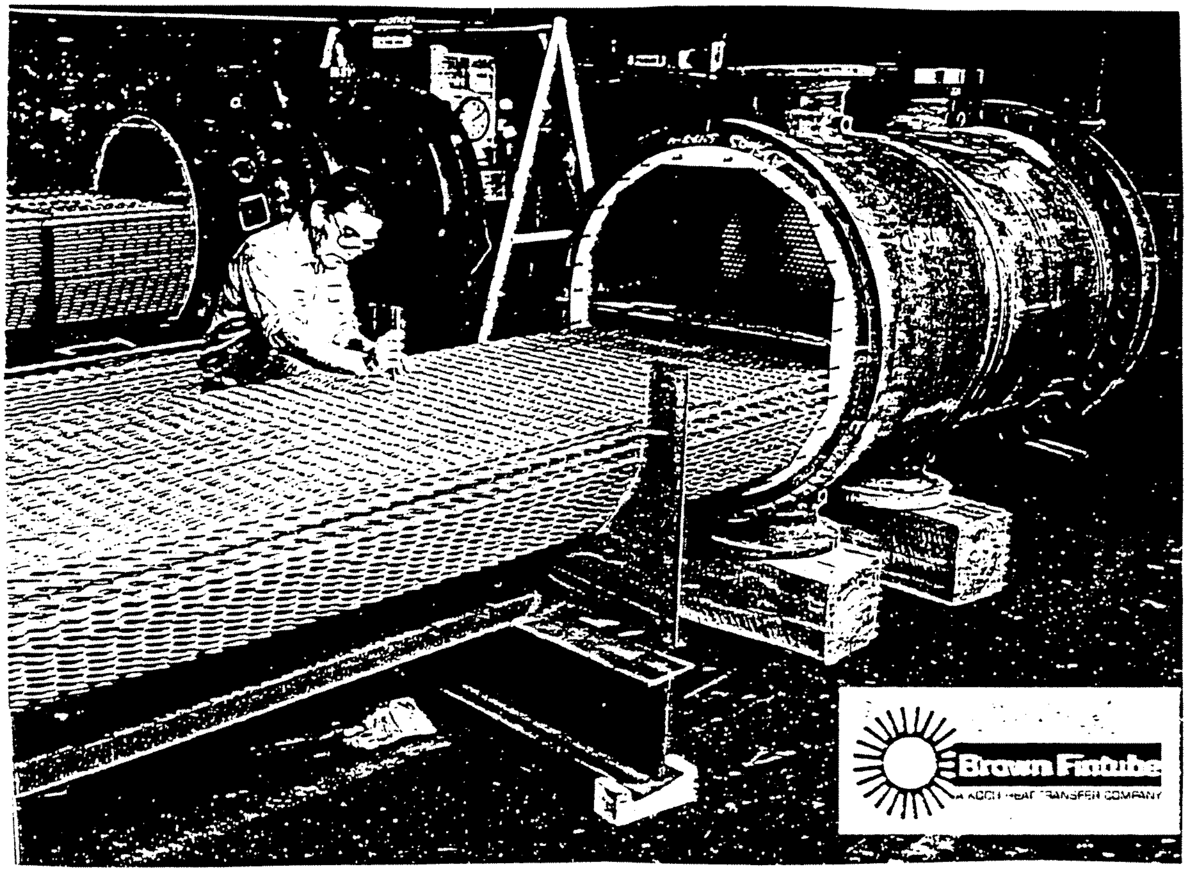

Figure 3. Bundle assembly

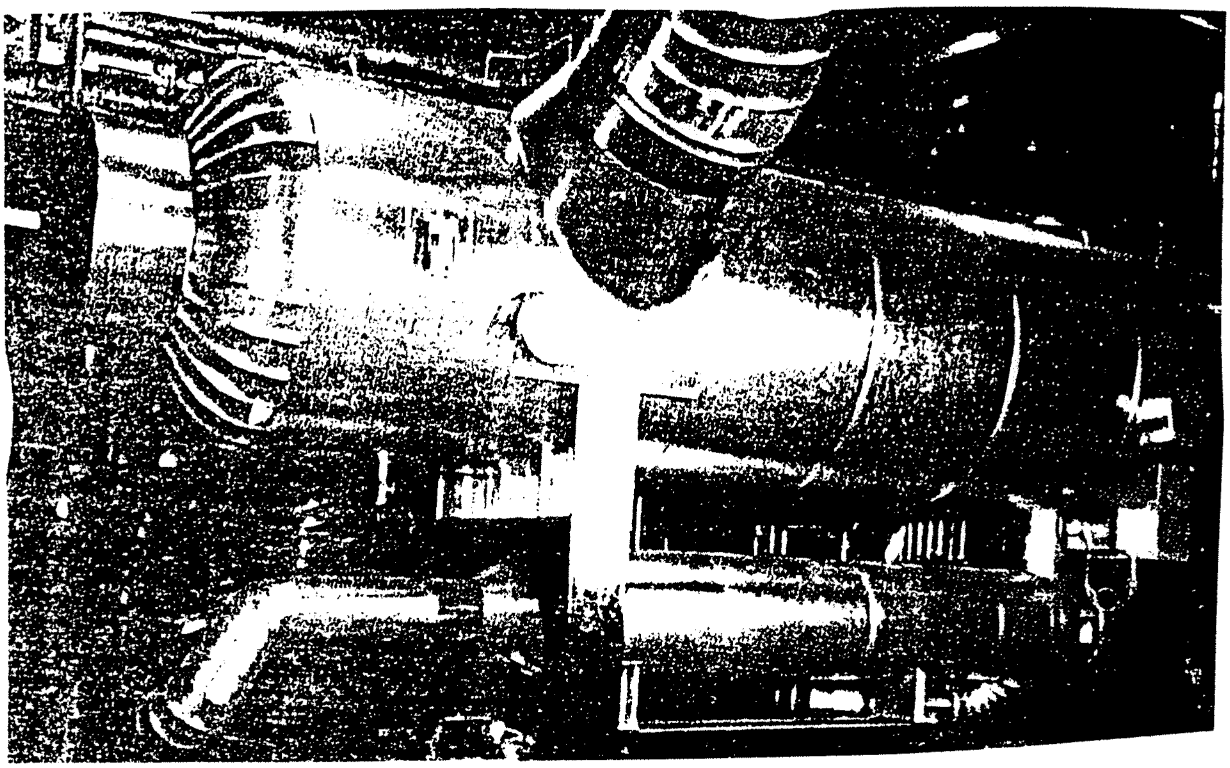

Figure 4. Twisted-tube exchanger as power condenser

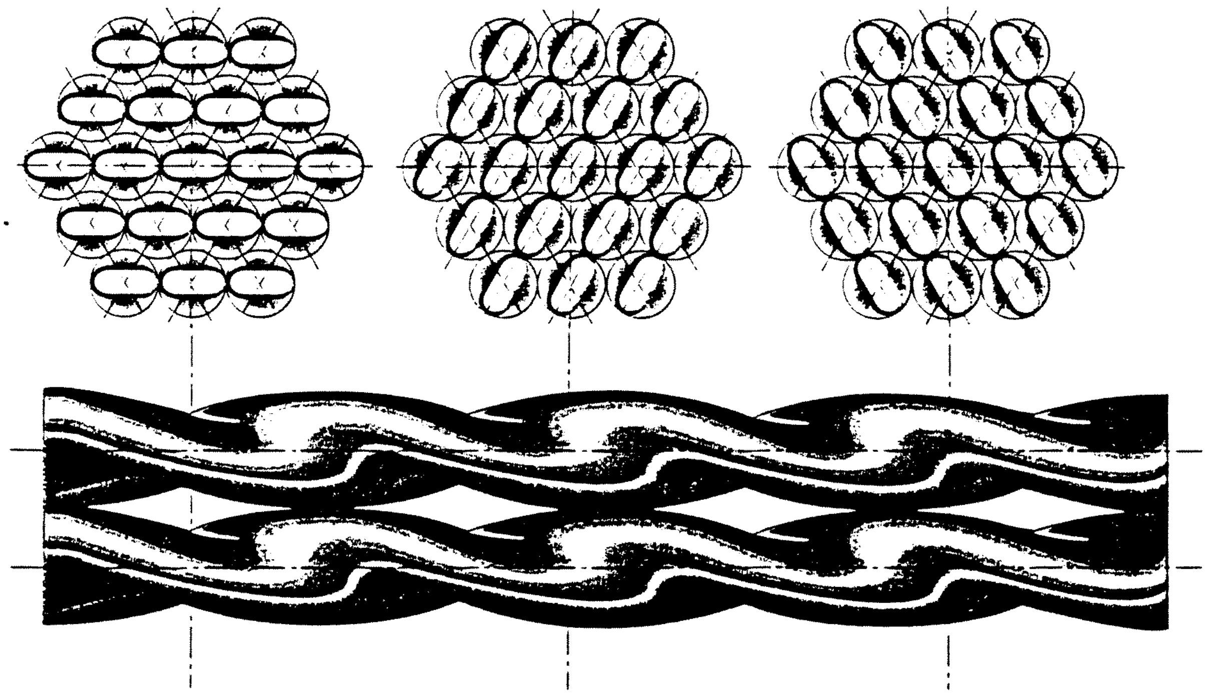

Figure 1. Twisted-tube bundle layout showing support system

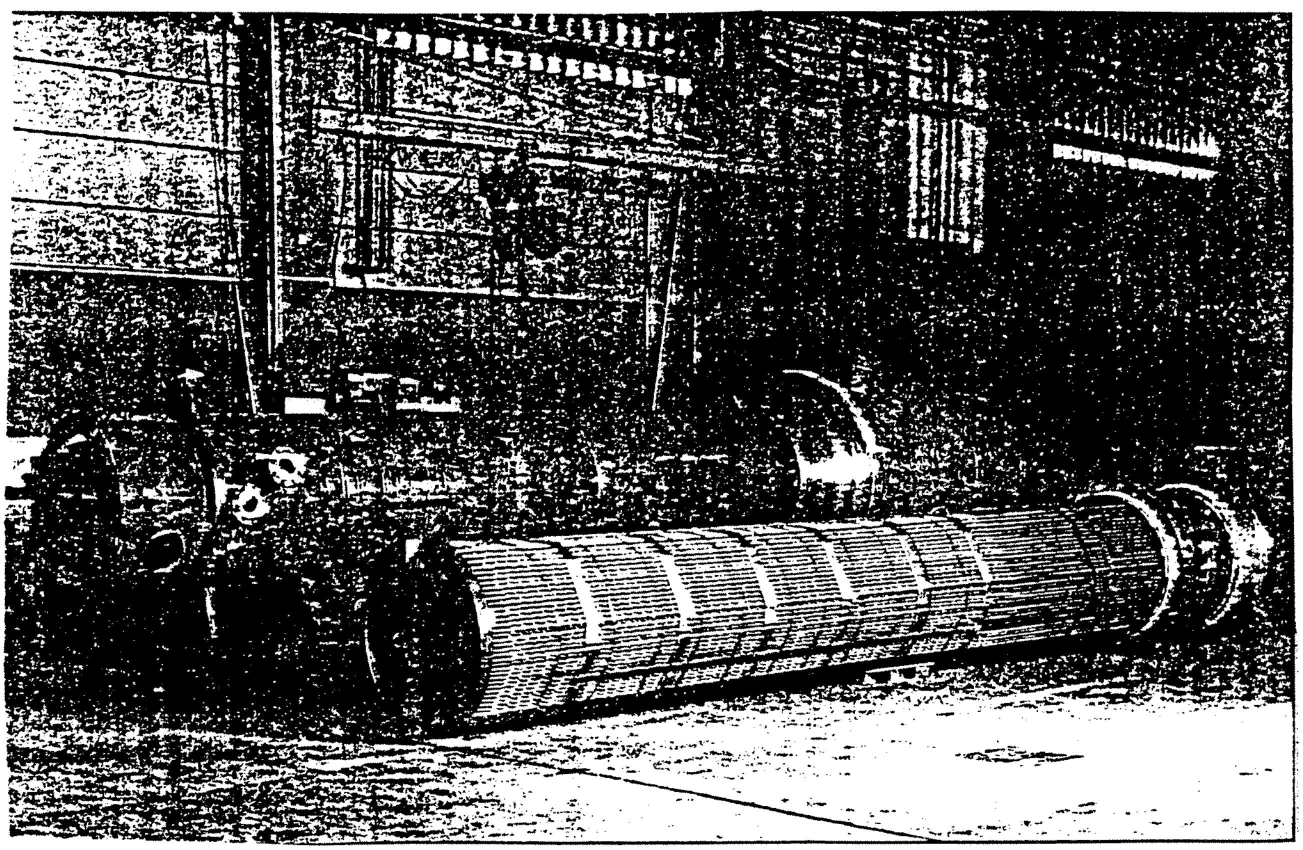

Figure 2. Fully-assembled bundle and shell