CASE STUDIES IN DEVELOPING COMPACT SHELL AND TUBE HEAT EXCHANGER DESIGNS WITH TITANIUM FINNED TUBE

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ABSTRACT

The use of titanium integral finned tube in shell and tube heat exchanger design contributes greatly to the development of compact designs. The increase in shellside heat transfer surface area, reduction in tube thickness for external pressure, fouling resistance, and applicability to severe services are demonstrated here with detailed case studies. A compact design increases the cost effectiveness of using titanium, or other reactive metals, in a heat exchanger.

KEYWORDS

finned tube, titanium, heat exchanger, Joseph Oat Corporation, High Performance Tube, Inc., compact, fine-fin, thermal performance

INTRODUCTION TO COMPACT SHELL AND TUBE HEAT EXCHANGERS

A compact shell and tube heat exchanger is one in which the heat transfer duty has been maximized within the unit's envelope. It offers the maximum amount of heat transfer for a given size of heat exchanger. As the size of the heat exchanger directly contributes to the cost (both in initial equipment cost and in surrounding structure cost), the compactness of the heat exchanger becomes an important consideration.

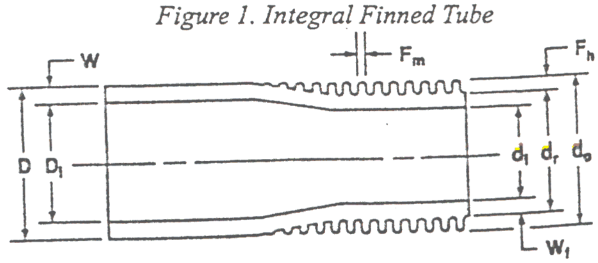
The general design goal for a shell and tube heat exchanger is to meet all the heat transfer, pressure drop, and vibration requirements within the minimum sized envelope. For maximum cost effectiveness when using titanium, or other reactive metals, the shell diameter and the tube length are to be minimized. Non-compact designs, with excess, inefficient, or ineffective heat transfer area, have large shell diameters, large foundation requirements, and high tubing cost. The shell diameter is especially important as thicknesses and weights of the shells and tubesheets increase significantly with an increase in diameter. Tubes must also be kept within reasonable lengths for plant layout.

In order to develop a compact shell and tube heat exchanger, the basic principles of heat transfer must be considered. The amount of heat transferred is a function of the heat exchanger geometry and configuration, the fluid thermal properties, and the heat transfer surface area. The geometry and configuration of the unit affects all of these parameters and must be varied until an optimum design is reached. The standard geometry and configuration options include, but are not limited to, baffle and support plate arrangements, placement of fluids, number of passes, tube patterns, and tube enhancements. All of these should be considered when designing a heat exchanger for cost savings.

TITANIUM INTEGRAL FINNED TUBE

Among the various means for maximizing the heat transfer duty within a given shell size, the means that this paper is primarily concerned with, is the use of extended or enhanced heat transfer surfaces. For shell and tube heat exchangers, integral finned tubes are the standard method of obtaining enhanced heat transfer surface. A detail of an integral finned tube is shown in Figure I.

Figure 1. Integral Finned Tube

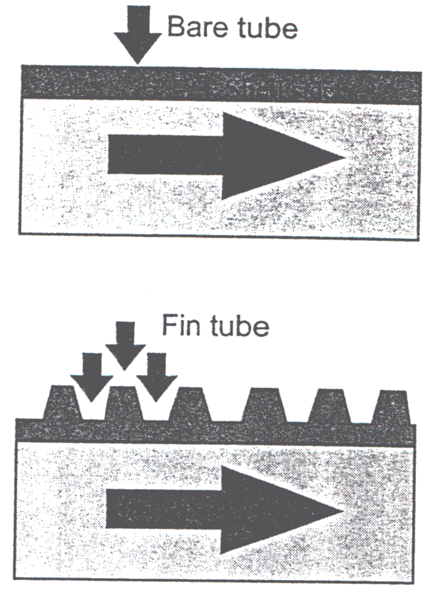


Integral finned tube has been available for many years in a variety of materials from carbon steel to stainless steels, copper alloys, nickel alloys, and aluminum alloys, as well as the reactive metals titanium and zirconium. Consequently, their benefit to heat transfer due to increased available surface area are well known and remain the primary reason for selecting integral finned tubes for a shell and tube heat exchanger application. Heat exchangers that are more compact than comparable bare tube units are possible with finned tubes.

The use of titanium finned tubes leads to compact heat exchangers because of the increased shellside surface area per unit length. The typical increase in area for finned tubes versus bare tubes is greater than $2 1/_2$ times. Taking advantage of this increased area by placing the flow with the poorer film coefficient on the shellside of the heat exchanger is the primary way of utilizing the benefits of the integral finned tube. Figure 2 shows pictorially the process of balancing the film coefficients on both sides of the tube. Using finned tube in place of bare tube in a heat exchanger design could result either in a unit with the same duty in a much smaller envelope or in a unit with the same envelope with a much higher duty.

In addition to the heat transfer benefits of titanium finned tube, several other factors should be considered to extend the usefulness and benefits of titanium finned tube in compact heat exchanger design. These factors include: 1) the contribution of the fins against collapse of the tubes for high pressure service, 2) the suitability of finned tube for fouling service, and 3) the retention of the corrosion resistance of the original metal in finned tube. These factors will each be discussed below and demonstrated through a case study of the design and operation of a wellstream production cooler on an offshore oil platform.

Figure 2. Balancing Film Coefficients



SHELL AND TUBE HEAT EXCHANGER CONFIGURATIONS

All of the standard heat exchanger geometry and configuration options listed above are compatible with finned tube design. This includes the various baffle and tube-support arrangements. Standard plate baffles block the shellside flow from running along the tubes and force it to run across the tube-field. These can be used in segmental or in "no tubes in the window" arrangements. These tend to yield high heat transfer coefficients because of vigorous cross-flow. Other tube-support arrangements, such as Rod-Baffles® by the Phillips Petroleum Company and Strip-Baffles™ by the Joseph Oat Corporation, allow axial flow for lower pressure drop, although the heat transfer coefficient may be less than for plate baffles. A hybrid baffle arrangement, the Helixchanger® by ABB-Lummus, allows flow to spiral through the tube-field, neither fully axial nor fully cross-flow. The goal, with all of these baffle or tube-support arrangements, is to maximize the heat transfer duty in as compact a shell as possible. Different applications, with different fluids and requirements will result in different configurations; no one configuration is always better than another. One kind of arrangement may have a high heat transfer coefficient but have a small surface area, thus having a lower duty than an arrangement with a lower heat transfer coefficient and a larger area. The use of finned tube should also be considered in addition to these other options. A successful design is the one in which the heat transfer, pressure drop, and vibration requirements are met in the smallest envelope.

CASE STUDY HEAT EXCHANGER DESIGN PARAMETERS

The unit used for the case study is the well-stream production cooler on the Chevron, South Nemba offshore oil platform off the coast of Cabinda, Angola, West Africa. The platform was designed and constructed by Daewoo, of the Republic of Korea. The Joseph Oat Corporation designed and built this heat exchanger as a compact heat exchanger, using titanium finned tube. A well-stream test cooler, smaller but of the same design, was also designed and supplied for this platform. Delivery was in March 1997 to the platform manufacturer. The platform was erected and under operation by mid 1998. The platform operator, Chevron, is pleased with the performance of the titanium finned tube units.

The service of both sides of the heat exchanger lead to the use of titanium for the tubes, tubesheets, and all the bundle material. The shellside of the heat exchanger receives and cools the two-phase, dirty well-stream flow directly from the well-head. The cooling medium, on the tubeside, is seawater, draw up from the surrounding waters. Both streams are challenging services for corrosion, fouling, and erosion. The material selected to handle them was SB-338 welded titanium Grade-2 tube. All the parts of tube bundle (tubesheet, baffles, tie-rods, and spacers) were also required to be titanium and the tubesheets were fabricated from SB-381 F2 forgings, 187 mm thick.

It is evident that cost was an important consideration in the specification of materials for this unit. While the service of the unit pushed the tubes, tubesheets, and bundle material to titanium, the shell and the channel of the heat exchanger remained lower cost alloys. The shell, for the well-stream service, was 904L lined carbon steel, which is a common material for sour gas service. The channels, for the seawater service, were permitted to be any ferrous or nickel alloy containing 6% molybdenum; Avesta 254SMO, Allegheny AL6-XN, or Inco 25-6 were acceptable materials.

The units are two TEMA Type AEU heat exchangers in parallel with removable U-bundles and mounted horizontally. The design process parameters for flow and heat transfer for two shells is shown in Table I. The removable bundle design was specified for cleaning and allowed the use of the differing materials detailed above.

As this is an offshore oil platform, foundation space and weight are considered design criteria nearly as important as the thermal performance of the unit. From the platform layout, a maximum tube straight length of 4 meters was identified. This length would keep the heat exchanger plus its bundle pullout clearance to within the allotted foundation space.

Table I. Heat Exchanger Design Parameters

Fluid	WELL STREAM		SEA WATER	
Total Flow [kg/hr]	2,437,552		10,196,226	
Vapor (in/out)[kg/hr]	638,396	462,160	0	0
Vapor (in/out) [kg/hr]	1,799,156	1,975,392	10,196,226	10,196,226
Temperature (in/out) [C]	115.6	43.3	23.9	35.0
Dew Point [C]	115.6		---	
Inlet Pressure[MPa ga.]	3.79		0.31	
Design Pressure [MPa ga.]	4.53		1.59	
Test Pressure [MPa ga.]	6.86		2.41	
Fouling [$m^2 \cdot K/W$]	0.00053		0.00018	
Heat Duty [W]	27,089,454			

During the design phase of this project, both finned and bare tube options were developed and considered. For each tube option, designs that met all the heat transfer, pressure drop, and vibration requirements were completed. Then the compactness, weight, and foundation space were compared and the final designs were chosen. The resulting designs are shown in Table II below. In all respects, the finned tube design, which was chosen, is a more compact heat exchanger than the bare tube unit. The table shows that the finned-tubed unit costs and weighs approximately 40% less than the bare-tubed unit. Both of these indicate significant cost savings for the finned tube design. The Joseph Oat Corporation put the finned-tubed option forward in our bid for this contract, showing its technical and cost advantages.

DETAILED TUBE DESIGN

To use finned tubes to advantage in this application, several technical issues were to be addressed. On the unit addressed in this case study, these issues were 1) tube external pressure, 2) fouling concerns with fin-tube, and 3) corrosion resistance of the fin surface.

External Pressure

The finned tube chosen, for heat transfer and cost savings reasons was the High Performance Tube (HPT) number 365028, which has a 0.71 mm (0.028") average wall under the fins. However, the shellside design pressure and test pressure of this unit requires a 1.24 mm (0.049") average wall tube. This calculation is done per standard ASME Section VIII-1 external pressure formulas and charts, which do not consider the stiffening contribution from the fins.

A code case was written by the Joseph Oat Corporation that considers the stiffening contribution from the fins. The ASME Boiler & Pressure Vessel Code Committee approved it as Code Case 2149 on April 27, 1993. The case is written for SB-338 titanium tubing with integral fins in the range between 1181 and 1693 fins/m [30 and 43 fins/in]. The case involves collapse testing of three tube samples and then developing a maximum allowable external working pressure from the test data.

Table II. Bare/finned Heat Exchanger Comparison-two Shells in Parallel

	Finned tube HX		Bare tube HX	
Number of tubes	589 Units		1093 Units	
Tube straight length	3.66 m	12 ft	3.96 m	13 ft
Tube Description	HPT #365028 19 OD x 0.71 mm avg. under fin	$^3/_4$" OD x 0.028 avg. under fin	19 OD x 1.24 mm avg.	$^3/_4$" OD x 0.049 avg.
Total tube length	5014 m	16,450 ft	10640 m	34,910 ft
Total tube weight	1602 kg	3532 lb	3390 kg	7474 ft
Shell inside diameter	1159 mm	45.6 in	1727 mm	68.0 in
Weight	12500 kg	27500 lb	21800 kg	47950 lb
Total length	8.7 m	28.5 ft	9.6 m	31.5 ft
Fundation area	13.8 m^2	149 ft^2	21 m^2	226 ft^2
Equipment cost	$710,800		$1,242,000	

Use of the case increases the maximum allowable external working pressure of the HPT 365028 from 3.9 MPa to 12.0 MPa at design conditions. For reference the shellside design and test temperatures are 4.53 MPa and 6.86 MPa. The use of the Code Case 2149 eliminated an unnecessary 75% increase in tube weight and a decrease in heat transfer rate. Using the test data for a HPT 365028 tube, it can be seen that significant wall thickness savings can be realized if shellside pressures are high. This tube, with a thickness of 0.711 mm under the fins could be used with a shellside pressure of up to 12 MPa, whereas a 1.65 mm wall bare tube would have been required.

The Code Case 2149 has been subsequently validated by the Code Committee. As of the 1998 Edition of the Code, this Code Case was incorporated as Mandatory Appendix 23. (1)

Fouling Service

The shellside service, in which the unit is placed, is a severe fouling service. The shellside stream flows directly from the wellhead, through this heat exchanger, for cooling. Concern was raised that the fins on the tubes would act as small crevices or crud traps and would foul the tubes more quickly than if they were bare. Literature research showed that the opposite is true. This literature, some dating back to the 1960s, is the product of field research in refineries of finned tube applications in very dirty services. The findings were that, at worst, finned tubes were no more difficult to clean than plain tubes. Indeed, there was some indication that finned tubes would not foul as readily as plain tubes and that once dirty, they might be easier to clean (2). A photograph is attached showing selective fouling on bare tubes where a finned tube remains clean.

The results of this research and field study confirm that the finned tubes selected are suitable for the well-stream coolers. This was further confirmation for the design selection of finned tube.

Corrosion Resistance

Titanium was selected in this application for its corrosion resistance in severe services. In order to use finned titanium tube, it should be demonstrated that work hardening during the finning process does not reduce the corrosion resistance of the metal. Both corrosion tests and hardness studies have been performed by High Performance Tube (5) on finned tubes. Zirconium, Hastelloy, and titanium have been studied and no discernable decrease in corrosion resistance was discovered.

The studies confirmed the benefits of the finning process. The fins are rolled into the tube, rather than being cut. Consequently, the finned surface was found to be smooth with no discontinuities or tearing as would be expected in a machining process. The customer specified titanium for its corrosion properties and selection of finned tubes maintains these properties.

Well-stream Production Cooler Summary

Using the heat transfer advantages of titanium finned tube, as well as the high collapse pressure, fouling resistance, and corrosion resistance, a compact shell and tube heat exchanger was designed, fabricated, and delivered to a satisfied customer. The advantages of titanium finned tube were used to reduce the size and cost of the unit, while meeting all the thermal performance and service requirements.

A SECOND CASE STUDY: DE-BOTTLENECKING WITH TITANIUM FINNED TUBE

In this case study, a compact heat exchanger design is used to advantage, not for reduced size, but for maximizing performance within a given envelope. PT Badak in NGL Co., in Bontang, East Kalimantan, Indonesia needed to improve the corrosion resistance and heat exchange capacity of the refrigerant compressor after-coolers. Certain vibration problems were to be resolved in the new design. The existing units were copper-nickel bare tubed heat exchangers using seawater on the tubeside to cool the high-pressure refrigerant on the shellside. Titanium was chosen as the metal to combat the corrosion problems and a Phillips RODbaffle system was chosen to solve the vibration problems.

The titanium bare tube design proved to be too costly. The heavy tube wall thickness from the high shellside pressure and the lower thermal conductivity of titanium contributed to a shell size that was much larger than the existing units. The resulting cost per unit was approximately $3.2 million, not including the cost for foundation and piping rework.

A titanium finned tube design was then developed that met the performance requirements within the size of the existing units. High Performance Tube #365028 with 1417 fins/m (36 fins/in) and 0.711 mm (0.028") tube wall thickness was used. The Joseph Oat Corporation justified the use of such thin tubes by considering the stiffening effect of the fins according to ASME Code Case 2149. The result was that these heat exchangers cost approximately $1.6 million each and no foundation or piping rework was necessary. This represents a 50% cost savings over the bare tube design.

Once installed, these heat exchangers exhibited a 47% increase in heat exchange capacity over the previously existing units. A subsequent compressor retrofit project increased the plant capacity by 11%. This increased capacity was realized at the same time as corrosion and vibration problems were eliminated.

CONCLUSION

From the case studies shown above, it can be seen that the use of titanium finned tube can contribute greatly in the development of compact shell and tube heat exchanger designs. The benefit of compact shell and tube heat exchanger designs is that they lead to cost savings either in original equipment and installation cost due to reduced size, or in increased production economies due to increased capacity.

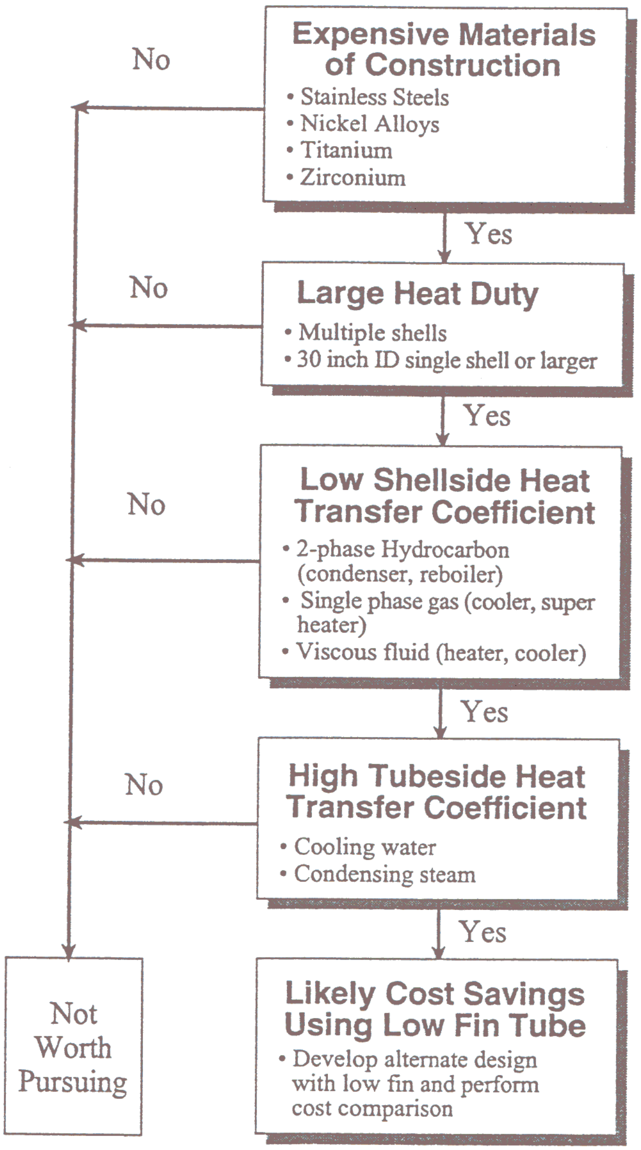
Figure 3. When to Use Titanium "Fine-Fin"

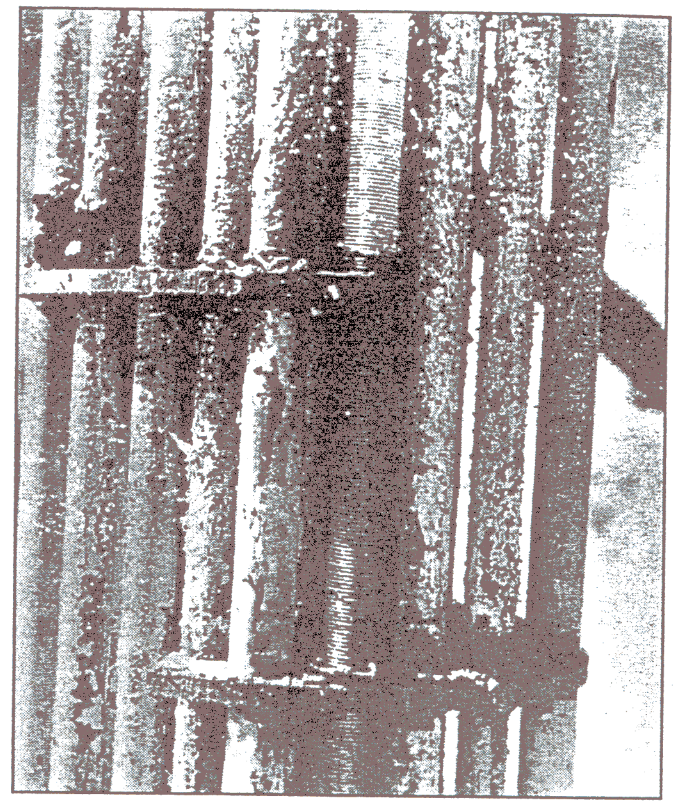
- Shell side heat transfer coefficient is controlling
- Sea water tube side
- Shell side gas being cooled or condensed
- Space is limiting
- Debottlenecking existing heat exchanger
- Condensing steam tube side/boiling shell side

When is it beneficial to use titanium finned tube in a heat exchanger design? Figure 3 shows a list of services where finned tube has been used successfully. Figure 4 is a decision tree for the development of compact heat exchanger designs. This decision tree is a general guideline for when to consider titanium finned tube; the actual decision should be made after both an optimum bare tube design and an optimum finned tube design have been developed and compared. The successful design will be the one that meets the all the design requirements in a minimized size, thus increasing the cost effectiveness of using titanium in a heat exchanger design.

The photograph following demonstrates a finned tube's unique tendency to repel fouling in a bundle where bare tubing does not. Here, we are condensing steam on the tubeside and superheating process cooling tower water on the shellside. The fouling matter is crystalline and also contains deposits of mud and other detritus. Here, the single finned tube remains clear of fouling matter and the bare tubes do not.

Figure 4. A Decision Tree for the Development of Compact Heat Exchanger Designs





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