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STRENGTH DESIGN ASPECTS OF HEAT EXCHANGERS WITH FIXED TUBE SHEET

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Abstract
The aim of this study is to present a short but comprehensive presentation of the strength dimensioning of one of the most common chemical equipment, the heat exchanger, in particular the shell-and-tube type. This equipment is classified as a pressure vessel, which means all aspects of design, manufacture and investigation are subject to standard specifications. As these heat exchangers are essential equipment for the chemical industry and related technologies, they typically operate at pressure other than atmospheric, the operation is also subject to regulatory requirements, which are contained in the Pressure Equipment Directive (PED) specifications. This article summarizes the design aspects of the tube sheet, a typical structural element of the shell-and-tube heat exchangers.

Keywords: *shell-and-tube heat exchanger, tube sheet, comparison, design calculation*

1. Introduction

Heat exchangers are chemical devices that transfer heat between usually two or, less often, several media of different enthalpies without mixing the media. It is difficult to name an area where this type of equipment does not operate. They are used in chemical plants, pharmaceutical factories to provide the temperature required for chemical processes and reactions, and in the food industry to provide the energy required for preservation or distillation (Kállai et al., 2018). This also includes the electricity sector. Whether the electricity comes from nuclear or fossil power plant, in both cases a steam generator connects the two water circuits (Goldberg and Jabbour, 1965). But they are not only used in industry, but also in households and transportation. Examples of the former are air conditioning and heating systems, and the latter are automotive radiators.

As mentioned earlier, the media do not mix during the heat transfer process. To increase the amount of heat transferred, the geometry of the heat exchanger and the flow conditions can be modified. These two characteristics, together with the phase properties of the flowing media, influence the type and geometric dimensions of the heat exchanger (Tjelta, 2012; Beldar and Komble, 2018). Some parameters that influence the design are described below.

For heat-sensitive materials or for low flow rates, a double pipe design should be used. In this case, the equipment is composed of only two concentric pipes. The heat transfer surface is relatively small compared to the dimensions of the enclosure. From a safety point of view, however, these are among the safest installations, as the probability of tube rupture and other resulting problems is very low.

Plate heat exchangers are advantageous for low pressure and low flow applications. These types have the highest heat transfer surface/volume ratio.

In cases where one of these media is gas phase (for example some process gas needs to be cooled or preheated, or ambient air is to be used for some cooling function), it is advisable to use finned tube heat exchangers. In these types of heat transfer processes, the heat transfer coefficient on the gas side is usually an order of magnitude lower than the heat transfer coefficient on the liquid side, so that the heat transfer performance can be achieved by increasing the heat transfer surface area, which is called fin tube heat exchangers. There are several techniques for increasing the surface area, which can be grouped according to the geometry (circular fins, rectangular fins, spiral fins), the way they are formed on the tube (radial or axial fins), the internal and external surfaces, or as louvered fins. Their most common application is in vehicle radiators. The present article was not intended to investigate the thermal performance of this type of heat exchanger, research in this field is available in the author's doctoral thesis and related articles.

If none of the limiting factors mentioned above apply, the right choice is a shell-and-tube heat exchanger. With these devices, almost all factors affecting heat output can be increased. A working schematic of such a shell-and-tube heat exchanger is shown in *Figure 1*.

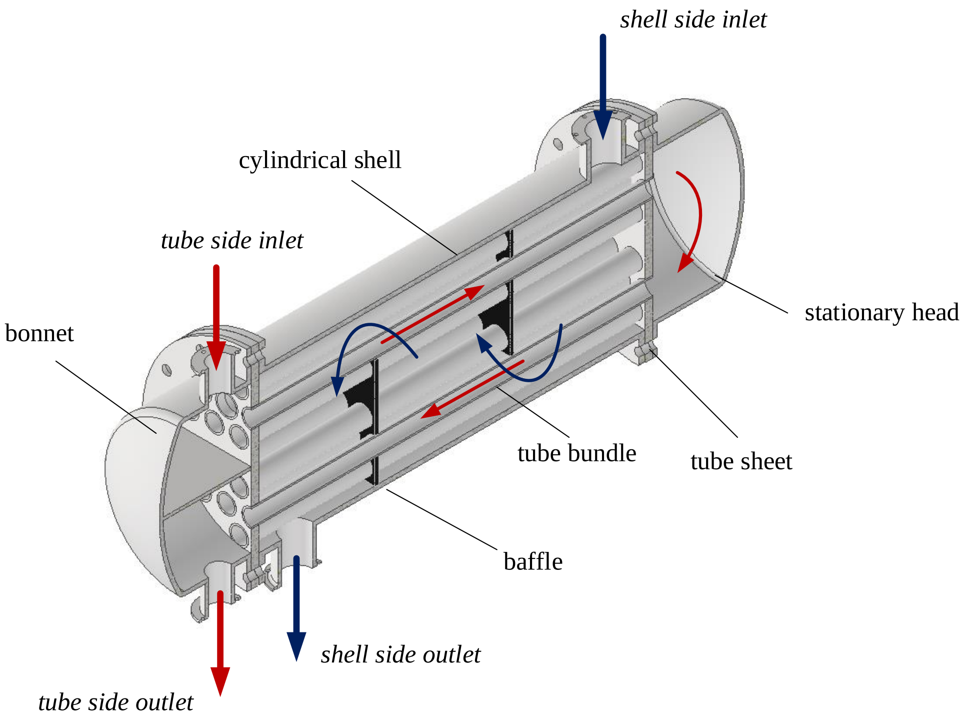

Figure 1. *Main parts of a shell-and-tube heat exchanger with flow direction*

As can be seen in *Figure 1*, this type of heat exchanger consists of 4 main parts: the shell, the tube bundle, the dished ends or heads and the tube sheets. Of these, the shell has the simplest function: it withstands the pressure in the shell side, and feeds and discharges the medium in the shell space. Its dimensions are identical to those of the shell of any other pressure vessel. A similarly simple function is performed by the heads, where the base load becomes the tube side pressure. It will be seen, however, that depending on the type of tube sheets, their design can already vary, to reduce the thermal loads, as discussed in Section 2. Pressure and temperature conditions, installation and maintenance details have led to a variety of designs, making their identification problematic. To remedy this, the Tubular Exchanger Manufacturers Association, (TEMA) was formed in 1939. The organisation groups heat exchanger equipment according to the type of shell and vessel bottom and provides recommendations for designers and operators (Krisdiyanto et al., 2021). They are currently on the 10th edition, which was published in 2019. In addition to the classification, it contains general information on manufacturing tolerances, production, installation, maintenance, strength design standards. It also includes knowledge of potentially dangerous phenomena that can occur during operation, such as vibrations caused by flow, phenomena resulting from thermal expansion, and the physical-chemical properties of materials. It should also be noted here that there is also a classification of this equipment depending on the industry. Equipment for general use is marked with the letter C, equipment for refineries and petrochemical plants with the letter R and equipment for chemical processes with the letter B.

The role of the tube bundle is not limited to strength aspects. Its function is to separate the two flowing media from a flow point of view and to connect them from a thermal point of view. The geometry of this structural element determines two of the factors that influence the thermal performance of the installation. On the one hand, the size of the heat transfer surface, which is proportional to the diameter of the tubes (external and internal diameters), the number of tubes and the length of the tubes, and on the other hand, it has a significant influence on the resulting heat transfer coefficient. Bearing these aspects in mind, it can be said that pipes with smaller diameters will result in a better structure from a strength point of view, since the reduction in diameter will result in a positive behaviour under both internal and external compressive loads. Although not the purpose of this article, it is worth outlining the changes in thermal behaviour (Ukadgaonker et al., 1996; Soler and Hong, 1984; Soler, Caldwell and Singh, 1987). Reducing the diameter has a positive effect on the heat transfer surface (more tubes can be placed in the same jacket), but a negative effect on the heat transfer coefficient. To demonstrate this, see *Figures 2–4*. To ensure comparability, the following boundary conditions were used. In this section, we started with the relationships and material properties given in the European EN 13445 and the compatible EN 10216 standards. The shell and the tubes shall be made of seamless P235GH material, and the shell size is Ø219,1 × 6,3. The sizing temperature is 200 °C, the length of the tubes is 2 m, the pitch is 1.25 times the outside diameter of the tube, the wall thickness was a constant 2 mm and the tubes are standard triangular pitch.

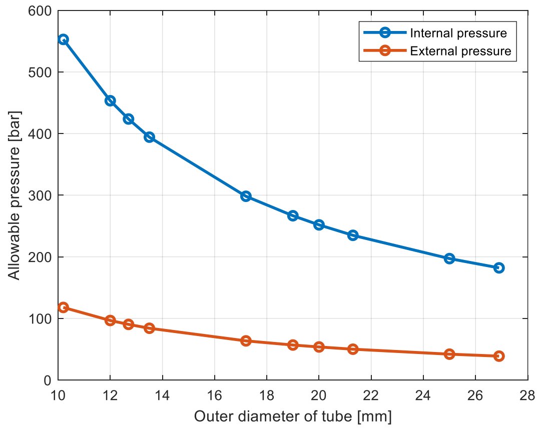

Figure 2. *The allowable internal and external pressures in the function of tube diameter*

Figure 2 shows the maximum allowable internal and external pressures as a function of the external pipe diameter. The figure clearly shows the conclusions drawn earlier, i.e., for a constant wall thickness, a decreasing diameter will improve the load carrying capacity. For this check, the number of tubes is still irrelevant.

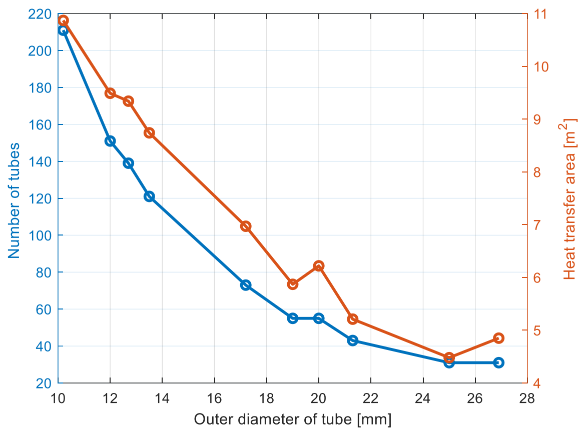

Figure 3. *Tube numbers and heat transfer area in the function of tube diameter*

Figure 3 shows the number of tubes and the heat transfer surface area for the selected tubes. Obviously, the two curves shown will follow a similar trend, but the number of tubes that can be placed in a given envelope space is of great importance. Two diameters need to be noted here. The same number of tubes with outer diameters of 19 and 20 mm and 25 and 26.9 mm can be installed, but the heat transfer surface will increase for these diameters. Of course, this phenomenon will also have a negative effect on the calculation of the wall thickness of the tube sheet.

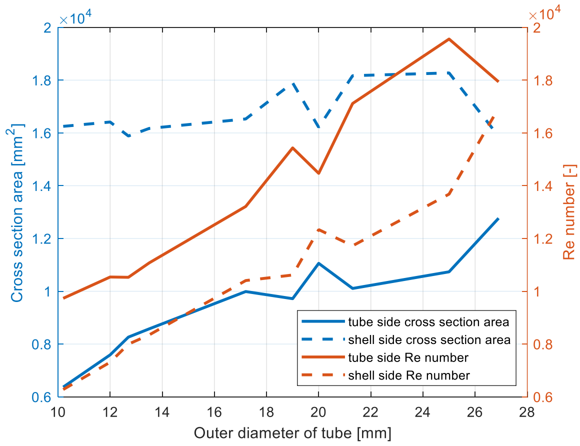

Figure 4. *Hydraulic and thermal characteristics in the function of tube diameter*

Figure 4 shows the hydraulic and thermal characteristics. The figure clearly shows that, as the tube diameter decreases, and the wall thickness remains constant, even though the envelope can accommodate considerably more tubes, the area occupied by the tubes will increase, so that the flow cross-section will decrease. For the calculation of Re number, a water flow rate of 10 l/s has been assumed on both sides, and smaller tube sizes will result in a poorer heat transfer coefficient in this case.

Naturally, the results shown in the figures only apply to geometrically similar tube pitches. In the cases outlined, this similarity is ensured by the type of pitch and the split spacing. The sizing of a heat exchanger is a very complex process. Looking only at the aspects considered so far, when choosing the parameters of a tube bundle, it is important to take into account not only the functional, strength, operational and maintainability aspects, but also the market availability.

In addition to the main types outlined above, several other design options can be presented depending on their function. Without claiming to be exhaustive, some of these heat exchangers are listed below.

- Heat exchangers with fixed tube sheet are suitable for changing the temperature of viscous and non-Newtonian fluids. In the case of these, a tube-in-tube type is envisaged, with a shaft in the inner tube on which scraper blades are fixed. The movement of these structural elements makes the movement of the viscous (typically food) material more vigorous, thus avoiding deterioration (Varga, Szepesi and Siménfalvi, 2017).
- The evaporator is a heat exchange device where the vapour space is left much larger due to the high gas formation. They differ from the boiling heat exchanger in that, while in the case of a boiling heat exchanger the entire amount of material is boiled, in the case of an evaporator only the solvent is boiled and only a part of it. Several sub-types can be distinguished and available from the literature (Shah and Peacock, 2013).
- In the case of field-tube heat exchangers, the tube space consists of two concentric tubes. One end of each tube is fixed, so that the tube fluid flows first through the inner part and then through the annular channel. It then comes into indirect contact with the jacket fluid and heat exchange takes place.

2. Design of a fixed tube sheet heat exchanger

In the previous chapter, the functions of the shell, the head and the tube bundle were described, and in this chapter the functions and design options of the fourth structural element, the tube sheet, which is typically used in heat exchangers, are discussed. The shell-and-tube type heat exchangers basically can be classified according to the thermal stresses: there are thermal stress sensitive and insensitive designs. This article deals with the first group of heat exchangers, i.e., rigid shell-and-tube heat exchangers. The second group is made up of finned and hairpin heat exchangers. In both types of tube stack, thermal stresses are generated (which are described in more detail in the next chapter), but in the case of the rigid tube stack these stresses are much higher (Atanasiu and Sorohan, 2016; Saraçoğlu, Uslu and Albayrak, 2020; Siménfalvi, 2012).

Whichever type is chosen, it can be sure of two functions: separating the tube side medium from the shell side medium and securing the tubes. Tubes can be fixed in two ways, by welding and by expending. Whichever technology is used, the tubes are subjected to greater additional stresses at the wall of the tube bundle (small diameter tubes are converted into large plate-like components with small wall thicknesses).

2.1. Head-tube sheet-shell constructions

The first step in the design process is for the designer to decide which of the two media should flow in the tube side and which should flow in the shell side. For some types this is straightforward (evaporators, condensers, boilers), but for others there are two aspects to consider. Which medium is more corrosive and/or which can cause deposits, and which is under higher pressure. The first aspect is of economic importance, since only the pipe components need to be made of corrosion-resistant material. The second aspect also raises safety concerns. However, neither of these affects the sizing of the tube sheet, as it is in contact with both media, nor is it relevant in terms of pressure loading.

The design is more influenced by the maintainability of the heat exchanger. Three basic design options are shown in *Figure 5–7*, which are compared based on the load capacity of the heat exchanger in addition to maintainability (Bouzid and Laghzale, 2016; 2020; Krisdiyanto et al., 2021; Thekkuden, Mourad and Bouzid, 2021; Alves, Afonso and Martins, 2022).

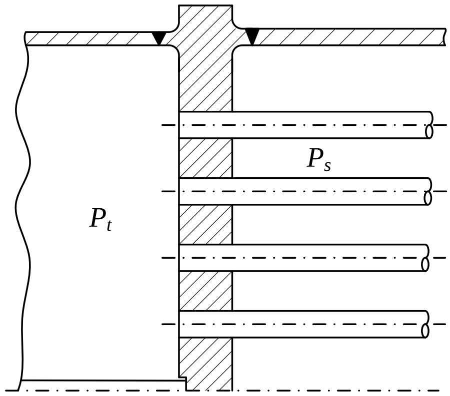

Figure 5. *Welded connection on both side*

Figure 5 shows the simplest design. In this case, all four structural elements form a single unit, joined by welds. This has the advantage that the tube sheet only performs its original function (separating two media and holding the pipes) without any other mechanical load. The disadvantage is that neither the tube nor the shell side can be cleaned.

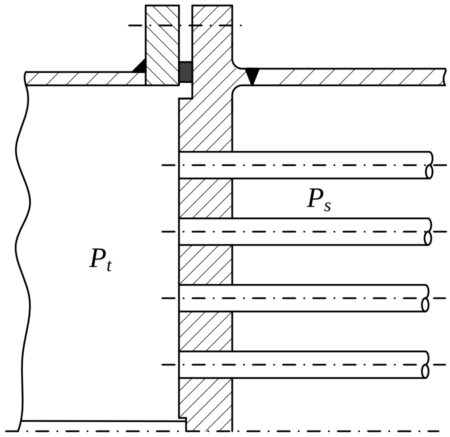

Figure 6. *Welded connection on shell side and flange connection on head*

Figure 6 shows a design where the head of the heat exchanger is connected to the shell-tube sheet unit by an apparatus flange. In this arrangement, the tubes can be retained, but additional loads are placed on the tube sheet due to the flange connection. It is also a more complex case from an installation point of view due to the choice of gasket and the correct design of the tightening torque.

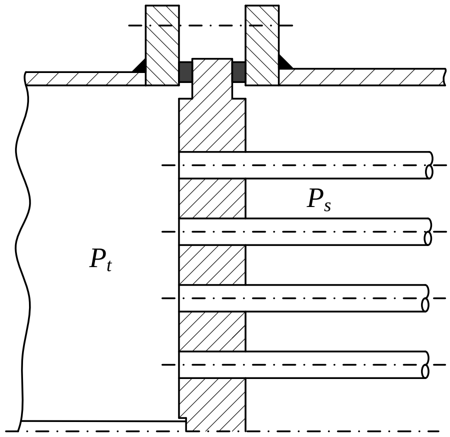

Figure 7. *Flange connection on both side*

In the design shown in *Figure 7*, both rooms can be built-in, i.e., the outside of the tube bundle can be cleaned. In this case, again, the wall of the stack does not act as a flange, but two seals are required, further complicating the installation (Sriharsha et al., 2012).

2.2. Flange constructions

The device flange shown in *Figure 6* is identical to the pipe flange in function and calculation method, except that it connects device elements rather than pipeline elements. Consequently, the sealing surface configurations are also similar and are shown in *Figures 8* and *9* (according to EN 13445).

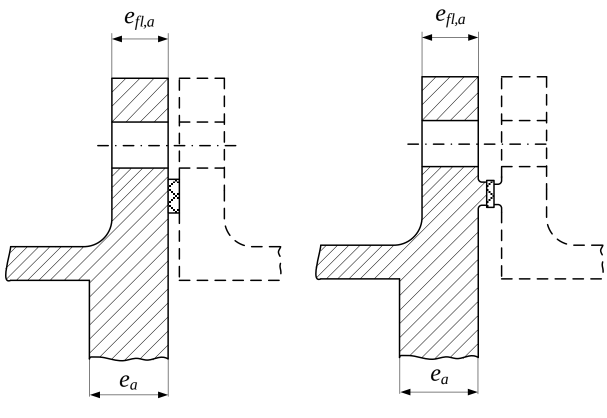

Figure 8. *Flat (left) and raised (right) facing*

Figure 8 shows the flat and raised facing. These two cases are the classic ones, requiring the use of flat gaskets available from many gasket manufacturers. They are more economical in terms of flange design but are more complicated from an installation point of view.

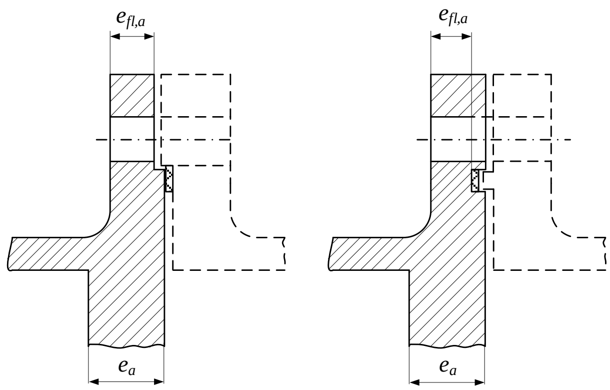

Figure 9. *Single (left) and double(right) tongue and groove*

Figure 9 illustrates the design options of tongue and groove. In these cases, the gasket must be placed in the groove side. They represent a more favourable case from the point of view of explosion safety and are characterised by less leakage. However, they have the disadvantage of being more costly from an economic point of view.

3. Thermal stresses

Thermal stresses are the mechanical stresses due to inhibited thermal expansion. They occur mainly in engineering structures where one dimension (length) is orders of magnitude larger than the other two. Common examples are bridges, railway tracks and pipelines. Because of their function, all three need to be protected in different ways. In the case of bridges and rails, the temperature variation is relatively slow (related to seasonal variations in temperate regions and to diurnal variations in desert regions) and the magnitude is not very large, but these structures do not allow the incorporation of thermal expansion compensators with small curvatures, and in return do not require a tight fit. For bridges, dilation gaps or tail-tooth designs are created. Expansion gaps used to be left in the case of rails (but this caused twisting, putting dynamic loads on the running gear, suspension, and wheels), but nowadays, with properly executed welding, a continuous rail system is no longer a problem. This requires properly sized foundations and welding at temperatures that are about the middle of the expected range. This ensures that no excessive stresses are generated at either extreme. Pipelines behave differently. On the one hand, the designer has more freedom to decide which track the pipe should follow. Thus, with this flexible track or with the help of compensators, damaging stresses can be ensured. The other difference comes from the temperatures. A much wider range and a much shorter duration can be influenced.

These thermal stresses must also be considered in the design because they can be used to determine the wall thickness of the tube sheet. However, these thermal stresses cause secondary stresses, mostly on the wall of the shell, and these secondary stresses can usually be determined by some numerical method. In this section, the relationships that are necessary for the finite element analysis of an operating rigid shell-and-tube heat exchanger are presented (Fonyó and Fábry, 2004).

The free thermal explosion of the tube bundle and the shell can be calculated with

$$\Delta l_s^* = L \cdot \alpha_s \cdot \left(T_{s,out} - T_{amb}\right) \tag{1}$$

and

$$\Delta l_t^* = L \cdot \alpha_t \cdot \left(T_{t,out} - T_{amb}\right). \tag{2}$$

where α is the thermal expansion coefficient of the structural material [1/K], *L* is the length of the tubes and shell [m], *T* is the temperature [°C], while subscript *s* refers to the shell and *t* refers to the tube bundle. Axial stress components arise from the inhibited thermal expansion, and these stresses can be calculated as follows:

$$\sigma_s = -\frac{A_t \cdot E_t \cdot \left[\alpha_s \cdot \left(T_{s,out} - T_{amb}\right) - \alpha_t \cdot \left(T_{t,out} - T_{amb}\right)\right]}{A_s \cdot E_s + A_t \cdot E_t} \cdot E_s, \tag{3}$$

$$\sigma_t = -\frac{A_s \cdot E_s \cdot \left[\alpha_s \cdot \left(T_{t,out} - T_{amb}\right) - \alpha_t \cdot \left(T_{t,out} - T_{amb}\right)\right]}{A_s \cdot E_s + A_t \cdot E_t} \cdot E_t, \tag{4}$$

where *A* is the cross-section area [m^2] and *E* is the Young modulus [MPa] in the function of medium temperature. From these, the acting forces can be determined.

$$F_s = \sigma_s \cdot A_s \tag{5}$$

$$F_t = \sigma_t \cdot A_t \,. \tag{6}$$

However, must not forget the axial stress in the sheath wall due to internal pressure. Taking this into account, the magnitude of the total force is

$$F_{total} = \frac{P_s \cdot D_m}{4 \cdot e_s} \cdot A_s + \left|F_s\right|, \tag{7}$$

which is the boundary condition to finite element analysis. From the relations presented earlier, the values of the real displacements can be determined. To do this, the elongation values must first be determined,

$$\varepsilon_s = \frac{\sigma_s}{E_s}, \tag{8}$$

$$\varepsilon_t = \frac{\sigma_t}{E_t}, \tag{9}$$

then the displacements

$$\Delta l_s = \varepsilon_s \cdot L, \tag{10}$$

$$\Delta l_t = \varepsilon_t \cdot L \,. \tag{11}$$

It should be emphasised that *Equation (8)–Equation (11)* are only valid for elastic deformations. The resulting values can be checked by assuming the following equation.

$$\Delta l_s^* + \Delta l_t = \Delta l_t^* - \Delta l_s \tag{12}$$

4. Other factors

As can be seen from the foregoing, the primary focus of this summary article is to present the basic characteristics required for the strength design of a rigid shell-and-tube heat exchanger (Gomez, Ruiz and Wilson, 2014). What follows is a discussion of the additional geometrical characteristics and other components, some of which are quantified in the context, but others are either neglected or simply ignored due to the number of unknowns.

4.1. Tube layout

For the figures presented in Section 1, the pipe pitch and pipe length were assumed to be constant. Basically, two types of pipe pitch can be distinguished, triangular and rectangular, an example of which is shown in *Figure 10*. Generally, a few more tubes can be placed in a triangular configuration with the same tube spacing (i.e., the heat transfer surface can be increased). From a flow engineering point of view, they represent a higher resistance, a much higher turbulence is generated with triangular distribution, so the heat transfer coefficient on the outside can be increased, and this also means that the number of deposits will be lower.

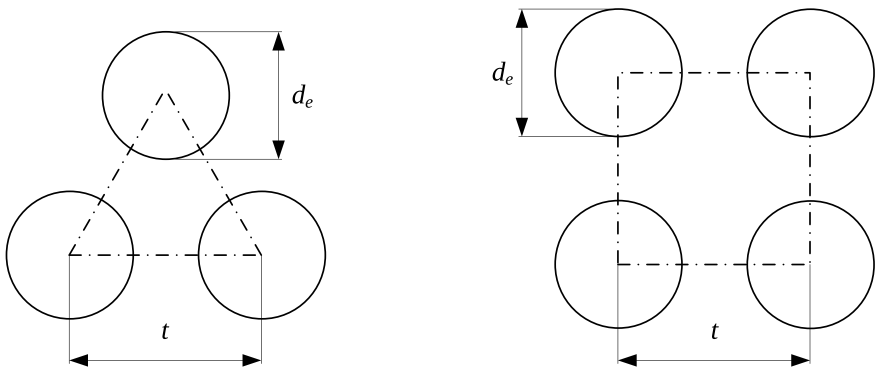

Figure 10. *Triangle and rectangular tube layouts*

The value of the tube pitch can also be changed, but this will present strength problems. Whether you consider a flat plate or a curved surface, the greatest stresses will be at the edge of the cut-out, and away from this, these additional stresses will die away. However, if there is another cut-out on this descending section, which is essential in the case of a pipe truss wall, the resulting decreasing stresses are superposed. Therefore, the highest stresses are found at the geometric centre of the three or four cut-outs. If these cut-outs are brought closer together, the incremental stresses will also increase.

4.2. Baffle plates

To intensify the heat transfer coefficient in the shell side and reduce dead zones, the pipe bundle is usually equipped with baffles. Their installation will have a positive effect on the load-bearing capacity of the pipes. In general, the tubes tend to deform more than the shell, so the tube bundle wall restrains this deformation. The presence of baffles will have a positive effect on this deflection process by reducing the deflection length of the pipes. An example of this is shown in *Figure 11*.

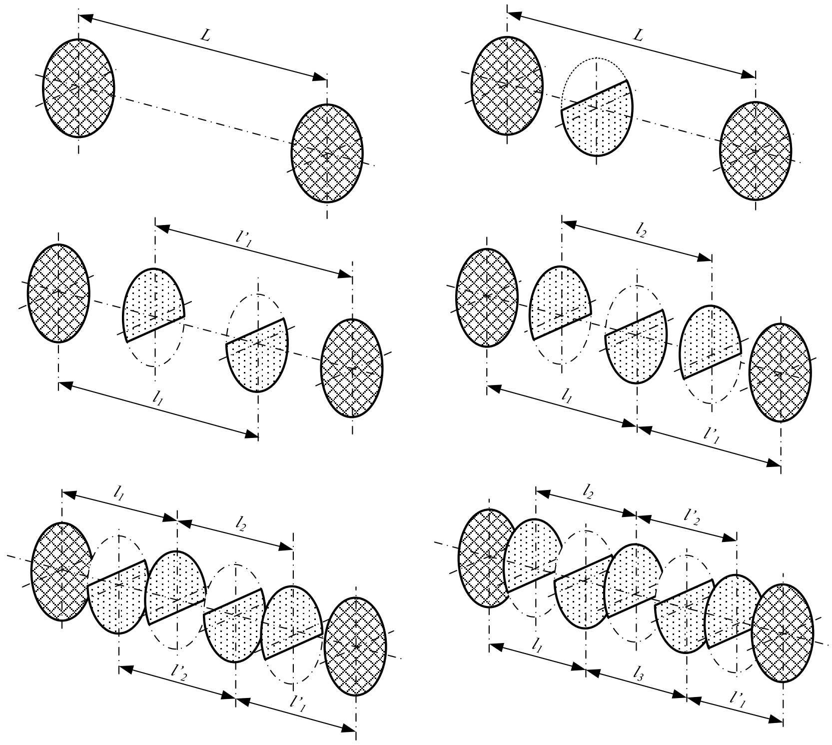

Figure 11. *Bucking length of tube for different number of baffles*

It should be noted that these baffles can also cause negative effects, for example there will be more dead zone in the shell side, the pressure drop of the shell side medium will increase, the fluctuations in the velocity of the fluid will cause the shell to fatigue. The segment-type baffles shown in the figure (but also the disk-and-donut type baffles) divide the mantle space medium into a flow direction perpendicular to and coincident with the axis of the heat exchanger. In inadequately sized cases, these two flow cross-sections are significantly different from each other, inducing a large variation in the media velocities. This will cause problems in the value of the heat transfer coefficient (locally there may be differences of order of magnitude), erosion, and in the values of pressure deflection and pressure loss. This should be avoided, and baffles should be designed to minimise these negative effects.

5. Summary

The aim of this paper was to present the most important aspects of the design of the most typical structural element of a fixed shell-and-tube heat exchangers, the tube sheet. The functions that this element can perform and the stresses to which it is subjected have been demonstrated. In practice, it can be stated that there is no structural element in the heat exchanger that does not have an impact on the loads on the tube sheet. From the above, it is clear how the operational and strength designers can help each other to ensure that the equipment can operate safely and efficiently. Therefore, it is of paramount importance that both experts are mostly familiar with each other's area of expertise and that there is good communication between them.

6. Acknowledgement

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