Optimum Profiles for PEP Internally Finned Radiant Coils

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Introduction

On any ethylene cracker the component which sets the throughput for the whole plant and has the greatest influence on plant economics is the cracking furnace. The amount of feed , either gas or liquid, that can be cracked is constrained by the level of heat energy that can be transferred to the feed as it flows through the radiant coil. The pyrolysis reactions, molecular and free radical, are endothermic in nature and require the addition of heat to maintain the reactions. Cracking severity is a function of the temperature of the cracked gas and net ethylene production is favoured by higher temperatures. It can be seen that the radiant tube surface area available for heat transfer is of ultimate importance. The larger the area, the greater the potential for maximising heat transfer and maximising production or run length.

Other design considerations which have to be considered are yield and selectivity, reliant on residence time and hydrocarbon partial pressure. These are influenced by the radiant tube dimensions chosen.

It is evident that the shape and dimensions of the radiant coil are of utmost importance if the correct yield of products is to be achieved. The maximisation of the useful products at a minimum cost is the ultimate aim of the coil designer.

Paralloy has recognised the importance of maximising the heat transfer surface area while considering the other design issues. Traditionally increasing surface area could only be achieved by changing the number, geometry or layout of the coils. The use of internally finned radiant coils can, however, provide a simpler and easier alternative. Internally finned tubes are not a new concept but they are frequently overlooked. See figure 1.

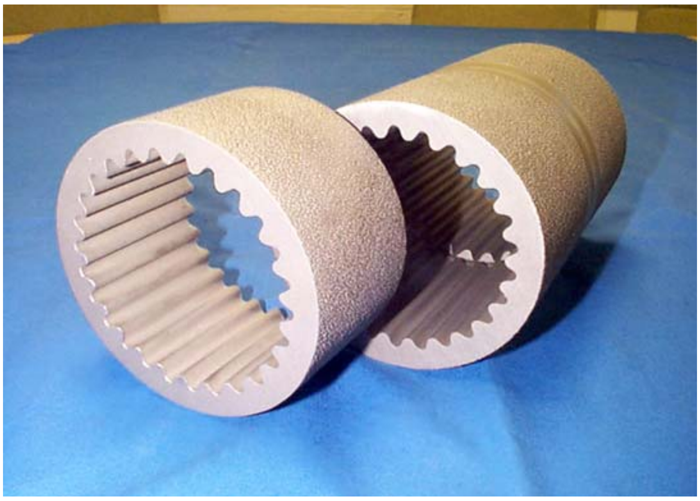


Figure 1: PEP Tube

This paper will discuss the relationship between different variables used to decide the optimum shape for Paralloy Ethylene Profiled (PEP) Tube, a longitudinally profiled internally finned tube.

Advantages From PEP Internally Profiled Tube

Paralloy Ethylene Profiled tubes (PEP tubes) have been shown to give substantial financial benefits on both gas and liquid feed when compared to plain bore tubes. These benefits are due to the increased feed rate and run length available when cast radiant tubes have longitudinal fins machined on the bore surface. Papers documenting the advantages of using PEP tubes have been published by Paralloy [1 2]

The concept of increasing tube bore surface area by profiling is not new. Prior to the availability of Paralloy's patented cast PEP tubes, the only finned tube available was in small sizes and produced by wrought processes. PEP tubes are currently available in sizes up to 150mm diameter. Wrought tubes have in addition to a size limitation, a temperature limitation brought about by the absence of creep strengthening secondary carbides. It is the secondary carbides which gives cast PEP tubes the recognised superior creep rupture properties when compared to wrought tubes. See figure 2. The electrochemical machining process used to form PEP tubes does not change the properties of the tube.

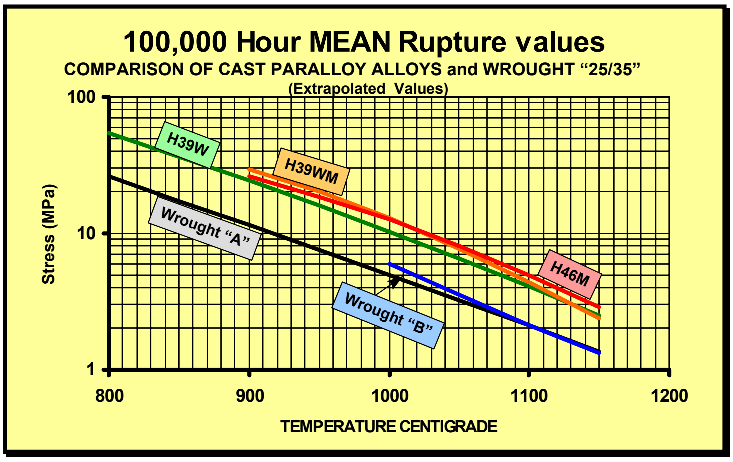


Figure 2: Increased Creep Strength with PEP

PEP Manufacturing Process

The starting point in the manufacture of a cast, internally finned tube, is a conventionally cast round tube. As additional material is required to facilitate the electrochemical machining process, the tube wall is cast thicker than with a traditional round tube to allow for the finning process. Having produced a sound round bore tube, the electrochemical machining process can then commence. The profile on the bore of PEP tube is formed by non-contacting electrochemical removal of material from the internal surface of the plain tube. See Figure 3. The tube to be machined is mounted on the machine and is carefully aligned to ensure concentricity of the bore. The precision shaped former, which reflects the shape of the required profile, is introduced into the tube leaving a small clearance, typically 0.5mm, between former and tube. The tube ends are sealed and a flow of electrolyte is established through the tube and also through the annulus between former and tube. The former tool becomes the cathode and the tube the anode in the cell. Material is removed electrochemically from the wall of the tube, but before it can de deposited on the cathode, which would reduce its effectiveness, it is washed away by the electrolyte flow. Once the machining parameters are set and machining commenced, the tube is fed at a constant rate over the former. Although the schematic diagram of the process shows the face of former tool being parallel, the tool is in-fact an intricate shape to allow the progressive removal of wall material as it progresses through the tube.

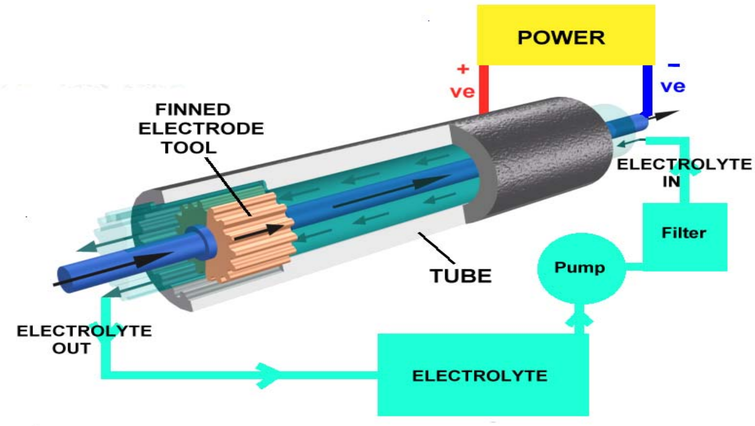


Figure 3: Schematic of Finning Tool

This method of manufacture gives a significantly smoother finish than that obtained on wrought tubes. The process of drawing a wrought tube through the shaped die can cause marks, striations and small tears especially along the peaks of the fins. These defects can provide convenient sites for initial coke formation and can allow the ingress of carbon into the surface due to the problematic formation of protective oxide at these defects. See Figure 4. The smooth, defect free, surface of the PEP tube arguably contributes to the improved furnace run length.

Wrought Tube PEP Tube

Figure 4: Comparison of Surface Finish

All of the common cast, high temperature, alloys ranging from HK40 through to the 35Cr-45Ni Micro and oxide dispersion strengthened Paragon Alloys can be electrochemically machined in the manner described above. Furnace operators can therefore continue to work with alloys with which they are familiar.

General Considerations

Having decided which benefits to pursue the furnace operator must decide which profile is appropriate for the application. There will be an optimum profile for each furnace revamp with respect to both additional heat transfer and pressure drop. The profile chosen must provide a balance between these two variables, allowing benefits to be maximised. Through experience gained working with furnace vendors and customers Paralloy can advise customers on profile choice.

Interaction Between Design Variables

This paper looks at the interaction between the design variables and discusses how these interactions influence the choice of bore profile chosen.
Figure 5 shows a generic PEP tube with the important parameters highlighted.

The to be discussed PEP-profiles are all based on a **Fin Tip Radius**, a **Fin Trough Radius** and a tangential transition in between. The angle between the tangents is the **Trough Angle** respectively the **Fin Angle** and there is a simple equation between the angles of such a profile: the angle between two fins, α(fin), equals fin angle minus trough angle. These variables allow a very flexible design and lead to a profile with very smooth transitions. It is far more flexible than a strictly sinusoidal profile and furthermore it allows to create larger wetted area.

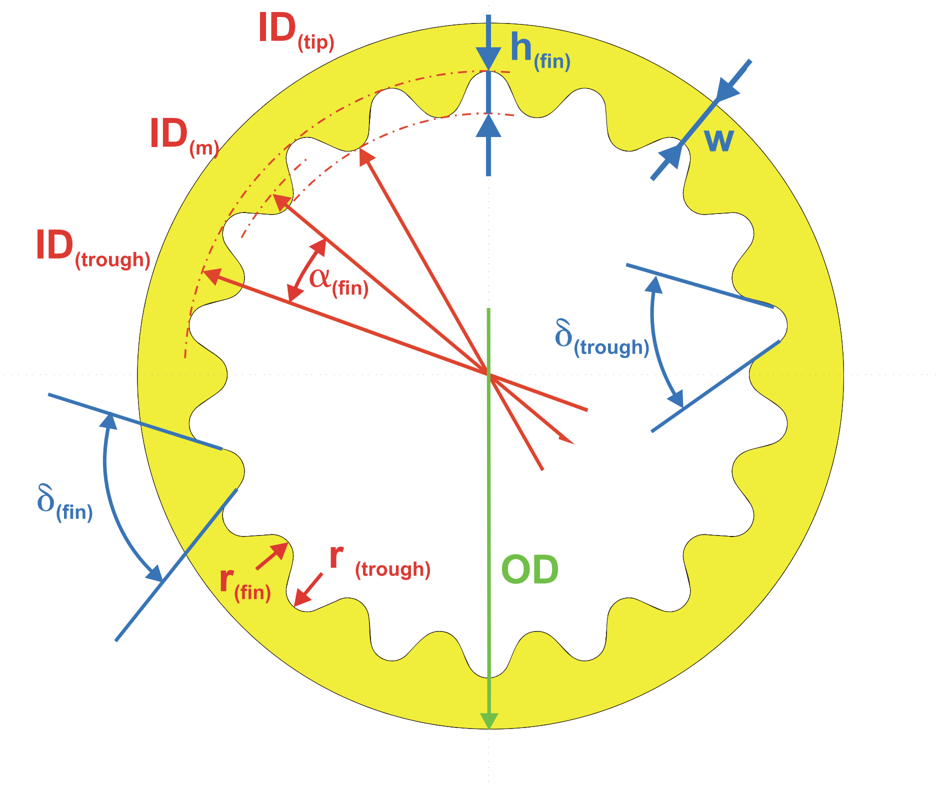


Figure 5: PEP tube Parameters

Heat transfer efficiency of internal fins is mainly dependent on the fin design. But numerous operational factors like coking, or fluid dynamics do not allow easy evaluation. CFD (Computational Fluid Dynamics) - analysis is the only way to trace the effect of different fin profiles on the heat transfer efficiency of fins. However, an initial assessment of the profile geometry can be made by looking at the following profile parameters:

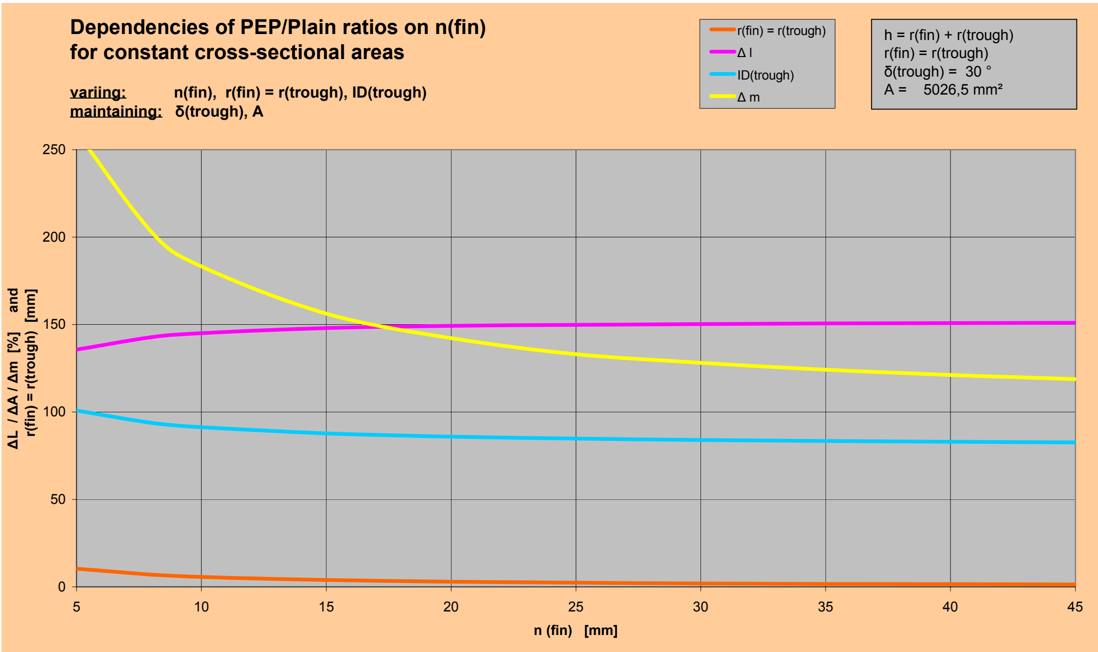
ΔL - Perimeter Ratio
Ratio between Perimeter Length (wetted length) of a PEP tube and Perimeter Length of a comparable plain tube. Very expressing is the Perimeter Ratio for PEP / plain tubes having equivalent internal cross-sections for the product flow.

ΔA - Internal Cross-Section Ratio
Ratio between internal cross-section of a PEP tube and internal cross-section of a plain tube.

Δm - Weight Ratio
Ratio between weight of a PEP-tube and weight of a plain tube.

Optimum Fin Number

Mostly a fin design is utilized having equivalent fin and trough radii and a fin height which is twice the fin or through radius. Maintaining the through gradient in addition leads to a fin shape always having equivalent relative proportions. Tubes with equivalent relative fin proportions and constant size of cross-sectional area are used in Figure 6 to show the dependencies on fin number.
As can be observed, bore perimeter length respectively heat transfer surface area increase and the tube weight decrease as the number of fins machined on the tube bore increases. Theoretically the maximum benefit would be obtained with an infinite number of thin fins. In practice this would not be possible to machine. Rapid coking of the valleys would also prevent this option being considered as the potential for additional heat transfer would at least be reduced. Ultimately the number of fins chosen gives the optimum balance between additional surface area and detrimental coking reactions . The graph shows that perimeter length is not changing significantly the more fins are used but the additional weight compared to a plain tube with equivalent cross-sectional area is still decreasing significantly.



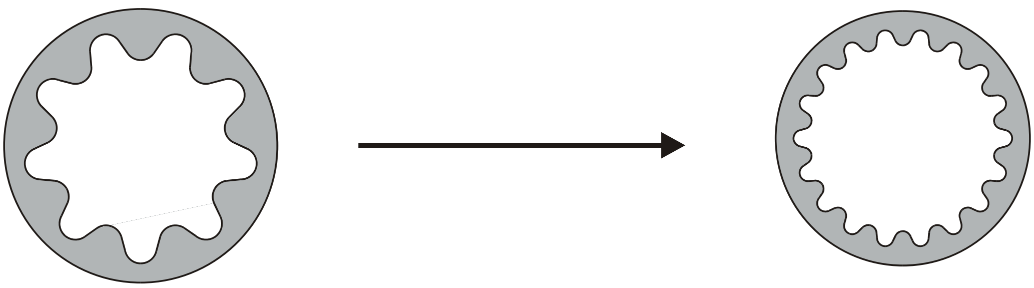


Figure 6: Effect of varying fin number for tubes with constant internal cross-sectional area

Effect of varying fin thickness

As the trough radius increases, maintaining the number of fins and fin height, there is a corresponding decrease in the fin tip radii and thus the fins are getting smaller and the troughs are getting wider. The volume of material removed increases with increasing trough radius giving a reduction in additional weight. See figure 7.

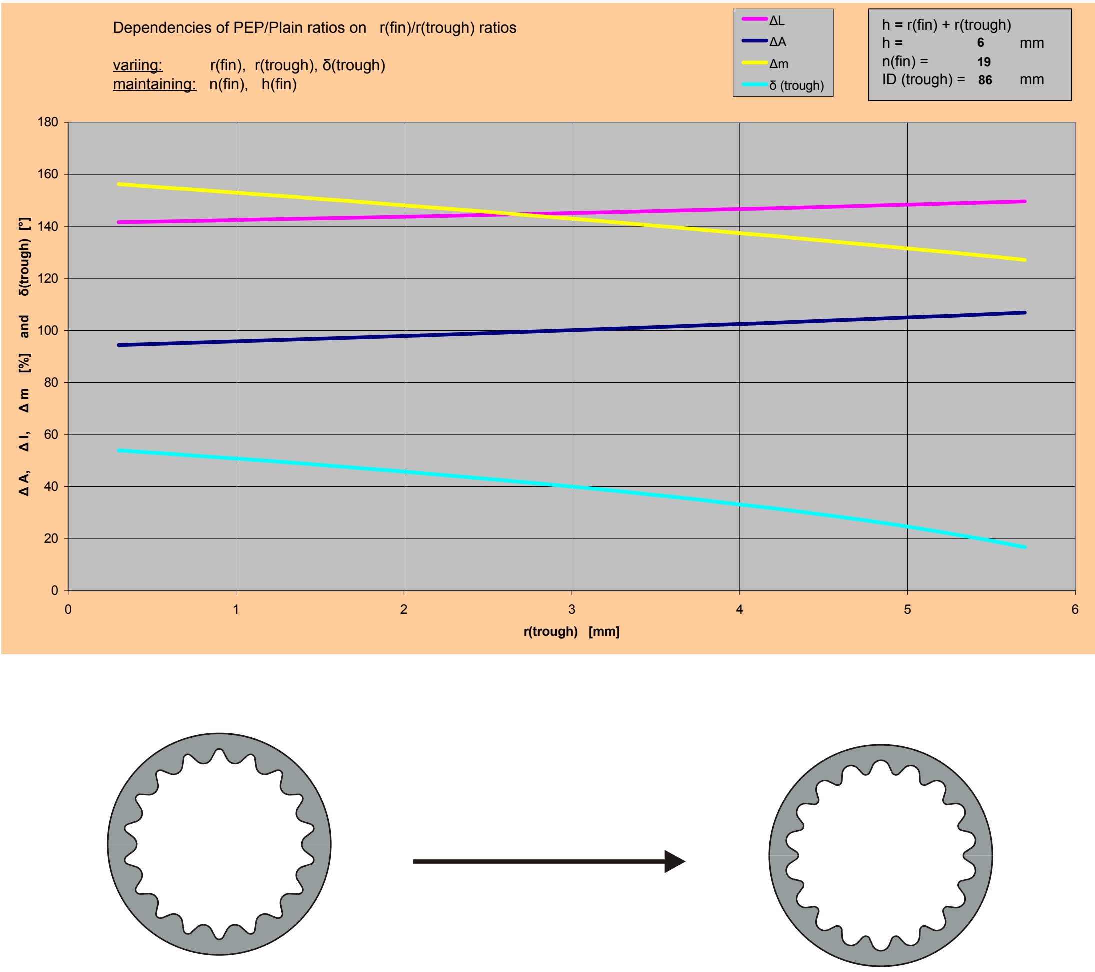


Figure 7: Effect of varying fin thickness for tubes having equivalent diameter

Thinning the fins and by it widening the troughs increase both the perimeter and area ratios giving increasing benefit. Theoretically infinite thin fins would optimise all design parameters. However, production methods preclude trough angles less than 30 degrees and tip radii less than 2 mm. But for maximum benefit in heat transfer it is furthermore necessary to look at the heat transfer efficiency of the fins. It is an important parameter to determine the optimum thickness of a fin. It is obvious that a very thin fin is not able to conduct enough heat from the fin root through its cross section to the fin tip. The temperature is cooling down to quickly and the additional heat transfer benefit of the fins will be low. Unfortunately determination of the heat transfer efficiency is a very complex calculation. Furthermore the efficiency is changing with coke formation due to the different thermal conductivity of coke.

Effect of varying fin number by changing trough angle

While maintaining fin height and both trough / fin radius it is possible to vary the fin number and the associated trough angles. As can be seen in Figure 8 there is a steep decline in trough angle as the number of fins increase. While the perimeter ratio increases with fin number there is only a relative small increase in the ratio of PEP to Plain tube cross sectional areas.

Again, production methods preclude trough-angles less than 30 degrees. Operationally the smaller the trough angle the greater the likelihood of stress concentration with the possibility of crack initiation. Coke formation is more likely within the valley of a fin with small angles and decoking could be more difficult. The area of coke in contact with air and steam during de-coke becomes less as the included angle decreases. However, Paralloy's experience has shown trough angle with 30° are not detrimental but giving a good balance between the desired properties.

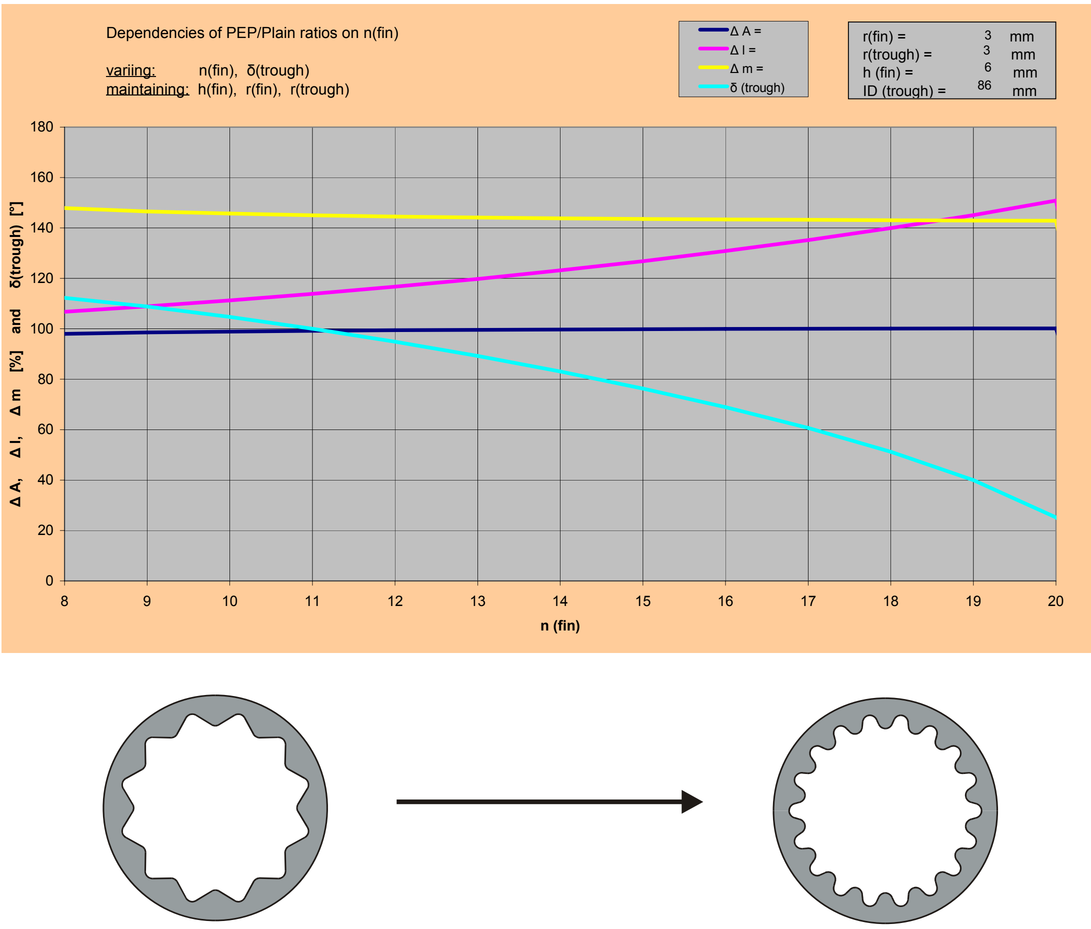
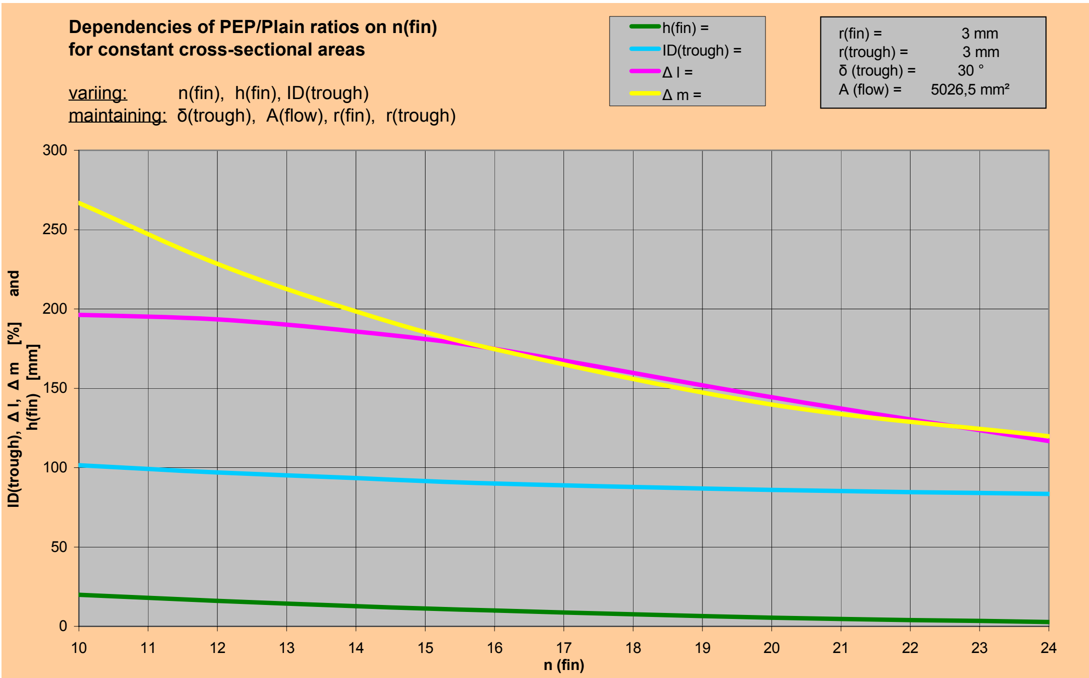


Figure 8: Varying fin number by changing trough radii for tubes having equivalent diameter

Effect of varying fin number by changing fin height

It is also possible to vary the number of fins, keeping the trough angles and fin/trough radii constant. This is achieved by varying the height of the fins. In Figure 9 it is shown the effect on fin height variation for tubes having equivalent cross-sectional area. This obviously is only possible if the tube ODs are varying as well. For increasing fin heights perimeter ratio is increasing significantly. As additional heat transfer, directly linked to perimeter ratio, is required to maximise feed rate or run length any increase would be beneficial to tube design. But increased fin height has a financial penalty due to the increased amount of material which has to be removed by electrochemical machining and required diameter increase to obtain equivalent cross-sectional area. Moreover the pressure drop of the gas stream will rise with increased fin height and de-coking of troughs will be more difficult.



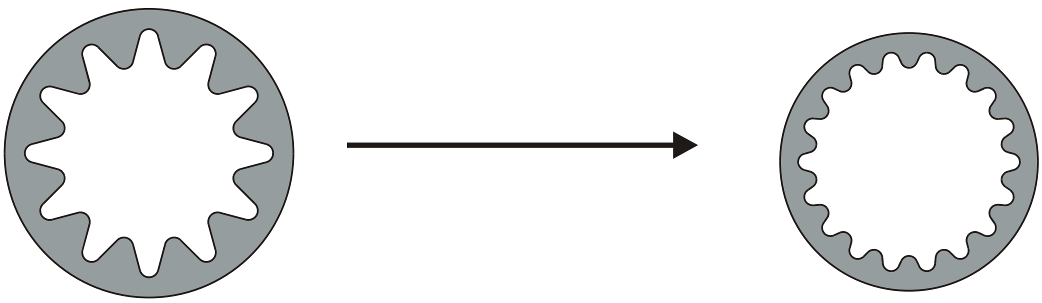


Figure 9: Varying fin number by changing fin height maintaining internal cross-sectional area

Dimensional changes

When utilising PEP tube there is, in some instances, a need to make a small increase in the outside diameter of the tube. This ensures both the correct minimum wall thickness and unchanged cross sectional flow area compared to the original plain tube. It has been shown that a change of 2mm in the OD in certain tubes can allow up to 40 % additional surface area. Figure 10 shows that outside diameter change is a function of the fin geometry. Whereas the number of fins has got a minor effect on the required OD increase (only for small number of fins each additional fin is creating a considerable change of the OD) the fin radius and thus fin height has got a major effect. A change of trough angle again has got a minor effect only.

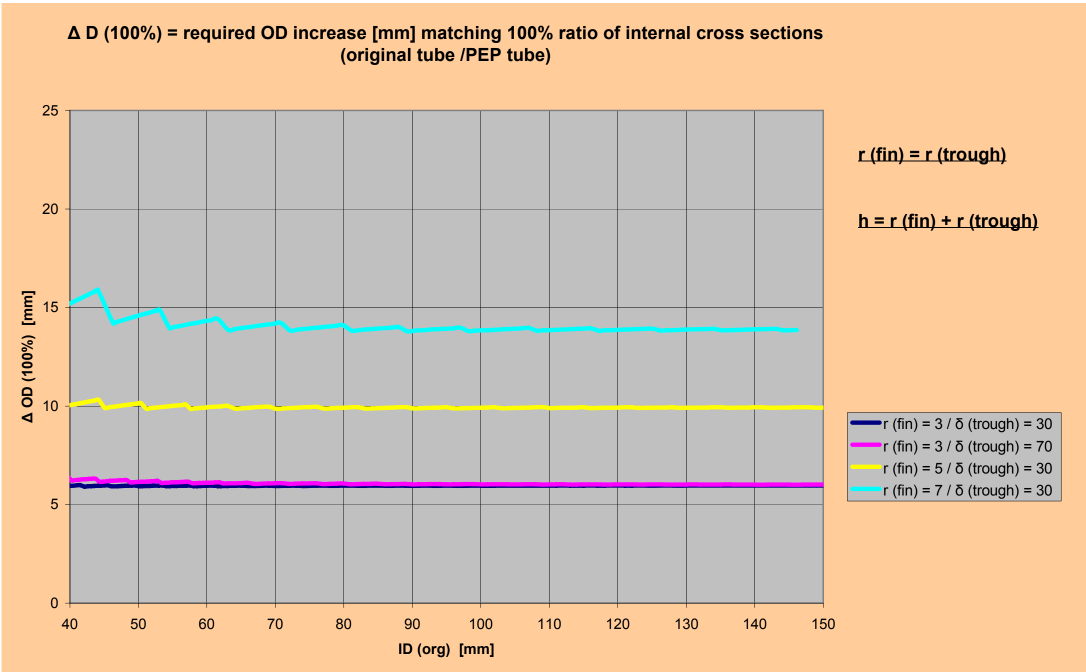


Figure 10: OD Dimensional Changes related to Fin Geometry

The increase in heat transfer surface available by using PEP tube could theoretically be obtained by using a plain tube of larger internal diameter. Both tubes giving the same wetted area for heat transfer. A fin geometry of fin / trough radii 3mm and a fin height of 6mm is considered in Figure 11. This illustrates the change of inside diameter required in a plain tube compared to PEP tube to give the same surface area. The required bore diameter for plain tube increases linearly with increasing original ID whereas PEP tube remains constant. For a given diameter the PEP tube flow cross sectional area remains equivalent to the original tube. However, to gain the equivalent perimeter in a plain tube the flow cross sectional area has to increase.

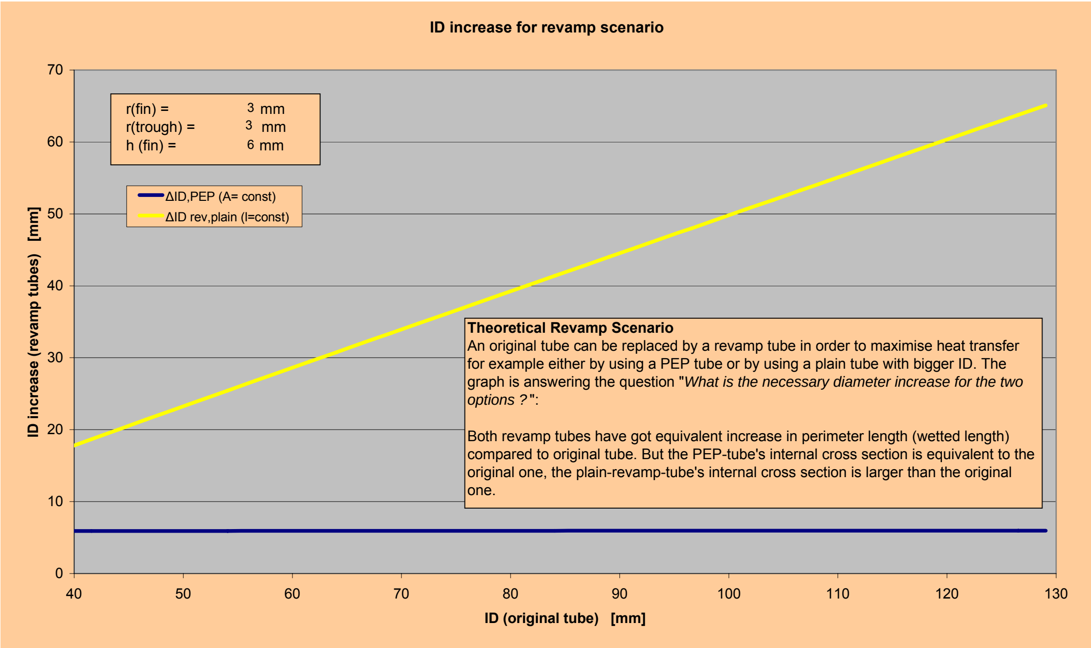


Figure 11: PEP / Plain tube inside diameter comparison.

This dimensional comparison shows that the use of PEP tube is a more efficient use of space within the radiant firebox compared to plain tube. Increasing plain tube diameters are constrained by the need to avoid shadowing of adjacent tubes and the change in yield due to increased residence time within the tubes.

Profile Recommendations

It is impossible to specify a fin profile suiting all operational requirements. It is necessary to find compromises between desired properties. The following scheme shall give general recommendations and shall help to find the right balance.

1. Fin Radii

Generally a profile with **radius(fin) + radius(trough) = height(fin)** is positive. Thus a pronounced profile is created which leads to large wetted areas without being forced to utilize to high fins.

2. Trough Angle

The largest wetted area can be obtained by utilizing minimised trough angles. Due to constraints in electrochemical production the smallest trough angle is 30°. The smaller the trough angles the more difficult de-coking of the troughs and the higher the risk of crack initiation. However, the experience of Paralloy has shown that a trough gradient of 30° is not detrimental but a beneficial balance.

3. Fin Thickness

Fin thickness is with r(fin) + r(trough) = height(fin) and trough angle = 30° a function of r(fin) to r(trough) ratio only. A fin, as thin as possible, which means small fin radius and large trough radius is beneficial for maximizing perimeter length, minimizing additional tube weight and easy de-coking of troughs. Due to constraints in electrochemical production the smallest radius is 2 mm. But the optimal r(fin) to r(trough) ratio is based on maximised heat transfer efficiency of the fins which can only be determined by numerous calculations or CFD analysis.

4. Fin Number and Fin height

Assuming that above made recommendations are utilized fin number and fin height are directly linked. The higher the fin height the greater perimeter length will be. But under normal conditions it is detrimental to choose. Extensive costs caused by long machining operations, great material loss, increased additional tube weight, increased tube diameter to obtain same cross-sectional flow area, higher pressure drop and probably longer de-coke for the troughs prevent from gaining the benefit. Furthermore due to the heat transfer efficiency of the fins the fin height with optimised perimeter length is not necessarily the fin height with maximised heat transfer.
Plenty of small fins are as well no solution as they are likely to loose the biggest proportion of their benefit in heat transfer as soon as coke has smoothed down the fins. Depending on the tube diameter Paralloy's experience has shown that fin heights between 4 and 8 mm showing a good balance.

Conclusion

PEP tube is the most flexible method of achieving increased heat transfer available on the market. This is achieved by increasing the surface area available for heat transfer. The design of the profile, electrochemically machined on the bore of cast tube, can be optimised to meet the production requirements.

Paralloy PEP profile is based on fin height, fin tip / trough radii and trough angle. To date, most users of PEP tube have chosen a geometry which has equivalent fin tip and trough radii. This does not have to be the case. Maximum perimeter length can be obtained by having different radii at tip and trough. Paralloy can advise customers on a suitable profile to maximise furnace production or run length.

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