



## High Flux Steam Reforming

by

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### Abstract

*Topsøe has introduced the High Flux Steam Reformer (HFR), with lower cost than conventional side fired reformers. The High Flux Steam Reformer is applicable for all steam reforming processes such as hydrogen, synthesis gas, methanol and ammonia. Together with Topsøe's advanced steam reforming concept it offers improved production economics, both in investment and operating cost. The High Flux Steam Reformer takes full advantage of today's new tube materials and catalysts, staying within industrially proven operating conditions.*

### Introduction

Recent years have shown progress in steam reforming technology resulting in less costly plants not the least because of better materials for reformer tubes, better control of carbon limits, and better catalysts and process concepts with high feedstock flexibility [1,2]. The new tube materials together with improved understanding of heat transfer and the influence of temperature levels and temperature gradients on tube life make it possible to design tubular reformers for tube wall temperatures up to 1050°C, which is well known from ethylene crackers. It has been historical practice to use the average heat flux as a measure for operating severity in reformers, but it appears

that the most critical parameter is the maximum temperature difference over the tube wall. This parameter can be controlled in the side wall fired design in such a way that very high average heat flux can be obtained without exceeding critical values. Side fired tubular reformers are today designed for operation at average heat flux almost two times higher than what was industrial standard 20 years ago. High average heat flux leads to lower tube weight, smaller reformer furnaces and thus reduced cost as indicated in Fig. 1.

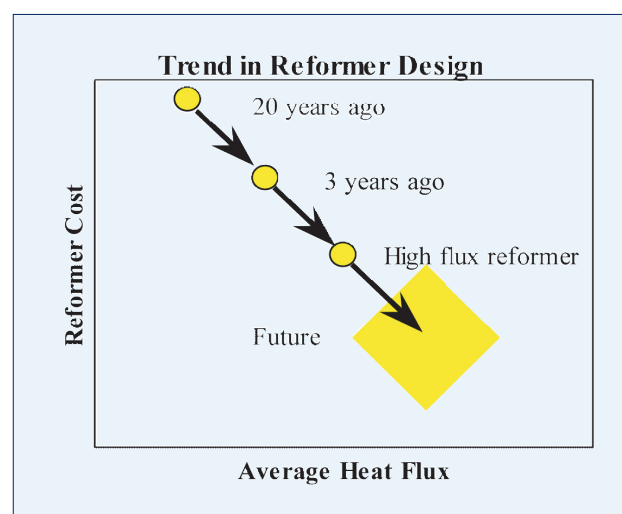


Fig. 1 The trend in reformer design has been towards higher average heat flux resulting in lower cost reformers.

## Tubular Steam Reforming

In industry, the reforming reactions are typically carried out in a heated furnace over a nickel catalyst. An example [2,3,4] of this tubular reformer is shown in Fig. 2. Such reformers are built today for capacities up to 300,000 Nm<sup>3</sup> H<sub>2</sub>/h (equivalent). The furnace consists of a box-type radiant section with side wall burners and a convection section to recover the waste heat contained in the flue gases.

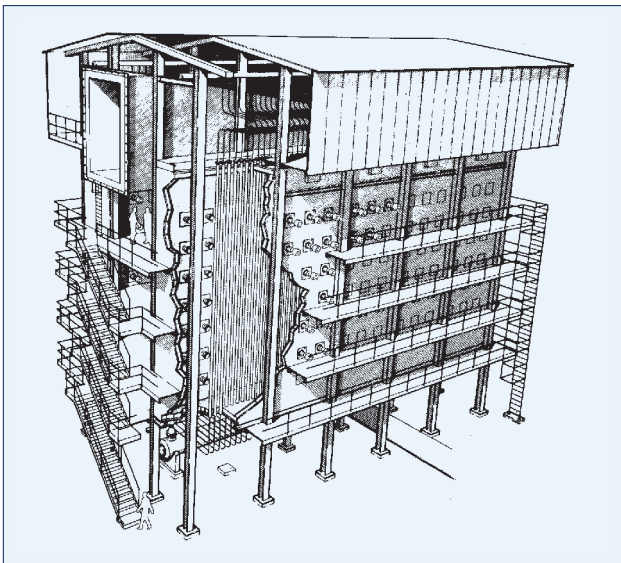


Fig. 2. Topsoe side fired tubular reformer

## Design of tubular steam reformers

The design of reformer tubes is normally done according to API-530 for an average lifetime before creep rupture of 100,000 h. Main parameters in the design are the maximum operating pressure, the design temperature and the creep rupture strength of the material used. However, the determination of these parameters is not unambiguous, and each reformer technology licensor applies his own procedures to determine the parameters and to introduce design margins as desired, without sacrificing the implied safety standards.

The calculation of the design temperature is demanding since it requires detailed understanding of the interplay between the radiant chamber heat transfer to the tube and the consumption of heat by the reactions inside the

tube. The modelling of the radiant chamber is complex [4]. It must include:

- Radiant heat transfer from the furnace internals (furnace walls and neighbouring tubes) and from the gas, including the flames
- Convective heat transfer from gas to tube wall
- Conduction through the tube wall
- Convection from the inner tube wall to the catalyst and the reacting gas, inside the tube

Furthermore, understanding of the reaction mechanism [5], the interplay between catalyst, reacting gas, and reformer tube, is also essential for the prediction of local gas compositions, temperatures and pressure drop, and thereby the limits for undesired carbon formation (Fig. 3).

Understanding of these phenomena was obtained through extensive R&D work using bench scale equipment, full size monotube pilot unit, and analysis of data from industrial units [1,6]. Based upon this significant data collection and analysis, a detailed two dimensional homogeneous reactor model was established for the design of advanced reformers [4,7].

$$\frac{\partial}{\partial z}(v \cdot C_A) = \frac{D_{r,eff}}{r} \cdot \frac{\partial}{\partial r} \left( r \cdot \frac{\partial C_A}{\partial r} \right) + R_A \cdot \rho_{bulk} \quad \text{Mass}$$

$$\rho \cdot C_p \cdot v \cdot \frac{\partial T}{\partial z} = \frac{k_{r,eff}}{r} \cdot \frac{\partial}{\partial r} \left( r \cdot \frac{\partial T}{\partial r} \right) + \sum_{j=1}^{REAC} R_j \cdot \rho_{bulk} \cdot (-\Delta H_j) \quad \text{Heat}$$

$$-\frac{dP}{dz} = -\left( \frac{\Delta P}{\Delta z} \right)_{Leva} \quad \text{Momentum}$$

Fig. 3. Reactor Modelling – Tube side

## Development in the design of tubular steam reformers

Tube failures, which are very rare events, appear to be caused mainly by transients [8] including start-up and shut-down or by operating errors leading to catalyst poisoning,

carbon lay-down, or over-firing. Operation at design conditions does not result in tube failure in well designed and well operated reformers. Tubes in side fired steam reformers experience well over 120,000 hours of operation.

Looking at the fundamental design equations for a steam reformer, the total transferred duty  $Q$  can be calculated from:

$$Q = n \cdot A \cdot q_{avg}$$

Where  $n$  is the number of tubes,  $A$  the tube surface area (inner wall) and  $q_{avg}$  the average heat flux. Using tube inner diameter  $ID$  and length  $L$ , the equation can be rewritten as

$$Q = n \cdot \pi \cdot ID \cdot L \cdot q_{avg}$$

At the same time the total transferred heat is proportional to the feed flow, which means that it is proportional to the space velocity,  $SV$ , times the total tube volume as shown below:

$$Q \propto SV \cdot n \cdot \frac{\pi}{4} \cdot ID^2 \cdot L$$

Now by setting the two equations for  $Q$  equal to each other they reduce to

$$q_{avg} \propto SV \cdot ID$$

It has been shown that the catalyst activity is significantly higher than required [1], which means that the  $SV$  is not an issue when a prereformer has been installed upstream of the tubular steam reformer. Thus the  $q_{avg}$  and tube  $ID$  can be chosen independently to provide an optimum reformer design. The local heat flux through the tube wall  $q$  can be approximated by the temperature gradient over the tube wall  $DT$ , the tube wall thickness  $t$ , and thermal conductivity  $k$ .

$$q = \frac{k}{t} \cdot \Delta T$$

This means that the maximum allowable local heat flux increases with decreasing tube

diameter, as the required tube wall thickness decreases.

However, as the tube diameter decreases the total cross sectional area available for the process gas decreases and the pressure drop increases. Therefore, there is a trade off between the size of the reformer and the pressure drop. By selecting specially shaped catalysts it is possible to limit the increase in pressure drop, allowing the reformer to be designed with a very high flux.

The total heat input can be expressed as a function of the average tube wall temperature gradient:

$$Q = \frac{k}{t} \cdot \Delta T_{avg} \cdot n \cdot \pi \cdot ID \cdot L$$

The tube wall thickness is a simple function of the tube  $ID$ , given a constant design temperature and pressure. Assuming that the wall thickness is proportional (by a factor  $c$ ) to the tube diameter the number of tubes can be expressed as:

$$n = \frac{c}{k \cdot \pi} \cdot \frac{Q}{L \cdot \Delta T_{avg}}$$

This means that the number of tubes is independent of the tube diameter. For a given transferred duty  $Q$  the only way to decrease the number of tubes is to make them longer and to design the reformer with a maximum  $DT_{avg}$  without exceeding critical values.

In order to take full advantage of this approach for reformer design it is thus important to be able to operate the reformer with the maximum allowable temperature gradient across the tube wall along most of the length of the tube, while at the same time seeking to minimise the maximum tube wall temperature of the tube by gradually reducing the flux and thus the temperature gradient towards the outlet as illustrated in Fig. 4. This will maximise the average heat flux and thus minimise the number of tubes and the cost of the reformer.

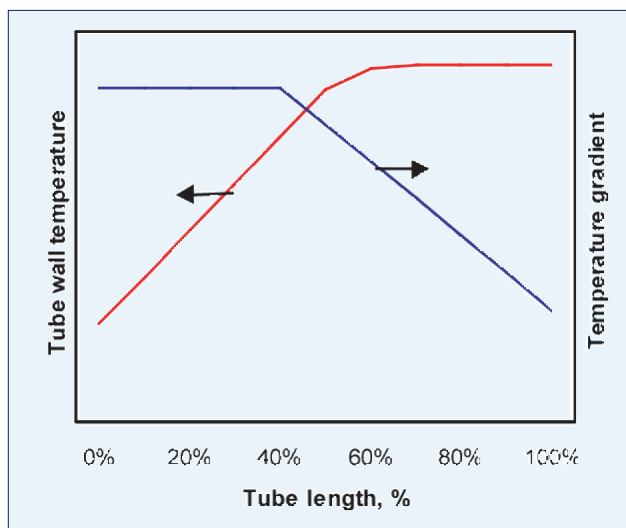


Fig. 4. Tube wall temperature and tube wall temperature gradient profiles

The side fired tubular reformer is ideally suited for this optimisation, as the desired heat input along the length of the tube can be achieved through proper selection of burner size and burner elevation.

Since it is possible to place tubes with a smaller diameter with a closer centre to centre spacing, a more compact reformer design is now possible. The following presents our experience with high flux reforming and a case study comparing Topsøe's classical design with the new high flux design.

### High Flux Reforming – Carrying the Experience Forward

As stated earlier the new high flux reformer design does not operate outside already industrially proven conditions for the critical design parameters. One of these is the local temperature gradient across the tube wall, which is closely related to the local heat flux.

Feedback from industrial operating plants has given valuable information. Several of Topsøe's reforming catalysts have been operating satisfactorily at very high local heat fluxes (max. local heat fluxes close to 150,000 kcal/m<sup>2</sup>h).



Fig. 5. Side fired tubular reformer

To supplement the industrial experience the HFR concept was tested in Topsøe's full scale process demonstration unit (PDU) in Houston, Texas, USA with the objective of fine tuning our reformer design tool and to investigate operating conditions beyond the industrial experience for future further optimization of the reformer design. Model simulations had shown that the reformer could safely be operated at heat fluxes beyond the industrial experience, and this needed verification in the PDU.

In Topsøe's PDU, a full-size monotube reformer, the reformer tube and reformer catalyst were exposed to operation at very high heat fluxes, average fluxes ranging from 100,000 to 175,000 kcal/m<sup>2</sup>h, which means local fluxes and temperature gradients far exceeding industrial experience. Also several trips, shutdowns and restarts of the reformer were simulated. The total test period lasted three months and valuable data on catalyst performance and useful data for verification of our reformer design model were obtained. After careful examination of the catalyst tube, it was concluded that the tube did not show any damage of the many trip and restart tests, showing that there as expected is room for still further reduction in the size of the reformer. Thorough risk analysis exercises were performed internally and with one of our customers, showing that the new HFR design provides the high reliability the Topsoe side fired reformer always has been known for.

## High Flux Reforming – Case Study

The following case study is based on an existing tubular reformer in a naphtha based hydrogen plant. The hydrogen plant has a capacity of 47,250 Nm<sup>3</sup>/h hydrogen, and it includes a prereformer with reheat of the prereformed feed before introduction to the tubular reformer. The existing design is compared to the HFR design at unchanged operating conditions. In addition to the increased heat flux, certain minor improvements in the mechanical design were also introduced.

As expected from the equations derived above the number of tubes is virtually unchanged. However, the new HFR design shows significant reduction in the size of the reformer itself. The main difference is that in the HFR design the diameter of the tubes is reduced by 25%. The heat flux is increased by 30% to an average heat flux of 100,000 kcal/m<sup>2</sup>h. Since today's high activity reforming catalyst contain ample activity, the reduction in catalyst volume by about 45% in the HFR design will not influence the reformer performance.

### **HFR – Cost Reduction Radiant Section**

The cost reduction for the HFR is mainly in the radiant section and the hot parts of the reformer. Compared to the design practiced 2-3 years ago the cost reduction is in the range 10-30% for the

main components (tubes, inlet distributor, cold collector, burners and steel & refractory). The largest cost reduction is realized for the catalyst tubes, the cold collector, and the catalyst. The smaller tube diameter in the HFR results in a lower total tube material weight, and the corresponding shorter spacing in a smaller size of the reformer box and outlet collector. The saving on the burners is mainly due to increased heat release per burner resulting in a lower number of burners.

### **Commercialisation of the high flux reformer**

Bringing forward Topsøe's vast experience in reformer design stemming from industrial experience, know-how, research & development efforts, model development, catalyst development, new tube materials and pilot plant testing has resulted in the high flux reformer design. The HFR design has first been offered for hydrogen plant clients, followed by syngas, methanol and ammonia clients.

The improved performance and reduced cost has resulted in sale of industrial HFR reformers. The first is part of a medium-size hydrogen plant in a European refinery. The plant was started in the first quarter of 2002. At present, three further reformers based on the HFR concept are being designed with expected start-up in 2003.

*Table 1. Comparison between the new HFR design and old design*

Relative values	Old Design	New Design (HFR)
Number of Tubes	126	124
Tube Diameter	Base	75%
Reformer Radiant Box Plot area	Base	75%
Number of Burners	Base	66%
Catalyst Volume	Base	55%
Heat Flux, average, kcal/m <sup>2</sup> h	75,000	100,000
Cost Index (incl. waste heat section)	100	85

## Conclusion

The high flux reformer technology is based on proven elements known from the steam reforming and other industries. Experience, know-how, and extensive development and testing has allowed the design of the high flux reformer, which offers a 15% reduction in cost as compared to the side fired steam reformer of 2-3 years ago.

The key is use of the best tube materials available coupled with a better utilisation of the tubes obtained through designing the reformer with smaller diameter tubes, which can be placed closer together. The temperature gradient across the tube wall can be controlled in the side wall fired design in such a way that very high average heat flux can be obtained without exceeding critical values. Side fired tubular reformers are today designed for operation at average heat flux almost two times higher than what was industrial standard 20 years ago. This leads to smaller reformer furnaces and significantly reduced cost.

The high flux reformer technology presented above will in the future form the basis for further innovative developments of the Topsoe steam reforming technologies.

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