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# Numerical and experimental study of enhanced heat transfer and pressure drop for high temperature applications

Marco W.M. van Goethem[a],*, Ellert Jelsma[b]

[a] Technip Benelux B.V., Boerhaavelaan 31, P.O. Box 86, 2700 AB Zoetermeer, The Netherlands
[b] FlowMotion, Leeghwaterstraat 21, 2628 CA Delft, The Netherlands

## ABSTRACT

This paper focuses on the passive heat transfer enhancement where the flow surface is modified to increase the heat transfer. This field is narrowed by considering only techniques that are suited for high temperature applications in the range of 600–900 °C of the "cold" fluid.

The scope to enhance heat transfer by the active method is limited due to the metallurgical properties of the tubes applied. Therefore several techniques have been proposed and applied to reduce the heat transfer resistance at the "cold" side, such as internally finned tubes, swirl inducers and helical shaped tubes.

The penalty associated with enhancing the heat transfer is an increase in friction, which can be an important phenomenon for the application, for example in the production of ethylene by means of thermal cracking. In this study the results are presented to find the optimal heat transfer enhancement technique that has the lowest penalty in pressure drop for high temperature applications.

The work has been executed by means of numerical simulations (CFD) of eight different available techniques. The numerical model is validated with heat transfer and pressure drop measurements for helical tubes. The validated model is subsequently applied on all the different heat transfer enhancement geometries.

The results are compared with a reference straight tube as well. It is concluded that the helical tube yields the highest heat transfer at the lowest penalty with respect to pressure drop. The solid fins yield the lowest heat transfer enhancement and the highest penalty on pressure drop.

*Keywords:* Enhanced heat transfer; High temperature; CFD; Steam cracking; Ethylene; Swirl flow tube

## 1. Introduction

The steam cracking process was discovered half a century ago and its understanding has evolved from an empirical description to a detailed knowledge of its fundamentals, in terms of chemical mechanism, kinetics, process requirements, design methods, etc. The practical state-of-the-art in steam cracking has reached a stage of maturity in which improvements in yield and product selectivity are becoming increasingly difficult due to engineering restrictions (van Goethem et al., 2007). Typically, the ethylene yields are improved by raising the cracking temperature to increase cracking severity and the residence time is reduced to increase selectivity. These severe conditions are constrained by the metallurgy of the applied cracking tubes in the furnaces. Currently the maximum tube metal temperature for tubes made of Cr–Ni alloys is approximately 1200 °C. The heart of a cracking furnace is the radiant coil through which the hydrocarbons flow diluted with steam in a turbulent plug flow regime. These hydrocarbons are alkanes such as ethane, liquefied petroleum gas (LPG), naphthas, gas condensates, and gas oil. The temperature increases from approximately 600–900 °C in 0.001–1 s. In first instance the alkanes are cracked to the desired olefins, mainly ethylene and propylene and smaller alkanes. This is referred to as primary cracking which is described accurately with first order kinetics. However, secondary reactions take place. This is the subsequent cracking, dehydrogenation, condensation, etc. of the (desired) products from the primary

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* *Corresponding author*. Tel.: +31 630373069.
E-mail addresses: mvangoethem@technip.com, m.w.m.vangoethem@gmail.com (M.W.M. van Goethem).

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cracking to diolefins, aromatics and eventually coke. Second-order kinetics describes the secondary cracking quite well. It is well known that second order reactions are promoted by higher pressures. The steam is added to reduce the partial pressure of hydrocarbons to suppress the secondary reactions and the coking rate.

To optimize the design of a steam cracking furnace, in other words maximizing the ethylene yield, the residence time of the coil has to be reduced at the same or higher temperature level. This implies that the required energy must be transferred in a shorter period of time, resulting in higher energy transfer rates. These higher rates can be achieved by increasing the heat flux through the coils which means higher tube metal temperatures. This is defined as the active heat transfer enhancement. Currently furnaces are designed close to the maximum feasible tube skin temperatures that are close to 1200 °C with a residence time up to about 0.25 s.

There are several technologies available to increase the heat transfer or in other words to reduce the tube skin temperature. This is defined as the passive heat transfer enhancement. Not all of these technologies can be applied in high temperature applications like steam cracking furnaces. In this paper we will investigate what the best heat transfer enhancer is for high temperature applications such as steam cracking furnaces. This will be done by means of Computation Fluid Dynamics (CFD). The CFD modelling has been experimentally validated for one particular heat transfer enhancer. This experimentally validated model will be applied to the other considered heat transfer enhancers.

In the next section we will elaborate on which heat transfer enhancer techniques are considered. In the subsequent sections the experimental set-up, the interpretation procedure and the applied numerical CFD procedure are explained. Thereafter the experimental results will be discussed followed by a section wherein the different heat transfer enhancers are discussed. This paper is closed with some concluding remarks.

## 2. Enhanced heat transfer devices

The different type of enhanced heat transfer devices can be divided into two classes based on the physical explanation of the increased heat transfer, namely increase in internal surface area or enhancing the flow mixing (some of them benefit from both).

### 2.1. *Increased internal surface*

The most straightforward are the internally finned tubes as shown in Figs. 1 and 2. This type of finning is amongst others proposed by Albano et al. (1991) and is labelled in this writing as Solid Fins and abbreviated as **SF**.

Another example of the extended internal surface class which has been intensively studied and industrially applied are the straight internally finned tubes as described by Albano et al. (1988) and Schietekat et al. (2013), produced amongst others through Electro Chemical Machining (Brown, 2004). A schematic of the straight internally fined tubes (**ECM-S**) is shown in Fig. 3. Brown (2004) shows that the increase in heat transfer is linearly dependent on internal surface increase.

### 2.2. *Enhanced flow mixing*

Enhanced heat transfer devices by means of enhanced flow mixing improve mixing particularly in radial direction of the tube, and as a consequence yields a more homogeneous process temperature and higher heat transfer rates. This principle can be found in the helical type of ECM, abbreviated in this work by **ECM-H**, see Fig. 4. Another industrially applied mixing device to enhance the heat transfer is the mixing element radiant tube (MERT) from Kubota (Torigoe et al., 1999). Torigoe et al. (1999) claim an increase of the heat transfer by 20–50% relative to the straight tube while the surface area increase is less than 2%. Two optimisations of this type with respect to pressure drop are the so-called SLIT-MERT and the X-MERT. The standard MERT, SLIT-MERT and X-MERT give for a heat transfer increase of 40%, a penalty on the pressure drop of respectively 300%, 240% and 210% (Györffy et al., 2009). Fig. 5

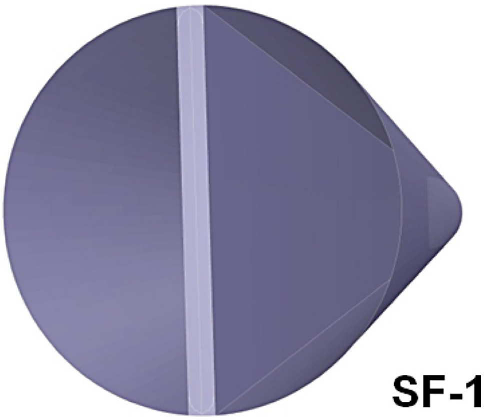

**Fig. 1 – Schematic of solid fins type 1, SF-1 (cross section extended in 3D).**

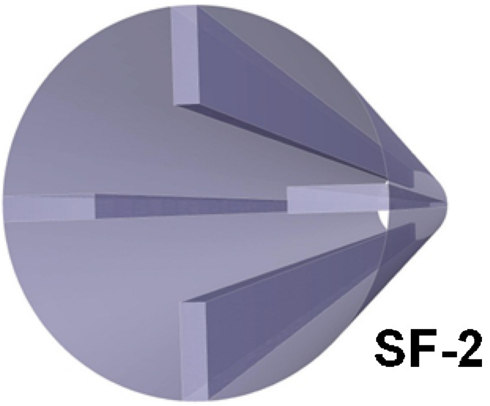

**Fig. 2 – Schematic of solid fin type 2, SF-2.**

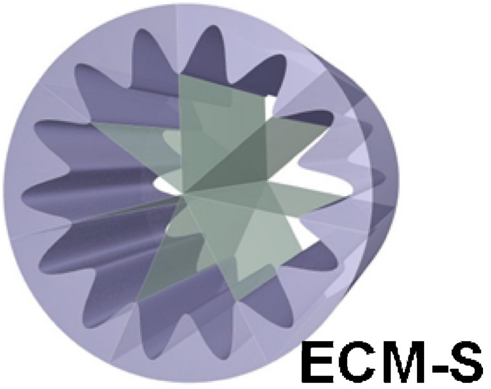

**Fig. 3 – Schematic of straight internally finned tubes produced by electro chemical machining, ECM-S.**