Modelling of intensified catalyst-coated plate-fin heat exchanger reactors: Impact study of a surface reaction on the fin behavior, on reactive fin efficiencies and on by-pass factor.

Jean-Patrick Barbé[1,2,3]*, Jean-Marc Commenge[1,2], Matthieu Flin[3],
Solène Valentin[3], Marc Wagner[3], Laurent Falk[1,2]

1 Université de Lorraine, Laboratoire Réactions et Génie des Procédés, UMR 7274,
1 rue Grandville, BP 20451, 54001 Nancy Cedex, France;
2 CNRS, Laboratoire Réactions et Génie des Procédés, UMR 7274,
1 rue Grandville, BP 20451, 54001 Nancy Cedex, France;
3 Air Liquide, Centre de Recherche Paris-Saclay, 1 chemin de la Porte des Loges,
Les Loges-en-Josas, BP 126, 78354 Jouy-en-Josas, France.

**Corresponding author: jean-patrick.barbe@univ-lorraine.fr*

Highlights

- A one-dimensional reactive fin model is proposed.
- The impact of a surface catalytic reaction on the fin behaviour is studied.
- Reaction heat absorption has non-negligible effects on the fin behaviour.
- This one-dimensional model correlates well with Computational Fluid Dynamics (CFD).

1. Introduction

Compact heat exchanger reactors are promising technologies for intensification of heterogeneous catalytic processes since they enable reducing heat and mass transfer limitations. By supplying/removing heat directly to/from a wall-coated catalyst, internal heat and mass transfer limitations are considerably reduced compared to conventional fixed bed reactors, and as a consequence, both the reaction and safer operating conditions are promoted [1].

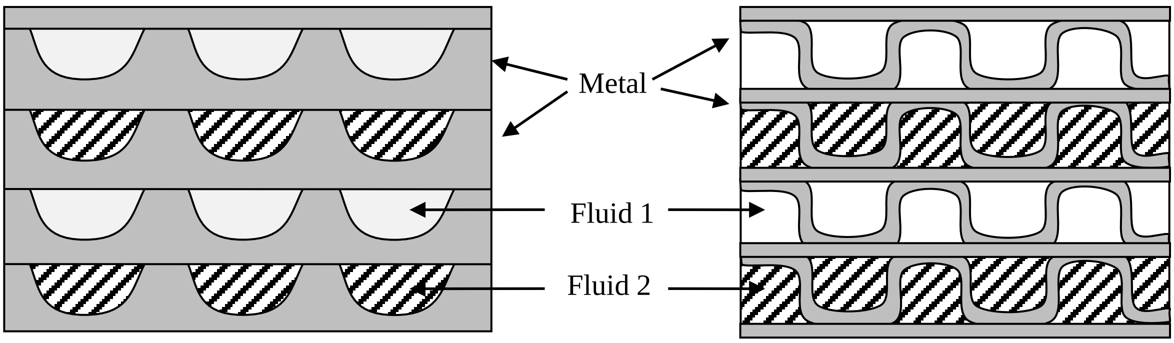

Figure 1. Schematic cross-sectional views of a millichannel heat exchanger reactor (left) and a plate-fin heat exchanger reactor (right).

Compact heat exchanger may be conceived as a stack of either flat and etched plates or plates and embossed fins for Plate-Fin Heat Exchangers (PFHE), which are soldered together and determine alternate fluidic channels, usually about few millimeters in diameter (Figure 1). These heat exchangers are usually constituted of tens to hundreds of types of passages where up to twenty different fluids may circulate. In these channels, heating (resp. cooling) fluids circulate to heat up (resp. cool down) other layers of channels where potentially one or more chemical reactions occur. Due to the high potential of heat transfer intensification, PFHE are a wide-spread technology for cryogenic applications [2].

A PFHE features very specific geometric characteristics: in a layer determined by two plates, adjacent channels are separated by a very thin and very long fin. As a consequence of these geometries, the overall heat-transfer performance results from the competition between heat conduction in the section of the wall/fin and heat convection along its surface, and non-negligible temperature gradients often appear. For modelling purposes, the impact of the gradients occurring inside fins is usually taken into account via a fin efficiency which is a function of the heat transfer coefficient, geometry and material of the fin [2 - 4].

Due to the high number of fluids and passages of a PFHE, heat flows between the fluids in the passages may not be well distributed in the stack height, and temperature gradients may appear between two adjacent plates of the stack. With this driving force, the total conductive heat flux entering the fin at its base may not be entirely transferred to the fluid: part of it may partially be transferred to other plates by conduction without interacting with the fluid. This conductive heat flux between two adjacent plates is called a by-pass flux and is usually modelled thanks to a by-pass factor in PFHE models. [4]

In the case of wall-coated catalytic heat exchanger reactors, the chemical reaction occurring at the surface of the fins is likely to significantly affect their temperature profile by absorbing or releasing heat at their surface, thus modifying the overall performance of the reactor [5 - 7]. The coupling of these thermal effects with catalytic reactions has to be quantified for proper design of these new technologies.

2. Methods

In order to study the cumulative effects of surface heat absorption/production, external mass transfer at the catalyst surface, heat conduction in the fin and fin geometry on the fin temperature, on the fin efficiencies and on the by-pass factor, heat and mass balances have been written for a first-order irreversible chemical reaction $A \rightarrow B$ occurring at the wall/fin surface. Relevant dimensionless numbers, such as Arrhenius, Biot and Damköhler numbers have been then identified as parameters of the problem.

3. Results and discussion

Numerical solution of this one-dimensional set of equations demonstrates that strong deviations may occur if only the thermal theory is applied in the case of a reactive fin, which highlights the necessity of taking surface reaction heat absorption/production into account.

Three-dimensional CFD simulations have been performed to check the accuracy of the one-dimensional fin efficiency and by-pass factor expressions, for a simplified $A \rightarrow B$ reaction and turbulent flow on one hand, and for the case of the Steam Methane Reforming (SMR) reaction and laminar flow on the other hand. This last reaction was chosen because of its good representativeness of a general chemical reaction. The one-dimensional efficiencies predict results in good agreement with those of the CFD simulations.

4. Conclusions

For PFHE reactors modelling purposes, this one-dimensional fin model was shown sufficiently simple to be solved and sufficiently reliable to be implemented inside global PFHE reactors models.

References

[1] J.-M. Commenge, L. Falk, J.-P. Corriou, M. Matlosz, Chem. Eng. Technol. 28 (4) (2005) 446-463.
[2] R.K. Shah, A.D. Kraus, D.E. Metzger, Compact heat exchangers, Hemisphere Publishing Corporation, New York, 1990, pp. 727-742.
[3] B.S.V. Prasad, Int. J. Heat Mass Transfer 40 (18) (1997) 4279-4288.
[4] D. Averous, PhD thesis, I.N.P.T. Toulouse, France, 2000.
[5] S.M. Senkan, Analysis and Design of Catalyst-coated Fins/Spines, Industrial & Engineering Chemistry Process Design and Development 19 (4) (1980) 680-688.
[6] K. Okuyama, A. Ogawa, JASME series B 42 (2) (1999) 255-261.
[7] K. Okuyama, A. Ogawa, JASME series B 42 (4) (1999) 683-690.

Keywords
Plate-fin heat exchanger reactor, Catalyst coated fin modelling, Reactive fin modelling, Fin efficiency.