OPTIMIZED HEAT TRANSFER PERFORMANCE OF CATALYTIC REACTORS WITH NOVEL STRUCTURED SUPPORTS: ASPECTS FOR PROPER DESIGN

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Abstract

Metal foam supports represent a promising novel technology when used as catalyst carrier in tubular reactors for heterogeneously catalyzed reactions. They combine outstanding properties regarding geometrical aspects, fluid flow, and mass- and heat transport characteristics. In this work, extensive numerical simulations of conjugated heat transfer were performed to systematically investigate the role of different coupling scenarios between the metal support and the reactor wall. For this, a 3D scanned geometry of a real support sample is used to allow for validation of the simulation results with experiments. The contact area between the foam and the reactor wall was varied, starting from adiabatic conditions up to perfect contact for all struts. The contact area was increased by selecting randomly a certain (continuously increased) percentage of struts at the outer radius of the foam and considering them as perfectly connected with the wall. In addition, also the influence of the location of the connected struts was investigated. As a result of the numerical analysis we could identify that even if only few struts have direct contact with the tube wall, they can significantly enhance the heat transfer of the catalytic reactor system.

Keywords

Metal Foams, Heat Transfer, Process Intensification, Structured Reactors.

Introduction

The heat transfer performance of catalytic reactors is a key factor in highly endothermic (e.g. steam reforming) and exothermic (e.g. phthalic anhydride synthesis) processes. In this regard, structured supports provide the possibility to adjust their properties in an optimal manner, achieving a more precise control over the transport and reaction phenomena taking place in the reactor. Among the family of structured packings, open-cell foams are a novel class of cellular materials attractive as structured catalyst support because of their high geometric surface area, high void-fraction, low pressure drop (Inayat et al., 2011), and high gas/solid heat- and mass-transfer rates (Giani et al., 2005). Moreover, the interconnected solid matrix can provide a significant contribution by conduction inside the solid as additional mechanism for the heat transport, particularly for supports made of highly conductive bulk materials. Despite these promising features the knowledge about the influence of the local structure on the flow field and transport properties of open-cell foams is still limited. With our contribution, we aim at diminishing this knowledge gap in order to be able to exploit the full potential of these novel structures.

Numerical Method and Approach

In this work, a detailed study of fluid flow and heat transfer on a local scale was performed by means of numerical simulation and validated by data from previous lab-scale experiments. The aim was to develop a fundamental understanding of the relationship between the local support structure and the heat transfer characteristics. This knowledge was then used to derive correlations for the global transport characteristics of the support that can be applied in macroscopic "engineering" models.

Based on experimental temperature profiles that were collected in a lab-scale foam filled tube, the effective radial and axial thermal conductivities of the foam bed as well as the wall heat transfer coefficient were estimated. As a result of the experimental activities, the solid fraction and the bulk conductivity of the solid material were identified as the controlling parameters for the determination of the bed effective conductivity (Bianchi et al., 2013). In

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addition, experiments with gas-solid systems revealed a high temperature gradient confined at the foam-tube wall interface (Bianchi et al., 2012) when highly conductive supports (i.e. Al) were used. The wall heat transfer coefficient was found to depend strongly on the fluid conductivity and the pore density. However, in the experimental setup it was not possible to estimate directly the coupling between the foam and the reactor tube. For this reason, extensive simulations of conjugated heat transfer were performed to systematically investigate the role of different coupling scenarios (e.g. gap between foam and wall or perfect contact) between the support and the reactor wall, using a 3D scanned model geometry (Figure 1) to validate the simulation results with experiments. As a result, a new correlation for the heat transfer in structured catalytic reactors packed with metal foams and the related implications for the intensification of catalytic processes were recently presented (Bianchi et al., 2015).

By this detailed model analysis, a better understanding is possible on how the wall coupling (size of clearance) in a structured catalytic reactor packed with metal foam supports influences the heat transfer. This is of enormous importance for the industrial application, as usually the foams have a slightly smaller diameter than the tubular reactor in order to enable the loading and unloading of the reactor, but at the same time this clearance downgrades the thermal heat transfer performance of the reactor.

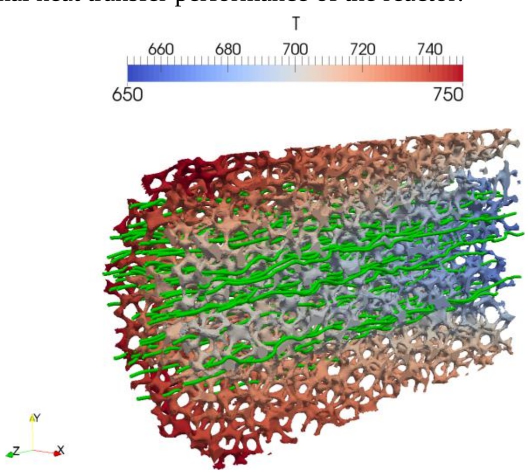

Figure 1. Simulated solid temperature (color scale) and fluid velocity field (streamlines) inside an open-cell solid foam.

Investigated Cases

In our current numerical investigations, carried out using the open source tool OpenFOAM, the focus is on the characterization of the contact area between the foam struts and the reactor wall. Starting from perfect contact between all struts and the wall, the contact area was decreased by randomly selecting struts and considering these struts as adiabatic (Figure 2). In addition, the location of the selected struts could be restricted to regions near the inlet or the outlet to investigate the influence of the strut location on the overall heat transfer performance. Finally, all connections between the struts and the reactor wall were considered adiabatic as a limiting case with heat transfer only occurring between the reactor wall and the gas phase, and then from the gas phase to the foam.

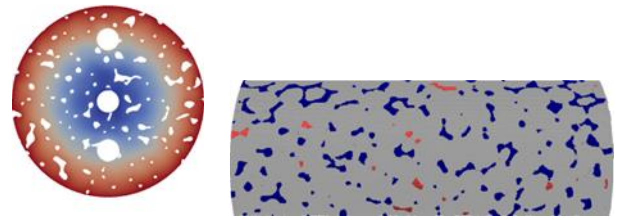

Figure 2. Radial temperature distribution in the gas phase (left) and location of the contact points for one selected case of 10% contact: red spots are connected to the wall, blue ones are set to adiabatic (right).

Corresponding to the experimental data collected in our previous work, we here study the flow of different gases through a foam with different solid material properties in order to investigate the influence of the thermal conductivity on the temperature profile. The numerical setup used was comparable to the previous experimental setup (Bianchi et al., 2013), a stainless steel tube of 28 mm internal diameter filled with a cylindrical foam bed of 10 cm length.

Results and Discussion

As a result of the numerical analysis we could identify that even if only a few struts have a direct contact with the tube wall and can thus contribute to the heat transfer, the overall heat transfer performance will be enhanced to a great extent.

A selected example is a heating experiment with 30 Nl/min Nitrogen flowing in an Aluminium foam. The average gas phase temperature in the reactor increases from 553.8 K in the adiabatic case to 589.8 K for 5% contact, and to 601.2 K for 10% of the strut area connected to the wall. In addition, the influence of different contact location for the same percentage was investigated, showing minor influence on the average gas phase temperature, but on the local temperature distribution.

The insights gained from the detailed numerical analysis can serve as a starting point for future optimization of structured catalyst supports, specifically to identify which percentage of the struts at which position in the reactor are actually required to have contact in order to significantly contribute to the heat transfer performance of the catalytic reactor.

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