Chemical Engineering Science 65 (2010) 420–426

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Heat transport in structured packings with co-current downflow of gas and liquid

Kalyani Pangarkar[a,c,*], Tilman J. Schildhauer[b], J. Ruud van Ommen[c], John Nijenhuis[c], Jacob A. Moulijn[a], Freek Kapteijn[a,*]

[a] Catalysis Engineering, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands
[b] Laboratory for Energy and Materials Cycles, Paul ScherrerInstitut, 5232 Villigen PSI, Switzerland
[c] Product and Process Engineering, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands

ARTICLE INFO

*Article history:*
Received 6 July 2008
Received in revised form 10 July 2009
Accepted 15 August 2009
Available online 21 August 2009

*Keywords:*
Heat transfer
Multiphase reactors
Packed bed
Convective transport
Structured packings
Energy dissipation

ABSTRACT

Improvements in catalyst activity make the heat transport in fixed bed reactors increasingly important. Structured packings operated in two-phase flow are expected to outperform randomly packed beds, but heat transfer data on structured packings is scarce. In this work structured packings such as OCFS (Open Cross Flow Structures), CCFS (Closed Cross Flow Structures), knitted wire, and foam were characterised with respect to the heat transfer performance. A dedicated set-up was designed and built which enabled us to measure the heat transfer rates in two-phase flow at ambient pressure in the absence of reaction. Benchmarking and set-up validation was carried out using glass beads. The structured packings—especially OCFS and CCFS—show heat transfer coefficients that are superior over those of glass beads, at lower energy dissipation.



## 1. Introduction

Structured packings such as OCFS (open cross flow structures), CCFS (closed cross flow structures), foams and knitted wire (Fig. 1) as catalyst supports have certain advantages over randomly packed beds due to their well-defined geometry (Pangarkar et al., 2008). OCFS and foams are well-known for their excellent radial mixing properties. Similarly, CCFS are expected to have good radial heat transport as flow in these structures is directed in radial direction towards the wall. Knitted wire is well-known for its high mass transfer efficiency in distillation (Bragg, 1957).

So far, almost no research effort has been put in heat transfer studies in structured packings for two-phase flow as they are hardly used in applications where heat transfer is a major issue. Some work has already been published regarding heat transfer measurements in single gas phase flow: for Katapak-M catalysts supports (von Scala et al., 1999), ceramic foam catalyst supports (Richardson et al., 2003), honeycomb monoliths (Groppi and Tronconi, 2005), OCFS packings (Eigenberger et al., 1993) and CCFS packings (Schildhauer et al., 2009).

In this work, we have quantified the heat transfer in two-phase flow of nitrogen and an organic liquid (Isopar-M) at various gas and liquid velocities. The four structured packings mentioned above and a randomly packed bed of glass beads are compared based on the observed heat transfer rates.

### 1.1. Structured packings

The *OCFS structure* consists of superimposed individual corrugated metal sheets, with the corrugations in opposed orientation such that the resulting unit is characterized by an open cross-flow structure pattern (von Scala et al., 1999), see Fig. 1. The radial convection in these structures is a part of mixing flow patterns between adjacent corrugated sheets.

The *CCFS structure* is derived from that of OCFS by inserting flat sheets between adjacent corrugated sheets. This way it is transformed into a monolith-like structure with a multiplicity of closed inclined triangular channels (Behrens et al., 2001), see Fig. 1. The flow in these structures is directed in radial direction without any mixing of adjacent flow paths. Mixing of flow paths occurs in the gap between structure and reactor wall (Schildhauer et al., 2009). Inside the structure, heat is transferred by conduction only from one channel through the corrugated sheet to the neighbouring channel.

The *knitted wire packing* is characterized by bundles of knitted strands of stainless steel wires which are flattened, crimped and rolled to give the desired diameter of the packing. The crimps run either from top left to bottom right or *vice versa*. The alternating arrangement of the crimped packing promotes fluid remixing at the changeover points. (Bragg, 1957). Additionally, the capillary nature of the filaments helps in spreading the liquid over the complete

* Corresponding authors. Catalysis Engineering, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands.
*E-mail addresses:* kalyanimv@hotmail.com (K. Pangarkar), f.kapteijn@tudelft.nl (F. Kapteijn).

0009-2509/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.ces.2009.08.018

cross-section resulting in high interfacial areas for heat and mass transfer.

*Foam materials* consist of small ligaments that are continuously connected in an open-celled foam structure. The cells have a certain orientation by which the motion of the fluids is promoted either axially or radially. The radial orientation of the cells is desired when convective heat transport in the radial direction is desired. The tortuous flow paths through the porous matrix promote turbulence and increase convective heat transfer (Richardson et al., 2003).

The structured packings, particularly the cross flow structures and foams are anisotropic: they do not possess the same properties in different radial directions. Therefore the heat transport will be different, resulting in different temperature profiles along different angular positions at the same axial position. Table 1 provides the properties of the structured packings and the glass beads that are used as a reference material in this study.

### 1.2. Definition of heat transfer parameters

In non-adiabatic reactors, heat flows have to be considered in both radial and axial directions (Elsari and Hughes, 2002) but the heat flow in the axial direction, characterized by $\lambda_{e,ax}$, is often neglected due to its limited contribution to the heat transfer process especially for long beds when the Peclet number of heat is relatively high. The extent of axial dispersion of heat should be of course checked for structured metallic packings as the conduction of metal is at-least an order of magnitude higher than of ceramic particles.

Radial heat transfer contains contributions of convective heat transport, radiation (neglected in this study) and thermal conduction through the fluids and the solid structure of the packing, i.e. structured internal or catalyst particles. Heat transfer in packed bed reactors has been mainly investigated using 2-dimensional pseudo-homogeneous models: i.e. by considering that in any location of the reactor the three phases (gas, liquid, solid) are at the same temperature (Lamine et al., 1996). In that case the heterogeneity of the packed bed is included in the values of two parameters which describe the radial heat transfer, viz. $\lambda_{e,r}$, the effective bed radial conductivity and $\alpha_w$, the wall heat transfer coefficient (Wijngaarden and Westerterp, 1992).

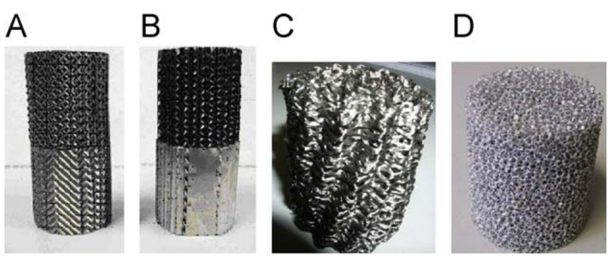


**Fig. 1.** Photos of the structured packings: (A) OCFS, (B) CCFS, (C) knitted wire and (D) Al-foam.

The apparent thermal conductivity of a packing (either a randomly packed bed or a structured packing) is no longer a material property but depends also on the flow and heat transfer conditions and on the size and shape of the packings. It is called the effective thermal conductivity, $\lambda_{e,r}$. In this approach the bed is considered a quasi-continuum and the conductive heat flux is described by means of the Fourier equation (Achenbach, 1995). The extra resistance to heat transport in the near-wall region is accounted for by the wall heat transfer coefficient $\alpha_w$, first introduced by Coberly and Marshall (1951). It is related to the near wall temperature jump, which is usually observed experimentally in non-adiabatic reactors. It describes the heat transport at the interface region between the fixed bed and the tube wall and stands for the complex interplay between fluid convection and conduction close to the heat exchange surface (von Scala et al., 1999).

The total heat transfer can be expressed by the overall heat transfer coefficient, $U_{ov}$, which is obtained from the overall heat balance of the reactor tube.

## 2. Experimental

### 2.1. Experimental set-up

Heat transfer rates for random packings were measured by Lamine et al. (1992) using the constant wall temperature approach. Babu and Sastry (1999) have measured heat transfer rates also in random packings by heating air–water mixture using hot water circulated in the jacket.

In this work, we employed a set-up using the constant wall temperature approach. Heat transfer measurements were carried out by measuring the radial and axial temperature profiles generated by cooling a heated mixture of Isopar-M (organic liquid consisting of $C_{13}$–$C_{16}$ isoparaffins) and nitrogen flowing co-currently downwards in a 60 cm long 'heat transfer' column (Fig. 2). The packing elements, each of which 50 mm in height with a diameter typically between 49 and 50 mm ( $< 50$ mm to fit inside the column tube) are packed into the column. Of each structured packing, 12 elements were placed in the column, giving a total height of 60 cm. The elements are rotated by 90° along the axis relative to the previous element to redistribute the flow. An insulated 'calming' column of 80 cm is installed on top of the heat transfer column to stabilize the flow and temperature profiles before the flow enters the heat transfer column. For all experiments, this calming column is loaded with the same packing as the one under investigation. The inlet temperature of the gas and liquid is measured before the calming column. All measurements were performed at ambient pressure and for a feed temperature of 60 °C.

A gear pump (Micropump series 223) circulates the liquid and the flow is measured via turbine flow sensors. The liquid is heated to 60 °C and distributed on top of the packing in the calming column via 51 point showerhead with a 0.5 mm point diameter. Nitrogen is supplied by a mass flow controller (Brooks instrument, 5853S, ± 1% full scale) and heated from room temperature to 60 °C. The gas enters through four inlets at the top of the calming column, in order to ensure proper distribution of the gas on the top of the packing.

**Table 1**
Properties of packings used in the measurements.

| Packing | Material | $\varepsilon$ (–) | $d_h$ (mm) | $a_v$ ($m^{-1}$) | $D$ (cm) | $\lambda_{static}$ (W/(m K)) | Supplier |
|---|---|---|---|---|---|---|---|
| Glass beads | Silica | 0.4 | 0.9 | 2000 | 5.0 | 0.08 | Fischer-Emergo |
| Open cross flow | Stainless steel | 0.84 | 1.8 | 1885 | 4.9 | 2–4 | Sulzer ChemTech |
| Closed cross flow | Stainless steel | 0.95 | 1.6 | 2400 | 4.9 | ~1 | In-house made |
| Knitted wire | Stainless steel | 0.9 | 1.9 | 1932 | 5.0 | 1–3 | Evergreen India |
| Foam | Aluminium | 0.9 | 2.4 | 1800–2000 | 4.9 | 20–25 | ERG Duocel |

$\lambda_{static}$ calculated for the various structured packings with a predictive equation valid for monoliths by Groppi and Tronconi (2005).