International Journal of Heat and Mass Transfer 101 (2016) 517–526

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Radial multiphase thermal conductivity and wall heat transfer coefficient of ceramic sponges in co-current multiphase flow – Experimental results and correlation

M. Wallenstein, M. Kind, B. Dietrich *

Institute of Thermal Process Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstrasse 12, 76131 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form 9 May 2016
Accepted 9 May 2016

Keywords:
Ceramic sponge
Open-cell foam
Radial multiphase thermal conductivity
Effective thermal conductivity
Radial heat transfer
Wall heat transfer coefficient
Multiphase flow

ABSTRACT

In this publication, experimental results for the radial multiphase thermal conductivity and the wall heat transfer coefficient of different ceramic sponges as column internals for trickle beds are presented. The experiments were performed in co-current mode with the fluids water and air. The material, porosity and cell density of the sponges were varied. A strong influence of the superficial liquid velocity and of the cell density on the radial multiphase thermal conductivity is found. Dimensionless correlations of the experimental data are given.

1. Introduction

Heat transfer is of high importance with respect to selectivity or catalyst deactivation in chemical reactors, especially for temperature sensitive reactions in trickle-bed reactors. In general, the problem is to remove the generated heat of the reaction. Four types of thermal resistances can be differentiated: the resistance between the trickle bed and the reactor wall, the resistance inside the trickle bed, the resistance between fluids and solid, and the internal resistance of the solid. The first two resistances are the most important ones in the case of moderate heat production or consumption. It is important to pre-estimate these heat transfer resistances by appropriate correlations when designing a trickle-bed reactor. In this publication, these resistances are determined for ceramic sponges as column internals for trickle-bed reactors. Furthermore, correlations for ceramic sponges are presented based on known approaches for packed beds of particles.

A packed bed of particles is typical for trickle-bed reactors and is used for enhancing heat and mass transfer. These particles can be simple spheres or more complex structures, such as Raschig rings, Berl saddles or Pall rings. These random packings are made of different materials (plastic, ceramic or metal) and the porosity is as high as 70% (ceramic particles) or more than 90% (plastic and metal particles). In general, particles made of ceramic are used for trickle-bed reactors due to their inert behavior. Typically, the volumetric surface area (equal to the specific surface area of the dry packing) is in the range of 50–300 m^2 per cubic meter packing volume [1]. This comparably low specific surface area and the point contact between the particles (high heat transfer resistance) are disadvantages of packed beds of particles. Ceramic sponges could be an alternative column internal to avoid these disadvantages.

Sponges are solid network structures with high porosity, typically of about 75–95%. They are often called open-celled foams in literature. In contrast to packed beds of particles, they have a continuous solid phase that offers advantageous heat transfer properties. Sponges induce a comparably low pressure drop due to their high porosity [2]. In addition to column internals, potential technical applications of sponges are porous burners, solar receivers, carriers for catalysts, lightweight constructions, sound and heat insulation, and heaters [3,4].

A homogeneous model is often used for modeling heat transfer problems in trickle-bed reactors and porous media. In contrast to the heterogeneous model, where the contribution of every phase to the total heat flux is considered separately, the homogenous model is obtained by generating a single combined heat transfer resistance of the solid and the fluid phases. Hence, the multiphase

* Corresponding author. Tel.: +49 721 608 4 6830; fax: +49 721 608 4 3490.
E-mail address: dietrich@kit.edu (B. Dietrich).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.042

Nomenclature

Latin symbols

A	area (m^2)
c	weighting factor (–)
c_p	specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
$\bar{c}_p$	substitute specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
d	diameter (m)
h_l	hold-up [V_l/V_{bed}] ($m^3\,m^{-3}$)
h	specific enthalpy ($kJ\,kg^{-1}$)
Δh	specific enthalpy change ($kJ\,kg^{-1}$)
Δh_{lv}	latent heat of evaporation ($kJ\,kg^{-1}$)
K	radial dispersion coefficient (–)
$\dot{m}$	mass flux density ($kg\,m^{-2}\,s^{-1}$)
$\tilde{M}$	molecular weight ($kg\,mol^{-1}$)
p	pressure (Pa)
p_l^*	vapor pressure of the liquid (Pa)
ppi	pores per inch (–)
r	radial coordinate (m)
S_v	specific surface area (m^{-1})
t	time (s)
T	temperature (K)
u_g	superficial gas velocity ($m\,s^{-1}$)
u_l	superficial liquid velocity ($m\,s^{-1}$)
x_f	mixing length (m)
z	axial coordinate (m)

Greek symbols

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
ϑ	temperature (°C)
κ	thermal diffusivity ($m^2\,s^{-1}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ν	kinematic viscosity ($m^2 s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ψ	porosity (–)

Subscripts

$3ph$	multiphase
0	stagnant fluid
ax	axial
b	bulk
calc	calculated
exp	experimental
f	fluid
g	gas
in	inlet
l	liquid
n	nominal
out	outlet
p	particle
r	radial
s	solid
v	vapor
W	wall

Dimensionless numbers

$Nu_W = \frac{\alpha_W \cdot x_f}{\lambda_f}$	wall Nusselt number
$Pe = Re \cdot Pr$	(molecular) Péclet number
$Pr = \frac{\nu}{\kappa}$	Prandtl number
$Re = \frac{u \cdot x_f}{\nu}$	Reynolds number

system is treated as a single continuous phase [5] and the phases are assumed to be in thermal equilibrium at any location. One important parameter in the energy balance of the homogeneous substitute system is the so-called radial multiphase thermal conductivity, $\lambda_{3ph,r}$, which is also often called the effective thermal conductivity in literature. This parameter describes the radial heat transport in a cylindrical coordinate system (heat transport perpendicular to the flow direction) and usually depends on the material of the fluid and the solid phase, on the porosity, and on the flow rates. A second important parameter is the wall heat transfer coefficient, α_W, which describes the thermal resistance between the bed and the wall.

In the past, some literature has dealt with the radial multiphase thermal conductivity, $\lambda_{3ph,r}$, and the wall heat transfer coefficient, α_W, in packed beds of particles. Several studies about heat transport phenomena in trickle beds have been performed [6–11]. Based on the theory of Yagi and Kunii [12] for the one-phase flow, Weekman and Myers [6] suggested that the radial multiphase thermal conductivity can be represented as the sum of the stagnant fluid thermal conductivity, $\lambda_{3ph,0}$, the conductivity due to radial mixing of the gas phase, $\lambda_{3Ph,g}$, and the conductivity due to radial mixing of the liquid, $\lambda_{3ph,l}$ (see Eq. (1.1)).

$$\lambda_{3ph,r} = \lambda_{3ph,0} + \lambda_{3ph,g} + \lambda_{3ph,l} \tag{1.1}$$

Hashimoto et al. [8] investigated the radial multiphase thermal conductivity of packed beds of glass and aluminum spheres, based on the work of Weekman and Myers [6]. The column had a diameter of 73.8 mm and the sphere diameter was in the range of 2.6–4.4 mm. The system was air–water or air–glycerin. The experiments were performed in co-current mode. They confirmed Eq. (1.1) and reported a linear increase of the term for radial mixing of the gas phase, $\lambda_{3ph,g}$, with the gas flow rate. A correlation for the radial multiphase thermal conductivity was derived by correlating the terms of Eq. (1.1) separately. The wall heat transfer coefficient was also investigated by the same research group and a correlation was developed [13].

Specchia and Baldi [10] performed experiments in a 0.141 m diameter test column with ceramic and glass spheres, as well as ceramic rings (6–12.9 mm). A water–air system was used. They also used the theory shown in Eq. (1.1) to describe the heat transfer in a trickle-bed reactor and developed correlations to describe the radial multiphase thermal conductivity and the wall heat transfer coefficient. It was found that the radial multiphase thermal conductivity only slightly increases with the gas flow rate. The liquid load has a significant influence on the radial multiphase thermal conductivity.

Lamine et al. [7] investigated the radial multiphase thermal conductivity and the wall heat transfer coefficient in a 0.1 m diameter tube packed with glass beads in the range of 2–6 mm and two different liquid–gas systems (nitrogen-water and nitrogen-aqueous ethylene glycol solution). In order to describe the radial multiphase thermal conductivity, the term accounting for the radial mixing of the gas, $\lambda_{3ph,g}$, was neglected due to the small influence. Only the stagnant fluid multiphase thermal conductivity, $\lambda_{3ph,0}$, and the term accounting for the liquid radial mixing, $\lambda_{3ph,l}$, were used to correlate the radial multiphase thermal conductivity. Additionally, an empirical equation for the wall heat transfer coefficient was developed.

Chu and Ng [9] developed a theoretical model to describe the radial multiphase thermal conductivity when neglecting the radial mixing of the gas. The stagnant fluid thermal conductivity was evaluated based on the effective medium theory and the radial dispersion of the liquid on a random walk analysis. No experiments were performed and the governing equation was compared to