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Heat transfer coefficients for solid ceramic sponges – Experimental results and correlation

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ABSTRACT

In this contribution, experimental results about heat transfer coefficients for different ceramic sponges (variation of material, porosity and pore size) are presented. A strong influence of the superficial air velocity and of sponge type properties on the heat transfer is observed. The experimental data is correlated with a Nusselt–Reynolds approach as it is usually done for heat transfer data. Furthermore, the applicability of the analogy between heat and momentum transfer – similar to the Generalized Lévêque Equation for packed beds or heat exchangers – is shown. A Nusselt–Hagen correlation has been developed allowing an easy and accurate estimation of heat transfer coefficients for any sponges from pressure drop data. This kind of correlation based on experimental results obtained for many different sponge types is not yet reported in literature.

1. Introduction

In literature, ceramic sponges are often called open-celled foams. These solid network structures are made of ceramics. Their porosities are typically in the range of about 75–95%. Due to this high porosity, sponges have a comparably low pressure drop [1]. Furthermore, the continuous solid phase seems to offer advantageous heat transfer properties. Compared with packed beds of spherical particles, sponges have a significantly higher thermal conductivity, which is interesting for chemical reactors performing highly exothermic reactions [2,3]. Potential technical applications for sponges are porous burners, solar receivers, carrier for catalysts, lightweight constructions or heat insulation [4,5]. For sizing of chemical engineering equipment, a heterogeneous model balancing the solid and the fluid phase separately is often used. The energy equations of the fluid and the solid phase are coupled by the heat transfer coefficient between these two phases. Up to now, only few publications dealing with experimental heat transfer coefficients for ceramic sponges exist and present models or correlations for the estimation of heat transfer coefficients based on a wide database. Furthermore no publication dealing with the estimation of the heat transfer coefficient from pressure drop data exists.

In this publication the experimental procedure for the determination of heat transfer coefficients for different ceramic sponge types (variation of material, porosity and pore size) is described. The presented experimental data shows the influence of the solid network material, the pore size and the porosity on the heat transfer coefficient. Varying the superficial air velocity from 0.5 to 5 m s^{-1}, heat transfer coefficients are determined within 40–550 W m^{-2} K^{-1}. Further, the experimental data was correlated in dimensionless form to offer an equation for estimating heat transfer coefficients at a given superficial air velocity for any sponge types. The applicability of the analogy between heat and momentum transfer for sponges is shown. It offers the possibility to estimate heat transfer coefficients from pressure drop data.

2. Literature study

The following section gives a compact overview of existing publications in literature dealing with the experimental investigation of heat transfer coefficients of sponges.

Younis and Viskanta [6] investigated sponges made of Al_2O_3 ($10 < ppi\ number < 66$; $83\% < \psi < 87\%$) and of Cordierite (20 ppi; $\psi = 85\%$). The volumetric heat transfer coefficient α_v ($\alpha_v = \alpha \cdot S_v$) was determined using a transient method by inserting the cold sponge sample into a hot gas stream and recording the temperature of the gas outlet during the heating-up process. The authors correlated the experimental values using a Nusselt approach with two fitting parameters (see Eq. (1)).

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Nomenclature

Latin symbols

C_{Re}, C_{geo}, C_{fit}, C	constants (–)
c_p	specific heat capacity (kJ kg^{-1} K^{-1})
d	diameter (m)
K	permeability (m^2)
k	constant (–)
l	characteristic length (m)
ΔL	sample length (m)
m	constant (–)
n	constant (–)
Δp	pressure drop (bar)
ppi	pores per inch (–)
r	radial coordinate (m)
S_v	specific surface area (m^{-1})
t	time (s)
T	temperature (K)
$u(r)$	radial velocity profile (m s^{-1})
u_0	superficial air velocity (m s^{-1})
x_f	friction fraction (–)
z	axial coordinate (m)

Greek symbols

α	heat transfer coefficient (W m^{-2} K^{-1})
α_v	volumetric heat transfer coefficient (W m^{-3} K^{-1})
ϑ	temperature (°C)
λ	thermal conductivity (W m^{-1} K^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ξ	pressure drop coefficient (–)
ρ	density (kg m^{-3})
ψ	porosity (–)

Subscripts

f	fluid
friction	friction
h	hydraulic
MRI	magnetic resonance imaging
pore	pore
s	solid
strut	strut = solid ligament
tube	tube
window	window

Dimensionless numbers (related to sponges)

$Bi = \frac{\alpha \cdot d_{strut}}{\lambda_s}$ Biot number

$Hg = \frac{\Delta p}{\Delta L} \cdot \frac{d_h^3}{\rho_f \cdot \nu_f^2}$ Hagen number

$Nu = \frac{\alpha \cdot d_h}{\lambda_f}$ Nusselt number

$Pr = \frac{\nu_f \cdot \rho_f \cdot c_{p,f}}{\lambda_f}$ Prandtl number

$Re = \frac{u_0 \cdot d_h}{\psi \cdot \nu_f}$ Reynolds number

$$Nu_{[6]} = \frac{\alpha_v \cdot d_{pore}^2}{\lambda_f} = C \cdot Re_{[6]}^m \quad \text{with} \quad Re_{[6]} = \frac{u_0 \cdot d_{pore}}{\nu_f} \tag{1}$$

For increasing ppi number, the fitting parameter C also increases whereas the fitting parameter m decreases. Correlating the experimental values of all Al_2O_3 sponges, the best fit for C and m was obtained with Eq. (2)

$$C = 0.819 \cdot \left[1 - 7.33 \cdot \frac{d_{pore}}{\Delta L}\right] \quad \text{and}$$
$$m = 0.36 \cdot \left[1 + 15.5 \cdot \frac{d_{pore}}{\Delta L}\right] \tag{2}$$

Eqs. (1) and (2) are valid for $5.1 < Re_{[6]} < 564$. The experimental values for the Cordierite sponges can not be described with Eq. (2) due to a large number of blocked pores inside these sponge samples. In contrast, the Al_2O_3 sponges had only open pores. Theconstants for Cordierite sponges were determined to $C = 2.43$ and $m = 0.42$.

Schlegel et al. [7] investigated sponges made of Cordierite ($10 <$ ppi number < 50; $85\% < \psi < 87\%$). The authors also used a transient method determining the gas temperature of the gas outlet when cooling the sponge from 300 °C down to ambient temperature. The experimental values were correlated similar to Eq. (1) using a Nusselt approach given by Eq. (3)

$$Nu_{[7]} = \frac{\alpha \cdot d_h}{\lambda_f} = C \cdot Re_{[7]}^m \cdot Pr^n \quad \text{with} \quad Re_{[7]} = \frac{u_0 \cdot d_h}{\psi \cdot \nu_f}, \quad d_h = 4 \cdot \frac{\psi}{S_v} \tag{3}$$

The exponent n was set to $n = 1/3$. The authors determined one set of the parameters C and m for each sponge type, an "universal" correlation is not published. For increasing ppi number, the fitting parameter m decreases. The fitting parameter C shows no tendency with the ppi number.

Calmidi and Mahajan [8] investigated sponges made of aluminum ($5 <$ ppi number < 40; $90\% < \psi < 97\%$). The authors used steady-state experiments for the determination of the heat transfer coefficients. The experimental values are correlated using the approach shown in Eq. (3) but with the strut diameter instead of the hydraulic diameter. The parameters are reported to be $C = 0.52$, $m = 0.5$ and $n = 0.37$. The applicability on ceramic sponges and sponges with lower porosities has not been tested. The range of investigated Reynolds numbers is $10 < Re_{[8]} = \frac{u_0 \cdot \sqrt{K}}{\nu_f} < 130$.

Decker et al. [9] investigated sponges made of CB-SiC, SSiC and Cordierit ($10 <$ ppi number < 45; $\psi = 76\%$ and 81%). The authors used an oscillating experimental procedure and correlated the experimental values based on the ppi number as stated in Eq. (4)

$$Nu_{[9]} = \frac{\alpha \cdot d_{strut}}{\lambda_f} = 4.8 \cdot \text{ppi}^{-1.1} \cdot Re_{[9]}^{0.62} \quad \text{with} \quad Re_{[9]} = \frac{u_0 \cdot d_{strut}}{\nu_f} \tag{4}$$

The major disadvantage of this correlation is the strong influence of the ppi number on the Nusselt number. In practice, the correct determination of the ppi number is difficult. The range of investigated Reynolds numbers is $5 < Re_{[9]} < 160$.

Richardson et al. [10] investigated a 92%-Al_2O_3 – 8%-Mullite sponge with 30 ppi and a porosity of 82%. The authors used steady-state experiments combined with a numerical evaluation. The experimental values are correlated by the Nusselt approach stated in Eq. (5)

$$Nu_{[10]} = \frac{\alpha}{\lambda_f \cdot S_v} = C_1 \cdot \psi \cdot T^3 + C_2 \cdot Re_{[10]} \quad \text{with} \quad Re_{[10]} = \frac{u_0}{S_v \cdot \nu_f} \tag{5}$$

The constants were determined to $C_1 = 6.06 \cdot 10^{-11}$ and $C_2 = 0.0306$ [10,11]. In 2004 Peng and Richardson [11] investigated a 99.5%-Al_2O_3 – 0.5%-Mullite sponge with 30 ppi and a porosity of 87.4%. Using the approach shown in Eq. (5) for the correlation of the experimental data the constants C_1 and C_2 had to be changed. Here, they were determined to $C_1 = 3.43 \cdot 10^{-11}$ and $C_2 = 0.0340$. The range of investigated Reynolds numbers is $0.2 < Re_{[10]} < 1.7$ for these experiments, for the experiments with the 92%-Al_2O_3 – 8%-Mullite sponge, no information is given. The results are less conclusive since only one sponge type was investigated.