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Mass transfer for woven and knitted wire gauze substrates: Experiments and modelling

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ABSTRACT

The study deals with the heat and mass transport properties of woven and knitted wire gauzes stacked in catalytic reactor. The experimental programme included heat transfer experiments performed for air flow (Re = 2–300) using three woven gauzes and one knitted gauze. The model based on the concept of laminar flow developing in a short capillary channel (gauze mesh) was put forward. The heat transfer data were then transformed to the mass transfer ones using heat–mass transfer analogy developed for laminar flow. The results were validated based on the reactive experiments performed.

1. Introduction

A number of catalytic processes, especially displaying fast reaction kinetics, are limited by mass transport of reactants to the catalyst. Catalytic combustion of volatile organic compounds (VOCs) is a good example. Due to high VOCs dilution the process may run in a diffusional regime, where the resulting process rate is strongly limited by the mass transfer between a flowing gas and catalyst surface (active sites). This might occur in the ceramic monoliths (automotive afterburners) that have become worldwide standards mainly because of their low flow resistance and high specific surface area. However, the most important disadvantage of using them is poor mass transport. Inside long capillary channels laminar flow fully develops causing nearly constant, low value of Sherwood number. Therefore new reactor fillings are being developed that have to display higher mass transport. Wire gauzes with a catalyst deposited on them are one of the designs that are currently intensely studied. The goal of our research is thus the design of a catalytic reactor for VOCs combustion that would secure intense mass transport and moderate flow resistance. Wire gauzes have been one of the designs considered.

Pressure drop problem of the stacked wire gauzes was already discussed in our previous studies [1,2]. The experiments and modelling performed proved that the governing mechanism for gauzes is laminar flow developing in a short capillary channel, namely wire mesh. Moreover, gauze flow resistance, although higher than that of monoliths, is substantially lower when compared with packed beds of grains.

Although wire gauzes have been used for years as catalytic reactor fillings for ammonia oxidation, their transport and friction phenomena seem still not to be described well enough. The studies published [3–11] dealt with single gauze types or very limited sets of them. The experimental methods based on heat transfer [5,6], gas-phase catalytic reaction [3,4,11], mercury evaporation [7] and electrochemical reaction in liquid [8–10]. The results (Fig. 1) were presented in terms of Colburn factor j correlated as a power function of Reynolds number Re_d (defined with wire diameter). The Chilton–Colburn analogy was applied to convert between heat and mass transfer representation. Taking into account a wide variety of gauze types and experimental methods, presented characteristics place close to one another. However, the scatter attains 100% making impossible to apply particular correlations without experimental confirmation. Till now more general models for gauzes are not available. Thus, in this work extended research on transfer properties of wire gauzes has been undertaken.

2. Experimental procedure

We have decided to measure heat transfer coefficients between electrically heated gauze sheets and flowing gas. The experiments have been planned to use the heat and mass transport analogy to further transform the results into the mass transfer representation. Although some studies applied catalytic combustion as the experimental method to estimate mass transfer coefficients for gauzes [3,4,11], the existing models do not describe properly the

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Nomenclature

a	specific surface (m^{-1})
a_T	thermal diffusivity ($m^2\,s^{-1}$)
C_A	concentration ($mol\,m^{-3}$)
c_p	gas specific heat ($J\,kg^{-1}\,K^{-1}$)
D_A	kinematic diffusivity ($m^2\,s^{-1}$)
$D_h = 4\varepsilon a^{-1}$	hydraulic diameter (m)
d_w	wire diameter (m)
f	Fanning friction factor
$Gz = Gc_p\lambda^{-1}d_w^{-1}$	heat Graetz number
$Gz^M = G\rho^{-1}D_A^{-1}d_w^{-1}$	mass Graetz number
G	mass stream ($kg\,s^{-1}$)
g_0, g	superficial, interstitial mass velocity ($kg\,m^{-2}\,s^{-1}$)
$j = Nu\,Re^{-1}\,Pr^{-1/3} = Sh\,Re^{-1}\,Sc^{-1/3}$	Colburn factor
k_C	mass transfer coefficient ($m\,s^{-1}$)
k_r	reaction rate constant ($m\,s^{-1}$)
L	reactor length (m)
$Nu = \alpha D_h\lambda^{-1}$	Nusselt number
Pr	Prandtl number
$Re = gD_h\eta^{-1}$	Reynolds number
$Re_d = gd_w\eta^{-1}$	Reynolds number
Sc	Schmidt number
$Sh = k_C D_h D_A^{-1}$	Sherwood number
T	temperature (K)
w_0	superficial gas velocity ($m\,s^{-1}$)
$\langle\mathbf{H}\rangle$, $\langle\mathbf{T}\rangle$	boundary condition (B.C.) of constant heat flux or surface temperature, respectively

Greek letters

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
ε	void volume
η	dynamic viscosity (Pa s)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
τ	time (s)

contribution of the homogeneous oxidation in the overall combustion process thus leading to erroneous results.

The experiments were carried out in a test reactor of a rectangular cross section, 45 mm × 30 mm (Fig. 2). The flowing gas was air at ambient pressure, the range of Reynolds numbers from 2 to 300 was covered. The reactor was filled with 2 till 6 stacked gauze sheets heated and 4–6 non-heated gauzes placed at both reactor ends to smooth the velocity profiles. It was proven that the number of gauze sheets did not influence the heat transfer results.

Four wire gauze types were studied: three woven gauzes (Nos. 1–3) and one knitted gauze (No. 4) (Fig. 2); their geometrical parameters are gathered in Table 1. The gauze void fraction ε and specific surface area a were calculated according to equations proposed by Armour and Cannon [12] and confronted with the weight of the structure (given the known density of the wire). The results were in excellent agreement. The void fraction and specific surface area, thus hydraulic diameter ($D_h = 4\varepsilon a^{-1}$), and the ratio of d_w to D_h, may be adjusted within wide ranges by changing the gauze weave, mesh size and the wire diameter d_w.

The gauzes were heated with electric current (up to 70 A) flowing directly through them, to attain an appropriate temperature gradient

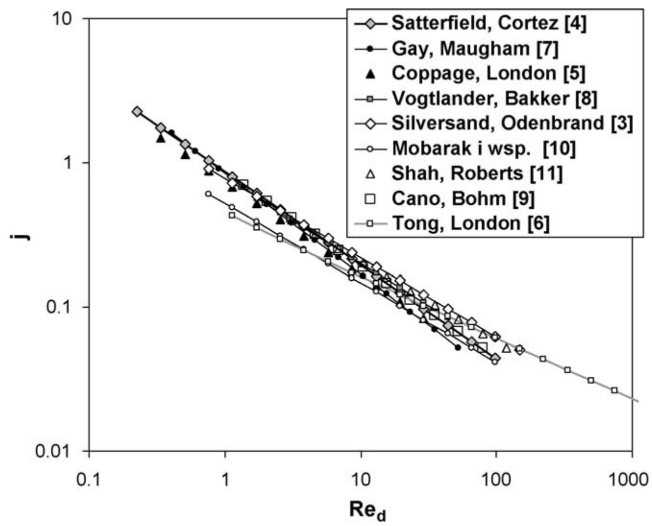

Fig. 1. Literature overview of wire gauze mass transfer properties.

between the gauze and flowing gas (air). In this way the boundary condition for constant heat flux ($\langle\mathbf{H}\rangle$) was secured. The temperature of each gauze sheet was measured at its both sides using four small thermocouples attached to the metal surface using special glue of excellent heat conduction and no electrical conduction as well. The inlet and outlet temperatures of the air stream were measured at both reactor ends using four thermocouples.

At the $\langle\mathbf{H}\rangle$ boundary condition, both sides of the gauze ("inlet" and "outlet" ones) showed different temperatures (temperature increases along the gas flow direction). A single gauze mesh can be regarded as a very short channel (tube) of both the length and wall thickness comparable to the wire diameter. The temperature difference between both gauze sides was approximately an order of magnitude lower than the difference between gauze and flowing gas that was kept within 15–30 K.

3. Heat transfer results

Usually, the heat transfer results for wire gauzes are presented in terms of Colburn factor j vs. Reynolds number Re_d (defined with wire diameter). The approach is presented in Fig. 3 for our experimental results. However, neither the j vs. Re_d nor the Nu vs. Re representation gives a single relationship for all the gauzes studied, in spite of a good experimental accuracy.

During our rigorous survey of flow resistance [1,2] it has been proven that a governing mechanism for wire gauzes is laminar flow developing in a short capillary (wire mesh) using the terminology of Shah and London [13]. We have followed the way for a transfer problem. Churchill and Ozoe [14] theoretically derived equations that describe short capillary circular channel in terms of Nu_H and Nu_T vs. Gz number (for $\langle\mathbf{H}\rangle$ and $\langle\mathbf{T}\rangle$ boundary condition, respectively):

$$Nu_H = \frac{2Gz^{1/2}}{\left[1 + (Pr/0.0207)^{2/3}\right]^{1/4}} \tag{1a}$$

$$Nu_T = \frac{1.2732Gz^{1/2}}{\left[1 + (Pr/0.0468)^{2/3}\right]^{1/4}} \tag{1b}$$

As during experiments the $\langle\mathbf{H}\rangle$ condition was assumed, we have chosen Eq. (1a) for Nu_H as the basis for the model equation. The experimental results are shown in Fig. 4 in terms of Nusselt vs. Graetz number together with Eqs. (1a) and (1b) for Nu_H and Nu_T. The

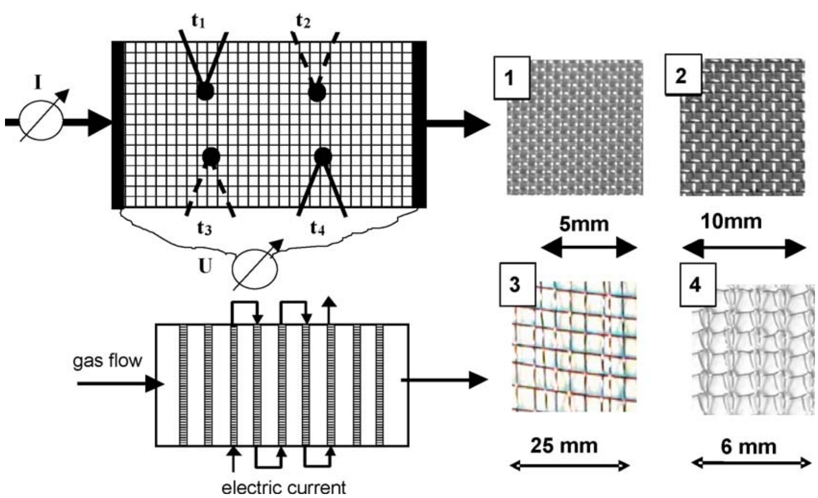

Fig. 2. Experimental set-up. t_{1-4}—Thermocouples for gauze temperature estimation (dashed lines—from the opposite gauze side). Studied wire gauzes: woven (1–3) and knitted (4) are depicted on the right-hand side.

Table 1
Description and parameters of the gauzes studied.

No.	Type	Mesh	d_w (mm)	a (m^{-1})	ε	$D_h = 4\varepsilon/a$ (mm)
1	Woven	61.72	0.16	8186	0.673	0.329
2	Woven	30.48	0.30	4005	0.700	0.699
3	Woven	23.50	0.14	3020	0.894	1.18
4	Knitted	17.45	0.0977	1355	0.967	2.85

wire diameter d_w was the longitudinal dimension in the Graetz number. It is noticeable that Eq. (1a) (for Nu_H) can reflect the experimental results with acceptable accuracy only for higher Graetz numbers, say $Gz > 80$. Thus, experimentally derived correction (2nd term in Eq. (2)) was introduced giving model equation:

$$Nu = \frac{2Gz^{1/2}}{\left[1 + (Pr/0.0207)^{2/3}\right]^{1/4}}(0.305 \cdot Gz^{0.213}) \qquad (2)$$

Eq. (2) is based on 1081 experiments performed using 4 wire gauzes and covers the range of Reynolds numbers from 2 to 300 (Graetz numbers Gz = 2.5 till 1960). The mean error is 9.7%.

While the Churchill and Ozoe Eq. (1a) for Nu_H is convenient for a higher Gz range, the solution for the Nu_T suits better the lower Gz range. The Nu_T values are approximately 50% smaller than the Nu_H ones. A proper choice from among the $\langle \mathbf{T} \rangle$ and $\langle \mathbf{H} \rangle$ boundary conditions poses an important problem, because a wire is circular which makes the imaginary tube (wire mesh) walls as thick as the tube is long. This leads to significant temperature smoothing along the model tube wall. For small Gz (low heat flux) the $\langle \mathbf{T} \rangle$ condition might be closer to the reality while for large Gz (larger heat fluxes), the $\langle \mathbf{H} \rangle$ one suits better. In fact, both Eqs. (1a) and (1b) require similar correction term to be introduced. Moreover, circular channel is a very rough approximation of the wire mesh. These reasons explain the differences between theory and experiment for the case.

4. Mass transfer problem

When considering the cited references [3–11] (Fig. 1), it can be noted that the results are compared neglecting the originally studied problem (heat or mass transfer) and the Chilton–Colburn analogy is accepted. However, the analogy is only valid for the

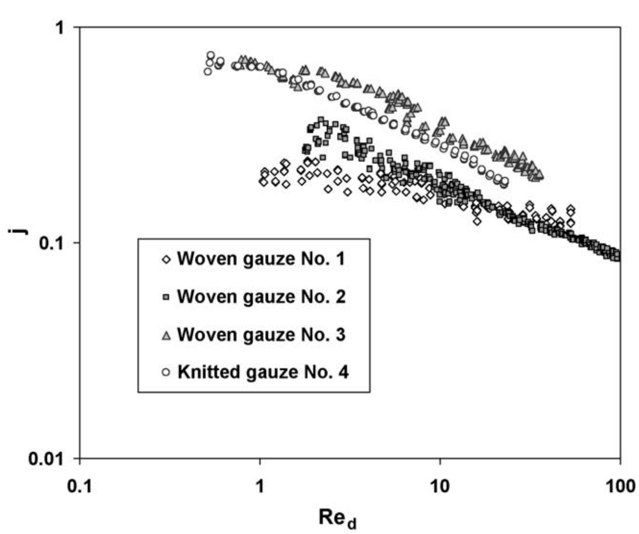

Fig. 3. Heat transfer experimental results: Colburn factor j vs. Reynolds number Re_d.

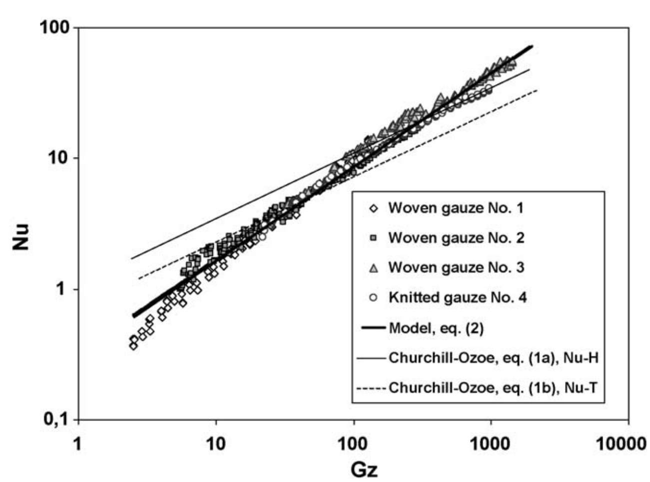

Fig. 4. Heat transfer experimental results: Nusselt vs. Graetz number. The thick solid line represents the model, Eq. (2); the thin lines show the Churchill and Ozoe Eq. (1a) (solid line —the **H** B.C.) and Eq. (1b) (dashed line—the **T** B.C.).

turbulent flow, although commonly applied for packed columns. Since we have proved that the flow and transport phenomena for wire gauzes may be regarded assuming the concept of laminar developing flow, the Chilton–Colburn analogy may not be longer valid. Instead, we have proposed the analogy for the laminar flow based on the Fourrier–Kirchhoff equations written for heat and mass transfer problem, respectively:

$$\frac{\partial T}{\partial \tau} + \vec{w} \cdot \nabla T = a_T \nabla^2 T \Rightarrow Nu_t = f(Gz) \quad (3)$$

$$\frac{\partial C_A}{\partial \tau} + \vec{w} \cdot \nabla C_A = D_A \nabla^2 C_A \Rightarrow Sh_t = f(Gz^M) \quad (4)$$

Eqs. (3) and (4) can be solved using analytical or numerical methods thus giving theoretical solution in terms of Nusselt (Sherwood) number as a function of the heat (mass) Graetz number (right-hand side of Eqs. (3) and (4)). Considering the same geometries, boundary conditions and flow fields, the functions $Nu = f(Gz)$ and $Sh = f(Gz^M)$ have to be identical. The only difference is replacement of Gz by Gz^M, as well as Pr by Sc and Nu by Sh. Thus, the heat–mass transfer analogy bases on the ratio of theoretical solutions of Eqs. (3) and (4):

$$\frac{Sh_{\exp}}{Nu_{\exp}} = \frac{Sh_t}{Nu_t} = \frac{f(Gz^M)}{f(Gz)} \quad (5)$$

The experimental heat transfer data can be transformed to the mass transfer ones through simple multiplying by a ratio of theoretical solutions. For the case under study, theoretical solution is given by Churchill and Ozoe Eq. (1a). The formula for the mass transfer is identical to Eq. (1a) but Gz is replaced by Gz^M, Nu by Sh and Pr by Sc. The resulting equation describing mass transfer data with the experimental correction term is:

$$Sh = \frac{2(Gz^M)^{1/2}}{\left[1 + (Sc/0.0207)^{2/3}\right]^{1/4}} \cdot \left[0.234 \cdot (Gz^M)^{0.213}\right] \quad (6)$$

The experimental data of heat transfer were transformed to mass transfer using Eq. (5). The function describing Sh_t and Nu_t was that in Eq. (1a). The mass transfer results are shown in Fig. 5. The accuracy is the same as for the heat transfer model.

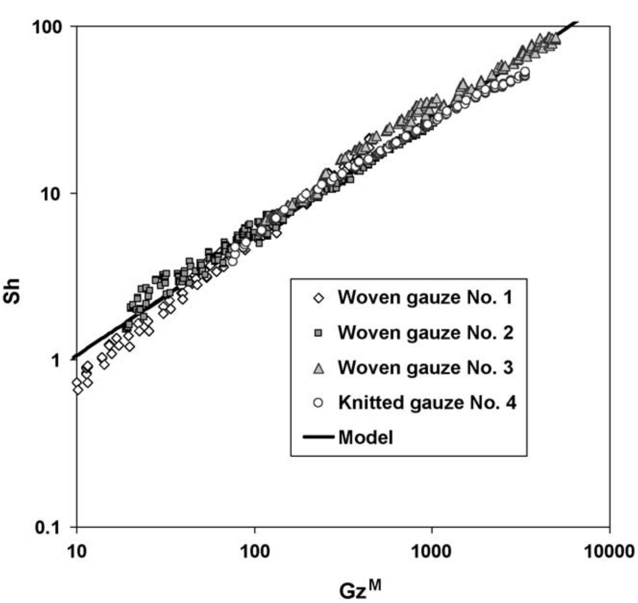

Fig. 5. Mass transfer results in terms of Sherwood vs. Graetz mass number Gz^M. Solid line—model, Eq. (6).

The derived analogy (5) with Eq. (1a) gives values close to the commonly applied Chilton–Colburn analogy (accuracy within 10%). The use of Eq. (1a) (for Nu_H) and Eq. (1b) (for Nu_T) in the analogy (5) leads exactly to the same results. In fact, when several literature equations describing laminar flow were implemented into the analogy Eq. (5), the results were always close to the Chilton–Colburn analogy.

According to the model developed (6), Sherwood number is proportional to $(Gz^M)^{0.713}$. The mass Graetz number can be rewritten in the following form:

$$Gz^M = \frac{G}{\rho D_A d_w} = \frac{\pi}{4} \frac{D_h \rho w}{\eta} \frac{\eta}{\rho D_A} \frac{D_h}{d_w} = \frac{\pi}{4} Re Sc \frac{D_h}{d_w} \quad (7)$$

Basing on the above equation it is obvious, that the mass Graetz number, and consequently, the Sherwood number may be adjusted within very wide ranges by changing the values of D_h and d_w. The hydraulic diameter may be adapted, to some extent, independently of the wire diameter by altering the gauze weave and the mesh size (number of meshes per unit length). Thus, the gauzes made from a very thin wire might display high mass transfer coefficients. This gives an opportunity to design structured gauze catalysts tailored for the individual process demands. However, the transfer-friction analogy is unavoidable and therefore enhanced transfer properties are always accompanied by increased flow resistance.

A comparison of wire gauze properties with packed bed of 2 mm grains and 100 cpsi monolith is presented in Fig. 6 for mass transfer (Sh vs. Re) and in Fig. 7 for the flow resistance (Fanning friction factor f vs. Re number). For packed beds, flow resistance was calculated using Ergun equation [15]; Sherwood number was derived using the Wakao and Kaguei [16] Eq. (8) (Sh_P and Re_P are defined with the grain diameter and superficial fluid velocity):

$$Sh_p = 2 + 1.1 Sc^{1/3} Re_p^{0,6} \quad (8)$$

For the monolith, flow resistance and Sherwood number were calculated using Hawthorne equations cited, e.g. by Cybulski and Moulijn [17].

The conclusion is that wire gauzes display mass transfer rates comparable with packed beds and substantially higher compared with monoliths. Although flow resistance of wire

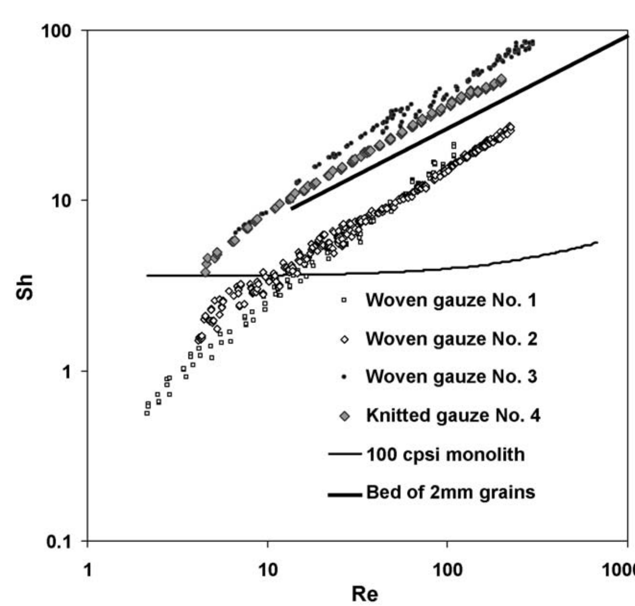

Fig. 6. Comparison of wire gauzes with packed bed and monolith: Sh vs. Re number.

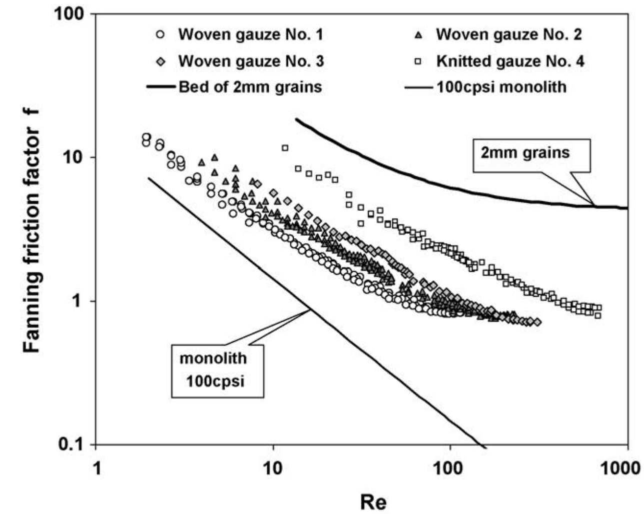

Fig. 7. Comparison of wire gauzes with packed bed and monolith: Fanning friction factor *f* vs. *Re* number.

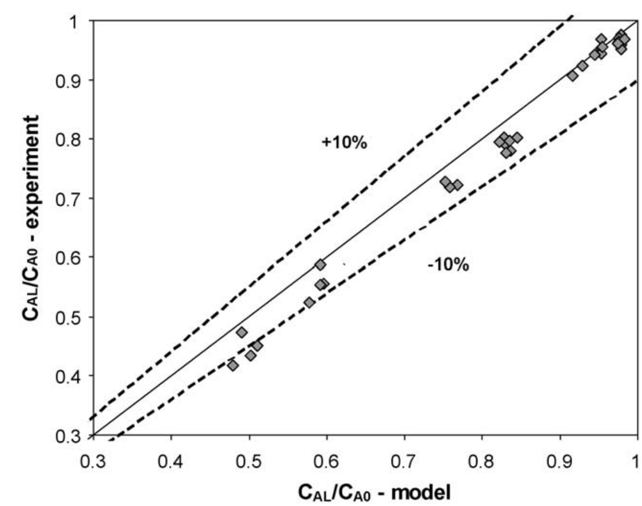

Fig. 8. Model validation in terms of experimental vs. modelled ratio of n-hexane outlet to inlet concentration (C_{AL}/C_{A0}).

gauzes is higher than that of monoliths, it is significantly lower compared with packed beds.

5. Mass transfer model validation

During our study, the heat transfer coefficients were directly measured, and the calculated mass transfer coefficients could only be regarded as "pseudo-experimental" lacking final experimental validation. Thus, for this sake the experiments of n-hexane catalytic combustion in air using a gauze reactor were performed. The test reactor of square cross section, 21 mm × 21 mm, and 42 mm long, was filled with stacked gauze sheets (No. 4) with the deposited cobalt oxide catalyst [18]. 36 experiments were performed in the temperature range 400–560 °C and the gas flow range g_0 = 1.36–3.36 kg m^{-2} s^{-1} (*Re* = 110–300).

The plug-flow reactor model [19] is given by Eq. (9)

$$w_0 \frac{dC_A}{dx} + k_c a \frac{k_r}{k_r + k_c} C_A = 0; \quad C_A|_{x=0} = C_{A0} \tag{9}$$

and its solution is:

$$C_A^L = C_A^0 \cdot \exp\left(-\frac{L}{w_0} \frac{a k_C k_r}{k_C + k_r}\right) \tag{10}$$

Mass transfer was described by Eq. (6). The first-order kinetics was derived in [18]. In Arrhenius equation, the pre-exponential constant equals to $k_\infty = 3.08 \times 10^5\ \mathrm{ms^{-1}}$ and the activation energy—to E = 107 kJ mol^{-1}.

Comparison of the experimental results with the model prediction is shown in Fig. 8. The average error is 4% and the scatter of experiments referred to the model 10%. The experimental database seems comprehensive enough to reliably validate the derived methodology.

6. Conclusions

A new model describing mass transfer in woven and knitted gauzes used as reactor fillers and catalysts carriers has been proposed. The model assumes laminar flow developing in a short capillary channel, i.e. gauze mesh. The model capillary is a short circular channel with a diameter equal to the gauze hydraulic diameter D_h and length equal to the wire diameter d_w.

It has been proven that the laminar flow development is a governing mechanism of transfer and friction phenomena for wire gauzes. The solution of Fourrier–Kirchhoff equation presented by Churchill and Ozoe [14], Eq. (1a), can be a starting point to describe transport phenomena for gauzes, however, a correction based on experimental results is necessary.

The mass transfer properties of wire gauzes may be adjusted within wide ranges by changing the wire diameter d_w and the gauze hydraulic diameter D_h. Since shortening the channels results in higher transfer coefficients, it is expected that wire gauzes made of thinner wires will display enhanced transport properties.

The validation of the mass transfer model based on experiments of n-hexane combustion in catalytic gauze reactor proved acceptable accuracy of the derived Eq. (6).

Wire gauzes can be interesting alternative, especially for fast chemical reactions. The gauzes display mass transfer close to packed beds and substantially higher than monoliths. Flow resistance of wire gauzes is higher than that of monoliths, but significantly lower compared with packed beds. The comparison presented in other paper [20] shows that catalytic wire gauzes can significantly shorten reactor with very moderate increase of pressure drop.

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