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POSTER COMMUNICATION

Innovative catalytic streamlined carriers with triangular channels

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Abstract
The paper presents research on a novel catalytic carrier, called "streamlined structure". The carrier is a short-channel monolith, whose walls are shaped like an airfoil profile (airplane wing). The intention is heat transfer intensification coupled with moderate flow resistance. Streamlined structures with triangular channel cross-section, 3mm, 6mm and 12 mm long, were designed and manufactured using the SLM (Selective Laser Melting) technique for the experimental verification. The structures were modelled using the CFD (Computational Fluid Dynamics) software to derive flow resistance, flow patterns and heat transfer coefficients. Compared to classic structures, CFD showed intensified heat transfer, combined with acceptable flow resistance increase. CFD proved the lack of an inlet vortex, which in classical structures seriously reduces the intensity of heat transfer. The CFD has been satisfactorily verified by experiments.

Keywords
streamlined catalytic carriers, short-channel structures, heat transfer, flow resistance, Computational Fluid Dynamics

1. INTRODUCTION

Many hazardous air pollutants are emitted to the atmosphere like methane or volatile organic compounds (VOCs). Pollution can be efficiently neutralized using structured catalytic reactors (Avila et al., 2005; Dumesic et al., 2008), although their constant improvement is necessary. A new type of catalytic carrier was developed, called "streamlined structures", based on short-channel structures (short monoliths) of diverse cross-sectional channel shape, displaying favorable transport-flow properties (Iwaniszyn et al., 2021; Kołodziej et al., 2011). The channel walls of the streamlined structures are shaped similarly to an aircraft wing, i.e. an airfoil profile. The classic monoliths with flat, cubic walls cause formation of eddies near the channel inlet, called "inlet vortex", strongly decreasing heat and mass transport (Iwaniszyn et al., 2021). The innovative streamlined structures are to allow the complete reduction of the inlet vortex to its absence thus intensifying the heat (mass) transport. The airfoil profile displays low drag coefficient ($C_D = 0.006$) in comparison to the cube ($C_D = 1.05$) (Heisler, 2002; Schlichting, 1979), so the flow resistance might be satisfactory low. Therefore, the aim of this study were streamlined structures with a triangular channel cross-sectional shape, with a length of 3, 6 and 12 mm, which were designed and manufactured using SLM (Selective Laser Melting). The properties of the structures were investigated using CFD (Computational Fluid Dynamics) and experimentally. Images of the exemplary structure are shown in the poster.

2. METHODS

CFD simulations were performed using ANSYS Fluent. Using the Ansys Mesher module, tetrahedral mesh was created, which was then converted to polyhedral one in the Fluent module. The computational domain and boundary conditions are shown in the poster. The air velocity was in the range of 0.1–10 m/s at ambient conditions. The structures were heated with a constant heat flux of 1500 W/m^2.

For experiments the structures were 3D printed using the SLM technique from 316 steel. Experimental set-up is presented in the poster. The test reactor had a rectangular cross-section (45 × 30 mm). The experiments were carried out for a single-phase air flow (0.0003–0.01 m^3/s). The metal structures were electrically heated by the Joule effect. The maximum current I_{max} was 290 A, the maximum voltage U_{max} up to 2 V. The temperature of the structure surface was measured with 8 type K thermocouples, which were attached to the surface of the structure with epoxy glue, ensuring good thermal conductivity and electric insulation. Temperature of the flowing air was measured at the inlet and outlet of the reactor (3 thermocouples on each side). Flow resistance was measured using a Recknagel micromanometer and a differential pressure transducer. A more detailed description of CFD and experimental procedure is available in Sindera et al. (2022).

3. RESULTS

The results of the CFD and experimental studies are presented in the poster. Good agreement was obtained between numerical and experimental analysis. As can be also seen on the plots of $(f \cdot \mathrm{Re})$ and Nu vs. L^+ or L^* (see the attached poster), vast majority of experimental points lie above the $(f \cdot \mathrm{Re})_{fd}$ and Nu_{fd} values characteristic for the fully developed flow thus confirming the presence of the developing laminar flow in the channels. The performed CFD simulations confirmed lack of the inlet vortex, which positively affected the heat transfer intensity in the channel inlet section. According to Iwaniszyn et al. (2021), the inlet vortex is formed in the inlet section of standard monolithic structures, just in the channel region, where the highest transfer coefficients should exist, thus significantly reducing transport rates over theoretical predictions. In consequence, the heat (mass) transport may be enhanced by using the streamlined structures.

However, in the outlet section and outside the streamlined structures, significant turbulences are generated. For both tested velocities of 0.3 and 6 m/s, vortices form behind the structures. The outlet vortices may not have a negative impact on heat transfer, but they cause energy dissipation and thus increase flow resistance. Note however, that the classic short-channel structures display also some turbulences in the outlet part and behind the structure (Iwaniszyn et al., 2021). Based on experimental data, correlations describing flow resistance $(f \cdot \mathrm{Re})$ and heat transfer (Nu) were developed, which approximate experimental points with average relative error of less than 9% and 12%, respectively.

4. CONCLUSIONS

The streamlined structures with triangular cross-sectional shape of the channels are characterized by intensive heat transport and acceptable flow resistance. The conducted CFD studies indicate the great potential of streamlined structures.

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SYMBOLS

d_h	hydraulic diameter, m
f	Fanning friction factor
h	heat transfer coefficient, W/(m^2·K)
k	thermal conductivity, W/(m·K)
L	channel length, m
L^+	dimensionless length for the hydrodynamic entrance region
L^*	dimensionless length for the thermal entrance region
Nu	Nusselt number
ΔP	pressure loss, Pa
Pr	Prandtl number
Re	Reynolds number
S_v	specific surface area, m^2/m^3
w_0	superficial velocity, m/s

Greek symbols

ε	porosity
η	dynamic viscosity, Pa·s
ρ	density, kg/m^3

Subscripts

corr	based on correlation
exp	experimental
fd	value for fully developed laminar flow

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INNOVATIVE CATALYTIC STREAMLINED CARRIERS WITH TRIANGULAR CHANNELS

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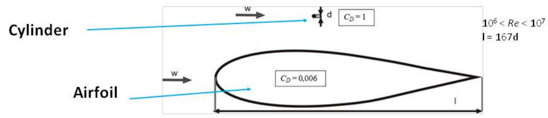
Aim:

to define transport-flow properties of new type, streamlined catalytic carrier.

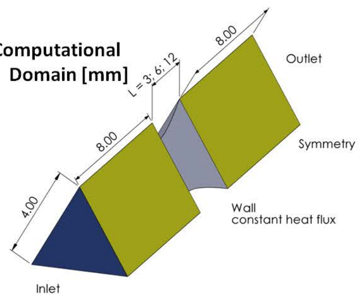


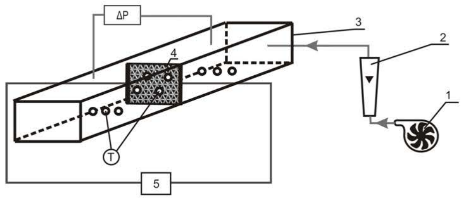
The same drag force

Materials and methods:

The carriers were tested using CFD (Computational Fluid Dynamics) and then 3D printed from powdered metal (by SLM - Selective Laser Melting) and experimentally tested. Three triangular streamlined structures of 3, 6 and 12 mm long were manufactured.

Computational Domain [mm]





Experimental set-up: 1 - blower, 2 - rotameter, 3 - reactor, 4 - structure tested, 5 - power supply, T - thermocouples

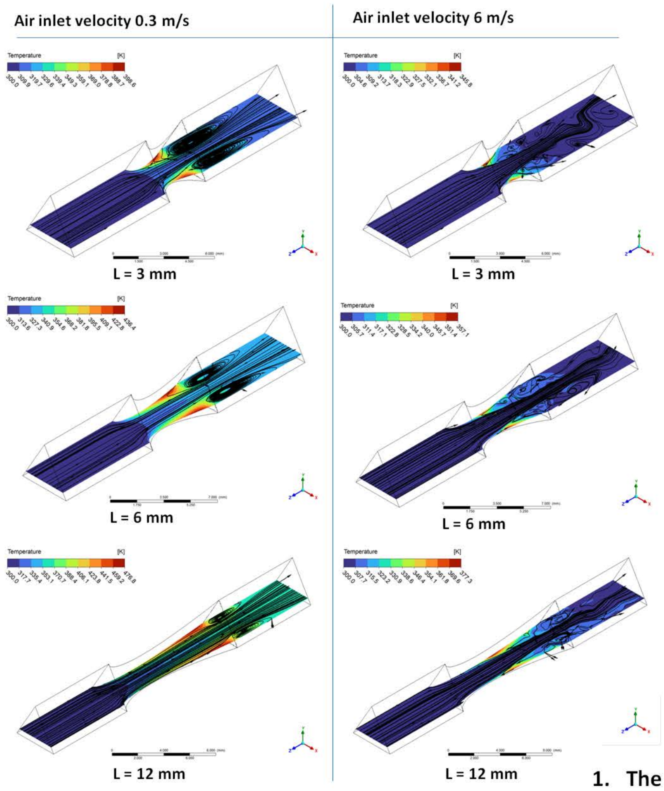
Experiments:

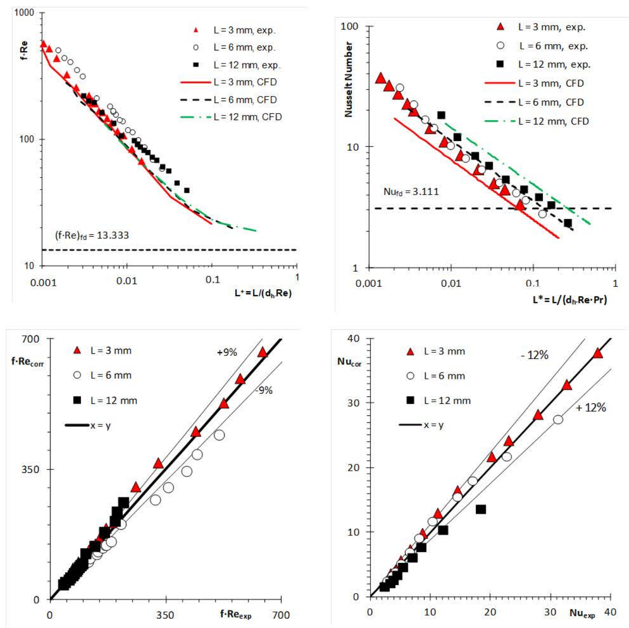
- **single-phase gas flow,**
- **structures heated by strong electric current (up to 290 A) flowing directly through the carrier body.**

$$Nu = \frac{h \cdot d_h}{k} \qquad Re = \frac{w_0 \cdot d_h \cdot \rho}{\eta \cdot \varepsilon}$$

$$\frac{\Delta P}{L} = 2f\frac{\rho w_0^2}{\varepsilon^2 d_h} \qquad d_h = \frac{4\varepsilon}{S_v}$$

Results:





$$f \cdot Re = 13{,}333 + 2{,}6781 \cdot (L^+)^{-0{,}7826} \qquad Nu = 3{,}111 \cdot 0{,}2366(L^*)^{-0{,}5971}$$

Conclusions:

1. **The streamlined structures studied display satisfactory high heat transport intensity accompanied with acceptable increase of flow resistance.**
2. **Streamlined structures are very interesting approach to catalytic carriers with favorable transport-flow properties.**
3. **CFD simulation results are in good agreement with experiments.**

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