C. R. Chimie 18 (2015) 1030–1035

Contents lists available at ScienceDirect

Comptes Rendus Chimie

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International Symposium on Air & Water Pollution Abatement Catalysis (AWPAC) – Catalytic pollution control for stationary and mobile sources

Novel intense metallic monolith for automotive applications: Experimental versus numerical studies

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ARTICLE INFO

Article history:
Received 28 October 2014
Accepted after revision 5 March 2015
Available online 9 September 2015

Keywords:
Heat transfer
Flow friction
Simultaneous development
Structured reactor
CFD

ABSTRACT

Three-dimensional numerical analysis for simultaneously developing fluid flow and heat transfer through triangular and sinusoidal channels is simulated in this paper. ANSYS FLUENT 12 was used for simulations. Numerical results were compared with experimental ones for the same channels dimensions. The research was conducted to verify that very short metallic monoliths could be applied to engine pre-turbo catalytic converters. It was shown that short monoliths have high potential to reduce HC/CO emissions due to higher temperatures and flow velocities in front of the turbocharger, resulting in increased heat and mass transfer and reaction kinetics accompanied with reduced flow resistance.

1. Introduction

Contaminant originated from vehicle engines (NO_x, CO, HC) is a major source of urban air pollution. Honeycomb-shaped catalytic monolithic reactors with noble metal catalyst are standard devices used in the automotive industry as the flue gas afterburners. Their construction is a complex function of the exhaust stream characteristics, including monolith geometry and catalyst characteristics. Mass transport from the bulk gas to the catalyst wash coated surface, and then inside the porous catalyst layer, as well as reaction rate limit the conversion of any reactive species (NO_x, CO, HC). Due to restricted emission requirements, catalytic converter designs need to be improved to achieve better conversion efficiency.

As described in [1–5], placement of very small and short catalytic converter (of about 0.025–0.045 L) before turbocharger provides 50–70% of the total conversion of exhaust gases. It is required that this pre-turbo catalyst (PTC) should work at gas velocities up to 100 m/s. Modified automobile catalytic systems should consist of two converters: (1) shorter just behind the cylinders outlet and (2) standard (see Fig. 1).

Typical automobile catalytic converter includes ceramic monolith having cell densities of 400–900 cells/in^2 and length of about 200 mm, thus the fully developed laminar flow exists in the major part of long channels [6,7]. For relatively fresh, fully warm, oxidizing catalysts, the rates of reaction of NO_x, CO and HC are limited primarily by convective mass transport through the developing laminar boundary layers in the monolith channels. Mass and heat transfer rates are higher in the entrance regions of these

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http://dx.doi.org/10.1016/j.crci.2015.03.010
1631-0748/

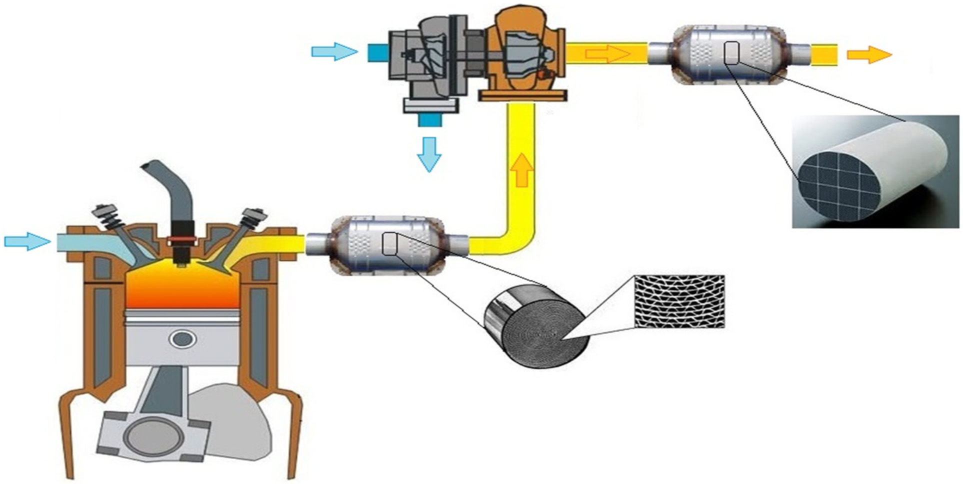

Fig. 1. (Color online.) Modified automobile catalytic system with pre-turbo converter.

channels than in the fully developed regions in the remaining part of long channels. Consequently, segmenting, or repeatedly slicing, the substrate normal to the flow direction, and separating the pieces improves conversion performance by exploiting the enhanced transport coefficients in the entrance regions.

Due to its position, the PTC has some advantages. Firstly, the pre-turbine catalyst required a shorter period of engine work to reach the light-off temperature of the catalytic reaction [5]. When comparing the temperature profile along the exhaust line, temperatures in the front of the turbocharger amount to 500–600 °C and are higher of about 100–150 °C than behind the turbocharger [8]. Moreover, in the PTC very high flow speed is reached, which leads to turbulent flow pattern in the converter channels. This results in a significantly increased mass transfer between exhaust gas and channel walls [2]. Another benefit is limited fuel consumption due to a reduction of the pressure drop [8,9]. The most important effect of additional afterburner before the turbocharger is a significant decrease of the HC and CO emissions [2–4].

2. Experiments

In our previous work [10], the experimental studies are described in details. The short channel structures of triangular and sinusoidal cross-sectional shapes and of 5 mm length were placed in a test reactor of rectangular cross-section, 20 × 35 mm. Strong electric current flowed through the structure to perform heat transfer. Thermocouples measured the temperatures of structure surface and the gas stream. The pressure drop was measured using the Recknagel micromanometer. The superficial velocity applied during the experimental study covered the range of u_0 = 0.3–51.5 m/s, which corresponds to the range of Reynolds numbers Re = 39–6810. During experimental investigations, the reactor filling (short channel structure) was comprised of several channels. The numerical analyzes concerned only a single channel, because every channel within the short channel structure behaves essentially alike.

3. Analysis

The three-dimensional approach was used to simulate the fluid flow and heat transfer in the channel. The physical models are shown in Fig. 2. Only a single channel was modeled using the CFD software because of limited computer yield. The simulations were performed using FLUENT code. Detailed description of numerical analysis is included in our previous work [11]. Uniform heat flux (q = 0.96–36.2 kW/m^2) was assumed on the channel walls. Uniform inlet velocity and temperature profiles were specified in the control region, as well as at the channel inlet for defining simultaneously developing flow conditions. The inlet temperature ranges from 20 to 75 °C. A pressure outlet boundary condition was set at the outlet. The assumed solid material and fluid are Kanthal steel and air, respectively. The following assumptions were made when modelling fluid flow and heat transfer characteristics in triangular and sinusoidal cross-sectional channels:

- the flow is laminar and steady;
- the fluid properties are temperature dependent, solid properties are constant, fluid is incompressible;
- the heat loss, radiative and gravitational effects are negligible.

The local convective heat transfer coefficients and temperature distributions were predicted by numerical simulations for specified flow velocity and heat flux. The heat transfer performance was evaluated using the average Nusselt number defined as:

$$Nu_{avg} = h_{avg} D_h / k \quad (1)$$

The Reynolds number was calculated based on the following expression:

$$Re = \rho u D_h / \mu \quad (2)$$