MECHANICS
Vol. 26 No. 1 2007

Barbara WORSZTYNOWICZ*

A NEW CONCEPT OF A CATALYST SUPPORT FOR INTERNAL COMBUSTION ENGINES

SUMMARY

Standard catalysis reactors are characterized by their channel structure. There are several channels per each cm^2 of the core's surface. At the same time the length of each channel exceeds 100 times the cross section size. This causes splitting of the incoming to the reactor fumes into thousand pieces. Such a construction is characterized by a low mechanical endurance, high flow resistance, high inertia and an inclination for corking of particular channels. The core, according to the new conception, is made of: central partition connected continuously along the whole length of the side wall and a series of side and middle elements situated symmetrically on both sides of the middle partition. The height of the element walls is the height of the side walls and together they form a two side system of a network with crossing passage channels. Those channels are open on the axis inflow-outflow as well as in a direction perpendicular to the mid intersection. Both the middle and the side elements have internal spaces forming respectively middle and side compartments. Those compartments form a common two side open space for each pair of elements situated symmetrically to the middle partition. Each compartment has a connection with the channel network through a particular crack. The catalyser with core of the new construction is characterized by the good flow and mechanical properties. Preliminary experimental tests have shown that the phenomena occurring during the flow through the catalyser are with good agreement with the assumptions.

***Keywords**: catalytic converter, thermodynamic transformation, unestablished stream, flow dynamics*

NOWA KONCEPCJA NOŚNIKA KATALITYCZNEGO DO SILNIKÓW SPALINOWYCH

Klasyczne reaktory katalityczne charakteryzują się budową kanalikową. Na cm^2 powierzchni rdzenia przypada kilkadziesiąt kanalików. Jednocześnie długość każdego kanalika przekracza ponad 100 razy jego wymiar poprzeczny. Powoduje to podział napływającego do reaktora strumienia spalin na tysiące części. Konstrukcja taka charakteryzuje się niską wytrzymałością mechaniczną, dużymi oporami przepływu, dużą bezwładnością oraz skłonnością do zatykania się poszczególnych kanalików. Rdzeń według nowej koncepcji tworzą: środkowa przegroda łącząca w sposób trwały, centralnie wzdłuż całej długości, boczne ściany, a także szeregi, usytuowanych pomiędzy nimi symetrycznie po obu stronach tej środkowej przegrody, elementów środkowych i bocznych. Elementy te mają ściany o wysokości ścian bocznych i kształtują razem dwustronny system sieci krzyżujących się przepływowych kanałów. Kanały te są otwarte w osi przepływu wlot – wylot oraz w kierunku prostopadłym do środkowej przegrody. Zarówno elementy środkowe, jak i boczne mają przestrzenie wewnętrzne tworzące odpowiednio komory środkowe i boczne. Komory te dla każdej z usytuowanych symetrycznie po przeciwnych stronach środkowej przegrody pary elementów stanowią wspólną obustronnie otwartą przestrzeń. Każda z komór ma połączenie z sieciami kanałów odpowiednimi szczelinami. Reaktor z rdzeniem nowej konstrukcji charakteryzuje się dobrymi własnościami przepływowymi i mechanicznymi. Wstępne badania wykazały, że zjawiska zachodzące podczas przepływu przez reaktor odbywają się zgodnie z założeniami.

***Słowa kluczowe**: reaktor katalityczny, dynamika przepływu, przemiany termodynamiczne, nieustalony strumień*

1. INTRODUCTION

Internal combustion engine designs are subject to constant changes. In spite of the advanced technologies of fuel injection systems, which secure better burning process, it is necessary to use emission control systems outside of engines. Catalytic converters are fundamental here.

A three way catalyst (TWC) is the most frequently used type of catalytic converters. Owing to keeping the excess air coefficient λ close to 1, simultaneous oxidation of hydrocarbons (HC) and CO and reduction of NO_x is possible. [2]

Efficient conversion of all toxic constituents of exhaust gases through the catalytic converter is possible in a very narrow range when the air – fuel ratio in the combustible mixture is closest to the stechiometric point (Fig. 1) and the temperature of the exhaust gases is higher than 300^{o}C. The highest efficiency of the catalytic converter is reached above 500^{o}C (Fig. 2) [2, 4, 7].

Unfortunately, the conversion efficiency for various reasons decreases with the operation time. One of the reasons can be decreased efficiency of the catalyst support due to processes which take place in the atmosphere of the chemically aggressive exhaust gases.

* Department of Power Installations, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology

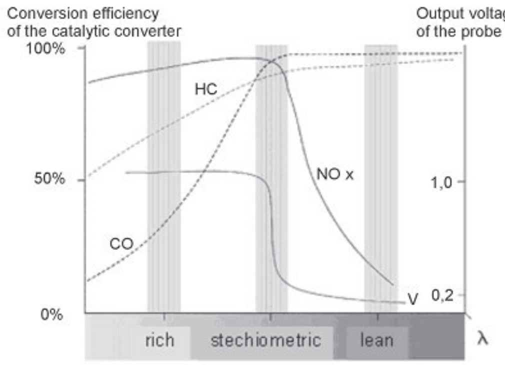

Fig. 1. Conversion efficiency of a catalytic converter and output voltage of a lambda probe as a function of the excess air coefficient λ [8]

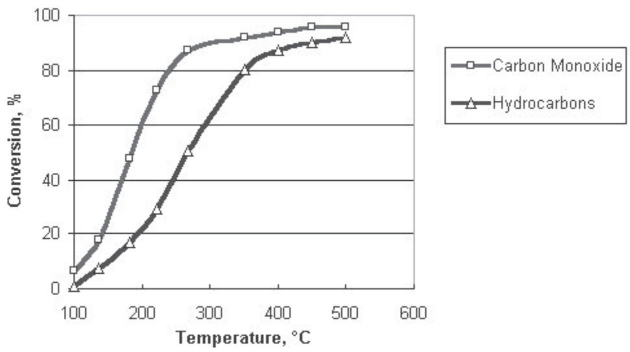

Fig. 2. Conversion efficiency of a catalytic converter as a function of temperature [9]

2. TYPES OF CATALYST SUPPORTS USED

The catalyst supports occur in the form of ceramic or metallic monoliths. However, the ceramic supports are used much more frequently, therefore the paper presents their characteristics. The ceramic support has a honeycomb structure. Its core consists of canals parallel to the flow direction of exhaust gases. The cross-sectional area of each canal is on the order of a square millimetre and the walls are a few tenths of a millimetre thick. Each canal is about 100 times as long as it is wide. The walls of the canals are covered with an interlayer with developed surface coated with catalyst. The ceramic support is embedded in an elastic coat. A metal casing represents an external part of the catalytic converter [1, 2, 4, 7].

Possibility of obtaining the high density of the canals is an advantage of the ceramic support. This secures large surface area of contact of the exhaust gases with the catalyst layer. Low thermal inertia of the support is also advantageous as it enables its rapid heating up, thus operating in a relatively short time after the engine is started. However, in the case of high temperatures, which can occur during heavy loads on the engine, sintering of the porous layer of the support can happen [4, 5].

Catalytic reactions occur selectively on the catalyst surface, which reduces the activation energy of reactive substances and this enables oxidation and reduction in the atmosphere of the exhaust gases. On account of higher affinity of O_2 to HC and CO, reduction of NO_x takes place mostly in the areas where, as a result of inhomogeneous composition of the exhaust gases, deficiency of oxygen occurs. Another disadvantageous phenomenon is represented by low-temperature oxidation of CO which leads to generation of nitrogen monoxide N_2O that is characterized by persistency in the atmosphere and easy combination with oxide to form nitrogen dioxide NO_2 [4, 5].

The stream of the gases entering the catalytic converter consisting of thousands of canals with small cross-sectional areas and long lengths encounters considerable resistance to flow is choked and the flow becomes almost laminar. In addition, the processes go on at constant enthalpy, which reduces the possibility of the reaction occurrence [3].

During the operation, the catalytic converters are subject to shakes and vibrations, thermal shocks, corrosion and erosion in the pulsating stream of hot gases. Apart from these, variable conditions of the engine operation result in corresponding variations in the pulsation degree and in the flow rate of the gases through the catalytic converter. The pulsating stream of the gases flowing at high speed through the canals of the converter causes erosion of sub-microscopic particles of the active constituent. The particles carried away by the exhaust gases transport, on their intensely developed surfaces, toxic substances to the environment, which can be dangerous for all forms of life. Other faults of the ceramic catalyst support with the honeycomb structure are: low strength, low resistance to thermal shocks and a tendency of the canals to clog up [4].

The facts presented above induce searching some new solutions of the catalyst converters, with different structures and ways of operation.

A solution where the flow of the exhaust gases would occur through larger cross-sectional areas seems to be interesting. It would reduce the surface area of contact of the exhaust gases with the active layer, but this can be compensated by changing the character of the gas flow.

3. A NEW CONCEPT OF A CATALYST SUPPORT

The monolithic ceramic core is composed of a central partition with side walls and repetitive central and side elements situated between these walls on both sides of the central partition. The central and side elements are of the same heights, equal to the height of the side walls (Fig. 3).

The central partition joins the side walls throughout the length of the catalyst support, creating with them a cross section in the shape of a symmetrical “H” letter. The central and side elements of the support are placed symmetrically towards each other and towards the central partition, and they form rows perpendicular to the flow axis (inlet – outlet). The first row is formed by at least two central elements. The second row is formed by at least one central element and two side elements. The third row and subsequent odd rows up to the last row are formed by the same number of central elements as in the first row. The fourth row and subsequent even rows are formed by the same number of central and side elements as in the second row. All the central elements are firmly connected to the central partition and the side elements to the central partition and the appropriate side walls. The central and side elements constitute a two-sided system of crossing canals for flow. These canals are open along the inlet – outlet axis of flow and in the direction perpendicular to the central partition.

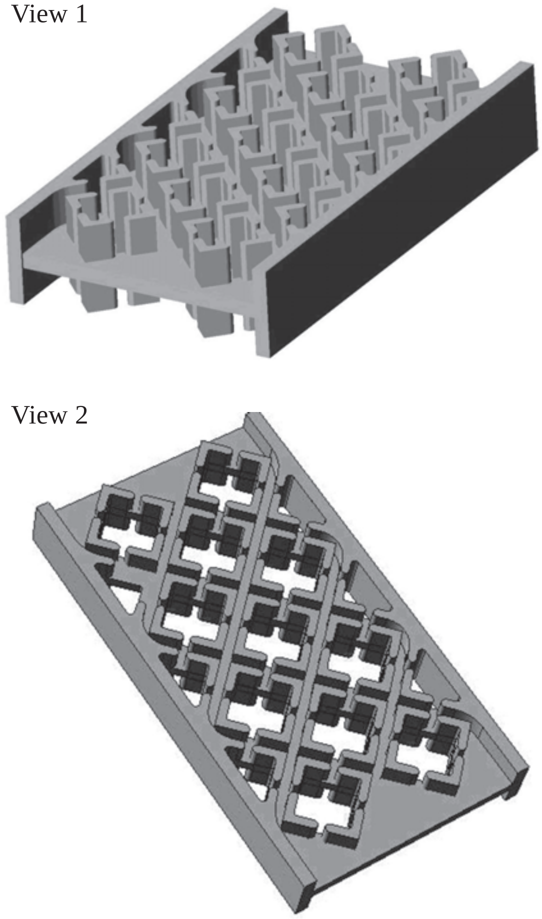

Fig. 3. Construction of the core

In the view perpendicular to the central partition, the central elements are square in shape and are arranged with one of diagonals parallel to the flow axis (inlet – outlet). Such the arrangement causes that the angle between walls of these elements and appropriate side walls are equal to 45 degrees. The side elements are halves of the central elements and are right-angled isosceles triangles in shape. The side elements are symmetrically situated relative to the central elements in such a way that their hypotenuses are in line with the appropriate side walls. Internal spaces of central and side elements form central and side cells, respectively. These cells create common, two-sided open space for the central or side elements which are symmetrically placed on both sides of the central partition. All the cells have connections with their adjoining sections of the canal network through gaps situated in the middle of each of four walls of the central elements and in the middle of two perpendicular walls of the side elements. The heights of the gaps are equal to the heights of the walls of the elements (Fig. 3).

The surface of the catalyst support is covered with an intermediate layer that constitutes the base for the catalyst. The catalyst support shielded by elastic braid can be placed inside a metal casing. The elastic braid made of appropriate material can also be a support for the catalyst. With such the solution, the surfaces of the catalyst support and of the braid can be coated with different catalytic layers, which can prove advantageous in some applications.

4. FUNCTIONS AND ADVANTAGES OF THE NEW-CONCEPT CATALYST SUPPORT

An internal combustion engine operates under variable load conditions which results in generation of exhaust gases with variable flow rate. The catalytic converter is subject to pulsating stream of the exhaust gases which have variable pressure and velocity and inhomogeneous chemical composition.

According to the described concept, the method of neutralizing the exhaust gases consists in subjecting them, when flowing through the catalytic converter, to thermodynamic transitions and oscillations with frequency of at least 5 kHz.

In the catalytic converter the exhaust gases are initially divided into two streams by the central partition of the catalyst support. They simultaneously enter the symmetrical systems of flow canals of the upper and lower networks which are connected by the resonating central and side cells with limited flow.

The fundamental thermodynamic transitions occur when the unsteady gas streams intermingle at the intersections of the canals. The oscillations are induced within the jointly acting oscillating ensembles connected together in parallel and in series. The ensembles are composed of the resonating cells with limited flow and adjoining sections of canal networks. The thermodynamic and flow-mechanic phenomena are caused through the appropriate conversion of energy of the pulsating, unstable stream of gases entering the catalytic converter. Pressure fluctuations in the streams which flow through the canals adjoining the cells act through the middle gaps and induce oscillations in these cells, with frequency equal to their free vibration frequency. These oscillations have reciprocal effects on the gas streams which flow through the canals. The intermingling of the pulsating gas streams is realized by perpendicular convergence of pairs of these streams, which is repeated at each intersection of the canals. As a result of aerodynamic interference, this induces oscillations in the sections of the canals. The oscillations in the canals are consonant with the oscillations in the cells and force the synchronous oscillation in the whole volume of the catalytic converter; the oscillation is independent of the variable parameters of the gases which enter the catalytic converter. The synergism of flow mechanics and thermodynamics realized in this way intensifies catalytic reactions and causes that they take place in the whole volume of the catalytic converter [3].

The reduction and oxidation reactions occur at increasing gas entropy, which is the result of the increase in total specific heat by specific heat of oscillation (1.1)– (1.6) [6]:

– exhaust pipe

$$dq_c = dq = c \cdot dT \quad (1.1)$$

– catalytic converter:

$$dq + dq_t = dq_c = c_c \cdot dT \quad (1.2)$$

$$c + c_{osc.} = c_c \quad (1.3)$$

$$dq_c = T \cdot ds \Rightarrow ds = \frac{dq_c}{T \cdot ds} \rangle 0 \quad (1.4)$$

$$T \cdot ds = c_c \cdot dT \quad (1.5)$$

$$ds = \frac{c_c \cdot dT}{T} = \frac{di}{T} \quad (1.6)$$

where:

dq_c – total heat,
dq – heat supplied from the outside,
dq_t – heat of friction,
ds – entropy,
di – enthalpy,
c – specific heat from the outside,
$c_{osc.}$ – specific heat of oscillation,
c_c – total specific heat,
T – temperature.

Intense internal friction caused by colliding streams will enable increase in the temperature of the exhaust gases, which will ease particularly the reduction process. The neutralization process executed at elevated thermodynamic parameters of the gas will prevent reverse reactions, so limiting the danger of generation of nitrogen monoxide (N_2O). The neutralization process will occur in the whole gas volume, not only on the surface of the catalyst coating. Owing to this, the influence of the degree of heating the core and flow rate of the exhaust gases on the conversion efficiency will be reduced. The collision of the gas streams together with the synchronous oscillation of the catalytic converter will intensify the process of mixing of the gases resulting in homogenization of their chemical composition. This will allow to control the composition of the prepared air – fuel mixture to reach values closer to the stechiometric point, which in itself limits the amount of toxic constituents of the exhaust gases, generated within the combustion zone.

A catalytic converter with the proposed catalyst support is characterized by high mechanical strength with simultaneous high thermal resistance. This results from the fact that the flow canals of the catalyst support have cross-sectional areas several hundred times the areas of the commonly used catalytic converters with supports of the honeycomb type. Such the new solution eliminates essential limitations of conventional catalytic converters, that is strong resistance to the exhaust gas flow and clogging of the canals which leads to gradual reduction of the active surface. Moreover, owing to large cross-sectional areas of the flow canals the risk of erosion of the catalyst layer is lower. Advantages of the presented solution of the catalytic converter appear also in the production stage. The catalyst support design is the reason why it will be easier to manufacture than the support of the honeycomb type. In addition, it requires using less catalyst, which can lead to lower production costs.

5. PRELIMINARY TESTS OF THE CATALYTIC CONVERTER

The preliminary stage of testing involved visualization of flow of working medium through a model of the catalytic converter. The purpose of the visualization was to check how far the theoretical assumptions of the dynamic phenomena due to the flow through the converter will be confirmed. In order to attain it, a model was constructed of transparent plastic which enables observation of phenomena occurring within the catalytic converter. A ceramic sieve was placed at the inlet of the converter. Afterwards the converter was connected with supply and offtake conduits and set in a vertical position on a test stand so that the supply conduit was at the bottom of the system (Fig. 4).

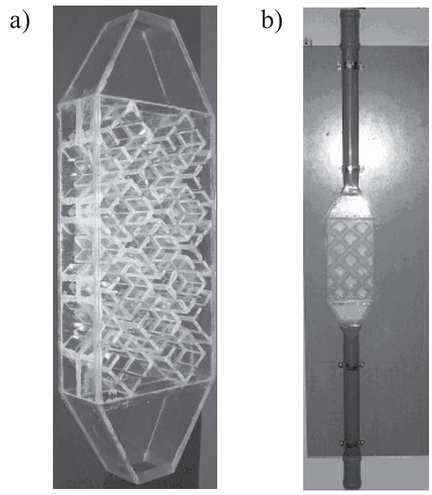

Fig. 4. Physical model of the catalytic converter (a) and the test stand (b)

The test consisted in passing the air bubbles through the catalytic converter filled with water. The compressed air was introduced through the supply conduit and the inlet sieve caused size reduction of the air bubbles and their uniform supply at the inlet surface. After initiating the air flow, the phenomena became stabilized. They were recorded digitally with the frequency equal to 30 frames per second. Characteristic images of the course of the phenomena are presented below.

6. TEST RESULTS AND THEIR ANALYSIS

The stream of the air bubbles entering the catalyst support of the model was divided into two portions by the central partition. Then it encountered the symmetrical systems of the canals and cells of the lower and upper networks where subsequent stages of the stream division took place.

When observing the flow it was noted that the front of disturbance of the pressure wave moved parallel through the canal networks and through the central and side cells.

The flow advanced through the canals and interpenetration of the streams took place at the intersections of the canal networks. On the other hand, the flow through the cells was reduced, in accordance with the assumptions. In the cells the air bubbles were broken up, which was evidenced by the decreasing number of large bubbles within succeeding cells. In addition, the pressure pulsation was observed in the cells and the pulsation proceeded into the surrounding canal networks. This evidences the close connection between the phenomena within the cells and the canal network. It should be noted that the phenomena in succeeding cells revealed a time shift (Fig. 5).

At the inlet of the catalytic converter, despite the presence of the breaking up sieve, the air bubbles tended to aggregate creating large bubbles which were broken up as they moved upwards, in accordance with the flow direction. As a result, only small bubbles could be observed at the outlet (Fig. 6).

The tests carried out with the use of the plastic model confirmed the theoretical assumptions about the flow, which justifies further investigation. The next stage will involve tests of real models and will enable analysis of dynamic phenomena during unstable flow of exhaust gases from internal combustion engines.

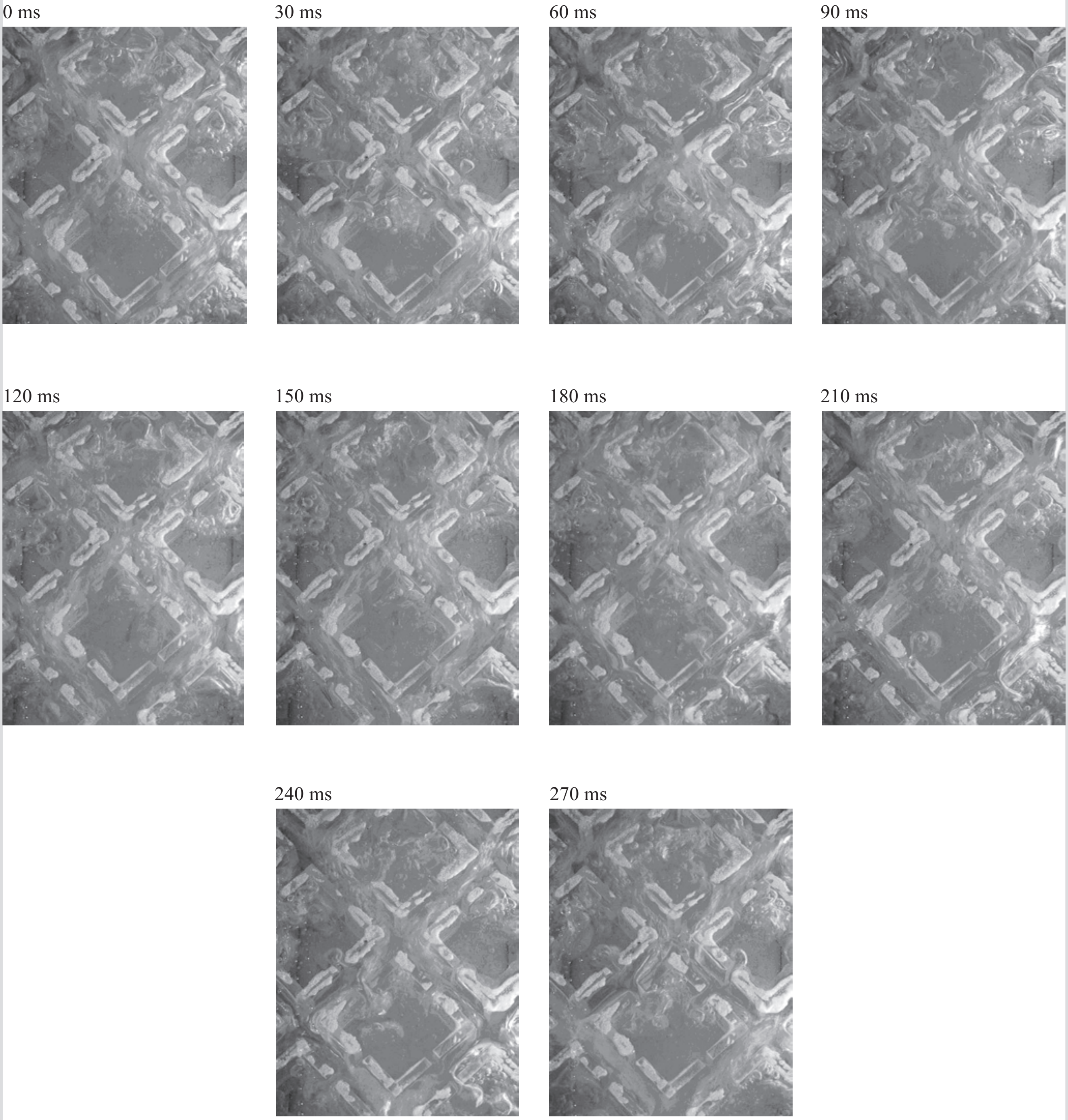

Fig. 5. Images of phenomena at the inlet and outlet of the catalytic converter

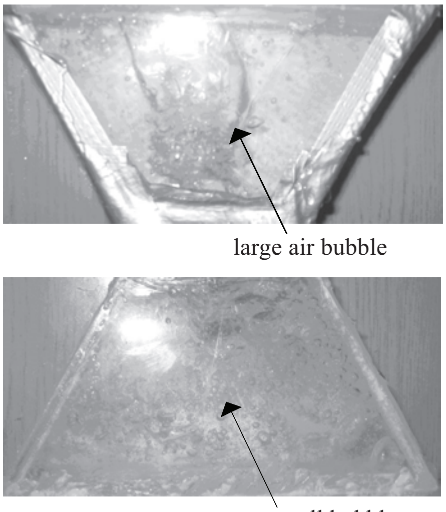

Fig. 6. Images of flow – still frames with 30 ms intervals

References

[1] Kruczyński S. 2001: *Perspektywy rozwoju reaktorów katalitycznych w zastosowaniu do silników spalinowych.* V Sympozjum Naukowo--Techniczne SILWOJ, Jurata, 17–19 października 2001, Wojskowa Akademia Techniczna, Warszawa

[2] Merkisz J. 1999: *Ekologiczne problemy silników spalinowych.* t. 2. Wydawnictwo Politechniki Poznańskiej, Poznań

[3] Prandtl L. 1956: *Dynamika przepływów.* Państwowe Wydawnictwo Naukowe, Warszawa

[4] Przyłuski J., Kolbrecka K. 1993: *Trójfunkcyjne reaktory katalityczne do oczyszczania gazów odlotowych silników spalinowych.* Ochrona Powietrza i Problemy Odpadów, 3

[5] Przyłuski J., Kolbrecka K. 1993: *Główne problemy katalitycznego ograniczania emisji szkodliwych gazów z silników samochodowych.* Ochrona powietrza i problemy odpadów, 4

[6] Wiśniewski S. 1980: *Termodynamika techniczna.* Wydawnictwo Naukowo-Techniczne, Warszawa

[7] Eberspächer 1985: *Abgasreinigung Katalysator – Rußfilter*

[8] Bonikowski L. 2006: *Silniki spalinowe.* (Niepublikowane wykłady)

[9] www.nett.ca