ARCHIWUM MOTORYZACJI
4, pp. 287-300 (2010)

Modeling of heat recovery system in diesel particulate filter

WŁADYSŁAW MITIANIEC

Cracow University of Technology

An additional energy for soot combustion is required for regeneration of particle filters (additional fuel or electric energy) after some period of the engine work as a result of closing of substrate pores by soot. The proposed method takes into account a self-regeneration of diesel particle filter by use of special heat recovery system. The paper shows one of possible design of DPF self-regeneration. The exhaust temperature behind the turbine and catalytic converter is very low and for an increasing of gas temperature before DPF and the heat from soot combustion can be used. The preliminary studies show a possibility of using the special DPF design with a heat recovery system. The paper presents the simulation results of such system and possibility of increasing the heat recovery ratio by change of geometry of DPF. The preliminary results of calculations show the possibility of increase of exhaust gases temperature in front of DPF about 20%, which enables a continuous regeneration of DPF. The method enables to recover some part of energy which is lost in the conventional DPF.

1. Introduction

Diesel particulate filter (DPF) requires a long time for deposit of soot on the walls of the inlet ducts. The total mass of soot in DPF is almost linearly proportional to time for modern compression engines. Filtration of soot and nanoparticles depends on structure of used material of the filter substrate, amount and size of soot in the gas, geometry of channels and thermodynamic parameters of exhaust gases. Filtration is not so effective in the clean DPF and after several hours the pores in the filter are partially clogged and filtration proceeds much more effectively. When the filter walls are filled by soot molecules the pressure drop increases in the filter. The level of the pressure drop is the signal for the beginning of regeneration process. Regeneration process can be done by several methods. However these methods require an additional energy for initiation of soot burning (additional fuel injection in DPF, heating by use of electric energy or post-injection of fuel). In compression ignition engines the exhaust temperature behind the turbine and catalytic converter is very low and particularly for HCCI engine the emission of particles is lower in comparison to conventional diesel engines.

Applying of particle filters requires special methods for their regeneration after some period of the engine work in a result of closing of substrate pores by soot. Filtration of nanoparticles in DPF and soot combustion is widely described by many authors: Konstandopoulos et al [1, 4], Bisset [5], Nakatani [6] and also by polish researchers Nagórski, Teodorczyk and Bernhardt [2].

2. Regeneration of DPF

Required temperature of exhaust gases should be higher than 600°C to initiate the burning of soot on the filter walls. In order to increase the temperature of inlet gases in DPF a special heat recovery system (HRS) is needed. During combustion of soot in DPF the outlet gases have higher temperature and this phenomenon can be used for heating the inlet gases in order to increase their temperature, which should cause quicker soot combustion. Such idea leads to applying of the heat recovery system.

The one-dimensional mathematical model can be used to simulate non-uniform distributions of soot along the DPF channels and the filter wall during the regeneration process. The model considers that under most common operating conditions of internal combustion engines, the spatial rates of change of fluid properties are far greater than the temporal ones, so quasi-steady flow conditions can be assumed and steady flow gas dynamic relations may be used. The model is primarily used for regeneration modeling though it is also able to extend of soot loading modeling. It was assumed the one-dimensional Bisset model [5] of filter regeneration shown in Figure 1 in order to determine the changes of DPF parameters during filtration and heat increase after soot combustion.

The soot is filtered by the walls of inlet channels and stays in pores. The model treats the filtered soot as an additional layer on the clean wall of inlet ducts and takes into account two layers wall (soot and clean wall).

The model of filtration and regeneration takes into account the following phenomena:

1. Balance of gas mass in the channels.
2. Balance of momentum of gas jets in the channels.
3. Balance of energy conservation.
4. Balance of oxygen.
5. Balance of PM mass.
6. Balance of energy in the filtration wall given for determination of exhaust gas temperature during soot combustion.

Full mathematical model of filtration and regeneration of DPF is out of the scope of the paper and some part are presented in the author's papers [7, 8]. For lower inlet temperature particularly for HCCI engine there is not possible to burn the soot in DPF, because temperature does not exceed 450°C.

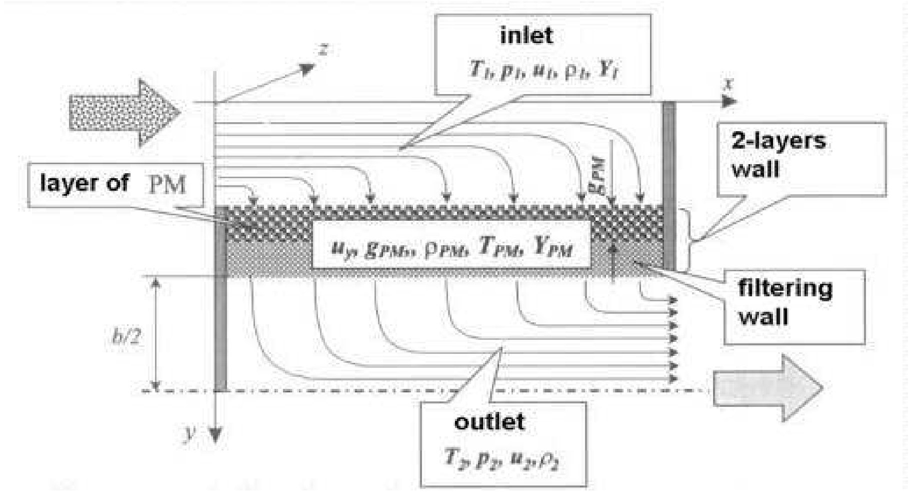

Fig. 1. One dimensional model of DPF filtration and regeneration, where symbols used are as follows: T - temperature, p - pressure, u, velocity, ρ - density, Y_{PM} - mass ratio of oxygen in the gas flown through the PM layer, Y_1 - mass ratio of oxygen in the gas flown in inlet duct, g_{PM} - thickness of soot layer, indices: PM - soot, 1, inlet duct, 2 - outlet duct.

Rys. 1. Jednowymiarowy model filtracji i regeneracji filtra cząstek stałych, gdzie symbole odpowiednio oznaczają: T- temperatura, p - ciśnienie, u - prędkość, ρ - gęstość, Y_{PM} - udział masowy tlenu w gazie przepływającym przez warstwę sadzy, Y_1 - udział masowy tlenu w gazie przepływającym przez kanał dolotowy , g_{PM} - grubość warstwy sadzy, indeksy: PM - sadza, 1 - kanał wlotowy, 2 - kanał wylotowy.

For that case an additional energy is needed in order to increase the inlet temperature. There are foreseen different regeneration strategies, for example post-injection as a source of soot ignition or increase the temperature in Diesel Oxidation Catalyst (DOC) for burning hydrocarbons (HC) and carbon monoxide (CO). During soot combustion outlet gases have higher temperature, which can be used for heating of the inlet gases in the heat exchanger. The first proposition is to use the separate heat exchanger with many heating pipes with cross flow of gases. The task of the heat exchanger is to increase the heat recovery ratio or increase the inlet temperature minimum 20%.

3. Thermal parameters of DPF during regeneration

The first assessment of the possibility to increase the temperature of the inflowing exhaust gas was done by use of the module in GT-Power program . The program was worked out by Gamma Technology Inc. (USA) and is commonly used in automotive research centers for simulation of engine processes with taking into account unsteady gas flow. The model of DPF regeneration enables to add the electric power source in order to begin the soot burning. The flowchart of the DPF regeneration is shown in Figure 2. The simulation of soot filtration and regeneration was carried out for real DPF made from cordierite with the data given by Aerosol & Particle Technology Laboratory (APTL) CERTH/CPERI in Thesaloniki (Greece) which are shown in

Table 1 Experimental tests carried out in APTL enabled simulation of DPF regeneration and verification of results.

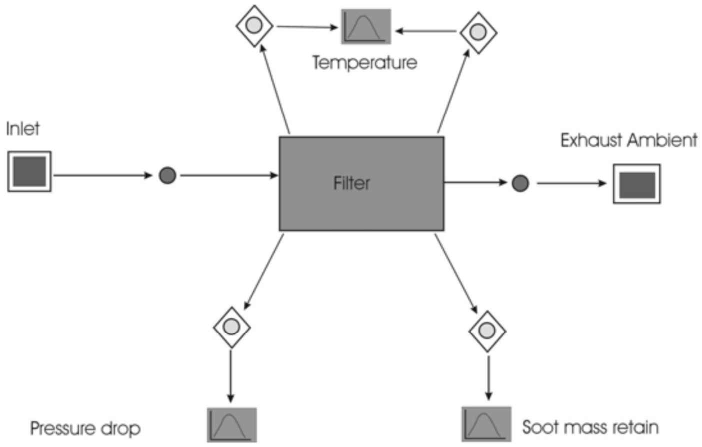

Fig. 2. Flowchart of DPF regeneration in GT-Power.
Rys.2. Schemat symulacji przebiegu regeneracji w programie GT-Power.

Table 1. Geometrical data and boundary conditions of DPF.
Tablica 1. Dane geometryczne i warunki brzegowe filtra cząstek stałych.

Geometrical data of DPF:		**Boundary conditions:**	
Trap diameter Srednica filtra	143.7 mm	Inlet static pressure Ciśnienie statyczne wlotu	1.023 bars
Channel length Długość kanałów:	152.4 mm	Inlet temperature (variable) Temperatura na wlocie	585 - 725 K
Channel width Szerokość kanałów	1.11 mm	Outlet pressure Ciśnienie wylotowe	1 bar
Wall thickness Grubość ścianek	0.31 mm	Outlet temperature Temperatura wylotowa	350 K
Number of inlet channels Ilość kanałów wlotowych	3700		
Pore diameter Średnica porów	0.011 mm		
Filter porosity Porowatość filtra	0.42		
Filtration area Powierzchnia filtracji	2.55 m^2		

For theoretical analysis one was assumed that exhaust gases contain only oxygen, nitrogen and soot, because the other chemical components have almost the same thermodynamic properties as the air. On the basis of experience it was found that for higher diesel engine load mass concentration of soot in exhaust gases is about 0.001 and for 2 l capacity engine working at 2000 rpm the air mass flow rate amounts 80 kg/h. On the basis of the above assumptions simulations for different geometrical parameters of the heat exchanger were carried out. Simulations show that pressure in the outlet channel increases rapidly after the soot burning and then reaches the constant value (Fig.3). The value x in % means the percentage length from the beginning of inlet duct (total length is 100%).

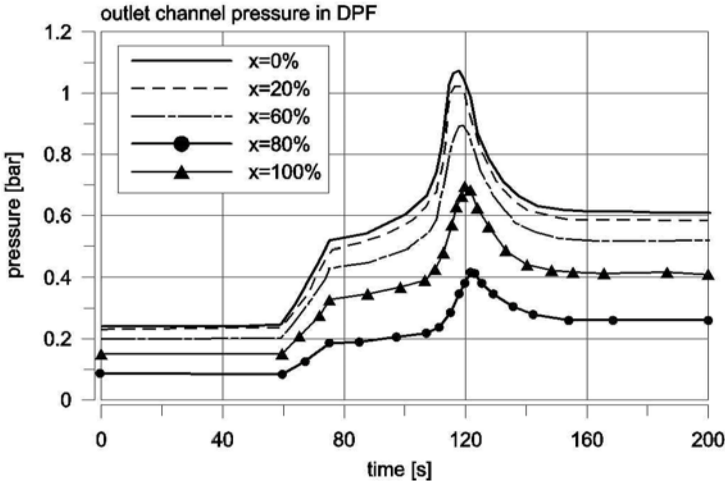

Fig. 3. Pressure along the outlet channels (x=0 - 100%).
Rys. 3. Przebieg ciśnienia wzdłuż kanału wylotowego (x=0 - 100%).

The higher temperature of the gas at the end of outlet channels is observed during burning of the soot when temperature of inlet gases is low (below 600 K). It is observed non-uniform temperature distribution along channels. An example of calculations for inlet temperature $T_{inl} = 600$ K is shown in Figure 4 during 800 s.

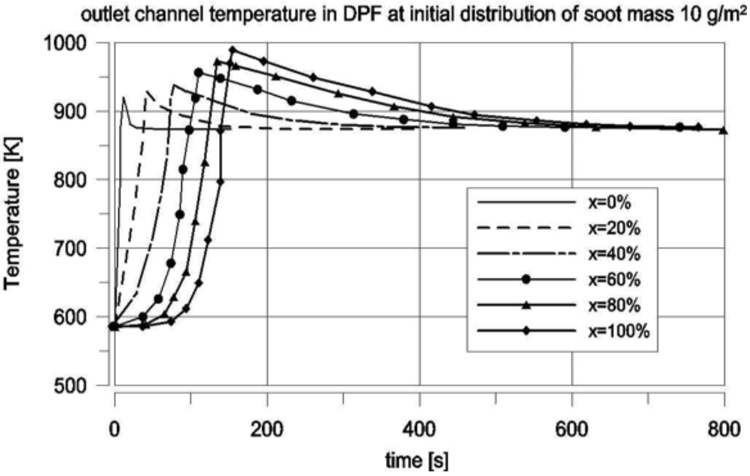

Fig. 4. Gas temperature in outlet channels during regeneration along the channel length as a time function at initial soot mass 10 g/m^2.
Rys.4. Temperatura gazów w kanale wylotowym w funkcji czasu podczas regeneracji przy początkowej masie 10 g/m^2.

It was assumed that regeneration process begun by use of external heating at time 0 s, when the pressure drop in DPF amounted 15 kPa and temperature of gases was about 585 °C. Total mass of soot deposited on the DPF walls amounted 12 g after 2.78 hrs of filtration. The regeneration process has an initial period, when an initiation of soot ignition occurs. The temperature in DPF is increased slightly and after that period the soot combustion occurred very fast. Simulations were carried out for 200 s from beginning of regeneration. The change of pressure drop in the DPF during regeneration is shown in Figure 5. Maximum of pressure drop takes place after 100 s and later the pressure drop decreases slightly.

The increase of pressure drop is observed after 50 s. It is caused by increasing of temperature, which is a barrier of gas flow through the wall. According to general gas state law an increasing of temperature causes an increasing of pressure, however gas density changes also.

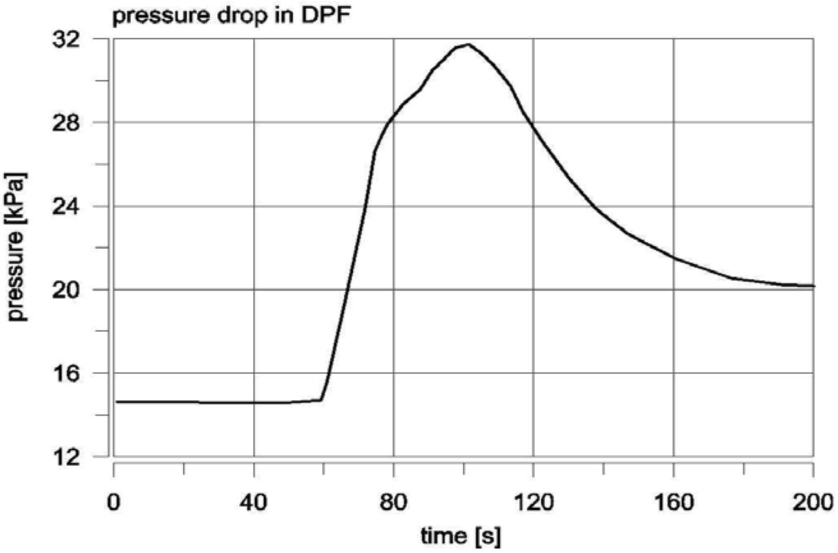

Fig. 5. Pressure drop in DPF during regeneration in DPF with inlet gas temperature 600° C.
Rys. 5. Spadek ciśnienia w DPF podczas regeneracji przy temperaturze wlotowej 600° C.

The change of soot deposit in DPF is shown in Figure 6 for different initial soot mass per area at the same gas inlet temperature 600 °C. It is observed a longer burning of soot for lower total deposit (mass). Medium time of full burning of soot amounts about 150 s.

Regeneration of the filter, which is caused by soot oxidation influences on the mass fraction of the oxygen, carbon dioxide and carbon monoxide. At the first step of oxidation there is more CO which is next converted to CO_2. At the end of regeneration there is enough of oxygen in exhaust gases (Fig.7) because the soot was fully burnt.

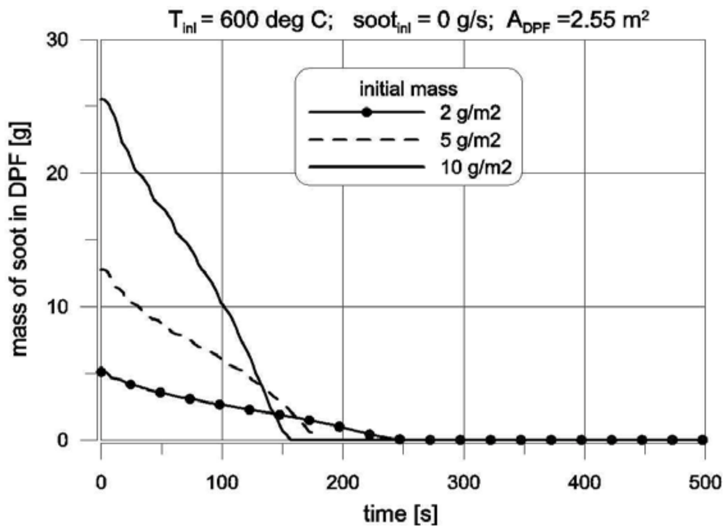

Fig. 6. Mass of soot in filter during regeneration for 3 values of initial soot: 2, 5 and 10 g/m^2 at DPF with inlet gas temperature 600° C.
Rys. 6. Spadek ciśnienia w filtrze cząstek stałych podczas regeneracji dla trzech początkowych wartości sadzy: 2, 5 i 10 g/m2 i przy temperaturze wlotowej 600° C.

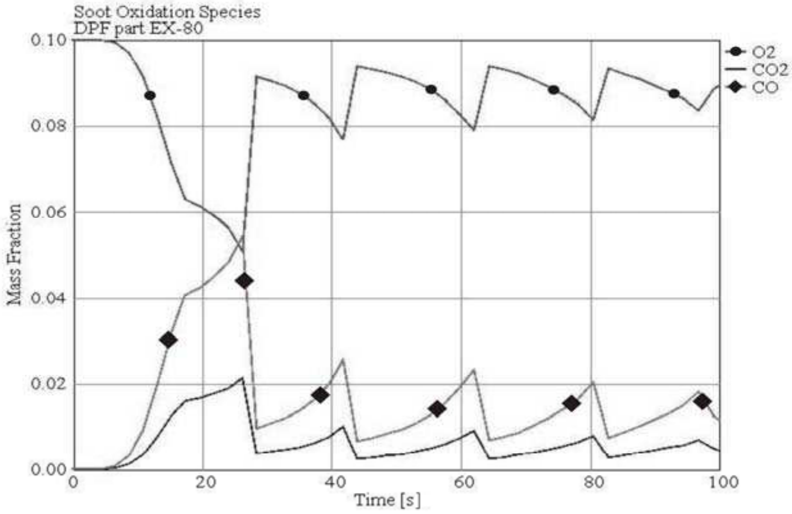

Fig. 7. Mass fraction of soot oxidation species in DPF with initial soot mass 10 g/m^2.
Rys. 7. Udział masowy sadzy w DPF przy początkowym masowym obciążeniu sadzą w ilości 10 g/m^2.

4. Discretization model of heat exchanger

The applied heat recovery system (HRS) is a special heat exchanger on the inlet side of DPF and it contains several pipes in front of DPF. The HRS was described by the author in other papers [7, 8]. The precise mathematical model of the DPF self-regeneration contains discretization of the system, because the temperature inside the pipes during heat exchange decreases as a result of heat transfer to the walls. The enthalpy of the mass of gas in the pipes decreases and on the pipes' outflow the temperature is higher than in the case without soot combustion in the DPF. The temperature in DPF depends on the amount of the burnt mass of soot and influences on the regeneration ratio. In simulation a different levels of ΔT_{DPF} were assumed. The diagram for the simple model is presented in Fig. 8. Regeneration takes place in the heat exchanger consisting a dozen of pipes joined the chamber and the outflow. The regenerating pipes was divided on small sections and marked with indices j.

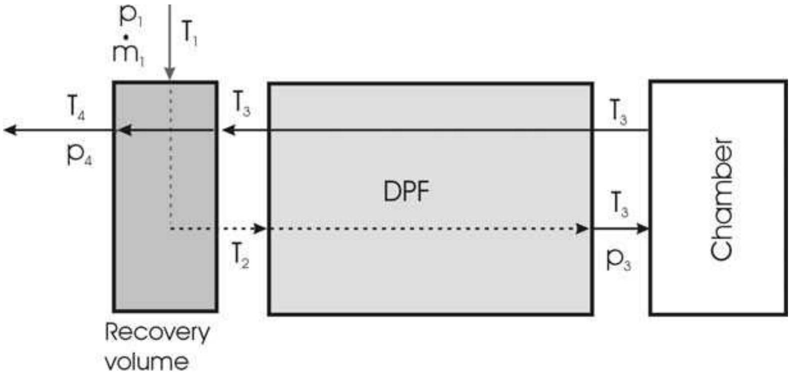

Fig. 8. Simple zero-dimensional regeneration model of DPF.
Rys. 8. Uproszczony 0-wymiarowy model regeneracji filtra cząstek stałych.

The heat exchange between the gas behind the outlet channels in DPF flown into the exchange pipe and the gas flown to the DPF the following simple energy equation for ideal gas is given:

$$\dot{m}_1 c_p(T_1)T_1 + \sum \dot{m}_j F k_j \left(T_{j3} - T_0\right) = \sum \dot{m}_{j2} c_p(T_{j2})T_{j2} \tag{1}$$

where:

$\dot{m}_j$ - mass flow rate of the exhaust gas in domain j,

T_1 - inflow gas temperature before the exchanger in domain j,

T_{j2} - gas temperature behind the exchanger in domain j,

T_{j3} - gas temperature behind DPF after regeneration in domain j,

$\sum F_j$ - total area of the exchanger in domain j,

k_j - coefficient of heat exchange in domain j.

For small changes of the temperature in front of and behind the exchanger the specific heat coefficient at constant pressure can be assumed as the same. During burning of the soot the temperature behind the DPF increases with value

$$\Delta T_{DPF} = T_3 - T_2 \tag{2}$$

The local heat exchange coefficient k_j is determined from the formula:

$$\frac{1}{k_j} = \frac{1}{\alpha_{j2}} + \frac{g}{\lambda} + \frac{1}{\alpha_{j3}} \tag{3}$$

Where λ is the heat conduction of materials and α_{j2} and α_{j3} are the coefficients of heat convection calculated from the known correlations:

$$\alpha_{2,3} = f(Nu_{2,3}, d, \lambda_{2,3}) \qquad \mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr}) \tag{4}$$

The temperature T_j of the gas inside the pipes:

$$T_j = T_{j3} - \frac{k_j F_j}{\dot{m}_{j2}\left(c_p\right)_{j2}}\left(T_{j3} - T_{j2}\right) \tag{5}$$

The initial temperature T_j in the pipes is taken as T_{j-1} from previous volume j-1.

The inlet temperature in the pipes are taken as the outflow temperature T_3 of DPF and the wall temperature is taken from the heat exchange between gas inside the pipes and walls:

$$T_{wj} = T_j - \frac{k_j}{\alpha_{j3}\dot{m}_{j3}}\left(T_j - T_{j2}\right) \tag{6}$$

Amount of the heat involved in DPF is determined from the formula:

$$\dot{Q}_c = \dot{m}_1 \left(c_p\right)\Big|_{T_2}^{T_3} \left(T_3 - T_2\right) \tag{7}$$

where n is the number of discretization volumes.

The recovery heat (delivered to the gas outside of the pipes) is calculated as follows:

$$\dot{Q}_r = \sum_{i=1}^{n} \dot{m}_{1j}\left(c_p\right)_{1j}\left(T_{j2} - T_1\right) \tag{8}$$

Amount of heat loss can be determined from the formula:

$$\dot{Q}_t = \dot{m}_{3n} \cdot \left(c_p\right)_{3n} \cdot \left(T_{3n} - T_1\right) \tag{9}$$

The temperature of the gas outside of the pipes with taking into account the radiation is determined from the equation similar to the equation:

$$T_{j2} = \frac{\beta T_1 + \delta Q_{rad} + \alpha T_{j3}}{1 + \alpha} \tag{10}$$

where: $\delta = \dfrac{1}{\dot{m}_{1j}\left(c_p\right)_{1j}}$

$$\dot{Q}_{rad,j} = \varepsilon \cdot \sigma \cdot F_j \left(T_{wj}^4 - T_{1j}^4\right) \tag{11}$$

where: σ - Stefan-Boltzman constant = $5.67 \cdot 10^{-8}$ W/(m^2 K^4),
ε - material emissivity.

For calculation of a changed temperature in different places of the system a special computer program was prepared taking into account the presented above mathematical model. Heat recovery ratio increases with increment of number of heating pipes with the same length and diameter. At higher increment of soot combustion temperature in DPF the heat recovery ratio also increases, which is shown in Figure 9.

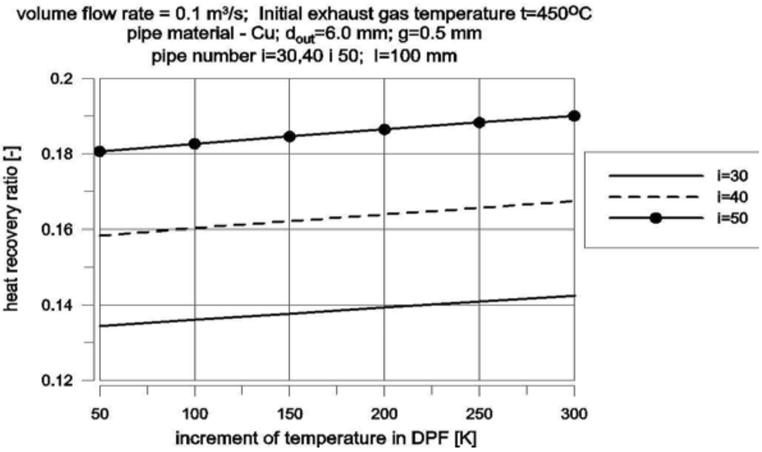

Fig. 9. Heat recovery ratio in a function of increase of DPF temperature for different numbers of heating pipes (30, 40 and 50) at the same length 100 mm.
Rys. 9. Stopień odzysku ciepła w funkcji przyrostu temperatury w filtrze dla różnej liczby grzejnych rurek (30, 40 i 50) przy tej samej długości 100 mm.

5. Simulation in CFD

The presented regeneration model is a certain modification of other considered systems and enables to get a symmetrical gas flow in the heat exchanger and contains two inlets of gas with the same total inlet area as others. Diameter of each inlet pipe has dimension 45 mm. The DPF model with the regeneration system is presented in Figure 10.

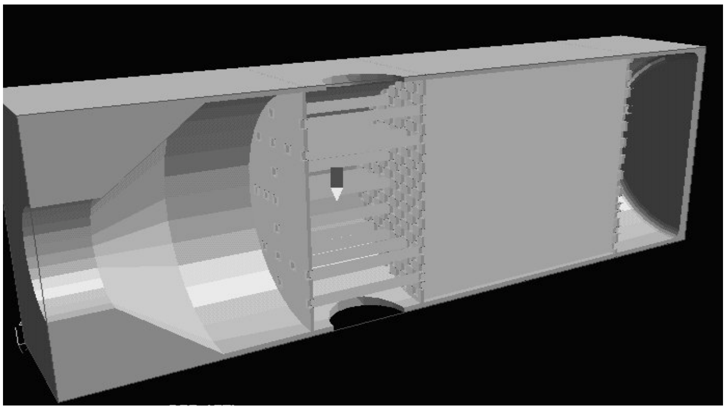

Fig. 10. Model of DPF heat exchanger.
Rys.10. Model wymiennika ciepła w filtrze cząstek stałych.

Distribution of pressure in the symmetric plane of DPF at flow rate 0.04 m^3/s is shown in Figure 11. The pressure drop between inlet and outlet amounts about 700 Pa which is caused by filtration and flow resistance in the regeneration pipes.

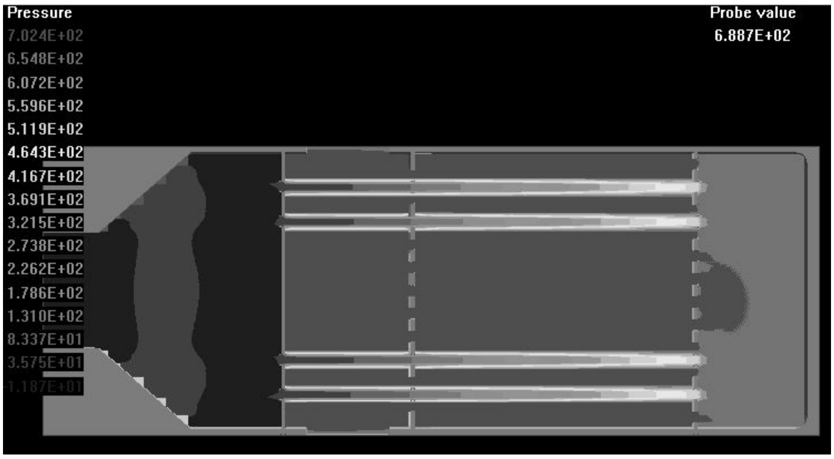

Fig. 11. Gas pressure in the symmetrical plane of DPF at flow rate 0.04 m^3/s
and inlet temperature 450 °C.
Rys. 11 Ciśnienie gazu w płaszczyźnie symetrii DPF przy masowym natężeniu przepływu 0.04 m^3/s
i temperaturze wlotowej 450° C.

At higher flow rate the pressure inside the DPF is bigger and amounts about 2000 Pa at flow rate 0.1 m^3/s. Pressure drop between reverse and outlet volume amounts 700 Pa. Temperature of gas is more uniform than in system with only one inlet side and gas is heated much more near pipes as is shown in Figure 12. Two opposite inflows causes the gas flow through the middle part of the substrate.

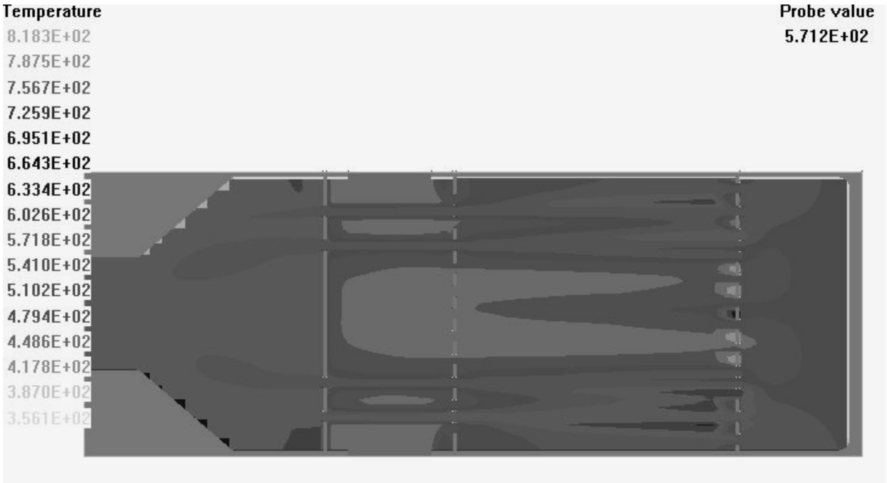

Fig. 12. Temperature in the symmetrical plane of DPF at flow rate 0.04 m^3/s.
Rys. 12. Temperatura gazu w płaszczyźnie symetrycznej DPF przy natężeniu przepływu 0.04 m^3/s.

Much higher heat convection takes place around the pipes near DPF walls which is illustrated in Figure 13 at the perpendicular plane of the heat exchange volume. Temperature in this space reaches value above 650 °C. In the inlet stream space the gas has lower temperature about 530 °C. However at assumption of the same temperature of the substrate 750 °C and higher volumetric flow rate 0.1 m^3/s, the gas in the heat exchange volume show lower increase of temperature.

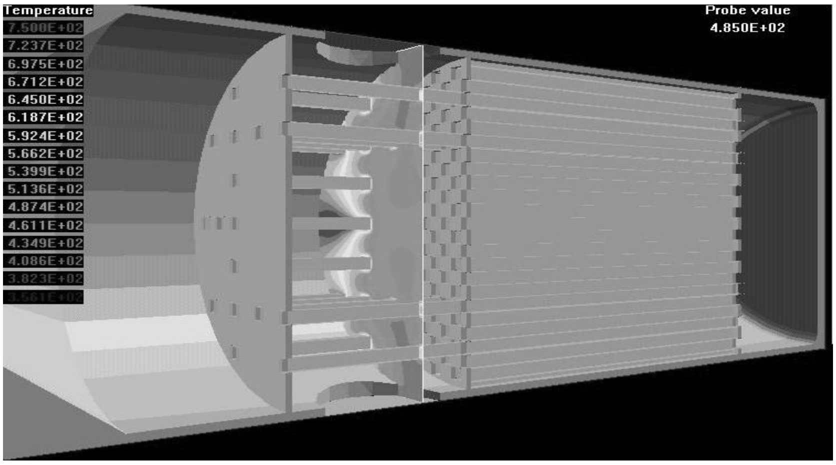

Fig. 13. Temperature in the perpendicular plane of DPF heat exchanger at flow rate 0.04 m^3/s.
Rys. 13. Temperatura w przekroju poprzecznym DPF przy natężeniu przepływu 0.04 m^3/s.

Much more uniform increase of the temperature was observed for higher mass flow rate. For this system velocities of the gas have symmetrical distribution and highest values (about 47.5 m/s) are reached in the regenerating pipes. Velocity vectors for the mass flow rate 0.04 m^3/s are shown in Fig. 14.

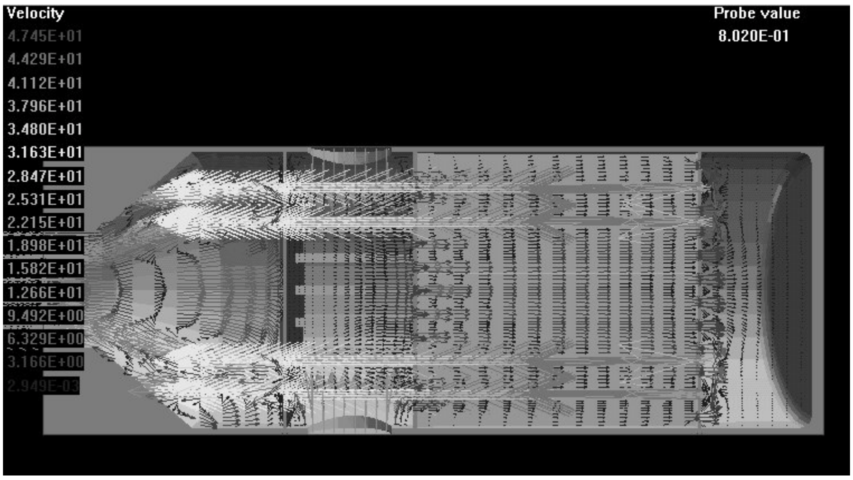

Fig. 14. Velocity vectors in the symmetric plane at flow rate 0.04 m^3/s.
Fig. 14. Wektory prędkości w przekroju symetrycznym przy masowym natężeniu przepływu 0.04 m^3/s.

The gas flow through the DPF substrate is uniform in the case of lower flow rates and the highest velocity occurs in the middle part of substrate at higher flow rate. At flow rate 0.1 m^3/s maximal velocity value is about 50 m/s. Higher velocities in the second case cause a swirl in outflow volume. For this case the symmetry of the flow is observed for both cases of flow rates in the perpendicular plane of the heat exchanger. Higher gas velocity takes place in the pipes located on the outside part of this volume.

6. Conclusions

1. Applying of heat exchanger at inlet side of DPF enables to achieve additional energy for increasing of inlet temperature and thus more possible soot combustion in DPF.
2. The increase of inlet temperature about 20% can help the soot combustion during regeneration particularly for HCCI engines.
3. For HRS-system a high rate of regeneration requires more than 30 regenerating pipes and their location should be optimized in dependence of the inlet system. The higher width of the heat exchanger can help to increase the gas temperature.
4. The increase at the heat recovery above 20% requires the increment of the mean temperature outside the pipes more than 90°C and can be achieved at the increment of the temperature in DPF after soot combustion on the level 200°C in HRS-model A.

5. HRS can increase the mean temperature in the heat exchange volume with constant soot combustion rate about 80-90 °C, which gives the heat regeneration ratio 18 - 20%.

References

[1] KONSTANDOPOULOS A., KOSTOGLOU M., HOUSIADA P., *Multichannel Simulation of Soot Oxidation in Diesel Particulate Filters*. SAE 2003-01-0839, SP-1755. SAE World Congress, Detroit 2003.

[2] NAGÓRSKI Z., TEODORCZYK A., BERNHARDT M.: *Regeneracja samochodowych filtrów spalin. Tendencje rozwojowe, modelowanie, badania symulacyjne*. Politechnika Warszawska. Warszawa 2003.

[3] HUYNH C.T., JOHNSON J., YANG S. L., [ET AL.]: *A One-Dimensional Computational Model for Studying and Regeneration Characteristics of a Catalyzed Wall-Flow Diesel Particulate Filter*. SAE 2003-01-0841, SP-1755. SAE World Congress, Detroit 2003.

[4] KONSTANDOPOULOS A.G [ET AL.]: *Fundamental studies of diesel particulate filters. Transient loading regeneration and aging*, SAE Paper No. 2000-0101016. Warrendale. USA 2000.

[5] BISSET E.J., SHADMAN F.: *Thermal regeneration of Diesel Particulate Monolithic Filters*, AIChE Journal. Vol. 31. No. 5, pp.753-758.

[6] NAKATANI K., [ET AL.]: *Simultaneous PM and NOx reduction system for diesel engines*. SAE Paper 2002-01-0957. Warrendale. USA 2002.

[7] MITIANIEC W.: *Simulation of heat recovery in diesel particle filter*. Combustion Engines, 2009-SC-045, pp.121-127. Bielsko-Biała 2009.

[8] MITIANIEC W.: *Heat recovery system in a future diesel particle filter*. Journal of Kones Powertrain and Transport. Vol.16, No 4, pp. 333 – 342. PAN, Warszawa 2009.

Modelowanie systemu odzysku ciepła w filtrze cząstek stałych

Streszczenie

Regeneracja filtra cząstek stałych wymaga dodatkowej energii w celu spalenia sadzy po pewnym czasie pracy, kiedy następuje zatkanie porów filtra. Innowacyjna metoda uwzględnia automatyczną regenerację filtra cząstek stałych przez zastosowanie specjalnego wymiennika ciepła. Artykuł przedstawia jedno z możliwych rozwiązań automatycznej regeneracji. Temperatura gazów spalinowych za turbiną i konwerterem katalitycznym jest bardzo niska i w celu zwiększenia tej temperatury przed DPF, wykorzystuje się do tego celu ciepło ze spalania sadzy. Wstępna analiza wykazuje możliwość zastosowania specjalnego wymiennika ciepła wbudowanego w konstrukcję DPF. Artykuł przedstawia wyniki symulacji numerycznej takiego systemu i możliwości wzrostu stopnia odzysku ciepła przez zmianę geometrii filtra cząstek stałych. Wstępne wyniki obliczeń wykazują możliwość wzrostu temperatury gazów spalinowych o około 20%, co umożliwia ciągłą regenerację filtra. Metoda ta umożliwia odzysk pewnej części traconej energii w konwencjonalnych filtrach cząstek stałych.