SELF-REGENERATION METHOD OF DIESEL PARTICULATE FILTER

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Abstract

Compression ignition engines have no possibility for self-regeneration of DPF and regeneration requires additional energy for soot combustion (additional fuel or electric energy) after some period of the engine work as a result of closing of substrate pores by soot. The innovation 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, the heat from soot combustion can be used. The preliminary studies show a possibility of using the special design of DPF with heat recovery system. The paper presents results obtained from simulations based on one-dimensional model of such system and analysis of increasing the heat recovery ratio by change of geometry of DPF. The gas heat exchange formulas between DPF and the heat exchange model are partly included in the paper. The preliminary results of calculations show the possibility of increase of exhaust gases in front of DPF about 20%, which enables a continuous regeneration of DPF. Heat recovery ratio is depends on soot combustion rate on the wall of DPF monolith. The method enables to recover some part of energy which is lost in the conventional DPF. The paper is a part of further work in European project FP6 IPSY.

Keywords*: diesel engines, exhaust emission, DPF*

1. Diesel particulate filter research works

Conventional diesel engines and HCCI diesel require a reduction of solid particles emitted to atmosphere. Applying of particle filters desires 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 was widely described by many authors: Konstandopoulos et al [3, 4], Bisset [1], Nakatani [7] and also by polish researchers Nagórski, Teodorczyk and Bernhardt [6]. Diesel particulate filter 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. In clean DPF filtration is not so effective and after some time the pores in the filter are partially clogged and filtration proceeds much more effectively. The pressure drop in the filter increases when the filter is filled by soot molecules. The level of the pressure drop is the signal for the regeneration process. Regeneration process can be done by several methods. However these methods require an additional energy for initiation of soot burning. 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 low in comparison to conventional diesel engines. Normally the temperature of inlet gases in diesel engines reaches value 450°C at partial engine loads and in HCCI engines is significantly lower. Emissions of NOx and particulate matters for HCCI engines at two compression ratios 14 and 16 are shown in Fig. 1 for NADI IFP engine [8]. There is seen a decrease of soot emission at higher engine loads and in comparison to conventional compression ignition engines this emission is about ten times smaller. The 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 temperature of outlet gases have higher temperature and this phenomenon can be utilized in the recovery heat system.

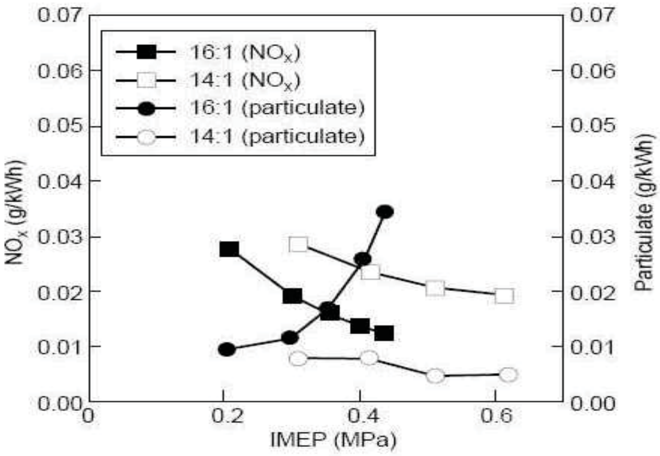

Fig. 1. Emission (NOx and PM) in HCCI engine at different compression ratios and 1500 rpm [8]

2. Filtration and regeneration model

The one-dimensional mathematical model can be used to simulation the non-uniform distributions 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 modelling though it is also able to extend to soot loading modelling.

It was assumed the one-dimensional Bisset model [1] of filter regeneration shown in Fig. 2 in order to determine the changes of DPF parameters during filtration and heat increase after soot combustion.

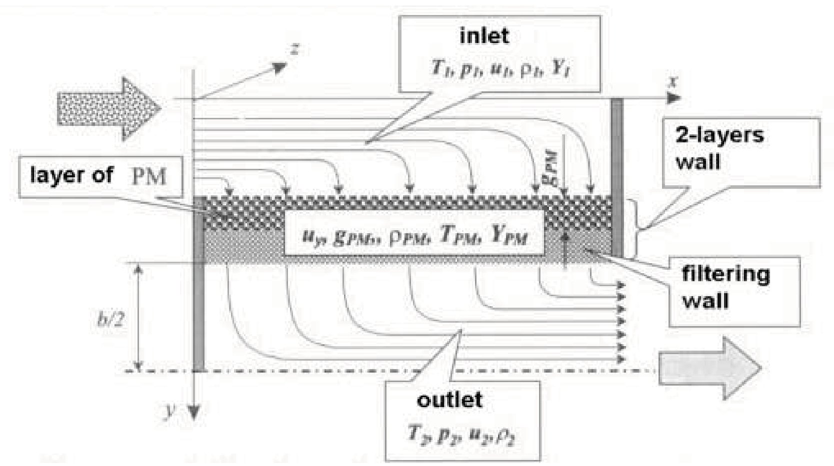

Fig. 2. One dimensional model of DPF filtration and regeneration [1]

The whole model of filtration and regeneration was described by authors [8]. The numerical scheme for filtration and regeneration of the half inlet and outlet channels with soot on the wall is shown in Fig. 3. All variables are determined for each cell along the whole length (0 – L) as a function of time *t*.

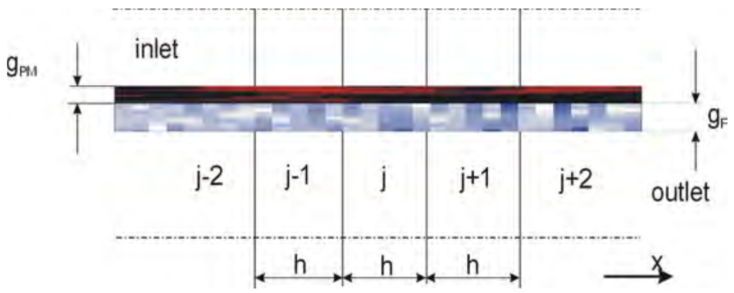

Fig. 3. Numerical scheme of the calculation mesh along the channel's length

3. One-dimensional simulation model of heat recovery system

3.1. Model description

The precise mathematical model of the DPF with recovery system B contains discretization of the heat exchange area. 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 increases during burning of soot and influences on the recovery ratio. In simulation a different levels of ΔT_{DPF} were assumed. The calculation model of DPF with recovery system B is presented in Fig. 4.

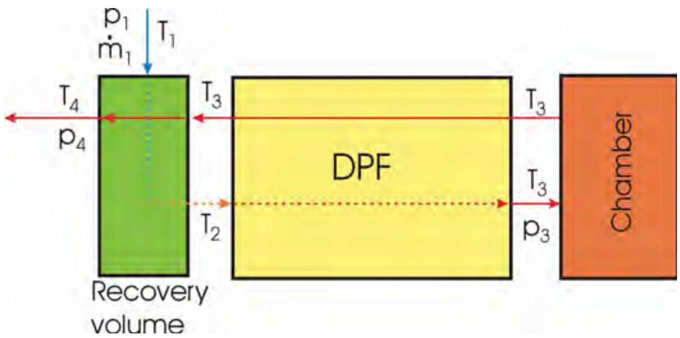

Fig. 4. Diagram of mathematical model of heat recovery system

The calculations were carried out for MFR designed by APTL as most promising to obtain higher recovery ratio. The diagram shown in Fig. 5 explains, how to calculate mean gas velocity in the perpendicular direction to the pipes. This velocity is a function of geometry and mass flow rate $u_m = f(\dot{m}_1, D, d, i_p, l_p)$.

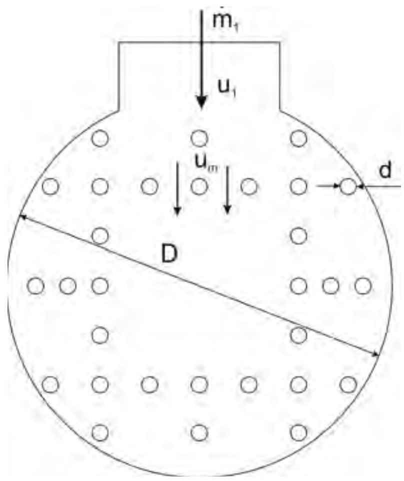

Fig. 5. Mean gas velocity in the recovery volume

The increase of the exhaust gas temperature from T_1 to T_2 and internal energy caused by the soot combustion effects is realized by the heating of the pipes, which are set perpendicularly to inflow of the gas. Heat exchange between the walls of the pipes and the exhaust gases increases their temperature from T_1 to T_2.

3.2. Mathematical model of recovery system

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. After regeneration 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 (4).

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

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 is 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:

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

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:

$$T_{j2} = \frac{\beta T_1 + \delta Q_{rad} + \alpha T_{j3}}{1+\alpha}, \quad \delta = \frac{1}{\dot{m}_{1j}\left(c_p\right)_{1j}}, \quad \dot{Q}_{rad,j} = \varepsilon \cdot \sigma \cdot F_j \left(T_{wj}^4 - T_{1j}^4\right), \tag{10}$$

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

3.3. Calculation results

The computer program written in C++ language enabled to calculate the heat delivered to the gas during DPF regeneration. During soot deposit on filter walls the pressure drop increases. The increase of the soot mass and pressure drop during 1000 s is shown in Fig. 6 with using of Konstandopoulos formulas [3].

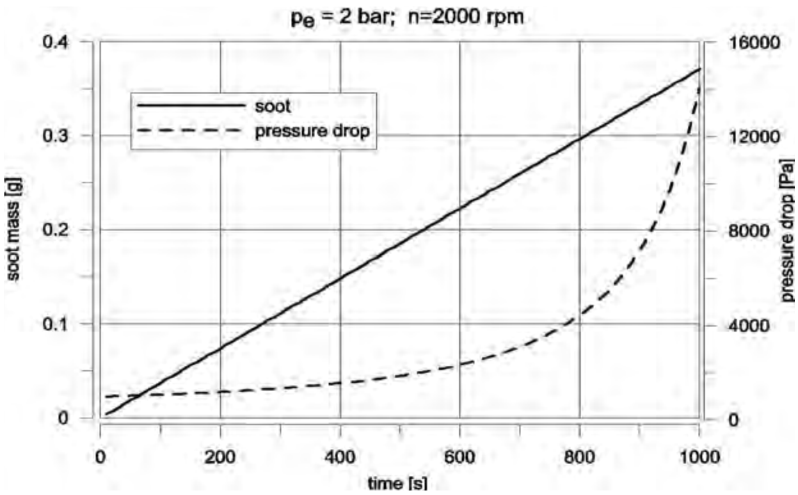

Fig. 6. Pressure losses in DPF according to formula of Konstandopoulos [1]

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 Fig. 7. More pipes and higher temperature of gas in the ceramic monolith during regeneration (soot combustion) enable achieving a higher heat recovery ratio. However, more evidence is influence of number of the pipes.

The heat recovery power can reach value 4000 W at 50 heating pipes with constant length 100 mm (Fig. 8) at an increment of temperature in DPF at value 300 K.

For the same number of heating pipes the heat recovery power is higher with increasing of the pipe length in the recovery volume. The change of heat recovery power is proportional to the length. The change of increment of gas temperature near the pipes is shown in Fig. 9 in a function of pipe length. With lengthen of pipes it follows the increment of temperature near pipes. The decrement of temperature is observed along the pipes. The highest increment of temperature is at the beginning of pipes. The increment of DPF inlet temperature of gases can be extend by applying of longer pipes in the heat exchanger and for 30 pipes with length 20 cm the gas temperature

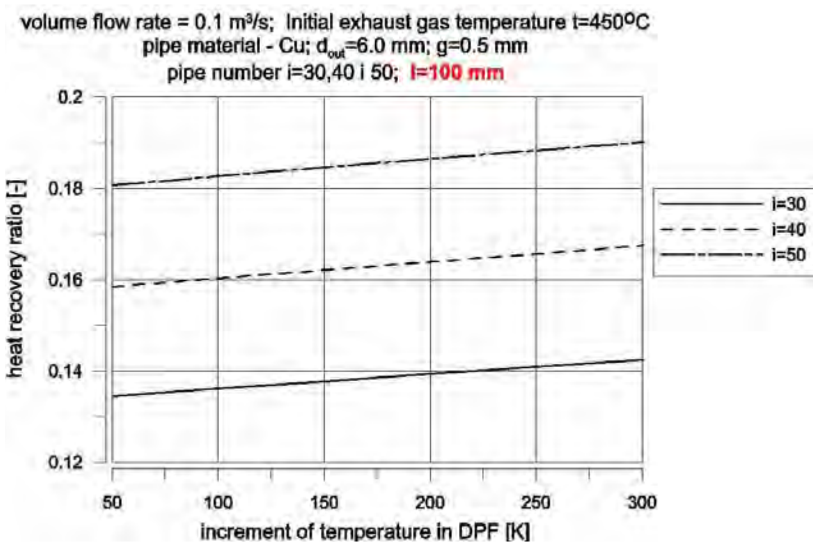

Fig. 7. Heat recovery rati o in a function of increase of DPF temperature for different numbers of heating pipes (30, 40 and 50) at the same length 100 mm

is increased about 60 degrees. Fig. 10 shows a change of total heat power, radiation heat power, regeneration heat power and power of heat losses at i = 30 pipes and l = 100 mm. Change of every part of heat power (radiation, regeneration, losses and total) is linearly proportional to the increment of temperature in DPF monolith during soot combustion.

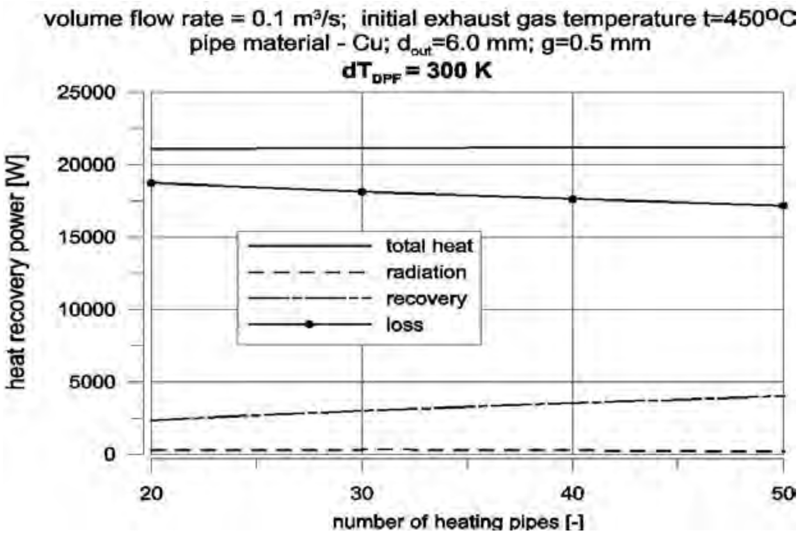

Fig. 8. Influence of pipes number on heat recovery power at ΔTDPF = 300 K, constant pipe length 100 mm and outer diameter 6 mm

4. DPF data and initial conditions

At each time step, the solver first calculates flow filed along the channel length for both inlet and outlet channels, based on the quasi-steady state assumption. Once flow solutions (e.g. gas pressure, temperature, and velocity) are obtained, soot mass retained and filter substrate temperature are integrated using a standard ordinary differential equation (ODE) solver at the current time step. All solutions are then advanced for next time step. Simulation of filtration and regeneration processes in DPF by using of mathematical models described by Huynh et al (4) was carried out in the commercial program GT-Power. The simulation was done for geometrical data of DPF and thermodynamic parameters of gas at the DPF inlet given in Tab. 1. The data concern to the real diesel particulate filter applied in 2.0 l diesel engine, where the substrate is made from cordierite. The initial values of fluids for calculation were as follows: mass concentrations O_2 = 0.100, N_2 = 0.899, soot = 0.001 and mass flow rate amounted 80 kg/h.

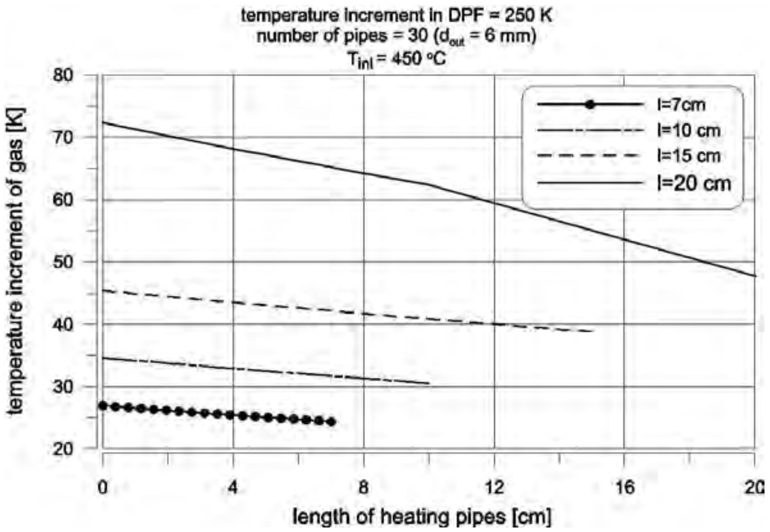

Fig. 9. Increment of temperature in the recovery volume at 30 pipes with outer diameter 6 mm

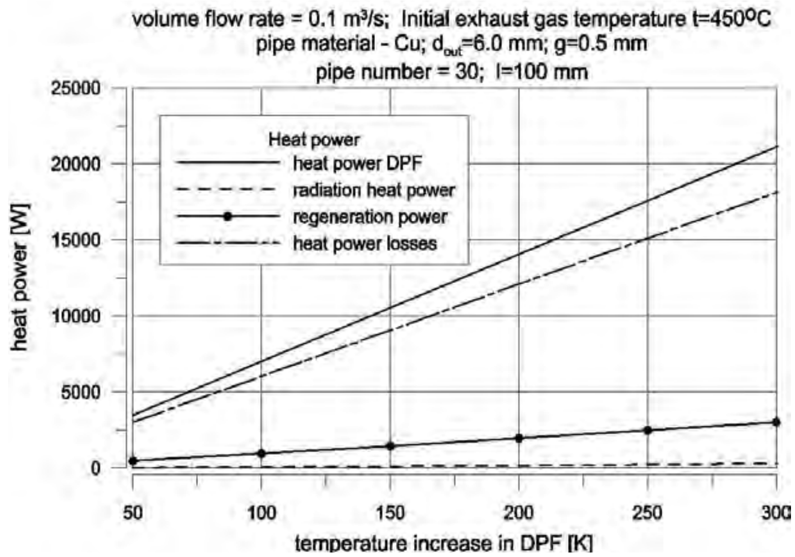

Fig. 10. Heat power of HRS at increase of DPF temperature for 30 pipes and heating length 100 mm

Tab. 1. DPF data

Geometrical data of DPF:		Boundary conditions:	
Trap diameter	143.7 mm	Inlet static pressure	1.023 bar
Channel length	152.4 mm	Inlet temperature	585 - 725 K
Channel width	1.11 mm	Outlet pressure	1 bar
Wall thickness	0.31 mm	Outlet temperature	350 K
Number of inlet channels	3700		
Pore diameter	0.011 mm		
Filter porosity	0.42		
Filtration area	2.55 m^2		

5. Thermal parameters of DPF during regeneration

The paper includes only chosen results from simulation of DPF characteristic. In was assumed that regeneration process begun by use of external heating at time 0 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 10 000 s 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 Fig. 11 on the left. Maximum of pressure drop takes place after 90 s and later the pressure drop decreases slightly.

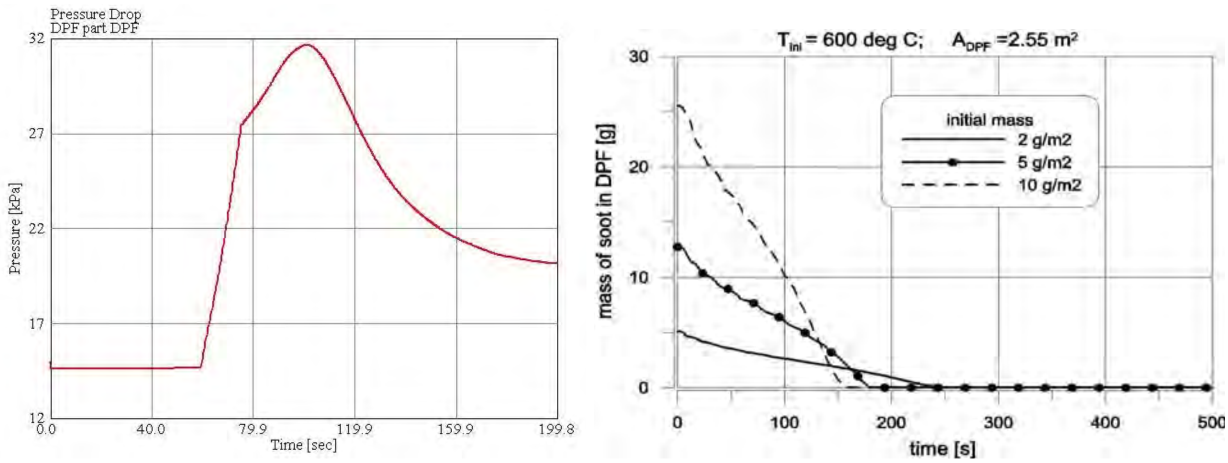

Fig. 11. Pressure drop in DPF during regeneration (left) and mass of soot in filter during regeneration for 3 values of initial soot: 2, 5 and 10 g/m^2 at DPF with inlet gas temperature 600°C

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 also changes. On the right of Fig. 11 the change of soot deposit in DPF is shown for different initial soot mass per area at the same gas inlet temperature 600°C.

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 described HRS-system a high rate of regeneration requires a bigger number of the regenerating pipes more than 30 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

7. Acknowledgement

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8. References

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