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# PARTICULATE MATTERS AND EXTREME INTERCOOLING OF CHARGE AIR

# CZĄSTKI STAŁE I EKSTREMALNE CHŁODZENIE MIĘDZYSTOPNIOWE POWIETRZA DOŁADOWANIA

A b s t r a c t

Quantity, composition and size of particulate matters (PM) in exhaust gases depend on the working regime of a combustion engine and achieved temperature in the system: cylinder – exhaust pipe – atmosphere. Part of hydrocarbon gaseous due to condensation fraction can, increase particulate matter emissions and reduce the quantity of hydrocarbon emissions. The quantity of absorbed hydrocarbons on soot particles depends on the working regime and technical conditions of an engine; on fuel consumed as well as on exhaust gas temperature. Hydrocarbons are absorbed on soot particles mainly in exhaust gases of a combustion engine working under low load conditions, i. e. under conditions of low temperatures in a combustion chamber. The particulate matter share increases as the engine load increases (influence of supplied fuel quantity and increase of temperature in the cylinders). The paper pays attention to the influence of extreme intercooling on particulate matter formation in exhaust gases of a diesel engine. In another paper we focus on production of gaseous emissions in the condition of extreme intercooling. The idea of extreme intercooling relates to a possible use of the cold produced by a non-conventional ”cooling combustion engine“.

*Keywords: emissions, particulate matters, engine, intercooling, charging*

S t r e s z c z e n i e

Ilość, skład i rozmiar cząstek stałych (PM) w spalinach zależą od warunków roboczych silnika spalinowego oraz temperatury osiąganej w systemie: cylinder – rura wydechowa – atmosfera. Część frakcji gazowej węglowodorów może, na skutek kondensacji, zwiększyć emisje cząstek stałych i zmniejszyć ilość emisji węglowodoru. Ilość węglowodorów absorbowanych przez cząstki sadzy zależy od warunków roboczych i technicznych silnika; zarówno od zużytego paliwa, jak i od temperatury spalin. Węglowodory absorbowane są przez cząstki sadzy głównie w spalinach silnika spalinowego pracującego w warunkach małego obciążenia, tj. w warunkach niskich temperatur w komorze spalinowej. Udział cząstek stałych wzrasta wraz ze wzrostem obciążenia silnika (wpływ ilości paliwa zasilającego oraz wzrost temperatury w cylindrach). W artykule zwrócono uwagę na wpływ ekstremalnego chłodzenia międzystopniowego na tworzenie się cząstek stałych w spalinach silnika wysokoprężnego. W innym artykule, koncentrujemy się na powstawaniu emisji gazowych w warunkach ekstremalnego chłodzenia międzystopniowego. Idea ekstremalnego chłodzenia międzystopniowego związana jest z możliwością wykorzystania zimna wytwarzanego przez niekonwencjonalny „silnik spalinowy z chłodzeniem”.

*Słowa kluczowe: emisje, cząstki stałe, silnik, chłodzenie międzystopniowe, doładowanie,*

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## 1. Introduction

The production of engine emissions is a negative effect of the combustion process of fuel-air mixture in the combustion chamber. The variety of reasons of pollutant emissions are quality of combustion, combustion velocity and chemical facilities of fuel-air mixture. Subsequently, the amount of emissions is needed to be monitored and analyzed. The correct monitoring and analyzing of harmful pollutants enable to reduce of impact on the environment. The paper deals with the influence of the temperature of charged air on amount of particulate matters. A mathematical model of amount of particulate matters and results of the measurements are dealt with in the article.

## 2. Specification of a measuring string

The measuring system consisted of a turbocharged diesel engine, two intercoolers, a measuring apparatus for particulate matters sampling and analyzing and a measuring apparatus used for recording and storing the data of temperatures and engine parameters. The intercooling system consisted of two intercoolers. The first intercooler was an air/air type and the second was a water/air type. The first intercooler was driven by an engine using the crankshaft. In the second intercooler of a water/air type the circulation of water was provided by submersible pump. The used intercooling system is described in the following subchapters.

### 2.1. Systems of intercooling

The process of cooling of charged air was performed in three steps. To compare the results and justify the idea of intercooling we also made measurements on the original work regime of the engine, it means, no intercooling was used.

The first step of intercooling was performed by the intercooler of an air/air type, Fig. 1 – left side. The air after turbocharger advanced to the cooler through the insulated pipe and alowed on to the engine. Charged air was pumped through the body of the intercooler and was cooled by the surrounding air, which was flowing through this intercooler and was stuffed into the engine subsequently.

The second step of intercooling was performed by the first intercooler followed by the intercooler of water/air type, Fig. 1 – right side. The cooled air from the first intercooler was advanced to this intercooler through an isolated pipe, too. The isolating of all pipes for pressed air guaranteed the minimal heating of the cooled air from the surrounding air in the laboratory. The body of the second intercooler cooled the flowing air by water which was powered through the intercooler by a submersible pump. Cooling water was in the tank of the volume of 2000 liters. There were constant inflows and outflows of water to and from the tank. The objective of using the tank was to stabilize the temperature of the water at steady value. The value of the temperature of the cooling water was about 15°C and it changed only nominally with a mode of the engine work.

The third step of intercooling was performed by both intercoolers, too. Unlike the second step, the third step of cooling of charged air was realized by ice-cooled water. The tank having a volume of 2000 liters was full of water and ice mixture, shown in Fig. 2. After getting the equilibrium state of the mixture, the temperature settled at the value of about 0.2°C. Charged air was cooled by a low temperature of this mixture by the second intercooler.

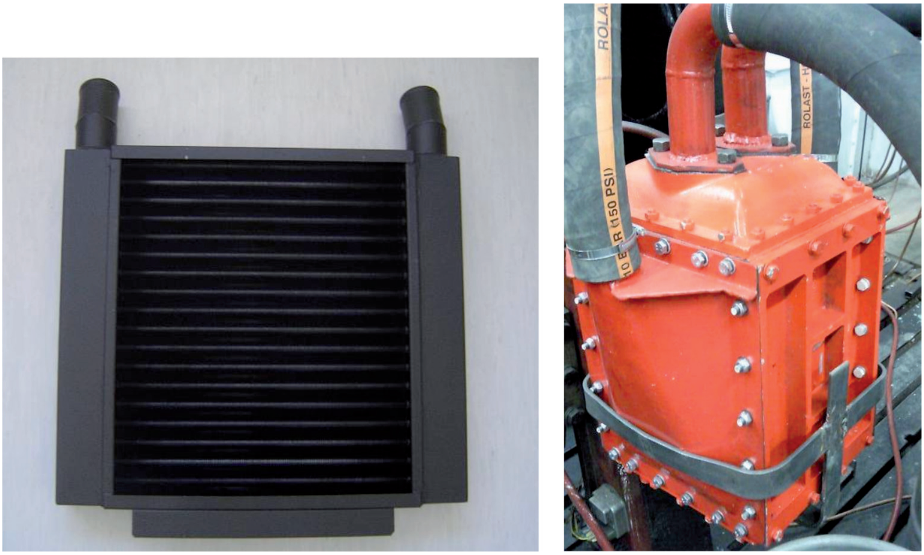

Fig. 1. Intercoolers: air/air type – left side, water/air type – right side

Rys. 1. Chłodnice międzystopniowe: powietrze/powietrze – typ lewostronny, woda/powietrze – typ prawostronny

Fig. 2. The tank of mixture of water and ice

Rys. 2. Zbiornik mieszaniny wody i lodu

### 3. Model of the PM amount

Nowadays, the process of modeling of the amount of particulate matters is taking place. It is based on the existing model which describes the formation and features of a quasi-steady diesel fuel jet, as shown in Fig. 3.

The conditions required by the model include: the cylinder pressure, mass rate of fuel injection, injection velocity, bulk mean temperature, energy release rate, and characteristics of injector nozzles [6]. The values of some necessary figures required for further calculations in the program FLUENT were calculated. For the modeling of combustion in FLUENT the "eddy dissipation model" was chosen and for simulating the creation of the soot the "one step model" at that same program was chosen [5].

The main idea and equation for creation of the soot is shown in the following formula, developed by Hiroyasu & Kadota (1976):

$$\dot{m}_s = \dot{m}_{sf} - \dot{m}_{so} \tag{1}$$

where:

$\dot{m}_s$ – is the net mass rate of soot formation,
$\dot{m}_{sf}$ – is the mass rate of soot formation,
$\dot{m}_{so}$ – is the mass rate of soot oxidation.

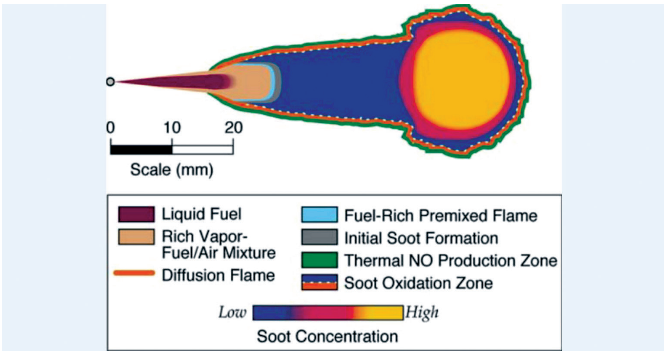


Fig. 3. Quasi-steady diesel combustion plume, presented by DEC (1997)

Rys. 3. Quasi-ustalona struga paliwa spalanego w dieslu, przedstawiona przez DEC (1997)

For calculating the mass rate of soot formation the following formula developed by Khan a Greeves (1974) will be used:

$$\frac{dm_{sf}}{dt} = C_{BS} \cdot \Phi \cdot m_f \cdot P^{0,5} \cdot \exp(-E_{sf}/R \cdot T) \tag{2}$$

where:

$C_{BS}$ – base soot formation constant,
$\Phi$ – equivalence ratio of the initial reaction,
$m_f$ – mass of fuel available to soot reaction,

$P$ – cylinder pressure,
$E_{sf}$ – activation energy of the soot formation reaction,
$R$ – universal gas constant,
$T$ – temperature in the soot formation region.

For alculating the mass rate of soot oxidation the following formula also developed by Khan a Greeves (1974) will be used:

$$\frac{dm_{so}}{dt} = C_{SO} \cdot m_s \cdot Y_{O2} \cdot P^{1,8} \exp(-E_{so}/R \cdot T) \tag{3}$$

where:

$C_{SO}$ – soot oxidation constant,
$m_s$ – mass of soot,
$Y_{O2}$ – molar fraction of oxygen presents,
$P$ – cylinder pressure,
$E_{so}$ – activation energy of the soot oxidation reaction,
$R$ – universal gas constant,
$T$ – temperature in the soot oxidation region.

## 4. Measurements

There was amount of the particulate matters depending on the temperature measured. The measured engine was a turbocharged diesel engine with a direct injection having the volume of 7.29 liters. At the external speed characteristic there were five points of rotational speed for analyzing the amount of the particulate matters selected. The amount of particulate matters was measured by a gravimetric method using the isokinetic system for sampling, described in the following subchapter.

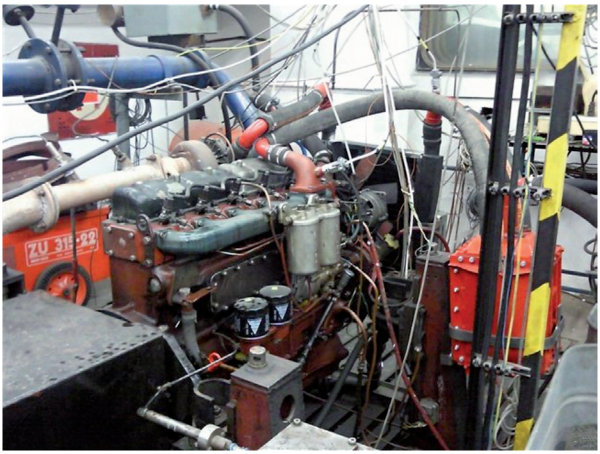

Fig. 4. Test bench

Rys. 4. Stanowisko badawcze

## 4.1. Measuring system

The measuring system consisted of the diesel engine, two intercoolers, isokinetic system for sampling and all the necessary equipment, see Fig. 4. The process of analyzing the amount of the particulate matters consisted of two main parts. The first part was sampling and the second one was weighing special of defined filters. For measuring the special defined filters made of glass fibers with diameter of 47 millimeters were used.

### 4.1.1. Sampling

The sampling process was made by a diluting mini-tunnel. The scheme of the used mini-tunnel is shown in Fig. 5. This equipment works on an CVS system. Two compressors reliably guarantee the isokinetic sample of the exhaust gasses. For the control of the right isokinetic sample the U-pipe was used. During the sampling process the set amount of the gasses was pressed through the pair special defined filters. Due to the different diluting ratio of mixture of the filtered air and exhaust gasses in every rotational speed the different volume of the pressed sample of mixture was set. But in every sample the content of the exhaust gasses was the same. The value of the net content of the exhaust gasses in every point of analyzed characteristic was 13.28 liters.

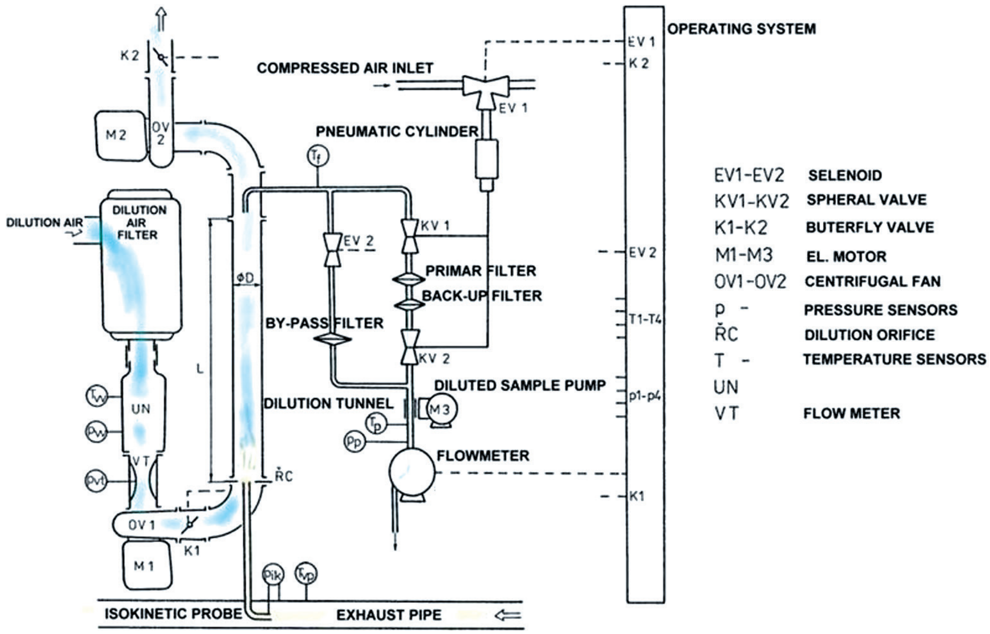


Fig. 5. Scheme of used diluting mini-tunnel

Rys. 5. Schemat zastosowanego mini-tunelu rozcieńczającego

### 4.1.2. Weighing

The weighing process consisted of stabilizing special filters before the sampling, stabilizing filters after the sampling and weighing the difference before and after the measuring. Before and after the measuring, the stabilizing filters were situated in a stabilizing chamber (Fig. 6).

The filters were stabilized for at least 8 hours. The temperature and humidity in the chamber were closely monitored and maintained by a digital thermometer and hygrometer KlimaGuard TA100. The value of temperature was about 25°C and the value of humidity was about 30%. These two values did not change significantly during all the measurements. From the stabilizing chamber to a diluting tunnel the filters were moved in Petri dishes only. As the mass difference measured on the filters before and after the measuring is too small, it was necessary to work with the utmost caution.

Fig. 6. The stabilizing chamber

Rys. 6. Komora stabilizacyjna

The weighting of glass fibers filters before and after the measuring was made on special scales – ABT 220-5DM (Fig. 7). The accuracy of these scales is for 0.00001 grams.

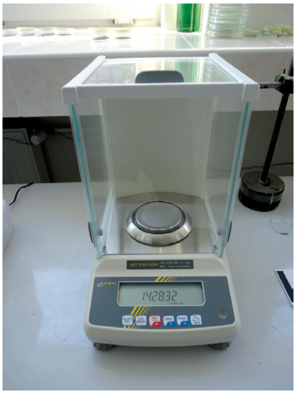

Fig. 7. Scales

Rys. 7. Waga

## 5. The achieved results

In Fig. 8, the graphic dependence of the temperature of the charged air on the speed rotation is shown. For the measurement five points of the external speed characteristic of the following values: 1200, 1450, 1700, 1950 and 2200 rpm were chosen. There are four lines representing four different temperatures of the charged air depending on the rpm.

The first line called “T org” represents the temperature of the charged air of the engine with no intercooler used. The value of the temperature at 1450 rpm was 51.4°C.

The second line “T ICIº” represents the course of the temperature of the charged air by the first step of intercooling used. At 1450 rpm the temperature of about 39.7°C was noticed.

The third line “T ICIIº” shows the temperature of the charged air by both intercoolers used at which the body of the second intercooler was cooled by water with temperature of about 15ºC. At the same rpm as in the first and second steps, the temperature of the charged air was about 18.4ºC, so the decrease of the temperature equivalents to 64.2% compared with the “org” mode.

The last line called “T ICIIº + ice” represents the temperature of the charged air by both intercoolers used, at which the body of the second intercooler was cooled by water and ice mixture. At 1450 rpm the temperature of the charged air of about 6.4ºC was noticed. So the drop of the temperature equivalents to 87.5% compared with the “org” mode.

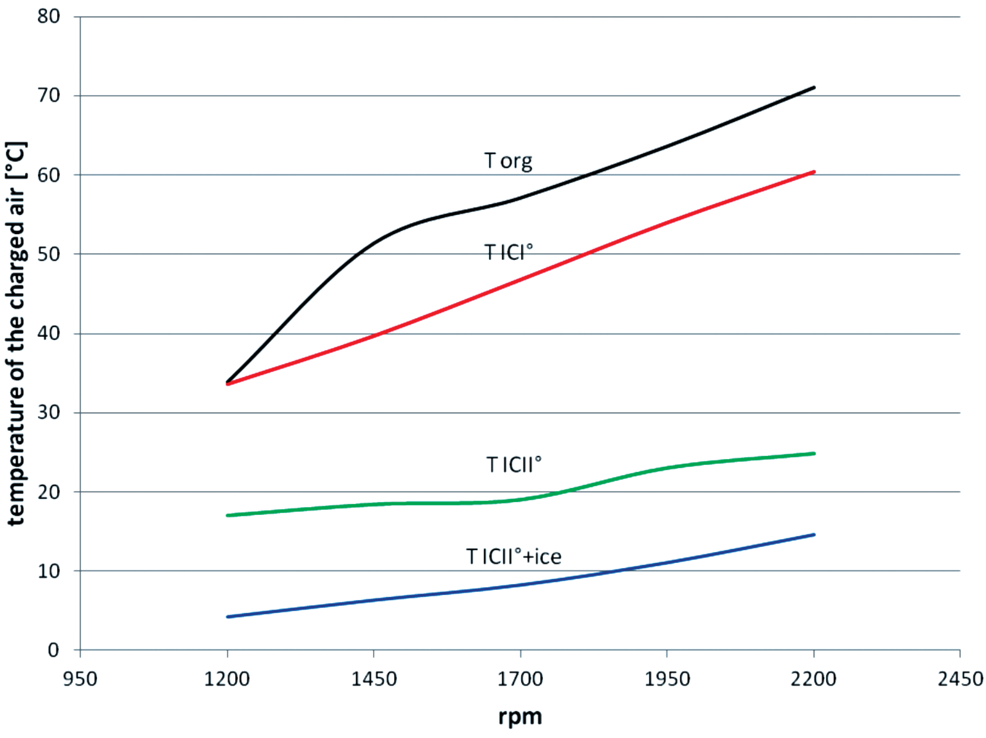


Fig. 8. Temperature of the charged air

Rys. 8. Temperatura powietrza doładowania

In the following figure, the graphic results of measurement of the amount of the particulate matters depending on the speed rotation are shown (Fig. 9).

The first line called "org" represents the dependence of the amount of particulate matters produced by the measured diesel engine at a normal working mode of the speed rotation, therefore, without intercooling of the charged air used.

The second line called "ICI°" represents the amount of the PM produced by the engine with cooling the charged air by the surrounding air by means of the first intercooler – air /air type. The difference between the amounts of PM at the original working regime and the first step of intercooling system is negligible.

The third line called "ICII°" represents the amount of the PM produced by the engine with cooling the charged air by both used intercoolers. The body of the second intercooler was cooling the air by cold water with the temperature of about 15°C. It is clear that the amount of the PM is lower by using both intercoolers particularly in the areas of 1200–1700 rpm and 1950–2200 rpm, but between 1700–1950 rpm the decrease is not significant. At the 1450 rpm the decrease of the amount of the PM is about 20.7%, compared with the "org" state.

The last line called "ICII° + ice" represents the amount of the PM produced by the measured engine with cooling the charged air by both intercoolers. The body of the second intercooler was cooling the air by the mixture of water and ice. Similarly at line "ICII°" the amount of the PM is lower in the areas of 1200–1700 rpm and 1950–2200 rpm. Comparing with the "org" the drop of the PM at the 1450 rpm was about 28.7%.

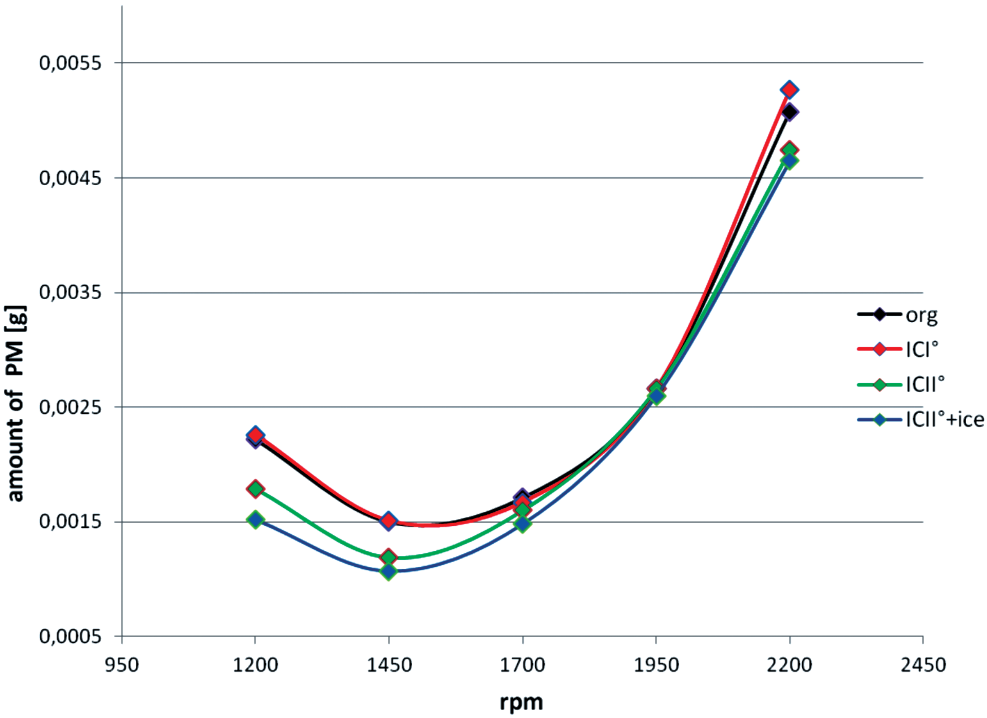


Fig. 9. Amount of PM

Rys. 9. Ilość PM

## 6. Conclusions

The measurements of the amount of the particulate matters depending on the temperature of the charged air in the combustion diesel engine were made. The influence of low temperatures of the boost air on the mass of particulate matters emissions was analyzed. Five points of the external speed characteristic were chosen. In these points the measurements of the amount of particulate matter by the gravimetric method were made. The compressed the air was cooled by three steps of intercooling. In the first step the charged air was cooled by the intercooler of an air/air type, in the second by both of intercoolers and at last step charged the air was cooled by both intercoolers but the second intercooler was cooling the air by water with ice mixture having the temperature of about 0.2°C. All three ways of cooling and achieved results are described in paper. The process of modeling the amount of soot in the program FLUENT is also described in the paper.

The measurements confirmed that the formation of particulate matters decreases with the cooling charged air, so their amounts depends on temperature of the compressed air after turbocharger. The results are proved for the measured turbocharged diesel engine only.

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