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EXTREME INTERCOOLING OF CHARGING AIR AND GASEOUS EMISSIONS

EKSTREMALNE CHŁODZENIE MIĘDZYSTOPNIOWE POWIETRZA ŁADOWANIA I EMISJI GAZOWYCH

Abstract

Recently we have theoretically dealt with some questions related to the formation of harmful gaseous emissions namely through a design of a mathematical model of flow and burning in an engine combustion space. We also paid attention to solutions enabling the reduction in quantity of harmful gaseous emissions and their verification through calculations, by means of mathematical modelling taking into account the mentioned solutions. Preparation of the CAD data was done in CATIA V5 software, the mesh preparation in the preprocessor Gambit and the calculation itself as well as visualisation of results were done in the Fluent. One of the suggested solutions was to use the cold produced by a non-conventional "cooling combustion engine" for extreme intercooling of the charge medium. In this paper we present results of the experiments carried out on a diesel combustion engine. The extreme reduction in the temperature of the charge air was done through two-stage intercooling.

Keywords: cooler, emissions, nitrogen oxides, charge air

Streszczenie

Ostatnio zajmowaliśmy się teoretycznie niektórymi problemami związanymi z powstawaniem szkodliwych emisji gazowych, mianowicie przez opracowanie modelu matematycznego przepływu i spalania w przestrzeni spalania silnikowego. Zwróciliśmy też uwagę na rozwiązania umożliwiające ilościową redukcję szkodliwych emisji gazowych i ich weryfikację przez obliczenia za pomocą modelowania matematycznego z uwzględnieniem wzmiankowanych rozwiązań. Przygotowanie danych CAD zostało wykonane z użyciem programu CATIA V5, przygotowanie siatki w preprocesorze Gambit, a same obliczenia i wizualizację wyników wykonano w programie Fluent. Jedno z proponowanych rozwiązań polegało na zastosowaniu zimna wytwarzanego przez niekonwencjonalny „silnik z chłodzeniem spalania" dla ekstremalnego chłodzenia międzystopniowego ładunku. W niniejszym artykule przedstawiamy wyniki badań doświadczalnych przeprowadzonych na wysokoprężnym silniku spalinowym. Maksymalna redukcja temperatury powietrza ładunku została dokonana przez chłodzenie dwustopniowe.

Słowa kluczowe: element chłodzący, emisje, tlenki azotu, powietrze ładunku

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1. Introduction

The combustion process of air-fuel mixture in the cylinder of the piston combustion engine runs as a fuel oxidation reaction with atmospheric oxygen. The combustion leads to the formation of products of complete combustion, for every 1kg of burnt fuel, there are about 1.1 kg of water steam and 3.2 kg of carbon dioxide produced. Unfortunately we can not create 100% efficient combustion and so there is also a considerable amount of products of incomplete combustion and these are carbon monoxide (denoted CO), hydrocarbons (vaporised fuel) and soot or smoke (actually hydrocarbons in a different form). In addition, the high temperature that occurs in the combustion chamber, promotes an unwanted reaction between nitrogen and oxygen from the air. That results in various oxides of nitrogen, commonly called NO_x. These emissions are legislatively regulated for most engine types by emission standards, which define the acceptable limits for exhaust emissions of new engines. The emission limits are supposed to be continuously decreasing according to the standards [4].

One of the ways to achieve acceptable emissions and high efficiency of an engine is a high degree of supercharging. Increasing pressure raises the temperature of charge air behind the turbocharger and thus affects air density adversely. To achieve sufficient engine power and to reduce heat stress of the engine components it is necessary to cool charge air. Reduction of charge air temperature increases the efficiency of the engine and as opposed to other optional solution, does not cause additional emissions of nitrogen oxides in the exhaust gases. In this paper are presented results of measurements on a special test bench to achieve low temperature of charge air [2, 5].

2. Mathematical model

In our department of automobile technology we have been engaged in the problems of gases emissions. Currently we deal with the impact of charge air temperature on the engine parameters. Before the tests of influence of extremely low charge air temperature on the engine's emissions started, a model had been created enabling us to verify the assumption of emissions reduction by lowering the temperature of charge air. The assumptions come out from theory that lowering the charge air temperature causes the decrease of a peak combustion temperature and, based on that and as the consequence of decreasing peak combustion temperature, the emissions decrease significantly.

The model is built based on the definition of speed of NO and N production, which are described in the following equations (1) and (2) [3].

$$\begin{aligned}\frac{d(\mathrm{NO})}{dt} &= k_{1f}(\mathrm{O})(\mathrm{N_2}) - k_{1b}(\mathrm{NO})(\mathrm{N}) + k_{2f}(\mathrm{N})(\mathrm{O_2}) - k_{2b}(\mathrm{NO})(\mathrm{O}) + \\ &+ k_{3f}(\mathrm{N})(\mathrm{OH}) - K_{3b}(\mathrm{NO})(\mathrm{H})\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{d(\mathrm{N})}{dt} &= k_{1f}(\mathrm{O})(\mathrm{N_2}) - k_{1b}(\mathrm{NO})(\mathrm{N}) - k_{2f}(\mathrm{N})(\mathrm{O_2}) + k_{2b}(\mathrm{NO})(\mathrm{O}) - \\ &- k_{3f}(\mathrm{N})(\mathrm{OH}) + K_{3b}(\mathrm{NO})(\mathrm{H})\end{aligned} \tag{2}$$

k_f – speed constant in a straight direction,
k_b – speed constant in a reversed direction.

These are the tools used to solve the model: CATIA, GAMBIT and FLUENT. First of all, a 3D model was created to imitate geometry of a combustion chamber by CAD software CATIA. Subsequently, a net of combustion chamber in GAMBIT was created. Eventually, the combustion and NO_x production were simulated. The simulation confirms the theory that lowering the charge air temperature causes the decrease of temperature in the combustion chamber and based on that and as a consequence of the decrease of combustion temperature, the emissions decrease significantly [5].

3. Specification of the measurement test bench

For the purpose of ascertaining the effect of charge media temperature change on the engine parameters a special test bench was created. The reducing of the charge air temperature is provided by two-degree cooling. The first degree of cooling the charging air is provided by the heat exchanger of air-to-air type, a variable fan powered by the crankshaft provides cooling air flow. The second stage of charge air cooling is designed as a heat exchanger of air-to-liquid type. A forced circulation of cooling fluid is driven by a circulator pump, which is included into the cooling circuit with a special mixing tank to provide low temperatures.

For measurements of the gas engine emission AVL DITEST 4000 probe is used. This probe is located in the exhaust tube behind the turbocharger emission measurement. [1]

For temperature measurements PT100 and thermocouple types J were used and for the pressure measurement DMP 331–400 kPa type sensors were used [4].

4. Measurements

The actual measurement was made in four steps. During all the measurements both intercoolers were linked to the charging pipe. This method was used to avoid difference losses in the charge-air tube for the individual measurements and thus assure equal conditions of measurements. In the first step emissions without cooling charging air were measured.

In the first measurement both intercoolers were coated with wool to insulate them, so the charge air was not being cooled.

In the second step the cooling of charge air was provided by the first degree cooling. In this measurement charge air was cooled only by the intercooler of air to air type. The intercooler of water to air type was connected to the charging line, but it was isolated to prevent heat dissipation.

In the third step charge air was cooled with both degrees of cooling. In this measurement the air first passed through the intercooler of air-to-air type, and then it passed through the intercooler of air-to-water type, with water having the temperature of 16°C.

Water was pumped by a water pump through the intercooler of air-to-water type from the mixture tank with a capacity of 1.5 cubic meters. The appropriate capacity of the tank should protect the system against significant change in the temperature of cooling water.

5. Results of experimental measurements

During the measurement is only one of temperature, parameters of performance and emission parameters were recorded. The values measured at each step are shown in the tables.

In Table 1 the values gathered from the first measurement are shown; the measurement without heat dissipation of charge air.

Table 1

Values measured without cooling of charge air

n [min^{-1}]	M_t [N · m]	P_e [kW]	m_{pe} [g · kW^{-1} · h^{-1}]	T_a [°C]	$T_{za\ \mathrm{TBD}}$ [°C]	T_{za} Turbínou [°C]	$T_{\mathrm{MCH\ 1}}$ [°C]	$T_{\mathrm{MCH\ 2}}$ [°C]	NO$_x$ [ppm]
2200	400	92.11	258.89	18	97.3	550	85.5	71	891
1950	440	89.80	239.86	18.6	84.2	550	74.2	63.6	1151
1700	457	81.32	230.42	18.6	71.9	544	63.6	57.1	1431
1450	460	69.81	226.05	18.5	61.6	510	55.2	51.4	1670
1200	433	54.38	227.48	17.7	46.6	480	37.2	33.9	1620

The values measured during the second measurement are shown in Table 2. During this measurement the charge air was cooled by the first degree. The cooler of air-to-air type was used for heat dissipation, though this cooler flows the ambient air with temperature T_a.

Table 2

Values measured with one degree cooling of charge air

n [min^{-1}]	M_t [N · m]	P_e [kW]	m_{pe} [g · kW^{-1} · h^{-}]	T_a [°C]	$T_{za\ \mathrm{TBD}}$ [°C]	T_{za} Turbínou [°C]	$T_{\mathrm{MCH\ 1}}$ [°C]	$T_{\mathrm{MCH\ 2}}$ [°C]	NO$_x$ [ppm]
2200	400	92.11	258.81	21.2	104.7	550	68.9	60.4	864
1950	440	89.80	240.93	21.5	91.7	543	60.7	54	1089
1700	458	81.49	229.00	21.3	76.9	530	51.5	46.8	1401
1450	466	70.72	224.46	20.1	66.2	507	44.8	39.7	1675
1200	430	54.01	229.11	19.9	51.3	477	36.3	33.6	1576

The values of the third measurement are shown in Table 3. In this measurement the charge air was cooled with two degrees. Heat dissipation of the cooler of air-to-air type was used as in the first step by air flowing with temperature T_a. Heat dissipation of the cooler of water-air type was provided by water which was pumped out of the tank across the cooler. The water temperature during the measurements was 18°C.

Table 3

Values measured with two degree cooling of charge air

n [min^{-}]	M_t [N ·m]	P_e [kW]	m_{pe} [g · W^{-1} · h^{-1}]	T_a [°C]	$T_{za\,\mathrm{TBD}}$ [°C]	T_{za} Turbínou [°C]	$T_{\mathrm{MCH\,1}}$ [°C]	$T_{\mathrm{MCH\,2}}$ [°C]	NO$_x$ [ppm]
2200	413	95.10	252.52	18.2	99.7	518.2	65.3	24.8	781
1950	451	92.05	236.50	18.6	87.9	515.1	57.7	23	977
1700	474	84.34	223.57	17.6	72.7	502.1	48.2	19	1265
1450	477	72.39	219.04	18.8	64.7	486.8	43.2	18.4	1615
1200	441	55.39	224.56	18.5	49.1	462.9	34	17	1587

Table 4 shows the values measured by using both degrees with ice. In these measurements charge air cooling was provided by two degrees. The first degree used the ambient air as in the previous case. In order to reduce the temperature to the lowest value, ice was mixed into the tank with cooling water. Adding ice into the water tank, the water temperature was reduced and, subsequently, it was possible to reduced the charge air temperature even more.

Table 4

Values measured with two degree cooling of charge air with ice

n [min^{-1}]	M_t [N · m]	P$_e$ [kW]	m_{pe} [g · kW^{-1} · h^{-1}]	T_a [°C]	$T_{za\,\mathrm{TBD}}$ [°C]	T_{za} Turbínou [°C]	$T_{\mathrm{MCH\,1°}}$ [°C]	$T_{\mathrm{MCH\,2°}}$ [°C]	NO$_x$ [ppm]
2200	415	95.33	253.40	19.3	99.1	518.1	64.5	14.6	755
1950	457	92.05	234.04	18	86.5	512.2	56.5	11.1	950
1700	466	83.98	224.31	17.5	72.3	497.8	47.9	8.3	1256
1450	474	71.63	218.07	17.1	62.9	479.4	42.2	6.4	1531
1200	437	55.01	221.58	17.3	47.8	455.2	33.3	4.3	1504

In order to simplify and clarify the evaluation of measurement the readings were converted into graphs. For reasons of clarity in the graphs the dependences of parameters on the speed were used.

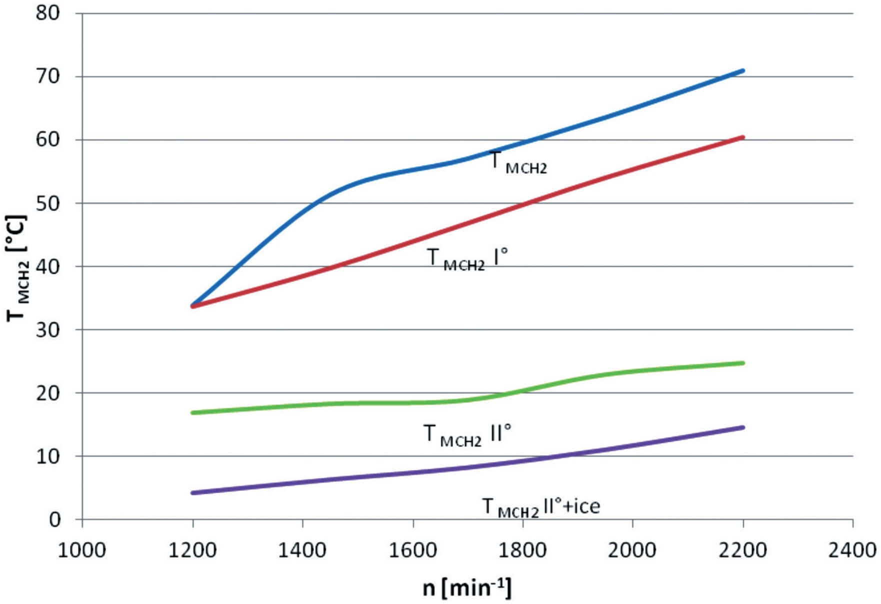

Fig. 1 Course of charge air temperature

Rys. 1. Przebieg temperatury powietrza ładunku

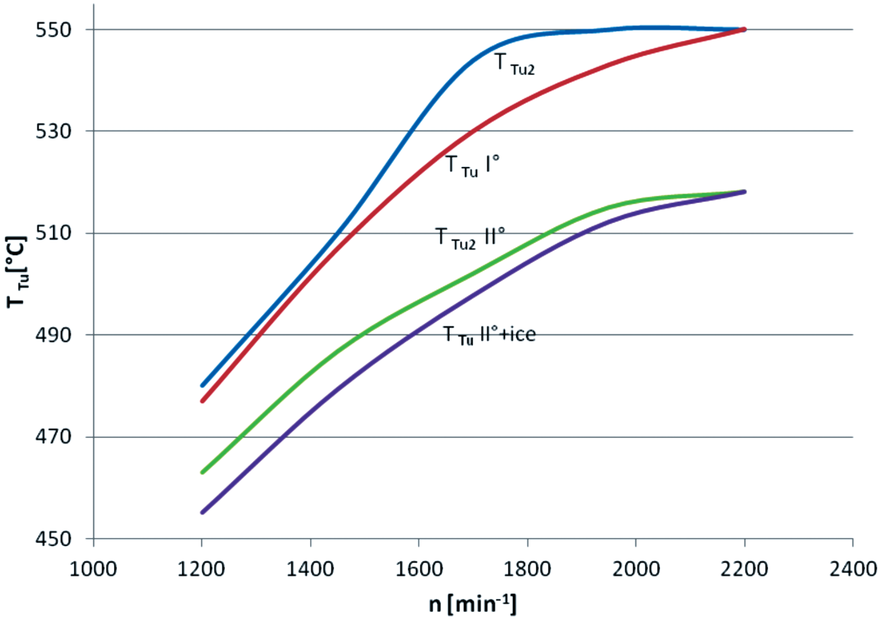

Fig. 2. Course of exhaust gas temperature behind turbine

Rys. 2. Przebieg temperatury spalin za turbiną

The diagram shows the course of charge air temperature depending on the engine load, the engine load being expressed in the RPM. In the Fig. 1 are shown the curves of 4 ways of measurements. In chart 4 the curves of 4 ways of measurements are shown. NO curve shows the development of the charge air temperature depending on the RPM measured without cooling charge air. NO_x I° shows the development the charge air temperature depending on the RPM measured with cooling air charge by the first degree. NO_x II° curve shows how the temperature of charge air changes by cooling with two degrees and NO II ° + ice curve shows the measured values using two cooling degrees charge air with ice.

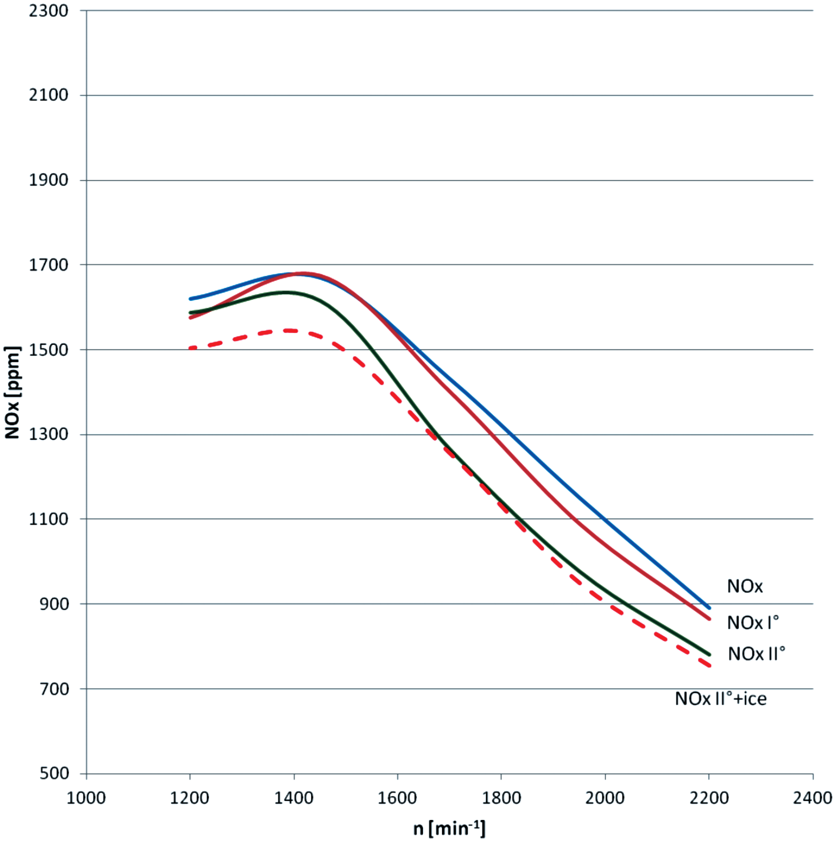

Fig. 3. Content of nitrogen oxides in the exhaust gas

Rys. 3. Zawartość tlenków azotu w spalinach

The influence of temperature of charge air on the exhaust gas temperature is shown in Fig. 2. The figure shows that the cooling of charge air also causes a reduction in exhaust gas temperature. Based on the temperature record of the exhaust gas it can be assumed that the change of charge air temperature is an appropriate tool to reduce the temperature in the combustion chamber. The curves are represented by same signs as in the previous figure T_{Tu}, T_{Tu} I°, T_{Tu} II° a T_{Tu} II°+ ice.

According to the theory of NO_x formation, temperature has a great influence on the formation of the NO_x, it means by reducing the temperature in the combustion chamber we can reduce the formation of NO_x. How the content NO_x was reduced by the temperature reduction is shown in Fig. 3. From the figure it is clear that the charge air temperature reduction causes the reducition of NO_x in exhaust gases.

6. Conclusion

The paper deals with the influence of the charge air temperature on production of nitrogen oxides. This paper presents the results measured on a special test bench to investigate the effect of low temperatures on the engine parameters. The measurements on the special test bench were made in a four modes: without charge air cooling, with charge air cooling through the cooler (type: air-to-air), charge air cooling through the cooler (type: air-to-air type plus air-to-water) and charge air cooling through the cooler (type: air-to-air plus air-to-water with using ice).

From the measured values for NO_x in the exhaust gas results the following: the reduction of charge air temperature leads to the reduction of NO_x formation. The reduction of NO_x in exhaust gas was caused by lowering the temperature in the combustion chamber, which is the cause of NO_x production. The measured result shows that reducing the charge air temperature is a suitable tool for reducing NO_x formation in combustion engines. The measurement confirms the result obtained from the mathematical model, namely that by lowering the temperature of charge air the content of NO_x in exhaust gases is decreasing. Currently we are dealing with and considering the models accuracy and comparing them with the measured data.

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References

[1] Toporcer E., Kovalčik A., Cisek J., *Intercooler for extremely low temperatures of charging*, Journal of KONES – Powertrain and transport, Vol. 17, No. 3, Warsaw 2010.

[2] Heywood J.B., *Internal Combustion Engine Fundamentals*, MacGraw-Hill, USA, 1988.

[3] Lábaj J., Kalinčák D., Kukuča P., Gajdoš J., Gerlici, J., Lack T., *Výpočtové metódy v dopravnej a manipulačnej technike*, ES ŽU v Žiline, 1997.

[4] Toporcer E., Kovalčik A., Tučník P., *Intercooler for extremely low temperatures of charging*, Journal of KONES – Powertrain and Transport, Vol. 17, No. 3, Warsaw 2010.

[5] Zeldovich Y.B., *The Oxidation of Nitrogen in Combustion Explosions, Acta Physico chemica*, USSR, 1987.