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THE INFLUENCE OF CHARGE AIR COOLERS CHARACTERISTICS ON THE PERFORMANCE OF HEAVY DUTY DIESEL ENGINES

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Abstract: *The paper presents research work done on a turbocharged direct injection diesel engine in order to increase power per unit of displacement by means of a better air charge intercooling. The truck engine type D2156MTN8R was tested on the dynamometric bench with two types of air coolers, being measured specific performances on full load - speed characteristics (power, torque, specific fuel consumption, air charge temperature and pressure) and smoke opacity in terms of light absorbtion coefficients.*

Key words: *heavy duty diesel engine, intercooling, charge air cooler.*

1. Introduction

In order to increase specific engine output expressed in power per unit displacement (kW/L), engine manufacturers applied different methods of increasing intake air pressure, getting higher air flow rate than in naturally aspirated engines of the same capacity [2], [4]. Secondly, the cooling of charge air allowed to supply the engine with a higher mass of air per cycle; air density was increased along with power output and fuel economy. As a result, at the same engine displacement the gain of performance was considerable, for example [6], a heavy duty diesel engine rated at 133 HP in naturally aspirated version reached 154 HP in turbocharged version and, finally, 170 HP when the engine was turbocharged and air charge was intercooled. For the latter case, the performance of intercooling can be increased finding the best solution of charge air cooling using a convenient heat exchanger. The most efficient cooling solution, air-to-water heat exchanger, is too complicated especially for vehicular applications, so the most spread solution of air charge cooling is air-to-air heat exchanger.

The present paper describes experimental testing of a direct injection heavy duty diesel engine type for the selection of the most efficient air-to-air cooler in terms of configuration and material.

2. Coolers Description

There were tested two types of air-to-air heat exchangers, a steel made (reference number 89.08101.6005) cooler and an aluminium made cooler (89.08101.6007).

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Heat exchangers characteristics Table 1

Cooler material	Steel	Aluminium
Reference no.	89.08101.6005	89.08101.6007
Fin shape and thickness	folded, 0.2 mm	undulated, 0.5 mm
Tube shape	circular	rectangular
Frontal area [m^2]	0.334	0.204
Total area [m^2]	3.11	13.50
Thermal conductivity [W/m·K]	76	238
Mass [kg]	34	18
Dimensions [mm]	590 x 560 x 75	676 x 300 x 60

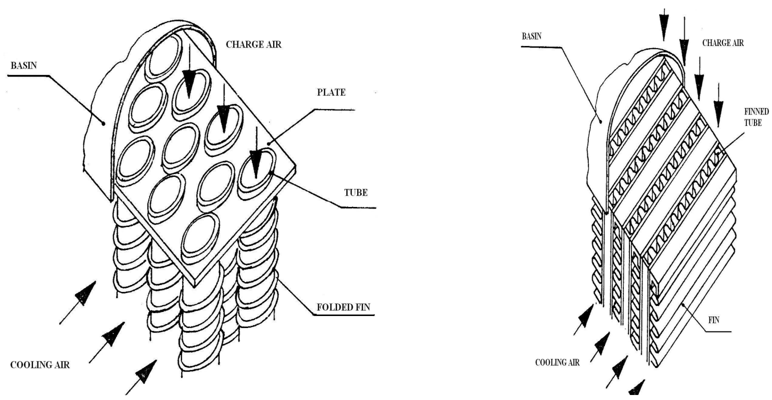

Fig. 1. *Air charge coolers: left-steel cooler, right-aluminium cooler*

The characteristics of the coolers were described in Table 1 [11]. The structure of the air charge coolers was different as it is presented in Figure 1. The steel made cooler has three rows of circular tubes with folded fins, through which the charge air circulating through the interior of the tubes. The aluminium made cooler has similar ducts for charge air and cooling air, in form of rectangular finned tubes which are perpendicularly oriented on the direction of external ambient air flows. The mechanical resistance of both coolers was previously tested in a special purpose rig, by applying an external pressure of 1.5 bar [5], [11]. The optimum cooler should also withstand to the maximum air temperature at the outlet of the turbocharger, around 110 °C, so it must be checked if the soldering alloy of the cooler joints would withstand to this temperature. The steel cooler was manufactured at Romradiatoare Braşov Company and the aluminium one at RAAL Bistriţa Company.

The assessment of coolers behaviour using conventional heat exchanger formulas is difficult and, in a certain extent, deceptive. The aluminium cooler has a total area four times larger, thermal conductivity is roughly three times higher, but the price is four times more expensive than the steel one. Previous heat transfer calculations based on coolers configurations and material properties [11] could evaluate the values of overall heat transfer coefficients, but there is a lack of data upon the convection coefficients and pressure losses, so engine experiments were required for a sound selection.

There are three performance parameters specific to air-to-air heat exchangers:

cooler effectiveness, cooler temperature drop and pressure loss. The effectiveness of the air-to-air heat exchanger (ε) is defined as the ratio of the real charge air temperature drop across the cooler core to the temperature differential available for cooling [3]:

$$\varepsilon = \frac{T_2 - T_3}{T_2 - T_1}, \quad (1)$$

ε - heat exchanger effectiveness;
T_1 - temperature of the ambient cooling air;
T_2 - temperature of charge air entering the cooler (approximately equal to compressor discharge temperature);
T_3 - temperature of charge air exiting the cooler (approximately equal to intake manifold temperature).

The temperature drop is defined by Equation:

$$\Delta T = T_2 - T_3. \quad (2)$$

The pressure loss is produced by air flow through the cooler and can be calculated using the following equation:

$$\Delta p = p_u - p_d, \quad (3)$$

with:
Δp - pressure drop across the cooler;
p_u - air pressure upstream the cooler;
p_d - air pressure downstream the cooler.

3. Engine Test Procedure

The main characteristics and performance of the turbocharged engine version, without intercooling is presented in Table 2 [1].

The testing principle was to experiment successively both coolers on the same engine, in the same operation modes, in identical conditions and to compare the results.

Engine technical data Table 2

Engine type	Diesel, 4 stroke, direct injection
Cylinder configuration	6-cylinder, in line
Bore x Stroke [mm]	121 x 150
Displacement [L]	10.344
Compression ratio	16:1
Rated power [kW]	185
Rated speed [rpm]	2100
Max. torque [N·m]	900
Max. torque speed [rpm]	1400

The tested engine was manufactured at Roman Truck Company (Brașov, Romania), being a turbocharged direct injection engine, having the series number 0739.

The engine performance (power, torque, specific fuel consumption) has been measured on the 300 kW MEZ-VSETIN dynamometric test bench at Road Vehicle Institute Brașov (INAR) [10]. The engine, type D2156MTN8, was instrumented with temperature sensors measuring cooling liquid, oil and exhaust gas temperatures, as well as pressure sensors to measure oil and air charge pressure. All the instruments met the accuracies imposed by engine testing standard [9]. During engine testing, the ambient temperature was 17 °C and atmospheric pressure was 717 mm Hg.

The engine performance was corrected according to pressure and temperature with correction coefficient α, with f_a atmospheric factor and f_m engine factor, with the formula [8]:

$$\alpha = f_a^{fm}, \quad (4)$$

$$f_a = \left(\frac{99}{p_s}\right)^{0.7} \left(\frac{T}{298}\right)^{1.5}, \quad (5)$$

p_s - atmospheric dry pressure expressed in kilopascals, T - atmospheric temperature in Kelvin degrees.

$$f_m = 0.036 \cdot q_c - 1.14\,, \tag{6}$$

$$q_c = \frac{q}{r}\,, \tag{7}$$

with: q - fuel flow in milligram per cycle and per liter of total swept volume (mg/(L·cycle) and r - air pressure ratio of compressor outlet and compressor inlet. The calculated values of α ranged in 0.9913-0.9987, the interval being included in the standard requirement of 0.9-1.1.

The measured values of effective power, torque and fuel consumption were corrected using the following formula, written for effective power:

$$P_{corr,ef} = \alpha \cdot P_{m,ef}\,, \tag{8}$$

with $P_{corr,ef}$ - corrected effective power and $P_{m,ef}$ - measured effective power.

The engine was equipped as follows:

- 6 blade cooling fan Φ 680 x 140 mm;
- unloaded alternator;
- bench air filter generating 320 mm column H_2O pressure loss on intake system;
- bench exhaust system generating 400 mm column H_2O pressure loss.

Besides the measurement of engine performance characteristics, it was measured the smoke opacity with Hartridge MK3 opacimeter which has the effective length of measurement tube of 430 mm and readings in HSU (Hartridge Smoke Units) or light absorbtion coefficients (m^{-1}).

The engine tests included two types of measurements:

A. Thermodynamic parameters of charge and ambient air (ambient air temperature, charge air temperature entering the cooler, charge air exiting the cooler, pressure loss on the cooler);

B. Engine speed characteristics at total load (power, torque, specific fuel consumption, smoke emission).

4. Interpretation of Results

The experimental results of the engine testing were performed at full load being presented comparatively in Figures 2-7, being marked with dashed line the behaviour of steel heat exchanger and with solid line that one of the aluminium heat exchanger.

A. Thermodynamic parameters of charge air were assessed in terms of measured temperature drop on coolers, ΔT, measured effectiveness, ε, as described in Equation (1) and measured pressure loss, Δp, according to Equation (3). The temperature drop is illustrated in Figure 2 along the whole range of speeds.

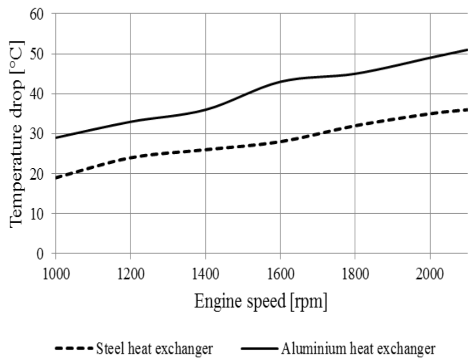

Fig. 2. *Temperature drops versus speed*

The aluminium heat exchanger produces a higher temperature drop than steel heat exchanger, in average higher with 10-14 °C. The effectiveness values represented in Figure 3 strengthened the advantage of aluminium cooler, the literature indicating fair values in 0.5-0.7 [3], thus undermining the behaviour of steel cooler.

The processes in the cooler should be a trade-off between cooling effectiveness, involving ε values as higher as possible and flow restrictions, involving Δp values as lower as possible. The measured pressure losses on coolers were similar, 5-10 kPa for steel cooler and 5-13 kPa for aluminium one.

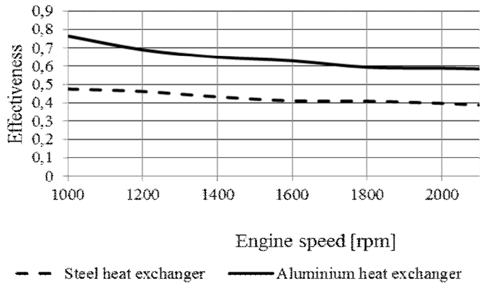

Fig. 3. *Effectiveness versus speed*

B. Engine speed characteristics at total load (power, torque, specific fuel consumption, smoke emission).

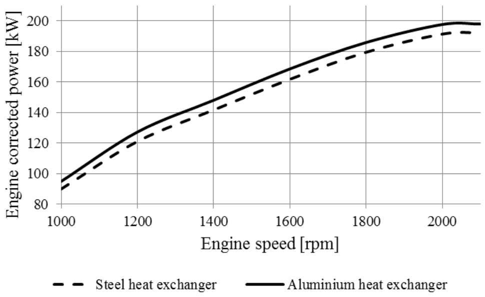

Fig. 4. *Engine power versus speed*

The advantage of better intercooling for aluminium solution was confirmed in terms of power (Figure 4), torque (Figure 5) and specific fuel consumption (Figure 6). The gains of power and torque for aluminium cooler were in average of 4.2% reported to steel results.

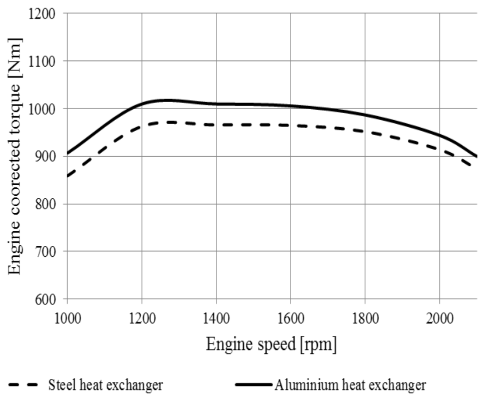

Fig. 5. *Engine torque versus speed*

Fuel economy was constantly improved for aluminium version as specific fuel consumption decreased in average with 2.6% compared to steel results.

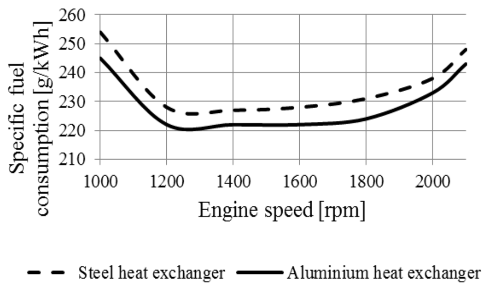

Fig. 6. *Specific fuel consumptions*

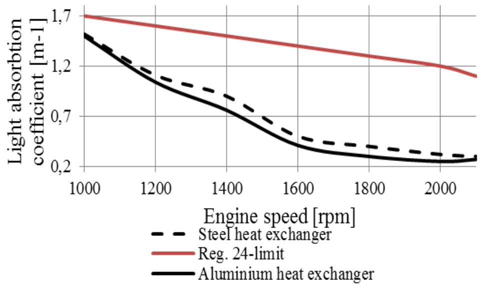

Fig. 7. *Smoke emissions versus speed*

The most relevant image for engine behaviour is in Figure 7 which represents engine smoke emissions The red line indicates which are the limits imposed by ECE Regulation [7]. In both experiments the smoke emissions complied with the limits, being lower enough especially in the range of most frequently used speeds,within the interval between maximum torque speed and rated speed (1400-2100 rpm). Nevertheless, the aluminium cooler provided a lower smoke emission, in average of 0.072 m^{-1} (approximately equivalent to 3 HSU), than the one of the steel cooler.

5. Conclusions

The paper summarizes research work performed to select the most efficient air charge cooler for the tested engine D2156MTN8R.

The solution of aluminium cooler proved to be more efficient than the steel cooler both in terms of thermodynamic parameters and performance indicators. Having half of steel cooler volume, the aluminium cooler is advantaged by a smaller mass and a smaller frontal area which provides better cooling of the engine coolant.

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