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The influence of fuel type on the cooling system heat exchanger parameters in heavy-duty engines

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Abstract. The paper discusses the problem of selection of cooling systems for heavy-duty engines fitted in city buses. Aside from diesel engines, engine manufacturers also have in their portfolio engines fueled with natural gas, whose design is based on that of a conventional diesel engine. Based on the parameters of the engines from this type-series (the same displacement and rated power) an analysis has been performed of the influence of the applied fuel on the heat flows directed to the radiators and charge air coolers, hence, their size and space necessary for their proper installation. A replacement of a diesel engine with a natural gas fueled engine of the same operating parameters results in an increased amount of heat released to the coolant and a reduced heat from the engine charging system. This forces a selection of different heat exchangers that require more space for installation. A universal cooling module for different engines is not an optimal solution.

1. Introduction
Natural gas is an alternative source of energy for combustion engines, exhibiting good calorific and emission-related parameters. Due to its low energy density (has to be accumulated under high pressure) and a limited distribution network natural gas is best for stationary engines or engines used in municipal service and public transit vehicles. The above is the main reason for the engine manufacturers to launch a new engine powered by natural gas whose design is based on that of a conventional diesel engine and whose operating parameters are comparable. The process of natural gas combustion, however, is characterized by a lower flame propagation rate leading to a greater engine thermal load, hence the heat flows rejected to the cooling and exhaust systems are greater.

2. Heavy – duty engine cooling system
Cooling systems of modern heavy – duty engines, similarly to other engine systems, are increasingly sophisticated, contain an increasing number of elements and in order to optimize the engine operating parameters the operation is continuously monitored by a variety of sensors. All the mentioned facts are due to the necessity of complying with the exhaust emission standards. Apart from the cylinders and the cylinder head, where the coolant chills the fuel injectors, the valve seats and valve guides, the cooling circuit also includes other components such as the engine oil cooler, the fuel cooler, the exhaust gas cooler in the EGR system, the heater core, the Urea heater (AdBlue) and the AdBlue injector cooler, the air compressor in the pneumatic system, let alone the supercharging pressure, EGR or DPF regeneration actuators (Figure 1). Sometimes, the engine coolant also cools the transmission or retarder fluid.
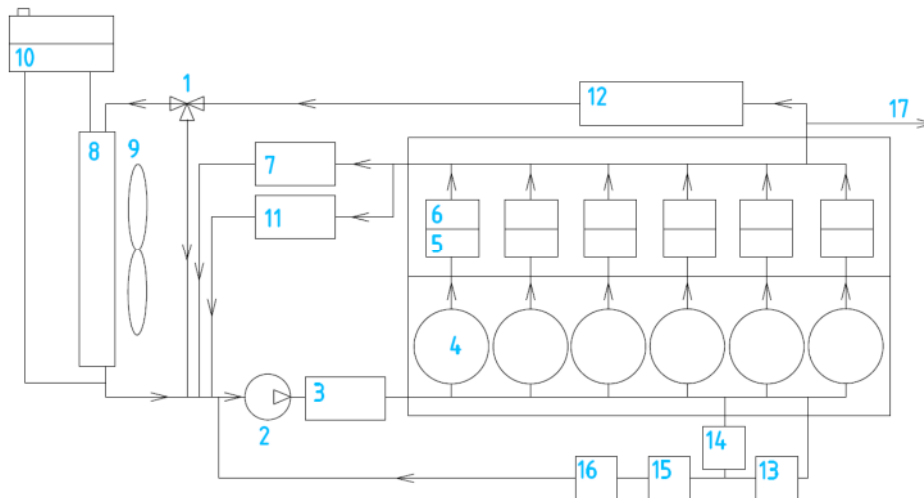
Figure 1. Diagram of the cooling system of a heavy – duty Euro 6 compliant engine [1]

1 – coolant thermostat, 2 –coolant pump, 3 – oil – water heat exchanger, 4 – cylinder, 5 – lower coolant level in cylinder head (fuel injectors and valve seats), 6 – upper coolant level in cylinder head (valve guides), 7 – heater core, 8 – radiator, 9 – fan, 10 – coolant expansion tank, 11 – urea heater , 12 – exhaust gas recirculation cooler, 13 – air compressor, 14 – fuel cooler, 15 – exhaust gas recirculation positioned, 16 – transmission oil – water cooler (optional), 17 – retarder (optional)

An increasing number of engine components requiring constant temperature (hence cooling) results in an increased heat rejection to the cooling system [1]. The temperature difference of the coolant obtained in the heat exchanger must be maintained at a constant level of approx. 6 – 8 K, because an excess temperature gradient may lead to the damage of engine components in contact with the coolant. Reception of excess heat is realized through increased coolant pump rate. The need to cool many engine components at the same time results in an extended coolant flow distance, hence greater major and minor head loss, directly affecting the pump load (its efficiency, Fig. 2).
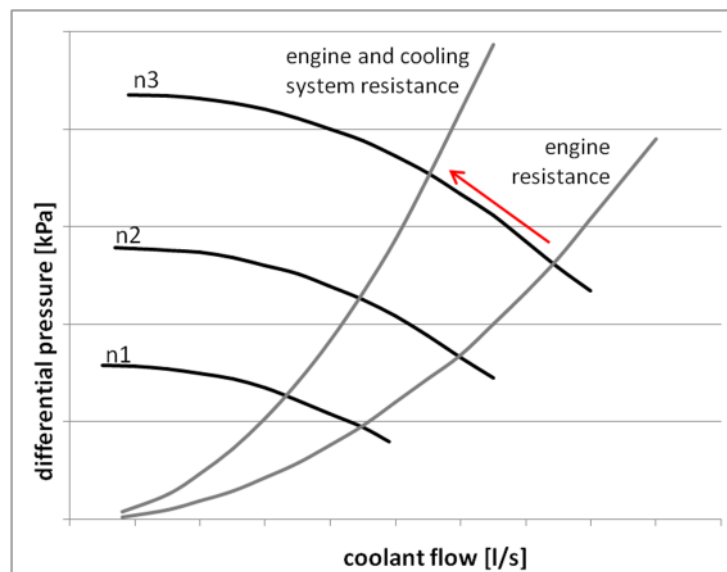
Figure 2. Characteristics of the coolant pump cooperation with the cooling system and the engine.

3. Engine characteristics

The engines selected for the analysis were EURO VI complaint, dedicated for city buses. From the point of view of natural gas used as fuel, this application is optimal. The analysed engine has six cylinders in a straight configuration, double overhead camshafts and four valves per cylinder. The engine block and cylinder head are made from cast iron and the crankshaft and the connecting rods are forged. In both fuel versions, oil-cooled aluminium pistons, fixed geometry turbochargers and cooled EGR systems were applied. The base diesel engine is a *Common Rail* direct injected engine fitted with the exhaust aftertreatment system composed of: an oxidation catalytic converter, a diesel particular filter and a reduction catalytic converter with an AdBlue system. The natural gas fuelled version is an indirect injected engine fitted with a three-way catalytic converter.

Both engines produce a torque of 1200 Nm in the same range of engine speeds (from 1200 rpm to 1600 rpm). The maximum power of 220 kW produced by the diesel engine is reached at 2200 rpm and 2000 rpm by the natural gas fuelled engine. As per manufacturer's specifications, minimum specific fuel consumption for the diesel engine is on the level of 190 g/kWh and for the natural gas fuelled engine - approx. 185 g/kWh.

The natural gas combustion process is characterized by a lower flame propagation rate compared to other fuels, the consequence of which is the extension of the combustion towards the power stroke and a greater thermal load of the engine, which is why the adaptation of a diesel engine to natural gas fuelling requires an increased efficiency of the cooling system. For the analysed engines, the amount of heat rejected to the cooling system is greater by approx. 13 % for the natural gas fuelled engine at a simultaneous reduction of the maximum admissible coolant temperature by 10 K (table 1). The lower difference of temperature between coolant and cooling air influence the reduction of the specific heat rejection of heat exchanger, consequently an application of greater space of heat exchange is necessary. The extension of the combustion process increases the exhaust gas temperature at the moment of exhaust valve opening, which, in the case of turbocharged engines, may improve the turbocharging efficiency.

Table 1. Selected engine data at ambient temperature of 25 ^{0}C

		Diesel engine	Natural gas fueled engine
Heat rejection to coolant	kW	152	172
Coolant temperature	^{0}C	105	95
Charge air temperature downstream of the turbocharger	^{0}C	175	180
Charge air temperature upstream of the engine	^{0}C	41	37
Exhaust gas temperature	^{0}C	420	540

4. Characteristics of the cooling system

Buses have their engines installed in the back of the vehicle and, consequently, the cooling modules are also in the back and are fitted sideways, which, compared to passenger vehicles and trucks, seriously inhibits the speed-induced airflow through the exchangers. Depending on the solution, the cooling module may be mounted on the level of the engine or, in the vertical configuration, above it. City buses frequently use the vertical mounting system, which is why the fan drive is rarely based on a belt transmission. Hydraulic fan drive is applied instead, or, as has recently become popular, several smaller fans with electric motors are used.

The analysis of the influence of the type of engine (diesel/natural gas) on the parameters and size of the cooling module was performed in several stages. In all calculations, a constant value of the coolant volumetric flow was assumed corresponding to the maximum admissible pressure drop in the cooling system for a given engine. Given the European climate, the calculations were performed for the ambient

temperatures of 45 ^{0}C for which the admissible temperature of the charge air is increased by 20 K respectively.

The calculations were performed in GT-SUITE using the characteristics of the BSPL heat exchanger cores.

4.1. Constant cooling air flow rate

Initially, the operation of the fan was not allowed for in the calculations. A constant value of the cooling air mass flow was assumed instead and the size of the heat exchangers for the coolant and the charge air were adjusted to obtain the cooling parameters defined in the engine characteristics. Because the diesel engine is the base unit, it was the engine for which the value of the airflow rate was adjusted. Figure 3 presents the calculation models shown in the same scale and table 2 contains the minimum theoretical size of the frontal area of the heat exchanger cores (the thickness was not modified) and respective temperature values obtained in the calculations.
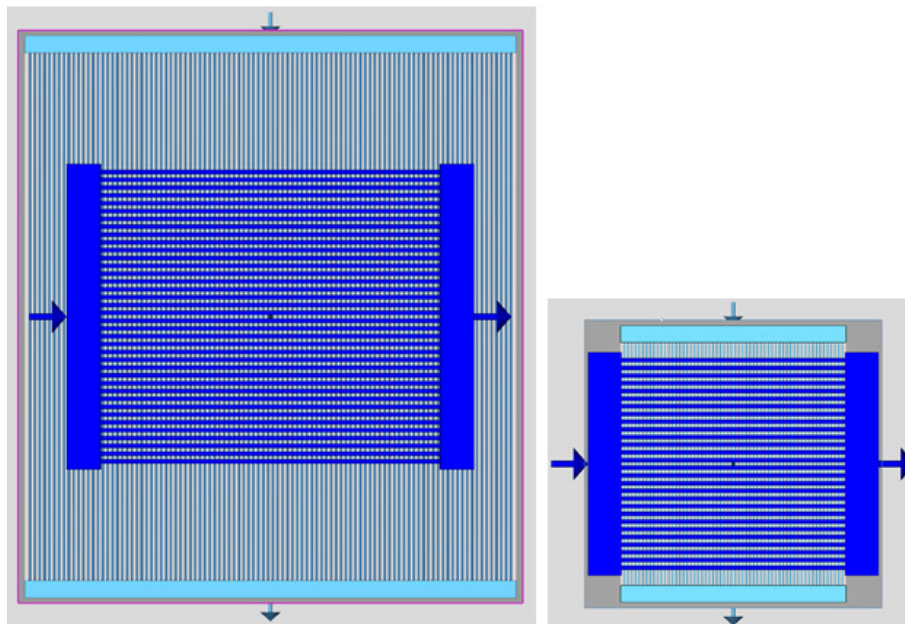
Figure 3. Calculation models of the cooling modules – NG engine on the left, diesel engine on the right.

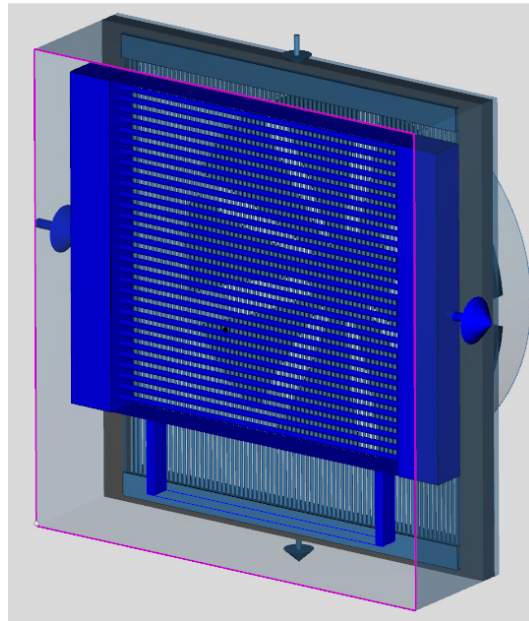**Table 2.** Calculation results for the cooling air flow of 4.5 kg/s (ambient temperature of 45 ^{0}C).

		Diesel engine	Natural gas fueled engine
Radiator core	mm	650x600	1400 x 1300
Coolant temperature downstream of the engine	^{0}C	104.3	94.9
Charge air cooler core	mm	600x600	900 x 800
Charge Air Temperature upstream of the engine	^{0}C	59.3	56.3

Obtaining the temperature values of the mediums defined in the characteristics for both engines, assuming the same cooling air flow rate makes the frontal area of the radiator core of the natural gas fuelled engine more than 4,5 times larger compared to the diesel engine. A further increase in the radiator size does not result in a measurable reduction of the temperature.

4.2. Constant size of the heat exchangers

The second stage of the analysis was performed for the cooling module composed of the coolant radiator, the charge air cooler, the fan with a hydraulic drive and the cooler of the fan hydraulic fluid. In this case, the size of the exchangers was constant and the required parameters were obtained through adjustment of the fan speed.

Figure 4 presents the calculation model of the cooling module, and table 3 includes the sizes of the basic components of the cooling module, calculated temperature values, the matching fan speeds and the resulting fan power demand.

Figure 4. Calculation model of the cooling module fitted with a axial fan.

Table 3. Calculation results for different fan speeds (ambient temperature of 45 ^{0}C)

		Diesel engine	Natural gas fueled engine
Radiator core	mm	800 x 750	
Coolant temperature downstream of the engine	^{0}C	100.4	93.1
Charge air cooler core	mm	650 x 640	
Charge air temperature upstream of the engine	^{0}C	58.9	49.8
Axial fan diameter	mm	702	
Axial fan speed	rpm	2000	3000
Cooling air flow	kg/s	4.64	6.31
Axial fan power consumption	kW	13.9	47.4

The components of the cooling module have been combined in such a fashion as to obtain (through a change of the axial fan speed) the parameters defined in the characteristics of both engines. As a result, for the diesel engine the fan speed of approx. 2000 rpm is sufficient while the fan speed for the natural gas fuelled engine must be higher (3000 rpm). For the fan speed of 3000 rpm, the power demand is approx. 3.5 times greater compared to 2000 rpm, which results in a significant engine power loss. A

standard assumption is that the fan power demand (at its maximum speed) should not exceed 10% of the engine power output. An increase in the fan speed also generates a greater noise.

4.3. Dedicated cooling systems
In actual conditions of the cooling system operation, additional pressure drops of the cooling air need to be allowed for. The pressure drops result from the flow resistance generated at the shutters of the cooling module and depend on its design. Another source of pressure drops is the shape of the channel through which the air flows. The operation of cooling systems is also influenced by other elements of the engine compartment, whose actual impact is hard to predict at the calculation stage. Additional safety margin should be added accordingly.

Figure 5 presents the calculation models of the cooling modules, selected individually for each of the engines. During the calculations, the author assumed pressure drops resulting from the fitting specificity and the safety margins for the radiator and the charge air cooler. Table 4 includes the dimensions of the basic components of the cooling module, calculated temperature values, the axial fan speeds and the resulting power demands.
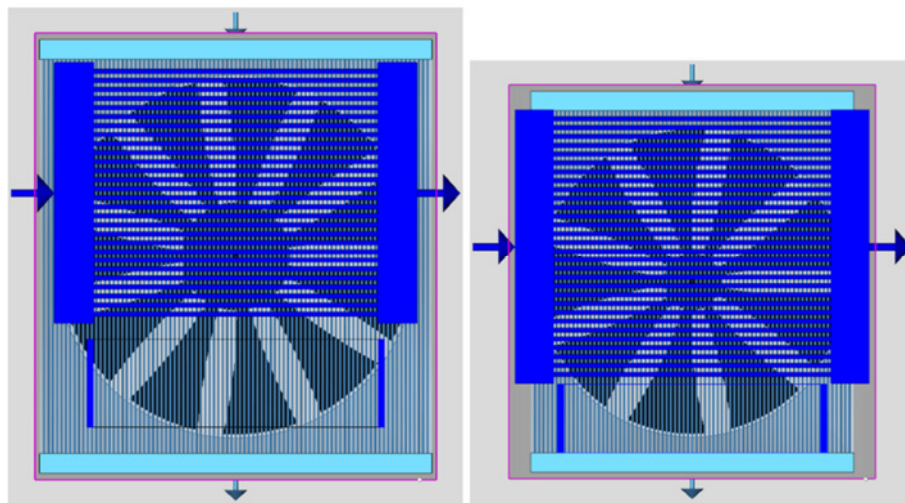
Figure 5. Calculation models of the cooling modules fitted with a radiator fan – NG-fuelled engine on the left, diesel engine on the right.

Table 4. Calculation results for the cooling modules (ambient temperature of 45 ^{0}C).

		Diesel Engine	Natural gas fueled engine
Radiator core	mm	800 x 750	900 x 900
Coolant temperature downstream of the engine	^{0}C	103.3	93.5
Charge air cooler core	mm	650 x 640	650 x 600
Charge air temperature upstream of the engine	^{0}C	58.3	53.5
Axial fan diameter	mm	702/ 9 blades	814/ 11 blades
Axial fan speed	rpm	2300	2000
Cooling air flow	kg/s	4.95	6.56
Axial fan power consumption	kW	21.3	28.6

A greater heat rejection (13%) of the natural gas fueled engine to the cooling system compared to the diesel engine, results in a larger frontal area of the radiator core by approx. 35 %. The fan drive power demand also increased by approx. 34 %.

5. Conclusions

Natural gas fueled engines are increasingly used in city buses. A replacement of an engine fitted in a given bus with an engine of a newer emission standard or of different operating parameters does not typically force a modification of the engine compartment. This may result in a very close fitting of the engine components that may have a thermal impact on one another, which may disturb their proper operation. A replacement of a diesel engine with a natural gas fueled engine of the same operating parameters results in an increased amount of heat rejected to the coolant and a lower heat from the charging system to the charge air cooler, which is a result of lower charge air mass flow to engine. Consequently, a selection of heat exchangers of different size is necessary, which requires more space for the fitting of the cooling module. A universal cooling system for different engines is not an optimum solution in terms of typical operation and may lead to significant loss of power due to energy needed for the fan drive (tab. 3).

References

[1]   Worsztynowicz B 2014 Thermal balance of havy – duty combustion engines in the aspect of exhaust emissions standards *Silniki spalinowe i ekologia - praca zbiorowa, opracowanie monograficzne.* **978-83-7242-763-2**
[2]   Mercedes-Benz – factory data
[3]   GT-SUITE