

Article

The Effect of a New Approach to Cooling the External Heat Exchange Surfaces of a Car Cooler with Air Nozzles on the Cooling Process

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Abstract: The paper deals with an experimental investigation of a new approach for cooling the external heat exchange surfaces of a cooler using an air pressure nozzle system. The G12+ coolant (50:50 ethylene glycol/water concentrate) is heated to an operating temperature of 80 °C and cooled by a cooler. Three ways of forced cooling of the external heat exchange surfaces of the cooler are experimentally compared—fan, nozzles, and a combination of nozzles and fan. The spacing between the nozzles and the cooler is variable from 60 to 170 mm in inline and staggered nozzle arrangements. Coolant temperatures in the cooler inlet and outlet pipes are recorded by thermistors. The air pressure nozzle system achieved an improvement in the cooling process compared to a conventional fan. At a spacing of 160 mm, the heat exchange surface is completely covered by the air flow, which leads to a reduction in cooling time and an increase in the temperature difference. The maximum temperature difference of 28.84 °C and 16.90 °C for staggered arrangement of nozzles at a spacing of 160 mm are achieved for the combination of nozzles with fan and nozzles, respectively. When comparing 60 mm and 160 mm spacing, there was an increase in thermal performance of 70.3%, 55.99%, 6.20%, and 1.83% for inline nozzles, staggered nozzles, fan with inline nozzles, and fan with staggered nozzles, respectively. The air nozzle system fully replaces the fan in the cooling process and achieves improved heat dissipation, making the cooling process significantly shorter and more efficient. In addition, the air nozzle system can also be used as an additional equipment for intensification of heat dissipation in combination with the fan.

Keywords: cooler; air nozzle; fan; cooling system; coolant



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1. Introduction

In recent decades, there has been a significant increase in the performance of internal combustion engines [1]. Decreasing overall vehicle weight and increasing engine efficiency can bring fuel savings and associated operating costs, reducing emissions that pollute the environment [2,3]. Engine performance, fuel economy and emissions are specific car parameters that directly affect convective heat transfer [4,5]. At the same time, there are increased demands on the cooling system as individual engine components are subjected to high thermal stresses, increasing the potential for damage due to the increase in combustion intensity [6–8].

The engine cooling system is designed to ensure that the engine operates at an optimum temperature while preventing overheating due to friction [9,10]. The cooling system of the internal combustion engine has remained almost unchanged for decades without significant modifications and improvements [11,12]. The main components of a conventional cooling circuit include a heat exchanger (cooler), a mechanical water pump, one or two fans and a wax thermostat [13,14]. Advanced heat dissipation technologies are essential for high-performance automotive engines [15]. For this reason, modified components have been introduced in cooling systems to reduce fuel consumption and engine emissions (e.g.,

electrically controlled airflow deflectors, electric fans, electromagnetic thermostatic valves, electric water pumps), allowing more flexible control of engine temperature and coolant mass flow [16,17]. It is the optimization of the conventional internal combustion engine cooling system that plays an important role in the development of highly energy-efficient vehicles that have high performance, low fuel consumption and low emissions [18,19]. Increasing the efficiency of a car's engine cooling system can also be achieved in a couple of other ways. Modifying the geometrical parameters of the fins and channels is the most common way to increase the heat dissipation rate, but it is now reaching its limits [20,21]. Therefore, the necessity to research and find new possibilities for more efficient heat dissipation is justified. One option to increase the cooling effect is to use a more efficient coolant and increase the flow rate in the cooling circuit [22]. Another option is to change the way the external heat exchange surface of the cooler is cooled by forced convection. The hot coolant flowing through the cooler is cooled by a forced air or fan. The main function of the fan is to ensure sufficient cooling air flow at low vehicle speeds through the various cross-sections in the cooler [23,24].

Currently, the fan drive is provided in two ways (mechanical or electrical). If the fan is driven by a belt from the crankshaft, it is not possible to regulate the amount of air flow. In this design, the crankshaft drive of the fan results in a loss of engine power, which has an overall negative effect on the economics of operation. The use of a fan or a pair of fans with an electric motor eliminates the above-mentioned shortcomings as the drive is provided by an electric motor which can be continuously regulated (switched on/off) as required. However, even such a design has its shortcomings (load on the electrical system, the weight of the electric motor, the unevenness of hot air removal from the heat exchange surface, vibrations and increased noise caused by the rotation of the fan [25–27]).

Considering these negative aspects, in our paper we focused on the design of modification of the method of cooling the engine cooler using air nozzles. The new method of cooling and at the same time cleaning of the heat exchange surface is provided by a set of high-pressure air nozzles mounted in front of the cooler. In our experimental investigations, the pneumatic suspension system of the car serves as both the source and the supply of pressurized air for the air nozzle system. One of the main tasks of a vehicle during its use is to ensure the highest possible level of safety and driving comfort. These quality criteria are strongly influenced by the type of suspension system used. The suspension system of conventional passenger cars uses conventional springs, such as coil springs, leaf springs, which have a linear spring characteristic. Nowadays, high ride comfort is no longer only required for more luxurious cars, but also for commonly affordable ones. For this reason, modern passenger cars are increasingly being fitted (also retrofitted) with air chassis operating with high-pressure compressed air, which support the steering system, vehicle braking, ensure constant comfort in the cabin and allow for a change in ground clearance [5,28–31]. Compressed air is also used for other applications in automobiles or machines and equipment; compressed air can also be used as an alternative drive in the form of a pneumatic motor [32]. The compressed air power unit can be integrated with a conventional internal combustion engine to form a hybrid system [33,34]. This system can be considered as a vehicle drive transition between a fossil fuel internal combustion engine and a zero emission drive system [35,36]. As in the case of an internal combustion engine, the linear motion of the pistons is transformed into a rotary motion of the output shaft in a pneumatic motor. Compressed air is used to drive the pistons in the engine [37]. In this type of drive, there is no combustion process, resulting in low noise levels, no battery discharge or other processes that create a carbon trace [35]. The operating temperature of such an engine is comparable to the ambient temperature. For this reason, no cooling, ignition or injection system is required. Compressed air is also used in air brake systems in vehicles [38]. This type of brake operates using compressed air as the working medium in a closed circuit [39]. The air supply is practically unlimited, so the braking system cannot run out of operating fluid like, for example, hydraulic brakes. The great advantage of compressed air is that it allows more power to be generated compared to other systems [40].

The leakage requirements of the circuit are lower compared to a hydraulic circuit, as less air leakage does not result in brake failure [41,42]. Compressed air is also commonly used to inflate tyres. The correct amount of compressed air inside a tyre has a significant impact on tyre life, driveability and also ensures lower fuel consumption. In addition to vehicles, pneumatic systems are also widely used in automation, mechanisation, robotics and also in the production of food and pharmaceuticals, where it is essential that the air does not act as a contaminant. A pneumatic circuit is always composed of a source, a control and a power part. The source part is made up of compressed air generating equipment—compressors. The control part is made up of distribution valves that are responsible for distributing the air flow to the other parts of the pneumatic circuit—throttling, check, pressure valves, actuators and logic units. The power part is made up of actuators, most often pneumatic cylinders. The actuators include suction cups or gripping devices.

The authors [43] experimentally investigated the cooling capabilities of two samples of coolant concentrates compared to pure water. They evaluated the boiling point, recording the temperature of the three coolants as a function of time. The authors [44] investigated the efficiency of an automotive cooler. They monitored the temperature of the coolant in the cooler inlet and outlet pipes as a function of time and the temperature of the cooling air in front of and in back of the cooler. They observed that with increasing engine running time, the efficiency of the cooler can be reduced. Increasing the fan (cooling air) rotation speed from 2000 to 3000 rpm did not result in significant differences in coolant temperatures. The authors [45] proposed a new design of the cooler, which consists of two flat plates placed inside the tube, in order to increase the fluid flow rate and reduce the pressure. They recorded the inlet and outlet temperature of the coolant and the air temperature in front of and back of the cooler. The operating temperature of the coolant was 90 °C. With the original design of the cooler, the outlet temperature of the coolant was 83.04 °C, while with the modified design of the cooler, the outlet temperature was lower, i.e., 78.2 °C. The efficiency of the modified cooler compared with the original design increased by 5.37%.

The conversion of accumulated energy from the combustion process into mechanical work is very inefficient [46,47], for this reason it is necessary to continuously improve this process. Reducing the cooling time of the coolant in the vehicle's cooling system directly affects combustion efficiency, engine operation and fuel consumption, thereby reducing the amount of hazardous gases produced and emitted, which are dangerous to the environment and human health. In order to reduce the carbon trace, increase energy efficiency and reduce operating costs, we focused on the design and implementation of a new cooling method that provides a reduction in the forced cooling time of the coolant through compressed air. In this paper, a newly proposed method of cooling and cleaning the external heat exchange surface of the cooler with compressed air is compared with a conventional fan mounted on the cooler. The paper also discusses the production of compressed air in the vehicle, which is necessary for the operation of the air cooling system. The presented study also fills a gap in the field of research focusing on new ways of cooling the external heat exchanger surfaces of heat exchangers. The potential for compressed air applications in vehicles is high and therefore research in this area is relevant and necessary. In the presented paper, a new approach for cooling the external heat exchange surface of the cooler is proposed and experimentally tested. For this purpose, a system of air nozzles is constructed, whereby the nozzles can be adjusted relative to the heat exchange surface in three axes. The temperature difference of the coolant at the inlet and outlet of the cooler when the nozzles are arranged inline and staggered with respect to the heat exchange surface when the spacing of the nozzles from the heat exchange surface is varied is investigated. Research is also carried out on the combination of an air nozzle system and a fan mounted on a cooler. The temperature differences of the coolant at the inlet and outlet of the cooler are compared with the standard situation when using only the fan on the cooler. For the most effective position and spacing of the nozzles from the heat exchange surface, the thermal performance is calculated.

2. Materials and Methods

2.1. Experimental Setup of the Cooling Circuit with the Fan

Engine cooling circuit with fan is designed and constructed according to a real cooling circuit in the vehicle, but adapted to the environment and conditions in the laboratory. The experimental setup of the cooling circuit with the fan and the fitted sensors of physical quantities is shown in Figure 1. The volume of coolant in the circuit is 6 L.

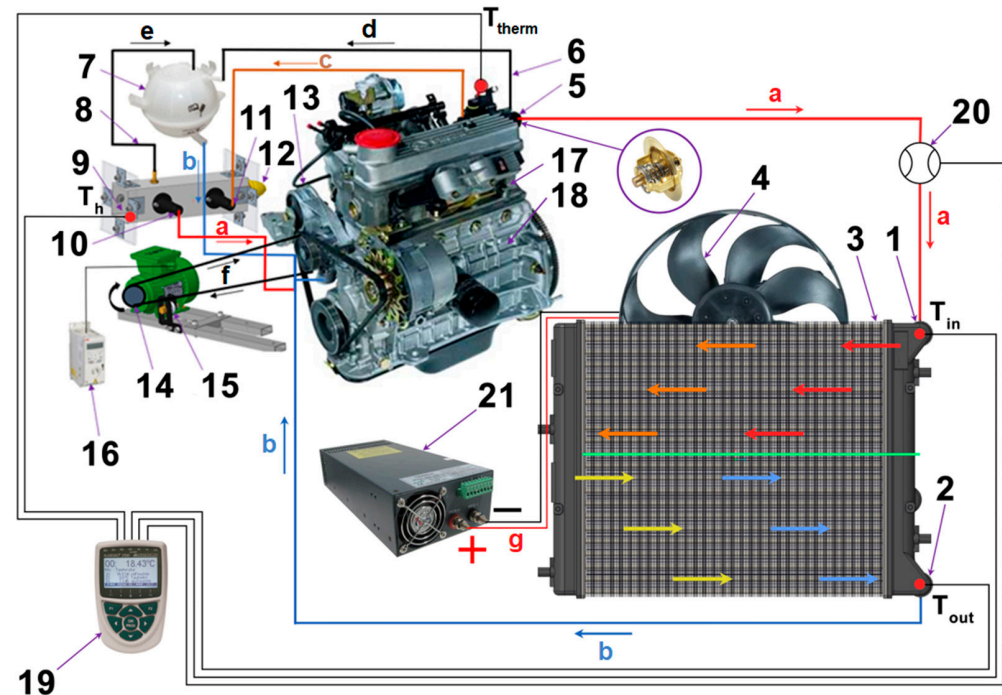


Figure 1. Experimental setup of the cooling circuit with the fan. 1—cooler inlet pipe, 2—cooler outlet pipe, 3—car cooler, 4—electric motor fan, 5—thermostatic valve, 6—reverse pipe, 7—expansion tank, 8—vent pipe, 9—heater with coil, 10—heater outlet sleeve, 11—heater inlet sleeve, 12—heating coil, 13—water pump, 14—electric motor, 15—belt tension mechanism, 16—frequency converter, 17—head of cylinders, 18—cylinder block, 19—data logger, 20—flowmeter, 21—power supply, T_{in} —coolant inlet temperature, T_{out} —coolant outlet temperature, T_{therm} —thermostat temperature, T_h —heater outlet temperature, a—hot coolant, b—cold coolant, c—gradually heating coolant circulating in a short cooling circuit, d—coolant flow from the thermostat to the expansion tank, e—coolant released from the heater into the expansion tank, f—direction of rotation of the V-belt, g—electric power supply.

The filling of the cooling circuit with coolant is carried out through the expansion tank (7). By actuating the electric motor (14) by means of the frequency converter (16), the water pump (13) starts to rotate. The pulley of the water pump is connected to the pulley of the electric motor by a V-belt which is tensioned by a mechanism (15). The experimental research simulates the operation of the engine at no-load (900 rpm), when excess heat has to be removed from the cooler by forcing, with a cooling time generally not exceeding 30 s. The experimental setup of the cooling system has (as in the real engine cooling circuit) two cooling circuits—short and long. Coolant only flows in the short cooling circuit when the temperature is below 80 °C. The short cooling circuit consists of a water pump (13) which, by means of its rotating impeller, ejects the coolant through the cylinder block (18), the cylinder head (17) and subsequently into the thermostatic valve body (5). From there, the coolant is forced to the inlet heater sleeve (11). In the heater (9), the coolant is heated by the coil (12), and the heated coolant flows to the heater outlet sleeve (10). If the heater (9) is vented or overflows, there is a sleeve on the top of the heater to connect the vent pipe (8) to the expansion tank (7). The outlet sleeve of the heater is connected to the water pump by a

rubber hose. When the operating temperature reaches 80 °C, the thermostat (5) starts to open and the hot coolant flows to the inlet of the cooler (1). If the hot coolant is not able to flow through the cooler tubes (3), some of it flows through the return pipe to the expansion tank.

The cooler (3) in the experimental setup is for a Škoda Fabia vehicle and the flow of heated coolant is divided into two parts with the flow in terms of arrows (Figure 1). Through the cooler outlet pipe (2), the cooled fluid flows back to the water pump (13) and from there back to the short cooling circuit until the temperature drops below 80 °C. The fan (4) is put into operation if the coolant is not cooled by the cooler (3) alone. The fan removes heat from the tubes and fins more intensively. In the presented experimental setup, the fan operation is controlled by a power supply (21). The outer diameter of the fan blades is 345 mm.

Temperature and mass flow sensors are incorporated in the experimental setup (Figure 1). Coolant flow temperatures are recorded in the cooler inlet pipe (T_{in}) and cooler outlet pipe (T_{out}), upstream of the thermostatic valve (T_{term}) and in the heater (T_h). For this purpose, NTC type thermistors ZA 9040-FS (Murata Manufacturing, Kyoto, Japan) with a measuring range from −50 °C to 125 °C and an accuracy of ± 0.01 °C are used. A flow meter FVA 915 VTH (Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany) (20) with a measuring range from 2 L/min to 40 L/min and an accuracy of $\pm 1\%$ is fitted in the pipe connecting the thermostatic valve (5) and the inlet pipe of the cooler (1). The measured values are recorded in the ALMEMO 2590-4S value logger (Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany).

2.2. Experimental Setup of the Cooling Circuit with the Pneumatic Pressure Nozzles

The modified experimental setup with the pneumatic circuit connected to the pressure nozzles is shown in Figure 2. Compared to the basic version of the experimental setup of Figure 1, a pneumatic circuit was added to the cooling system in order to cool the external heat exchange surfaces of the cooler (without fan). The principle of operation of the cooling circuit has remained unchanged (Section 2.1), but the method of cooling the coolant by means of a system of air pressure nozzles has been changed. When the operating temperature is reached in the short cooling circuit, the thermostatic valve (5) starts to open, from where the hot coolant flows to the cooler inlet (1). Coolant flows through the cooler outlet pipe (2) to the water pump (13) and from there to the short circuit until the coolant temperature drops below the temperature to which the thermostat is oversized (80 °C in our case). If the coolant is not sufficiently cooled by the engine cooler itself (3), the air pressure nozzles (28) are activated. The high pressure is generated in the pneumatic system of the air pressure nozzles by a pair of air compressors (19), which are connected by hoses to a pair of pressure (storage) tanks (22) with a total capacity of 38 L. The pressure (storage) tanks provide sufficient air reserve for the functionality of the pressure nozzle system and the possibility of re-supplying air to the heat exchanger surfaces of the cooler. The air compressors (19) are powered by a power supply (21). A pair of switching relays (20) is fitted between the air compressors and the power supply to restart the compressors.

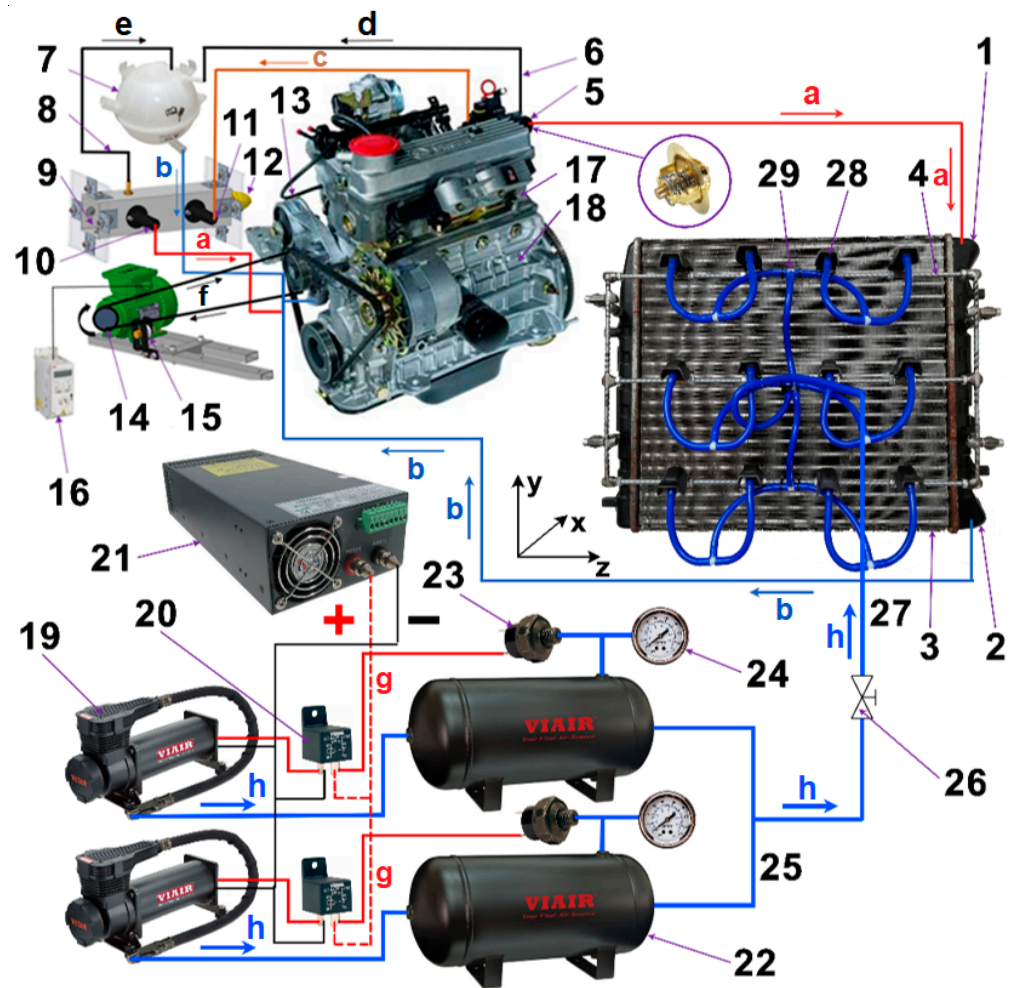


Figure 2. Experimental setup of the cooling circuit with the pneumatic pressure nozzles. 1—cooler inlet pipe, 2—cooler outlet pipe, 3—car cooler, 4—air nozzle system console, 5—thermostatic valve, 6—reverse pipe, 7—expansion tank, 8—vent pipe, 9—heater with coil, 10—heater outlet sleeve, 11—heater inlet sleeve, 12—heating coil, 13—water pump, 14—electric motor, 15—belt tension mechanism, 16—frequency converter, 17—head of cylinders, 18—cylinder block, 19—air compressor, 20—relay 12 V 40 A, 21—power supply 12 V, 80 A, 22—pressure (storage) tank, 23—pressure switch 7.5/10 bar, 24—pressure gauge, 25—high air pressure region, 26—regulating valve, 27—regulated air pressure region, 28—air pressure nozzle, 29—T-branch coupling, a—hot coolant, b—cold coolant, c—gradually heating coolant circulating in a small cooling circuit, d—coolant flow from the thermostat to the expansion tank, e—coolant released from the heater into the expansion tank, f—direction of rotation of the V-belt, g—electric power supply, h—compressed air directed to the nozzles.

The air compressors (19) achieve a maximum output air pressure of 13.79 bar. The pressure (storage) tanks (22) are fitted with pressure switches (23) that disable the air compressors (19) when the tanks are full. The operating pressure range of the pressure switches (23) is from 7.5 to 10 bar. If the pressure in the pressure (storage) tanks (22) drops below 7.5 bar (lower limit), the relays (20) close the contacts and the pair of compressors (19) is restarted until they fill the storage tanks to the required upper pressure limit of 10 bar. A pair of pressure gauges up to 220 psi (24) is installed in the pneumatic circuit to determine the pressure in the pressure (storage) tanks. In Figure 2, the region of high air pressure is shown by position (25). If it is necessary to cool the heat exchange surface of the cooler (3), a regulating valve (26) with a pressure range of up to 16 bar is opened, which releases the pressurised air into the regulated air pressure region (27), from where it continues to flow to the outlet of the individual air pressure nozzles (28). After the pressure

air is supplied to the nozzles, the heat exchange surface is cooled by the pressure air stream. Once the coolant has cooled sufficiently (below 80 °C), the regulating valve (26) shuts off the air inlet to the pressure nozzles (28) and the pair of compressors (19) come back into operation, filling the pressure (storage) tanks (22) until the pressure switch (23) puts them out of operation. The process is then repeated.

In the experimental setup of the cooling circuit with the pneumatic pressure nozzles are built-in temperature and mass flow sensors (see Figure 1), and in addition three pressure gauges, which are used to determine the actual operating pressure. A pair of pressure gauges (24) are located at the outlets of the pressure tanks (22), and their measuring range is from 0 to 15 bar. A third manometer is incorporated in the control valve (26) with a range of 0 to 16 bar, by means of which the value of the outlet regulated pressure from the air nozzles can be determined.

The novel designed and constructed air pressure nozzle system and its main dimensions are shown in Figure 3. The support console (1) consists of three adjustable cross-components, each of which is symmetrically fitted with four pieces of air nozzles (2) spaced 60 mm apart. The individual nozzles form flat triangular airflow on the cooler, and their size varies depending on the spacing between the nozzles and the cooler s . The adjustment screws (3) allow to variate the distance of the support console from the heat exchange surface in the range of $s = 60 \div 170$ mm. There are 12 air nozzles (2) mounted on a support console (1) attached to the engine cooler, which can be displaced and positioned in all three axes and rotated at different angles. The nozzles are interconnected with equal length silicone vacuum hoses to ensure constant air outlet pressure from the nozzles. The inner diameter of the hoses is 4 mm and they allow air flow at temperatures up to 290 °C. The position of the air pressure nozzles (2) was not varied during the experiments, but their angular rotation with respect to the cooler was varied. The experiments used an inline arrangement of nozzles perpendicular to the cooler (Figure 3a) and a staggered arrangement (two nozzles in one row perpendicular and two nozzles rotated by 25° with respect to the heat exchange surface in an offset arrangement) Figure 3b.

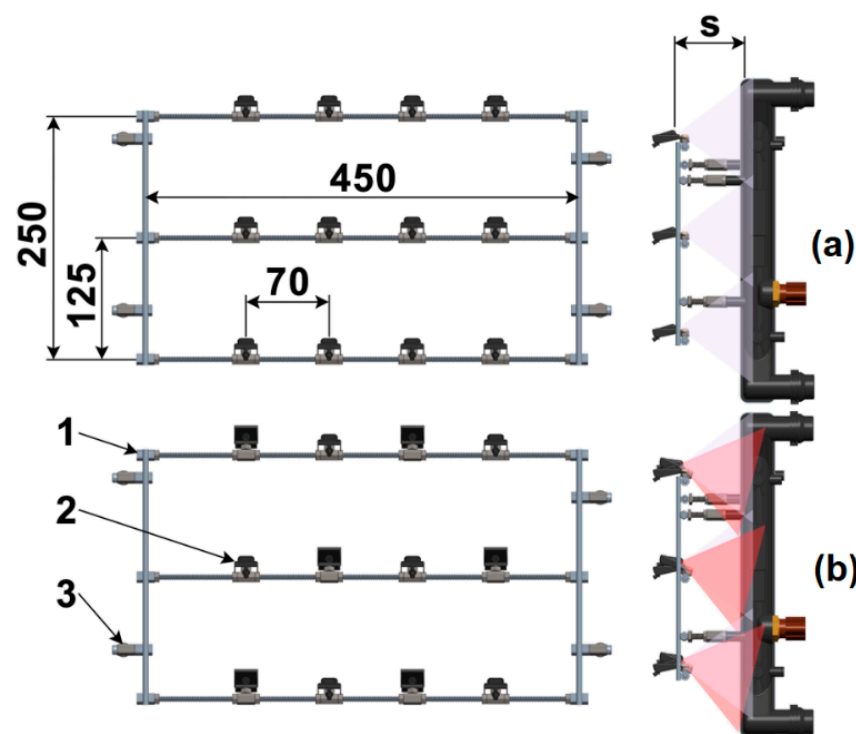


Figure 3. Basic dimensions and arrangement of the air pressure nozzle system in relation to the cooler. (a)—inline arrangement, (b)—staggered arrangement, 1—support console, 2—air pressure nozzle, 3—adjustment screw.

The Skoda Fabia 1.4 MPI engine cooler (Škoda Auto, Mladá Boleslav, Czech Republic) (Figure 4) of the liquid-to-air type was used in the experimental setup. The engine cooler consists of 44 aluminium circular tubes with an internal diameter $\varnothing 5$ mm in which the coolant flows in two rows in a consecutive arrangement (22 tubes in each row). The vertical spacing between the tubes is 20 mm and the spacing between the first and second rows is 10 mm. Throughout the entire height of the cooler (420 mm), 400 aluminium fins are tightly fitted on the tubes for more intensive heat dissipation. Each fin is 0.1 mm thick and 25 mm wide. The spacing between the cooler fins is 1.2 mm.

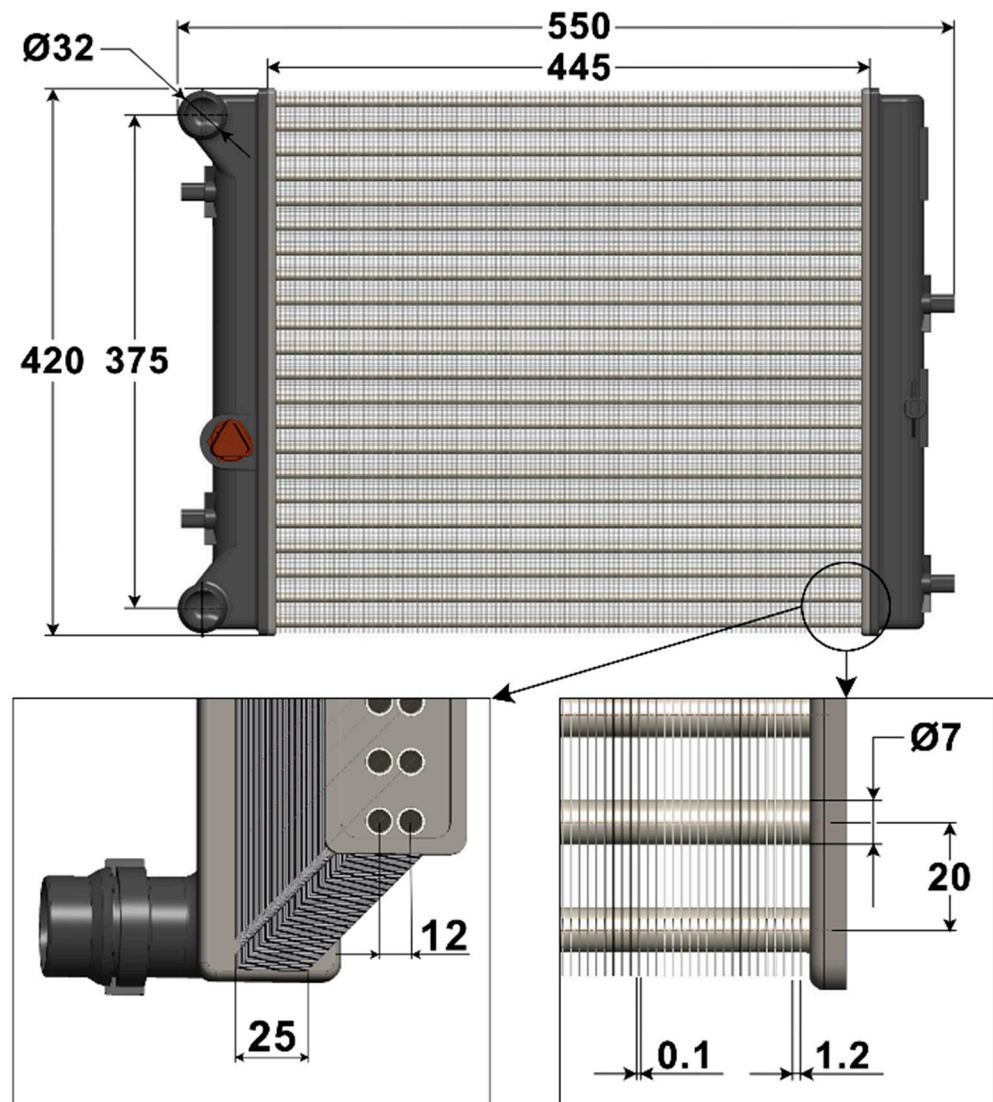


Figure 4. Basic dimensions of the Skoda Fabia 1.4 MPI engine cooler.

A G12 type coolant was circulated in the cooling circuit in concentration with distilled water to maintain the operating temperature within the operating limits. The coolant is the most compatible one specified by the manufacturer for the Skoda Fabia 1.4 MPI engine type and is free of ethylene glycol-based silicates and carboxylate compounds. A coolant in a ratio of 50:50 with distilled water at an ambient temperature 20 °C has a density of 1057 kg/m³, specific heat 3473 J/(kg.K), viscosity 4 g/(m.s), thermal conductivity 0.39 W/(m.K), freezing point 36.8 °C and boiling point 107.2 °C.

3. Results

In determining the most effective distance of the nozzles from the heat exchange surface of the cooler, it was necessary to perform a series of experimental measurements with different distances ranging from 60 to 170 mm. The mass flow rate of the coolant was varied from 0 to 2.6 m³/h depending on the actual position (opening) of the thermostat. The values were recorded after the thermostat was fully opened, when the mass flow rate of the coolant was a constant 2.6 m³/h. The cooling process started at a time of 45 min and 30 s for all experiments, when the coolant outlet temperature reached a value of nearly 75 °C. The cooling process lasted 90 s for all distances studied.

3.1. Inline Arrangement of the Nozzles

Figure 5 shows the cooling process waveforms of the inline arranged nozzles with respect to the heat exchange surface of the cooler at distances of 60 to 110 mm (Figure 5a) and 120 to 170 mm (Figure 5b). The distances were varied at 10 mm spacing. The initial condition for the investigation of the cooling process was a condition where the coolant was heated to the temperature released by the thermostat to the cooler. We focused primarily on the cooling process in the cooler, which significantly affects the proper operation of the internal combustion engine. Coolant temperatures were recorded using NTC type thermistors ZA 9040-FS mounted in the inlet and outlet pipes of the cooler.

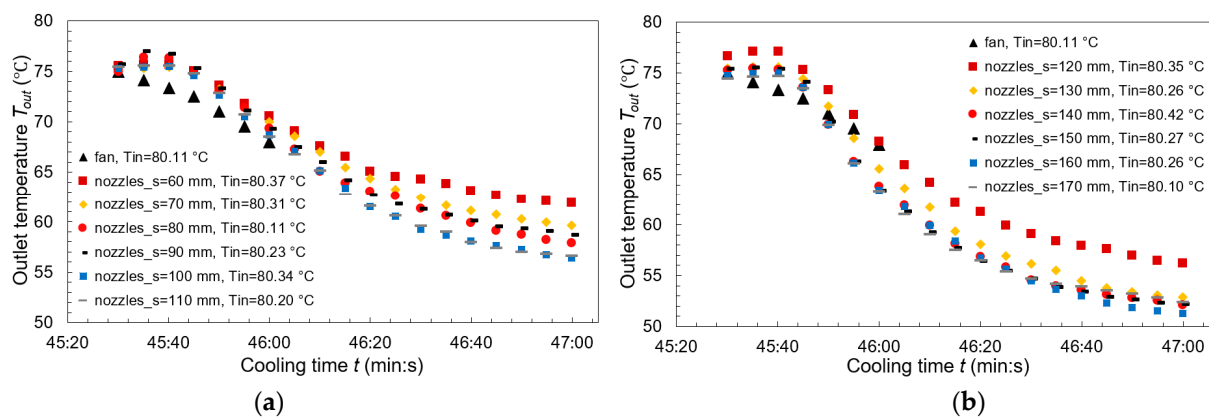


Figure 5. Comparison of the outlet cooler temperatures T_{out} for inline arrangement of the nozzles when varying the spacing of the nozzles from the cooler: (a) Nozzle spacing 60 mm to 110 mm compared to the fan; (b) Nozzle spacing 120 mm to 170 mm compared to the fan.

From the graphical waveforms (Figure 5), it can be observed that the time of the cooling process is shortened by gradually increasing the nozzle spacing from the heat exchange surface. This is due to the fact that the nozzle produces a flat conical air stream. The closer the nozzle is positioned to the heat exchange surface, the less heat is dissipated from the heat exchange surface, resulting in a longer cooling process and a higher consumption of pressurized air from the storage tanks. However, the optimum cooling process occurs only when the individual compressed air streams from the nozzle outlets begin to overlap. By overlapping the air streams, the outlet temperature of the coolant decreases significantly and at the same time the consumed air from the pressure tanks is used more efficiently. This is due to the fact that a smaller volume of air with lower pressure is sufficient for the required slight temperature adjustment below the operating temperature of the coolant.

The resulting flat conical shape of the compressed air from the nozzles also depends on the actual regulated pressure in the pneumatic circuit. As the air pressure increases, the area that the nozzle can cover increases (the angle of the air flow increases). On the contrary, when the pressure at the nozzle outlet is reduced, the area that the nozzle can cool is reduced (the angle of the airflow is reduced). It is obvious that with the type of nozzles we use (flat cone airflow) with inline configuration in relation to the cooler, there

are “empty” spots within the heat exchange surface that are not sufficiently covered and cooled by the airflow. Despite this, the inline arrangement with an outlet pressure of 6 bar achieves a shorter cooling time from a distance of 130 mm compared to the less efficient conventional fan (Figure 5b). With increasing outlet pressure (8 bar or 10 bar) there is the potential to reduce the cooling time even at a shorter distance. At the time of 46 min, the fan cooling process reached a temperature value of 67.97 °C at the outlet, while the nozzles arranged inline (spacing 130 to 170 mm) reached a temperature value in the range of 63 °C to 65 °C. This resulted in a cooling improvement of approximately 5 °C, with the most effective cooling process observed at a distance of 160 mm (Figure 5b). Distances of 60 to 110 mm (Figure 5a) were less effective in the cooling process by 46 min compared to fan-only cooling. This is due to the short distance between the nozzles (air jets) and the cooler. The breakpoint occurred at a distance of 120 mm at 46 min, when the cooling time by fan and nozzles were equal.

3.2. Staggered Arrangement of the Nozzles

Subsequently, the cooling efficiency was investigated for the staggered arrangement of air nozzles. Since the outlet air stream from the nozzles is flat, empty spots are also created in the staggered nozzle arrangement, but they are significantly eliminated compared to the inline staggered arrangement because a pair of four nozzles in a single row is rotated to the centre of the heat exchange surface (25° inclination).

At the beginning of the experimental measurements, it was possible to predict that the staggered nozzle arrangement would shorten the cooling time of the coolant precisely because of a more efficient coverage of the heat exchange surface by the cooling air stream. In addition to the fact that the individual air streams overlap each other in the row, the rotated nozzles from the first row and the second row also interfere with the air stream in the rows below them. Also in this case, we focused on recording the temperatures of the cooled coolant from the cooler, and the measured values when the nozzle distances from the heat exchange surface were varied (60 mm to 170 mm) were compared with the values obtained from cooling by the fan (Figure 6). The common operating temperature of the engine is between 80 °C and 90 °C, and when this value is exceeded, the thermostatic valve will release some of the hot coolant into the cooler. Only a few seconds elapse between the thermostat releasing the coolant and the water pump drawing in the cooled coolant; the time may vary depending on the actual operation and load on the engine. For forced cooling by means of a fan, a time period of 30 s has been considered (under normal operation and proper operation of the cooling circuit, this time period will not be exceeded).

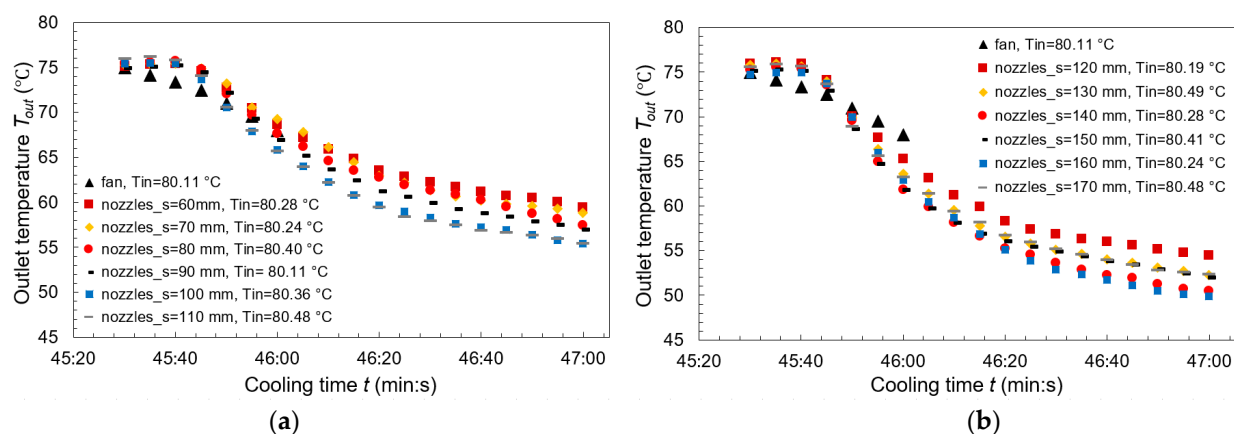


Figure 6. Comparison of the outlet cooler temperatures T_{out} for staggered arrangement of the nozzles when varying the spacing of the nozzles from the cooler: (a) Nozzle spacing 60 mm to 110 mm compared to the fan; (b) Nozzle spacing 120 mm to 170 mm compared to the fan.

From Figure 6, it can be concluded that the cooling capability was lower compared to the fan only at nozzle distances of 60 mm and 70 mm from the heat exchange surface. Within a time of 45 min and 55 s, the 80 mm and 90 mm distances already reached the same outlet temperature value as with fan cooling, and within 46 min, the mentioned distances were already 1 °C more efficient. The nozzles spacing of 80 mm to 170 mm have reached a more effective cooling efficiency throughout the entire cooling process compared to the fan. At a time of 46 min, the lowest temperature recorded was 61.84 °C at a nozzle spacing of 160 mm, which is more than 6 °C compared with the fan ($T_{out} = 67.97$ °C at the same time). The most effective cooling was achieved at a nozzle spacing of 160 mm, where at the end of cooling, the coolant reached an outlet temperature of 49.88 °C, nearly 10 °C less than the initial spacing of 60 mm.

3.3. Combination of the Inline Arrangement of the Nozzles and Fan

Figure 7 shows the outlet temperature waveforms for nozzles arranged inline in combination with a fan. The distance of the nozzles from the heat exchange surface was varied from 60 mm to 170 mm. The difference from the first measurement and hence Figure 5 is that the cooling process was carried out simultaneously using the nozzles and the fan at the same time. We hypothesized that the combination of the two types of cooling equipment would achieve significantly higher cooling efficiency compared to using them separately (fan or nozzles).

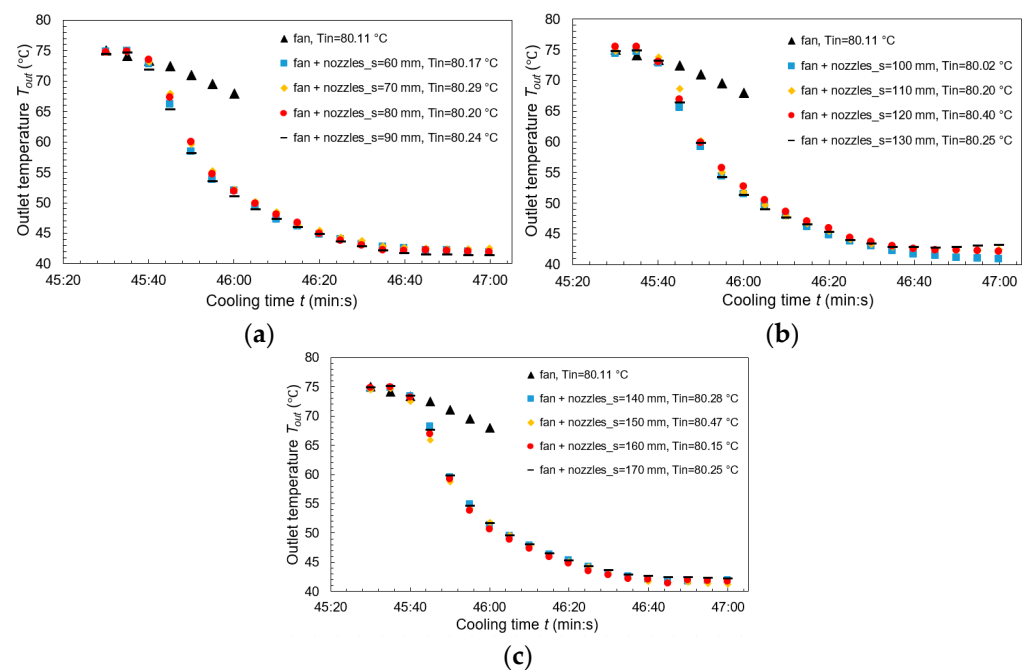


Figure 7. Comparison of the outlet cooler temperatures T_{out} for mutual fan and nozzles combination when varying the spacing of the inline arrangement nozzles from the cooler: (a) Nozzle spacing 60 mm to 90 mm compared to the fan; (b) Nozzle spacing 100 mm to 130 mm compared to the fan; (c) Nozzle spacing 140 mm to 170 mm compared to the fan.

It can be observed from Figure 7 that for the mutual combination of inline arrangement nozzles and fan, there is no higher efficiency of the fan alone during cooling at any of the distances investigated. At a time of 46 min, the fan-cooled coolant outlet temperature reached a value of $T_{out} = 67.97$ °C, while for the mutual nozzle and fan combination, the outlet temperatures ranged from 50.59 °C (160 mm) to 52.67 °C (120 mm) at the same time; a lower temperature of 17.38 °C was achieved compared with fan-only cooling. With the mutual combination of nozzles and fan, there was no more gradual increase in cooling efficiency by moving the nozzles away from the heat exchange surface. This is because the rotation of the fan not only moves the air behind the cooler (to the engine), but some of the

air also passes forward between the fins of the cooler, which will also affect the resulting cooling airflows from the nozzle outlets. When using a lower outlet pressure, the reverse phenomenon was true in certain cases in the measurements of the mutual combination of nozzle and fan as was the case when using nozzles only (the shorter the distance from the heat exchange surface, the higher the heat dissipation).

The experimental measurements also served as verification measurements to determine whether the air pressure nozzle system can be used as a full-fledged replacement for the conventionally used fan. The results showed that the nozzle system fully replaces the fan in the cooling process and even achieves improved heat dissipation, making the cooling process significantly shorter and more efficient. In addition to being a full-fledged replacement for the fan, the air pressure nozzle system can also be used as an additional equipment for intensification of heat dissipation in combination with the fan.

3.4. Combination of the Staggered Arrangement of the Nozzles and Fan

Figure 8 compares the coolant outlet temperatures during cooling process by the mutual combination of the nozzles in the staggered arrangement and the fan. The distances of the nozzles from the heat exchange surface of the cooler were in the range of 60 mm to 170 mm. We assumed that this combination of cooling equipment would be the most efficient of the options investigated. As with the combination of inline staggered nozzle and fan, no higher cooling efficiency was observed when the fan was used alone. All of the distances investigated achieved higher cooling efficiencies, but the outlet temperatures differed only minimally when compared with each other. The longest cooling time was recorded at a nozzle spacing of 70 mm; a value of $T_{out} = 42.38\text{ }^{\circ}\text{C}$ was reached at a time of 47 min. On the contrary, the nozzle spacing of 140 mm was the most effective, when the outlet temperature value was $1.08\text{ }^{\circ}\text{C}$ lower ($T_{out} = 41.40\text{ }^{\circ}\text{C}$) at the same time. With the distance of the staggered nozzles arranged 140 mm and the fan, the outlet temperature of the coolant was $T_{out} = 50.36\text{ }^{\circ}\text{C}$ at the time of 46 min (30 s after the start of the cooling process), which is $17.61\text{ }^{\circ}\text{C}$ less than that of using only a separate fan.

A single fan removes most of the heat only from the surroundings of the heat exchange surface or its second row of tubes, which makes its cooling efficiency significantly lower compared to a system of air pressure nozzles. Also, when only the fan is used, the entire heat exchange surface is not thoroughly covered with air due to the different construction shapes of the fan and the cooler. For this reason, a number of empty spots are created on the surface of the cooler, which are not sufficiently covered by the air flow from the fan. Another disadvantage of the fan itself is the lack of heat dissipation from the entire first row of cooler tubes, since the fan primarily removes hot air from behind the heat exchange surface and not from its core. To eliminate these deficiencies, we have developed a system of air pressure nozzles that cause complete removal of the hot air from the core of the heat exchange surface of the cooler. The airflow from the nozzles also covers the empty spots on the cooler from which the fan cannot remove the hot air. In addition to a more efficient cooling process (shorter coolant cooling time) by means of the air nozzle system, there is also the advantage of increasing the time for the necessary cooler re-cooling. Since, by cooling the entire cooler volume (not just part of it as in the case of the fan), the time for reheating the coolant in the small cooling circuit will be longer, causing a reduction in the number of cooling cycles and thus an increase in the efficiency and economy of the internal combustion engine operation.

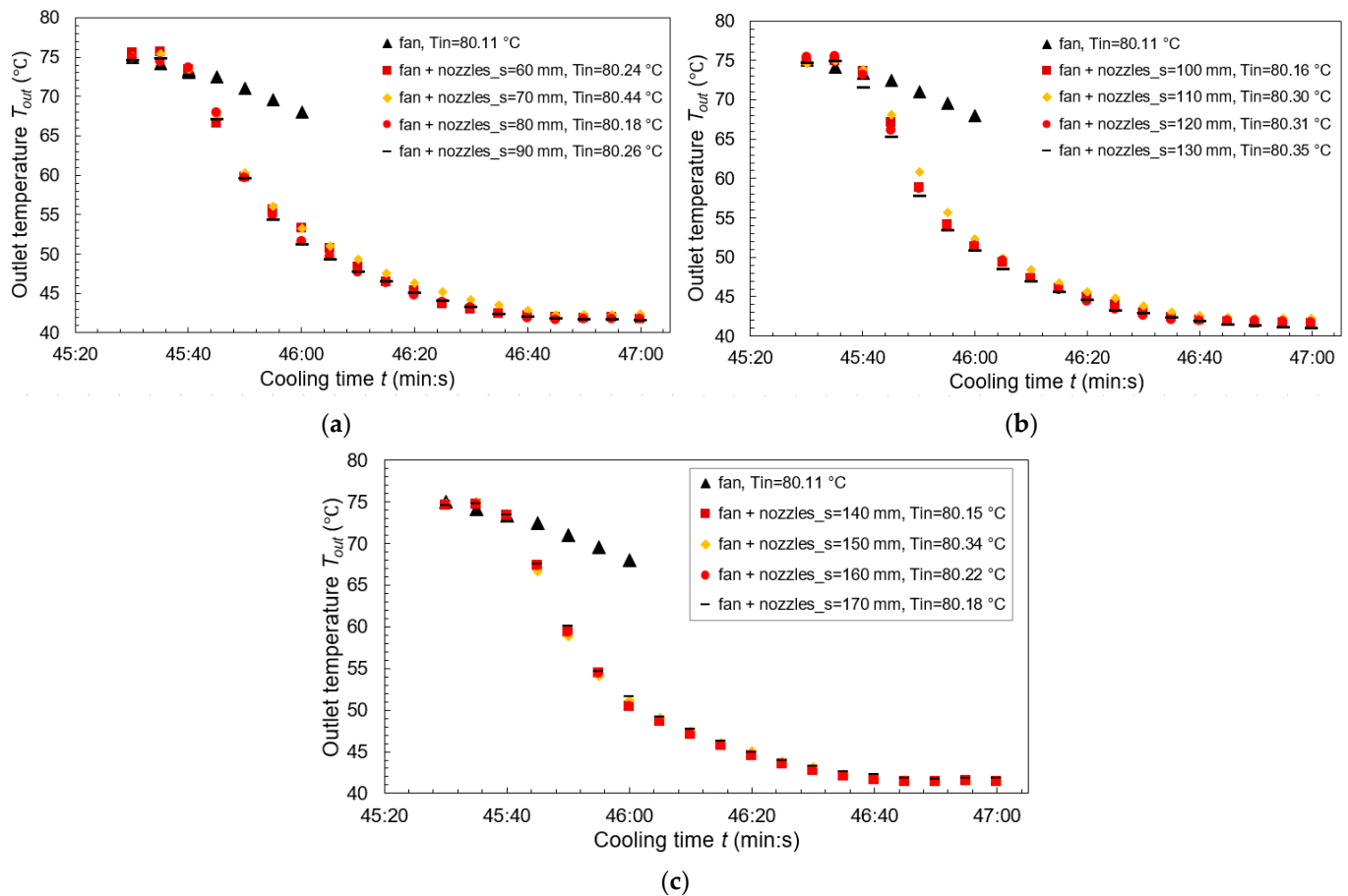


Figure 8. Comparison of the outlet cooler temperatures T_{out} for mutual fan and nozzles combination when varying the spacing of the staggered arrangement nozzles from the cooler: (a) Nozzle spacing 60 mm to 90 mm compared to the fan; (b) Nozzle spacing 100 mm to 130 mm compared to the fan; (c) Nozzle spacing 140 mm to 170 mm compared to the fan.

3.5. Comparison of the Combinations of Cooling Systems Studied

Figure 9 compares the outlet temperatures of the selected most efficient spacing for inline and staggered arrangement of the nozzles. Figure 9a compares the outlet temperatures of the coolant when using nozzles in an inline arrangement ($s = 160$ mm), when combining nozzles in an inline arrangement ($s = 160$ mm) and a fan, and when using a fan alone. It is important that the coolant temperature at the cooler outlet decreases as quickly as possible. The forced cooling time may be different depending on the volume of coolant in the circuit, engine load, ambient conditions, wear of the cooling circuit and its components. In a time of 46 min (30 s after the start of cooling) at a spacing of $s = 160$ mm, the outlet temperature of the cooled coolant reached a value of 63.48 °C when using nozzles in an inline arrangement. Compared to the fan, this represents a temperature decrease of 3.70 °C when a value of $T_{out} = 67.18$ °C was recorded at the same time. The combination of air nozzles and fan ($s = 160$ mm) reached $T_{out} = 50.59$ °C in 46 min, representing a decrease of 12.59 °C in the coolant temperature at the outlet of the cooler compared with the nozzle set alone, and a decrease of 16.59 °C compared with the fan set alone. Figure 9b compares the coolant outlet temperatures when using nozzles in a staggered arrangement ($s = 160$ mm), when combining nozzles in a staggered arrangement ($s = 140$ mm) and a fan, and when using the fan alone. The graphical plot for the staggered arrangement nozzles ($s = 160$ mm) shows a higher cooling efficiency at 46 min compared to the fan by 4.25 °C (Figure 9b). Comparing the nozzles in the inline arrangement (Figure 9a) and the nozzles in the staggered arrangement (Figure 9b) at the same spacing of 160 mm and the same cooling

time, the nozzles in the staggered arrangement achieved $T_{out} = 62.93\text{ }^{\circ}\text{C}$, which is $0.55\text{ }^{\circ}\text{C}$ less compared with the nozzles in the inline arrangement ($T_{out} = 63.48\text{ }^{\circ}\text{C}$).

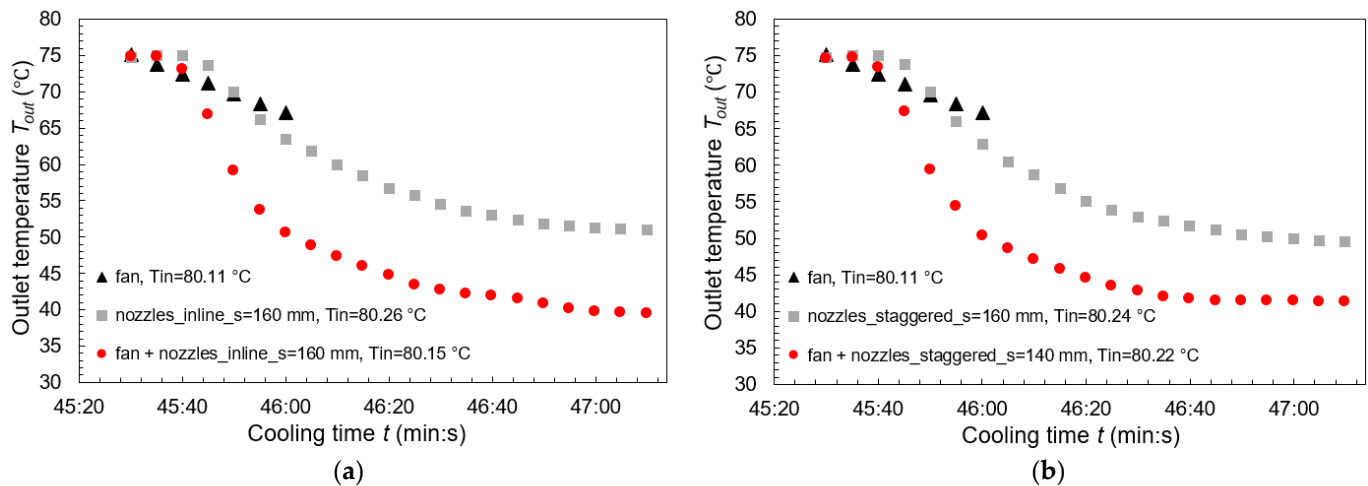


Figure 9. Comparison of the outlet cooler temperatures T_{out} for the most effective spacing for inline and staggered arrangement of the nozzles: (a) Nozzle inline spacing 160 mm and mutual combination nozzle inline spacing 160 mm and fan compared to the fan; (b) Nozzle staggered spacing 160 mm and mutual combination nozzle staggered spacing 140 mm and fan compared to the fan.

The most effective spacing $s = 140\text{ mm}$ for the combination of nozzles in the staggered arrangement and the fan was found (Figure 9b). The combination of the nozzles in the staggered arrangement and the fan (Figure 9b) achieved an outlet temperature of $50.36\text{ }^{\circ}\text{C}$ in 46 min, which is $0.23\text{ }^{\circ}\text{C}$ less compared to the combination of the inline nozzles arranged with the fan (Figure 9a). The cooling process by the nozzles (staggered) alone at a spacing of 160 mm achieved a value of $T_{out} = 62.93\text{ }^{\circ}\text{C}$ in a time of 46 min, while the combination of the nozzles (staggered) and the fan at a distance of 140 mm achieved a value of $T_{out} = 50.36\text{ }^{\circ}\text{C}$, which is $12.57\text{ }^{\circ}\text{C}$ less. From the values of the outlet temperatures of the cooled coolant, it can be concluded that the best nozzle arrangement is staggered (due to the wider coverage of the heat exchange surface by the cooling air stream). The lowest coolant outlet temperatures in the shortest time (fastest heat dissipation from the coolant) were achieved with the staggered nozzle arrangement.

The next important temperature is the coolant temperature recorded in the cooler inlet pipe (Figure 10). When T_{in} decreased below the operating value of $80\text{ }^{\circ}\text{C}$, we know that the thermostatic valve is closed and does not allow additional coolant into the cooler. The thermostatic valve closes when cooled coolant from the cooler outlet reaches its inlet. Even though a small amount of cooled coolant is able to flow back into the cooler inlet pipe, there is coolant in the pipe at the operating temperature limit. In order for the coolant of the long cooling circuit to be ready to be re-injected by the water pump after the thermostat has released the hot coolant, it is necessary to cool the coolant located in the inlet and outlet pipes but primarily in the heat exchange surface of the cooler. Figure 10 evaluates the inlet temperatures during the cooling process for the best nozzle spacing from the heat exchange surface with the shortest cooling time compared to the fan.

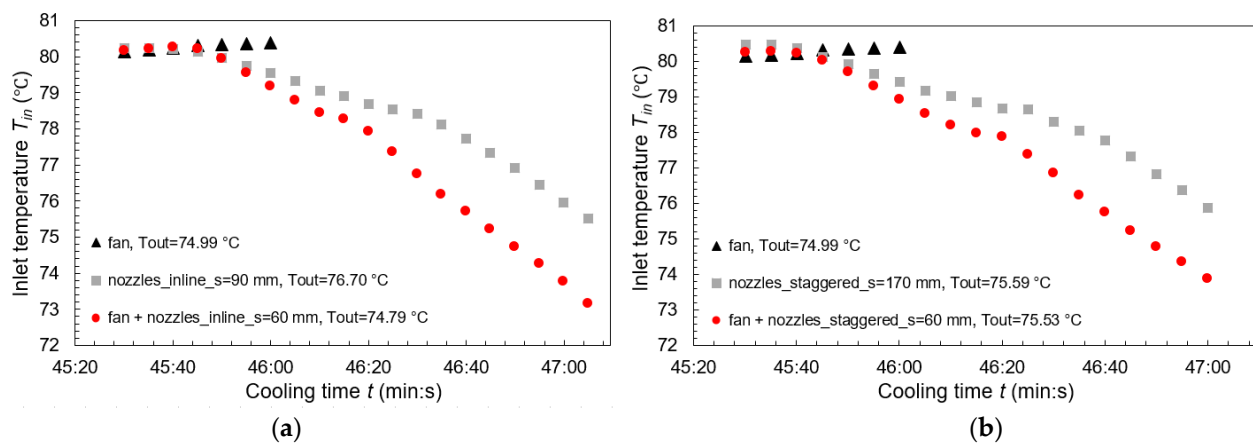


Figure 10. Comparison of the inlet cooler temperatures T_{in} for the most effective spacing for inline and staggered arrangement of the nozzles: (a) Nozzle inline spacing 90 mm and mutual combination nozzle inline spacing 60 mm and fan compared to the fan; (b) Nozzle staggered spacing 170 mm and mutual combination nozzle staggered spacing 60 mm and fan compared to the fan.

Figure 10a shows that the most effective cooling in the inlet pipe was observed for nozzles arranged inline at a spacing of $s = 90$ mm (nozzles alone) and $s = 60$ mm (combination of inline nozzles and fan). For the nozzle in staggered arrangement (Figure 10b), the fastest cooling was observed at $s = 170$ mm (nozzle alone) and $s = 60$ mm (combination of staggered nozzles and fan). After a lapse of 30 s at a time of 46 min, the temperature at the inlet of the cooler with the fan running was $T_{in} = 80.39$ °C. Hence, the thermostatic valve remained open and the coolant was not cooled below the required operating temperature, which reduced the efficiency of engine operation. Cooling by the air nozzle system at a spacing of 90 mm (inline arrangement) at a time of 46 min achieved a value of $T_{in} = 79.54$ °C, an improvement of 0.85 °C compared to the fan (Figure 10a). In this case, the thermostatic valve was fully closed and the coolant circulated only in a short cooling circuit, ensuring optimum engine operation.

Cooling by the combination of nozzle (inline) and fan at a spacing of 60 mm at the same time achieved a value of $T_{in} = 79.18$ °C, an improvement of 1.29 °C compared with the fan. For the nozzle staggered arrangement at a distance of 170 mm, the lowest value of $T_{in} = 79.43$ °C was recorded at a time of 46 min, an improvement of 0.96 °C compared to the fan and 0.11 °C compared to the nozzles at a distance of 90 mm (inline). For the combination of nozzle ($s = 60$ mm, staggered) and fan, a value of $T_{in} = 78.93$ °C was recorded, which represents a decrease and thus an improvement of 1.46 °C compared to the fan and 0.25 °C compared to the nozzle ($s = 60$ mm, inline) and fan.

Figure 11 represents the temperature differences of the coolant between the inlet and outlet tubes of the cooler when cooling with an air nozzle system (Figure 11a) and when cooling with a mutual combination of air nozzles and a fan (Figure 11b). The values are also compared with cooling using only the fan. From Figure 11a, it can be seen that the temperature difference increases with the spacing of the nozzles from the heat exchange surface of the cooler ($s = 60$ mm and $s = 160$ mm). As the distance of the nozzles from the cooler increases, complete coverage of the heat exchange surface by the air flow is ensured, which leads to a reduction in the cooling time of the coolant and an increase in the temperature difference.

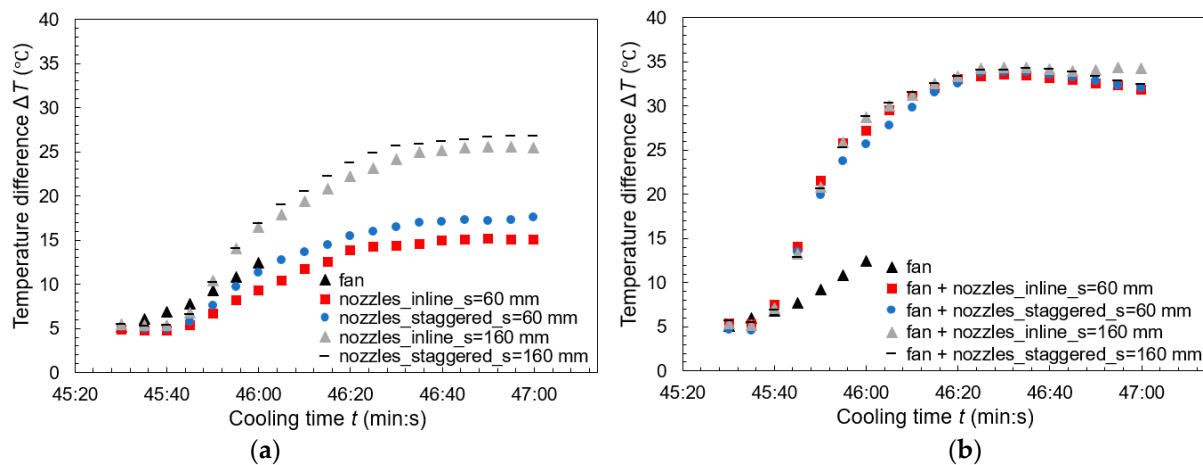


Figure 11. Comparison of the temperature difference ΔT for spacing 60 mm and 160 mm for all combinations investigated: (a) inline and staggered nozzles compared to the fan; (b) mutual combination of inline and staggered nozzles and fan compared to the fan.

When comparing the temperature differences for the fan and nozzle in an inline and staggered arrangement over a time of 46 min, the maximum $\Delta T = 16.9$ °C and 16.49 °C are achieved by the nozzles at a spacing of 160 mm in the staggered and inline arrangements, respectively. A minimum spacing of 60 mm is even less efficient than using only the fan (Figure 11a).

When comparing the temperature differences for the fan and combination fan and nozzles in an inline and staggered arrangement over a time of 46 min, the maximum $\Delta T = 28.84$ °C and 28.72 °C are achieved by the combination of fan and nozzles at a spacing of 160 mm in the staggered and inline arrangements, respectively (Figure 11b).

The thermal performance of the investigated combinations was expressed by [48]:

$$\varepsilon = \frac{Q}{Q_{\max}} = \frac{m_c \cdot c_{p,c} (T_{c,in} - T_{c,out})}{C_{\min} (T_{c,in} - T_{a,in})}, \quad (1)$$

where $C_{\min} = C_c$ for smaller heat capacity rate of hot coolant side,

$$C_{\min} = m_c \cdot c_{p,c}, \quad (2)$$

and Q —heat transfer rate, W; ε —thermal performance; m_c —mass flow rate of coolant, kg/s; $c_{p,c}$ —specific heat capacity at constant temperature of coolant, J/(kg·K); $T_{c,in}$ —coolant inlet temperature to the cooler, K; $T_{c,out}$ —coolant outlet temperature to the cooler, K; $T_{a,in}$ —air inlet temperature, K; C_c —heat capacity rate of coolant, W/K.

The maximum uncertainty of heat transfer rate is 6.96% for the lowest temperature difference between inlet and outlet coolant temperature.

The thermal performance of the investigated combinations (nozzles inline and staggered, fan with nozzles inline and staggered) for the spacing between the air nozzles and the cooler $s = 60$ mm and $s = 160$ mm calculated according to the Equations (1) and (2) is summarised in Table 1. The thermal performance increased as the spacing between the air nozzles and the cooler increased. When comparing 60 mm and 160 mm spacing, there was an increase in thermal performance of 70.3%, 55.99%, 6.20%, and 1.83% for inline nozzles, staggered nozzles, fan with inline nozzles, and fan with staggered nozzles, respectively. It can be concluded that the spacing between the air nozzles and the cooler and the method of cooling when using only air nozzles (without fan) are important aspects. When using air nozzle cooling with fan, the thermal performance is increased up to 1.4 times and 1.3 times compared to only nozzle cooling or inline and staggered arrangements for $s = 160$ mm.

Table 1. Thermal performance of the investigated combinations for spacing between the air nozzles and cooler of 60 mm and 160 mm.

	Nozzles Inline	Nozzles Staggered	Fan with Nozzles Inline	Fan with Nozzles Staggered	Nozzles Inline	Nozzles Staggered	Fan with Nozzles Inline	Fan with Nozzles Staggered
Temperature difference ΔT [°C]	15.09	17.62	32.97	33.84	25.41	26.96	34.31	33.93
Heat transfer rate Q [W]	35,842	41,851	78,311	80,377	60,354	64,036	81,494	80,591
Maximum heat transfer rate Q_{max} [W]	134,627	135,577	131,136	133,535	133,345	132,941	128,499	131,397
Thermal performance ε [-]	0.266	0.309	0.597	0.602	0.453	0.482	0.634	0.613
Spacing between nozzles and cooler	$s = 60$ mm				$s = 160$ mm			

4. Conclusions

The constructed and studied air pressure nozzle system achieved an improvement in the cooling process compared to a conventional fan. The results showed that the nozzle system fully replaces the fan in the cooling process and even achieves improved heat dissipation, making the cooling process significantly shorter and more efficient. In addition, the air nozzle system can also be used as an additional equipment for intensification of heat dissipation in combination with the fan.

The most significant results of the research can be summarised as follows:

- Inline arranged nozzles with a spacing of 130 to 170 mm achieved an improvement in the cooling process of about 5 °C compared with the fan in a time of 46 min.
- Staggered nozzle arrangement solves the problem of empty spots on the cooler that are not covered by air in the case of an inline arrangement. The staggered arrangement of the nozzles with spacing of 80 mm to 170 mm have reached a more effective cooling efficiency throughout the entire cooling process compared to the fan. At a spacing of 160 mm of the staggered arranged nozzles, the cooling process was improved by more than 6 °C compared with the fan in 46 min. When compared with the minimum spacing of 60 mm, the spacing of 160 mm of staggered arranged nozzles showed an improvement in the cooling process of nearly 10 °C.
- The combination of the inline arrangement of the nozzles and fan provided a decrease in the cooler outlet temperature of 17.38 °C for a spacing of 160 mm in a time of 46 min compared to fan-only cooling.
- The combination of the staggered arrangement of the nozzles and fan provided a cooler outlet temperature reduction of 17.61 °C for a 140 mm spacing in a time of 46 min compared to fan-only cooling. Further increase in the spacing was already causing an increase in the cooler outlet temperature and deterioration of the cooling process.
- As the distance of the nozzles from the cooler increases, complete coverage of the heat exchange surface by the air flow is ensured, which leads to a reduction in the cooling time of the coolant and an increase in the temperature difference.
- When comparing the temperature differences for the fan and nozzle over a time of 46 min, the maximum $\Delta T = 16.9$ °C and 16.49 °C are achieved by the nozzles at a spacing of 160 mm in the staggered and inline arrangements, respectively. A minimum spacing of 60 mm is even less efficient than using only the fan.
- When comparing the temperature differences for the fan and combination fan and nozzles over a time of 46 min, the maximum $\Delta T = 28.84$ °C and 28.72 °C are achieved by the combination of fan and nozzles at a spacing of 160 mm in the staggered and inline arrangements, respectively.

- The thermal performance increased as the spacing between the air nozzles and the cooler increased up to a spacing of 160 mm. Over this value, the cooling process already deteriorates. When comparing 60 mm and 160 mm spacing, there was an increase in thermal performance of 70.3%, 55.99%, 6.20% and 1.83% for inline nozzles, staggered nozzles, fan with inline nozzles and fan with staggered nozzles, respectively.

The air pressure nozzle system can be used in automobiles or as an additional equipment in machines and devices where it is necessary to intensify heat dissipation. For example, if the original heat dissipation equipment is no longer sufficient (its efficiency has decreased due to long-term operation under load), or its replacement with new equipment would not bring an effect. Another reason may be the need to increase the performance of the equipment where excessive heat is produced and the construction dimensions do not allow the installation of a larger cooler or fan. In addition to the cooling function, the compressed air also purifies the outer surfaces of the fins and tubes of the cooler. The pressurized air nozzle system can also be used for machines and equipment where there is extreme contamination of their external heat exchange surfaces. For machines and equipment equipped with a pneumatic circuit (e.g., brake circuit), the installation of a set of air nozzles for cooling and cleaning of heat exchange surfaces is fast, efficient and economically inexpensive. By removing impurities from the external heat exchange surfaces of the cooler, we set the conditions for more intense heat transfer and longer cooler lifecycle.

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