STUDY ON DIESEL CYLINDER-HEAD COOLING USING NANOFLUID COOLANT WITH JET IMPINGEMENT

by

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To improve the heat-transfer performance of a Diesel engine cylinder head, nanofluid coolant as a new fluid was investigated, and jet impingement technology was then used to study on how to better improve heat-transfer coefficient at the nose bridge area in the Diesel engine cylinder head. Computational fluid dynamic simulation and experiments results demonstrated that using the same jet impingement parameters, the different volume shares of nanofluids showed better cooling effect than traditional coolant, but the good effect of the new cooling method was unsuitable for high volume share of nanofluid. At the same volume share of nanofluid, different jet impingement parameters such as jet angles showed different heat-transfer performance. This result implies that a strong association exists between jet impingement parameters and heat-transfer coefficient. The increase in coolant viscosity of the nanofluid coolant using jet impingement requires the expense of more drive-power cost.

Key words: *cooling, cylinder head, Diesel engine, heat transfer, jet impingement, nanometer*

Introduction

To solve the problem of high heat density in the key components of a Diesel engine, *e. g*., cylinder and cylinder head [1], developing a highly efficient and accurate cooling system has become a focus [2-9]. Among the possible solutions, the use of a new type of coolant is one of the breakthrough points. Many papers described that mixing metal nanoparticles with traditional coolant can definitely increase heat-transfer coefficient and can provide more feasibility of developing more compact radiators and engines [4]. Many papers call this new coolant type as nanofluid [5-11]. Because jet impingement technology can enhance heat-transfer coefficient, it is considered as one of the best cooling technologies to solve local high heat density problems [12]. In the present study, these two technologies were integrated to solve the high heat density problem of a Diesel engine cylinder head using a test experimental system that we developed to explore the changing characteristics of heat-transfer coefficient using nanofluids with jet impingement technology. Many studies on nanotechnology, jet impingement technology, and their combination have been made globally. Among these representative works, Kim *et al*. [13] used

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three substances (alumina, silica, and diamond) to prepare three types of nanofluids and performed many heat-transfer experiments. The results revealed that the values of the heat-transfer coefficients of nanofluids are larger than those of pure water. Chun *et al*. [14], Nyuyen *et al*. [15], Katti and Prabhu [16], Lee *et al*. [17] and Gherasim *et al*. [18] demonstrated that using Si nanofluids with a tiny pipe flow can improve the heat-transfer characteristics of traditional water coolant. Using theoretical calculations, Palm [19] showed that suspended metallic nanofluids can effectively enhance the heat-transfer capacity in laminar flow state. Yang [20] developed a single-phase mathematical model in a radial-flow cooling system and simulated the heat-transfer capacity of nanofluid. His research results indicated that nanofluids can effectively enhance the heat-transfer characteristics. Kathiravan *et al.* [21] researched the boiling heat-transfer characteristics of pure water and nanofluids. The experimental results showed that carbon nanotubes can effectively enhance the heat-transfer characteristics of pure water.

The technological studies on jet impingement region are summarized: Koseoglu [22] investigated the effect of convective heat-transfer coefficient using jet impingement technology. Haustein [23] developed a heat-transfer coefficient measuring system at transient and steady-state flow using jet impingement technology. The research results indicated that using jet technology can effectively improve the heat-transfer coefficient. By comparing the Reynolds number and the heat-transfer effect, Katti and Prabhu [16] described the good heat dissipation performance of jet impingement. Lee *et al.* [17] researched on an unsteady 2-D flow model using a numerical simulation calculation method, which also showed that the use of jet impingement can achieve good heat-transfer characteristics.

The research results on the combination of nanofluid and jet impingement technologies are summarized: Li [24] performed a jet impingement cooling test using Cu nanofluid coolant, the result revealed that these two technologies can realize better heat-transfer coefficient, the highest rise was more than 30%. Mitra *et al*. [25] compared the boiling heat-transfer characteristics of water-TiO_2 and water-multi-walled carbon nanotube nanofluid. Also he comparatively studied the differences in heat transfer and boiling heat transfer using jet impingement and nanofluid technology, the results told that the average heat transfer of test system rose 12.4% after using nanofluid. Nguyen *et al.* [26] compared the heat-transfer characteristics in horizontal, vertical, and circular planes using jet impingement and nanofluid technologies. His test result mean using nanofluid and jet impingement technologies, the heat transfer coefficient of different type plane had obvious differences, that was to say, if you want to obtained better heat transfer performance, you must be under appropriate operating parameters using nanofluid and jet impingement technologies. Gherasim *et al*. [18] verified that combining jet impingement and nanofluid technologies can effectively enhance heat-transfer performance using numerical simulation, the researched results displayed that the average heat transfer coefficient rose 13.8%. Bellerova *et al*. [27] performed experiments and theoretical calculations to comparatively study how a jet impingement nozzle can improve the heat-transfer characteristics, result told that jet impingement nozzle with proper structure parameter can get better heat transfer performance than traditional cooling method.

Through these above-mentioned studies, we learned that the combination of jet impingement and nanofluid technologies can improve heat-transfer ability in high heat density areas. Thus, this advanced technology was applied to solve the cooling problem in areas with high heat density in a Diesel engine cylinder head. To study the performance of nanofluids with jet impingement, some effective works had been done. First, numerical simulation was used to research the effect of nanofluids and jet impingement technology on the heat-transfer coefficient of a Diesel engine cylinder head. Second, using calculation, we learned that the application of nanofluid coolant with jet impingement technology can effectively improve the heat-transfer coefficient in the nose bridge region of a Diesel engine cylinder. Third, we performed test experiments to verify the change trend of heat-transfer coefficient in a diesel cylinder-head using nanofluids with jet impingement. In this experiment, we developed multiple-hole jet impingement technology using nanofluids (Cu-ethylene glycol coolant) as engine coolant. Investigated the jet impingement cooling effect under different parameters such as jet impingement flow rate, jet impingement distance, jet impingement angles, *etc*., and briefly introduced the effect of using nanofluids on the power loss of an electronic-drive unit pump. The research results provided us with reference scientific ideas for in-depth study of future high performance of Diesel engine cooling systems.

Simulation analysis

Cylinder head temperature calculation

In this work, a six-cylinder turbocharged Diesel engine is studied. The commercial software FLUENT is used to establish the model and simulate the temperature field of the cylinder head. We use traditional coolant in the traditional cooling method, nanofluid coolant in the traditional cooling method, and nanofluid coolant with jet impingement, as shown in figs. 1 and 2.

The specific parameters of the Diesel engine are listed in tab. 1.

Table 1. Test Diesel engine performance parameters

	Vertical, inline, water cooled, four stroke, direct injection
Number of cylinders	6
Displacement (L)	7.255
Calibrated power/speed [(kW/rpm]	177/2300
Maximum torque/speed [(Nm/(r/min)]	890/1400-1600

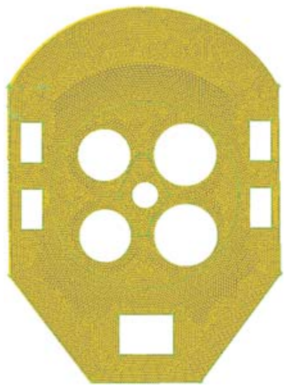

Figure 1. Geometry model and mesh grid

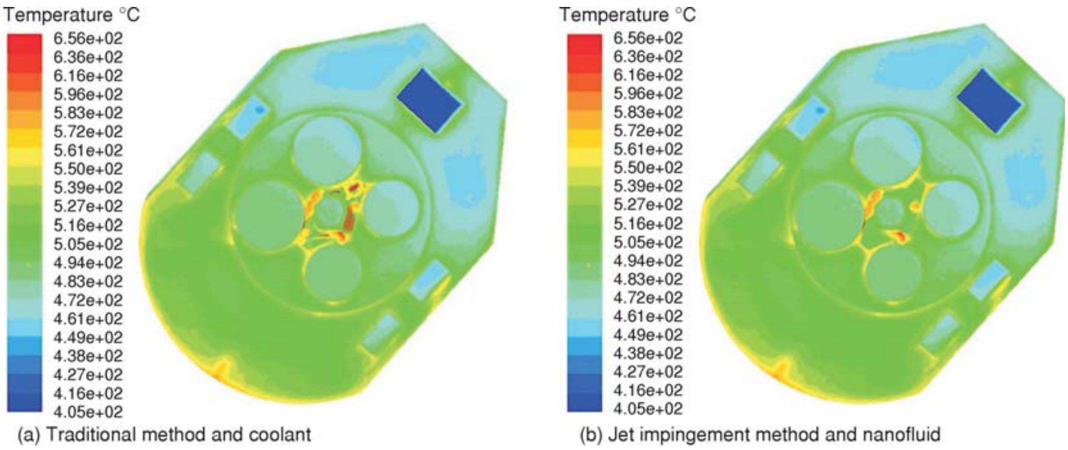

Figure 2. Calculation of the temperature field

The physical parameters of the configured nanofluid coolant are listed in tab. 2, and the new coolant type has to be revised in the software.

Table 2. Thermal properties of nanofluid coolant at a temperature of 300 K under different volume fractions

Volume fraction, φ [%]	0.5	1.0	1.5	2.0	2.5	3.0
Thermal conductivity, K_{nf} [(W/(mK)]	0.670	0.712	0.735	0.764	0.777	0.812
Nanofluid flow mixture density, ρ_{nf} [kg/m^3]	982.4	1062.7	1094.2	1145.8	1176.2	1223.3
Mixed-liquor constant pressure heat capacity, c_{pnf} [(kJ/(kgK)]	4.194	4.152	4.121	4.092	4.085	4.076

Note: In this study, Cu and ethylene glycol-water (base fluid) were composed of nanofluid coolant

In the calculation process, we consider the maximum torque operating point of the Diesel engine as the cylinder head calculation working point. We assume that the coolant is an incompressible fluid and its flow state is turbulent. The turbulent model uses the standard k-ε model. The boundary conditions are the following. The mass flow rate of the coolant into the inlet of the cylinder head is 3.8 kg/s, and the temperature is 355 K. The coolant pressure at the outlet is 122,233 Pa. In this working condition, the average temperature of the cylinder that contacts the fire surface is 1054 K, and the average convection heat-transfer coefficient is 5727 W/(m^{2}K). At the inlet port, the average temperature of air is 324 K, and the average convection heat-transfer coefficient is 3743 W/(m^{2}K). At the outlet port, the average temperature of air is 702 K, the average convection heat-transfer coefficient is 4920 W/(m^{2}K), and the set temperature in the surrounding environment is 304 K. The calculations in this study are described. First, we establish a thermodynamic model and calculate the whole cooling system using the commercial software AVL Fire. We obtain the rough heat-transfer situation of the cooling system in the cylinder head. Second, we map the calculated convective heat-transfer coefficient and coolant temperature into the cavity surface of the cylinder as the third category of thermal boundary conditions. Finally, we use the UDF program of the FLUENT to establish the temperature field model of the cylinder head. We encode the temperature field programs. Thus, the cylinder-head surface temperature field is calculated by FLUENT.

Figure 2 shows the temperature field distribution at the cylinder surface before and after the theoretical calculations. The results show that the temperature at the spacing interval of the intake and exhaust valves is the highest. The simulation results indicate that the use of nanofluids with jet impingement decreases the temperature range, which is bigger than that using traditional coolant in the traditional cooling method. This result shows that using nanofluids with jet impingement can increase the heat-transfer coefficient in a cylinder head with high heat density. To more clearly understand the contrasting results of the heat-transfer coefficient using different coolants and cooling methods, especially the heat-transfer coefficient, we perform the comparison written in the UDF program.

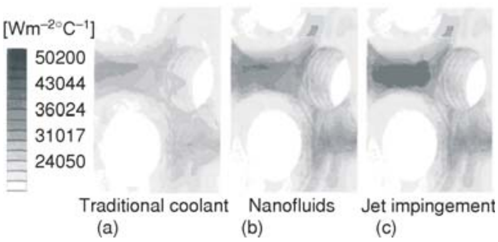

Figure 3. Comparison of the heat-transfer coefficient simulated values under three cooling experiments

Figure 3 shows the calculated values of the heat-transfer coefficient at the nose bridge between the intake and exhaust valves of the first cylinder head before and after the experiment using different coolants and different cooling methods. Figure 3(c) shows that after using nanofluids as coolant with jet impingement, the calculated value at the nose bridge between the inlet and outlet valves of cylinder head has improved.

Figure 4 shows that the internal flow structure inside the jet impingement chamber.

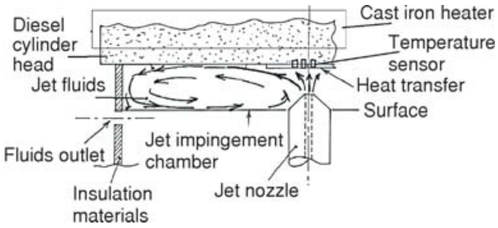

Figure 4. View of the internal flow structure inside the jet impingement chamber

From the theoretical calculations, we can observe the trend of the heat-transfer coefficient when nanofluids are used as a cooling fluid. Although, we can verify the change trend of the heat-transfer coefficient using nanofluids with jet impingement, this conclusion must be further proven by experiments.

Heat-transfer coefficient description

Average convective heat-transfer coefficient h, can be calculated from the following Newton's cooling law:

$$h = \frac{Q}{A(T_s - T_f)} = \frac{UI}{A\left(T - \frac{T_{in} + T_{out}}{2}\right)} = \frac{UI}{\pi\left(\frac{D_s}{2}\right)\left(T_s - \frac{T_{in} + T_{out}}{2}\right)} \tag{1}$$

where Q is the cast-iron heater power and U and I, are the cast-iron heater voltage and current, respectively, A is the area of the heater surface, and T_s, T_f, T_{in}, and T_{out} are the average temperature of the heated surface, temperature of the coolant, and the inlet and outlet temperatures of the fluid, respectively.

The Reynolds number and the averaged Nusselt number are defined:

$$\text{Re}_{nf} = \frac{v_f D}{v_{nf}} \tag{2}$$

$$\text{Nu}_{nf} = \frac{hD}{k_{nf}} \tag{3}$$

where v_f is the mean impinging velocity, D – the nozzle diameter. v_{nf} – the viscosity of the nanofluid, and k_{nf} – the thermal conductivity of the nanofluid. The experimental data of the thermal conductivity and the viscosity of the nanofluids are obtained from the reference [12, 21, 22, 24].

The following equations are used to compute the density, specific heat, and thermal diffusivity of the nanofluid:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{4}$$

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_p \tag{5}$$

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} = \frac{k_{nf}}{(1-\phi)(\rho C_p)_f + \phi(\rho C_p)_d} \tag{6}$$

Test system

Experimental test system

The composition and structure of the nanofluid cooling jet impingement experimental system is shown in fig. 5. Through the variable-speed electric pumps, different jet impingement fluid velocities exit from the jet nozzle to the heating surface. The heat can be transferred from the heating surface, and cooling of the hot surface can be achieved. The flow-control system stabilizes the jet working fluids to ensure constant jet-working fluid flow. A high-precision constant temperature box stabilizes the working-fluid temperature and adjusts the temperature value according to the experimental need. A high-precision liquid-mass flow meter is used to accurately test the jet working-fluid flow. To ensure accuracy of the experiment data, a high-precision NI (National Instruments) data acquisition is introduced.

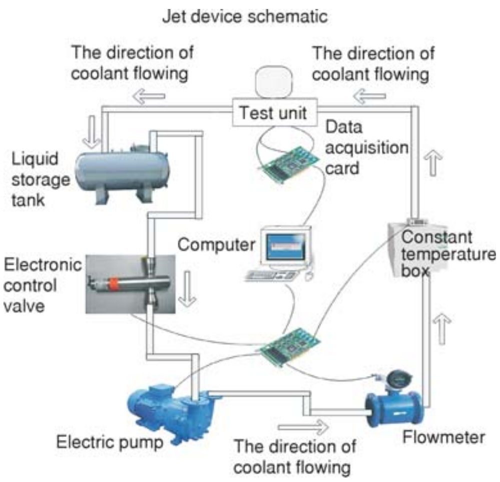

Figure 5. Bench schematic

The cooling-fluid flow is varied by the electronic pump through the flow control valves to adjust the cylinder cooling-fluid exhaust back pressure, and a cast-iron heater is used to replace the cylinder-head heat source.

The test systems mainly include the heating, jet, and insulation parts. The heating part includes the cast-iron heater, which is used to simulate the cylinder engine heat produced by burning. The jet part includes the working-fluid entrance, nozzle, jet room, exhaust, and stepping motor to control the nozzle movement. The insulation part ensures that all heat is transferred to the simulated cylinder head. Figure 6(a) shows the jet impingement devices and jet chamber structure. Figure 6(b) shows the heat-transfer physical model of this jet test device.

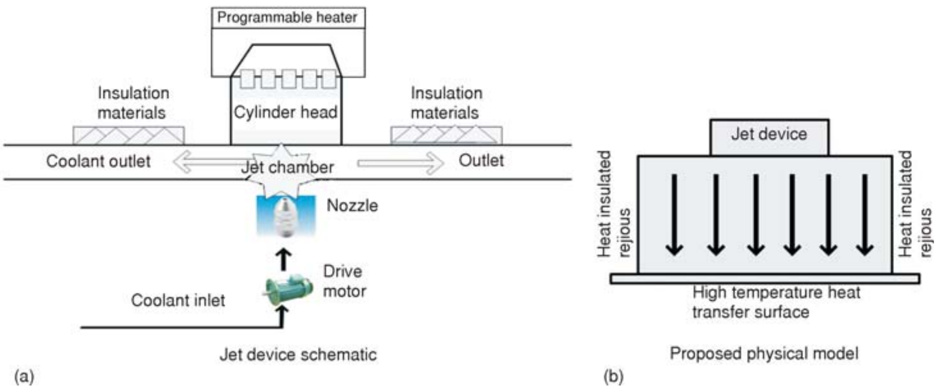

Figure 6. Schematic of the jet device schematic and proposed physical model

The test points for the cylinder-head temperature are shown in fig. 7. The locations of the jet-hole layout are shown in fig. 8. The temperature range of the high-precision surface was

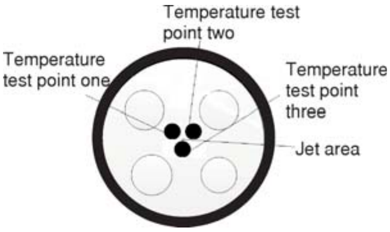

Figure 7. Temperature sensor layout positions at the cylinder head

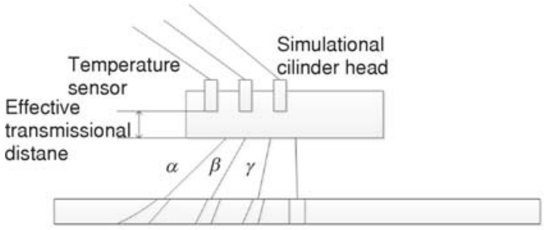

Figure 8. Jet-hole distribution location
α **= 30°,** β **= 50°,** γ **= 70°**

–20-600 °C, with precision ±0.1 °C, and the sensitivity is 0.1 s. In experiments, main parameters have been changed as follows: jet impingement heights (2.2, 4.1, 6.2, and 8.1 mm), jet impact angles (30°, 50°, 70°, and 90°), and jet velocities (2.7, 3.4, 4.1, 4.8, 5.5, 6.2, 6.9, and 7.6 m/s). All Experimental errors are given in tab. 3.

Table 3. Estimation of the experimental errors

Sources of errors	Explanation	Smallest measured data	Relative error
Voltage	The smallest scale is 0.1 V	100 V	0.1%
Current	The smallest scale is 0.01 A	1 A	1%
Length	The smallest scale is 0.01 mm	Dc = 16 mm D = 2 mm	0.125%
Temperature	The minimum scale is 0.2 °C	10 °C	2%
Velocity	The minimum scale is 0.02 m/s	3.32 m/s	0.6%
Thermal conductivity	–	–	3%
Viscosity pressure drop	The minimum scale is 87 Pa	3236 Pa	2.6%

Calculation specification for heat transfer coefficients

Because of thermal insulating materials, the heat transfer of programming heater can be simplified to 1-D heat conduction in the condition that programming heater is perpendicular to the simulation of cylinder head, physical model for heat transfer can be expressed as fig. 6(b).

Assume thermal density of heat transfer can be expressed:

$$q_1 = \frac{UI}{A} = \frac{Q}{\pi R^2} \tag{7}$$

where Q is the heat transfer power, A – the lower surface area of cylinder head, R – the cylinder head radial, and q_1 – the heat quantity of cylinder head from heat transfer.

In actual calculation, temperature sensor embedded in the cylinder head simulation, there is a distance (effective transmission distance) between sensor probe and jet surface, which means that sensor probe was not exposed to jet medium, when the medium was jet to the cylinder head surface, effective transmission distance was needed before the temperature sensor probe got the high heat, thermal resistance would be produced by this distance, the heat quantity can be expressed:

$$q_2 = -k\frac{\mathrm{d}T}{\mathrm{d}x} = -k\frac{T_\mathrm{s} - T_\mathrm{c}}{\delta} \tag{8}$$

where q_2 is the retention heat from thermal resistance, k – the heat transfer coefficient of cylinder head, T_s – the temperature of jet surface, T_c – the test temperature of sensor, and δ – the effective transfer distance.

The temperature of jet surface can be expressed:

$$T_s = T_c - k\frac{\Delta q\delta}{k} = T_s - \frac{(q_1 - q_2)(\delta_1 - \delta_2)}{k} \tag{9}$$

where δ_1 is the width of cylinder head, and δ_2 – the depth of temperature sensor inserted into the cylinder head .

The average value of nozzle inlet temperature and jet chamber outlet temperature was taken as average temperature of jet medium. The heat transfer coefficient of jet surface could be expressed:

$$h = \frac{q_1 - q_2}{T_s - T_j} \tag{10}$$

Experiment data analysis

During the experiment, the volume fractions of the Cu-ethylene glycol nanofluids are 0.5%, 1%, 1.5%, 2%, and 2.5%. The results indicate the difference in the jet impingement heat-transfer effects of these mixed liquor and traditional coolant and analyzes the different heat-transfer effects under different nanoparticle volume fractions, jet impingement distances, angles of jet impingement, and inlet jet velocities to the test sides of the cylinder-head device.

Figure 9 shows the changes in the jet impingement heat-transfer coefficients of the test nanofluids. We can see that by using nanofluids as coolant, the heat-transfer performance of the cylinder test part improves. When the jet velocity is 6.2 m/s, the ethylene glycol coolant heat-transfer coefficient is approximately 22,233 W/(m^2°C). In particular, the volume fraction improves by 2%, and the jet impingement transfer coefficient becomes 30,109 W/(m^2°C), approximately more than a 35% increase than the traditional coolant heat-transfer coefficient.

Using nanofluids as coolant increases the thermal conductivity of the fluid on the one hand. On the other hand, it strengthens the interaction between the particle and the wall because the Cu nanoparticles keep the heat transfer in the surface with their respective motion trend, which improves the heat-transfer performance between the wall and nanofluids. The results also show that the jet heat-transfer coefficient does not always increase with the increase in the volume fraction of the nanoparticles. A 2% volume fraction is the cut-off point of the volume frac-

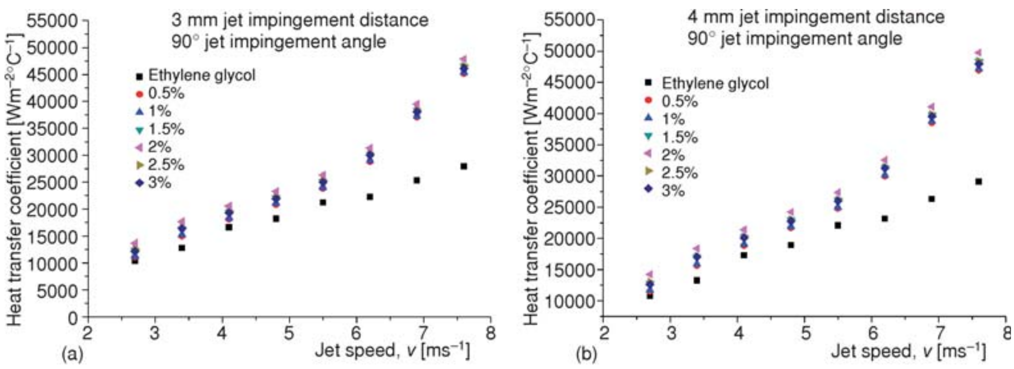

Figure 9. Change pattern of the jet impingement heat-transfer coefficient under different jet velocities using different volume fractions

tion in several trials. When the volume fraction is larger than 2%, however, the jet impingement heat transfer is reduced with the increase in the volume fraction. Figure 9 shows that not only a 3 mm jet impingement distance but also a 4 mm jet impingement distance can produce the above phenomenon, *i. e.*, the jet impingement distance cannot affect the above-mentioned trend. This phenomenon occurs because the increasing volume fraction of the nanoparticles increases the viscosity of the mixed liquor. When the viscosity increases to a certain extent, the jet energy decay accelerates, leading to the weakening of the jet heat-transfer effect.

Figure 10 shows that under different jet impingement angles, the trend of the jet impingement heat-transfer coefficient changes with different jet impingement speeds. When the jet angle increases, the heat-transfer coefficient also increases. When the jet impingement speed is set at a certain parameter, the jet impingement angle becomes smaller, and the jet impingement distance *S* (through the jet holes to the heat-transfer surface) becomes greater, which weakens the jet impingement energy.

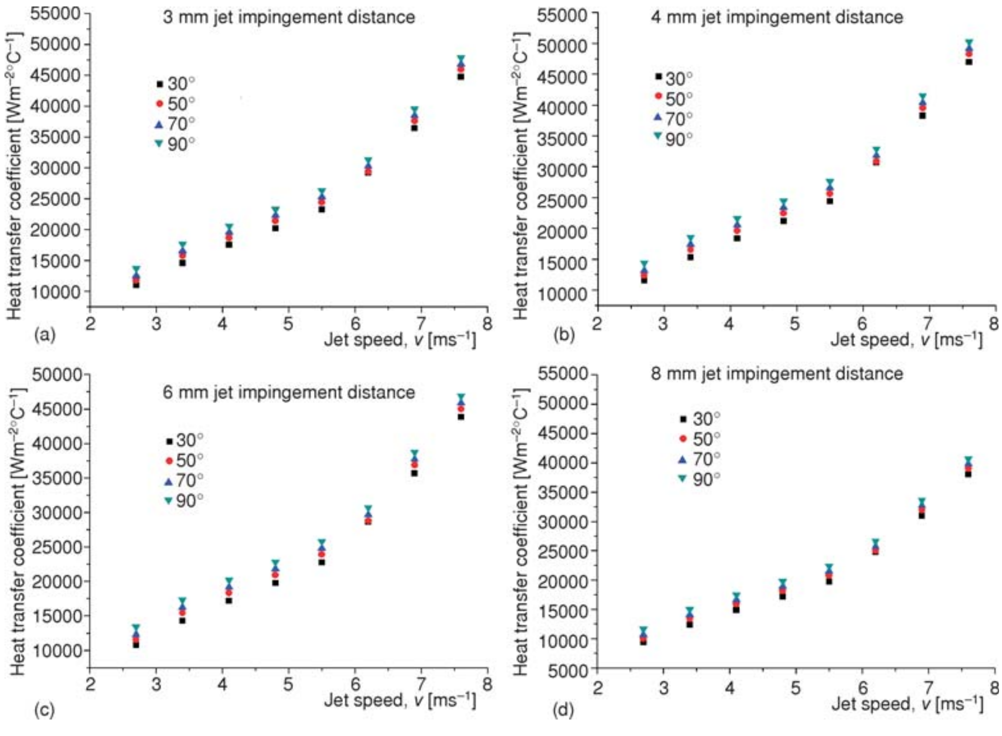

Figure 10. Four jet impingement angles causing change in the jet impingement heat-transfer coefficient under different jet speeds

Figure 11 shows the small change in the heat-transfer coefficient of the nanofluids under different jet impingement heights. The result shows that at a certain velocity range, the heat-transfer coefficient is best when the jet impingement height is 4.1 mm, and a 2.2-mm height yields the worst coefficient. The reason for this phenomenon is that the impingement height is too small. Before the jet fluid reaches the impingement plane (surface where heat transfer occurs), the jet flow is not fully developed. However, when the impingement height is large, the weakening of the jet impingement energy is also large, and the energy needed to reach the

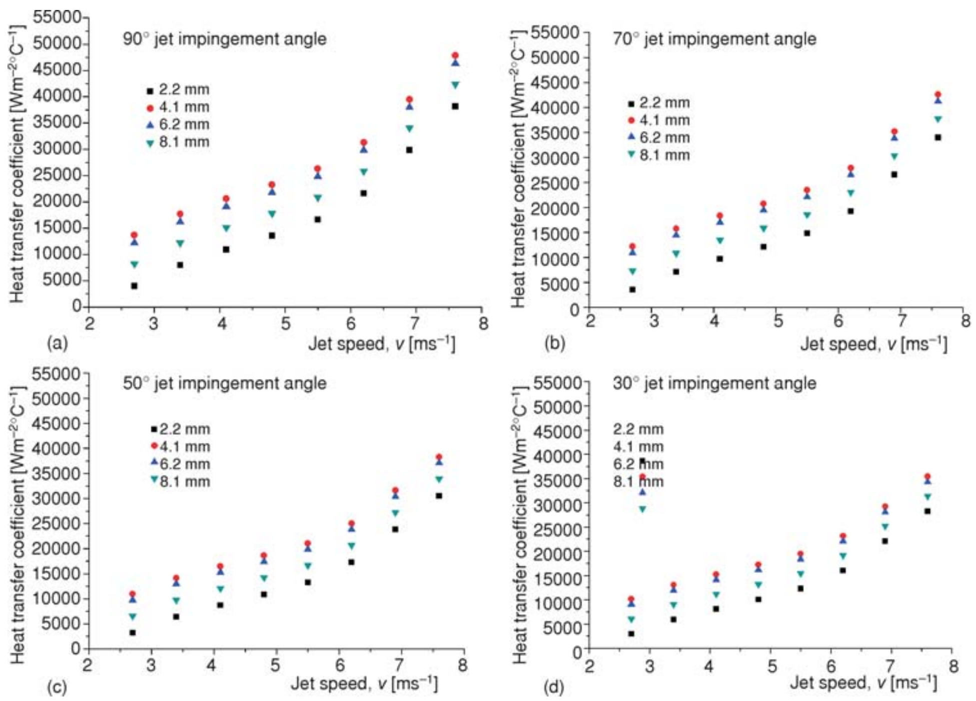

Figure 11. Effect of jet height on the jet-flow heat transfer

heat-transfer surface is smaller. Therefore, under a specific impingement height, the best effect of jet heat transfer can be achieved using nanofluids. Figure 11 shows that different jet impingement angles can also change the trend, but changing the jet angles makes the overall heat-transfer coefficient different.

Figure 12 shows that when the volume fraction of the nanofluid is improved, the electronic pump power also increases. The results indicate that nanofluid viscosity increases because of the increasing nanoparticle volume fraction.

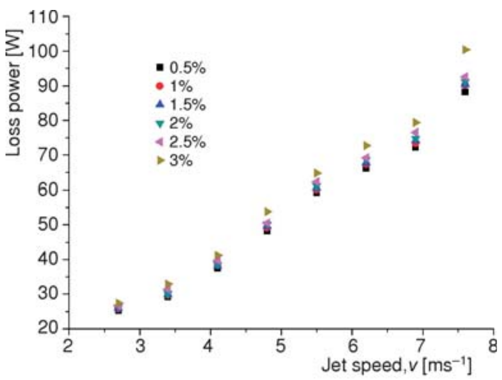

Figure 12. Co-operation of electronic pump power with different volume fractions using nanofluid coolant

Because only one jet impingement nozzle is used in this experiment, the jet working fluid from the jet nozzle to impingement plane is only a point, *i. e.*, a large number of heat-transfer performance differences exist between the jet impingement and around the part, expressed as different values by the three temperature sensors. To further explain the above difference, fig. 13 shows the different temperature values of the three temperature sensors. We call this phenomenon as temperature-consistency difference.

Figure 13 shows that with the development of the jet angle, the temperature becomes consistently better, and this consistency has noth-

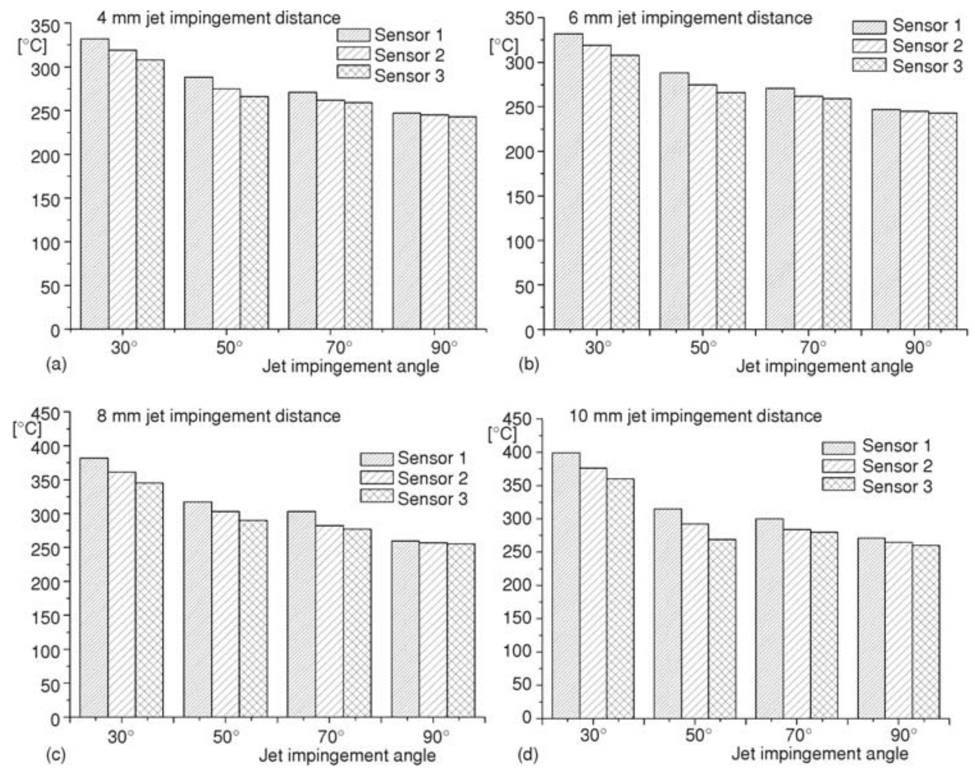

Figure 13. Temperature consistency difference

ing to do with the type of jet impingement working fluid. Figure 13(a) shows that when the jet impingement angle is 30 degrees, the difference between the minimum and maximum temperature from the temperature sensor is almost 30 °C, but the jet impingement angle changes to 90 degrees. The difference between the minimum and maximum temperature is less than 5 °C. Figure 14 also shows that with increasing distance, consistency of this temperature difference becomes more obvious. Figure 13(d) shows that this trend is even more obvious. At a 10-mm jet impingement distance, the difference between the minimum and maximum temperature in the temperature sensor is almost 40 °C.

During a Diesel engine operation, the temperature of the cooling medium is not static. Therefore, we need to know the change trend of the heat-transfer coefficient under different temperatures. In the progress of this experiment, we use four types of coolants as jet impingement medium to verify the change trend of the jet impingement heat-transfer coefficient. Figure 12 shows that with the increase in the temperature, the heat-transfer coefficient also increases. The reason for this phenomenon is that the increasing temperature strengthens the movement of the nanoparticles.

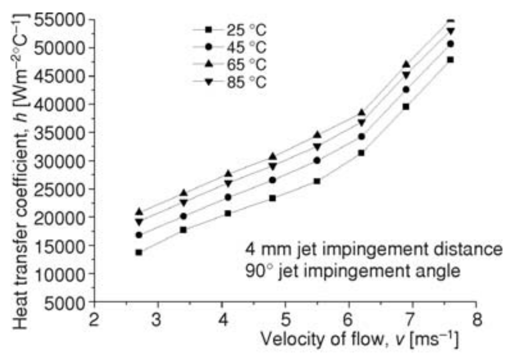

Figure 14. Change trends of the heat-transfer coefficient variation with jet initial temperature

Conclusions

- After the theoretical calculations and experimental study, we learned that using nanofluids as coolant can effectively enhance the heat-transfer coefficient in the high-heat area of a Diesel engine cylinder head.
- Through the self-built jet impingement test experimental devices, the ideal heat-transfer coefficient will be made, with the best jet impingement angles, the jet impingement distance, and ideal different volume fractions. The experimental results show that nanofluids have better heat-transfer coefficient than traditional coolant, but the increasing volume fraction plays a limited role in improving the heat-transfer coefficient.
- By developing jet-measured experimental devices to test the change trend of the heat-transfer coefficient of nanofluid under different jet impingement angles and speeds, we obtained the best heat-transfer coefficient at different jet impingement distances and jet speeds, that is to say, with nanofluid volume fractions was 2%, jet angel was 90 degrees, jet impingement distance was 4 mm, we can get the best transfer performance of test device.
- The simultaneous addition of nanoparticles into the coolant to improve the heat-transfer capacity also increased the viscosity and flow resistance, increasing the electronic pump power with the increase in the volume fraction of nanoparticles.

Acknowledgments

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