CHEMICAL ENGINEERING TRANSACTIONS

VOL. 59, 2017

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Zhuo Yang, Junjie Ba, Jing Pan

ISBN 978-88-95608- 49-5; **ISSN** 2283-9216

DOI: 10.3303/CET1759180

Study on Cooling Characteristics of Water-based Carbon Nanotube Nanofluids for Internal Combustion Engines

Haichao Liu[a, b], Xiaona Song[b], Yongwei Gao[a, b]

[a]School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China
[b]School of Mechanical Engineering, North China University of Water Resource and Electric Power, Zhengzhou 450046, China
dahai9915@163.com

In the cooling system of internal combustion engines, traditional cooling water is replaced by the water-based carbon nanotube nanofluids. To cope with the overall method of six cylinder diesel engine, the cooling system and the solid components of internal combustion engine are seen as a coupling, and the fluid solid boundary become an internal real-time boundary of nanofluids in internal combustion cooling system. In addition, heat transfer characteristics are studied in this paper. On the influence of law, different types, different volume fraction and different particle size of nanofluids have different effects on the heat transfer of internal combustion engine cooling system, which gives the coolant flow, the cooling water jacket of the heat transfer coefficient, pressure field and accurate temperature distribution. Thus, the thermal stress calculation for the internal combustion engine using water-based carbon nanotube nanofluids has laid a theoretical foundation in the application of diesel engine cooling water cavity. In this paper, the X-Y function can record the determination curve of aqueous carbon nanotube nanofluids. And then we discuss the effect of carbon nanotube content and temperature on the cooling characteristics of water carbon nanotube nanofluids. Finally, the results of experiments show that the maximum cooling rate of nanofluids increases gradually with the increase of CNT content, and the cooling performance of nanofluids decreases with the increase of quenching temperature.

1. Introduction

Adding the metal and non-metal the polymer solid particles in the liquid is an effective method to improve the heat transfer ability of the liquid. Based on this theory, Argonne National Laboratory firstly proposed that adding a small amount of nano particles, namely "nanofluids" concept, to improve the heat transfer performance of refrigerant comparing to the base fluid. The thermal conductivity of nanofluids increases obviously and the heat transfer ability is enhanced, while the flow resistance in the flow do not significantly increase. The enhancement of the nano fluid heat transfer mechanism can significantly improve the thermal conductivity, which can also produce heat diffusion in nano fluid so as to enhance heat transfer. In the literature, the mechanisms of thermal conductivity of nanofluids are studied, but many researches dosen’t focus on the mechanism of the nano fluid flow process (Oliveira et al., 2017). Although the flow and heat transfer of nanofluids scholars carried out experimental research and got some heat transfer data, it is difficult to establish the corresponding correlation for convection criterion due to the lack of experimental data for nano fluid finishing methods and the lack of detailed analysis of the mechanism. Some scholars of nanofluids in engine cooling system were applied to do the preliminary study (Esfe et al., 2017). The vehicle based nano fluid heat radiator was studied and analyzed about the heat transfer enhancement of the nano fluid mechanism. Then the parameter test with nano fluid thermal properties was replaced by the original cooling refrigerant, CFD numerical simulation on the application of nano fluid in the cooling system of the engine. And they found that the nano fluid heat transfer performance of engine cooling system had a very good strengthening effect, however, the thermal parameters only replaced the original cooling refrigerant without considering the nanoparticles micro motion and heat diffusion mechanism, which reflected the strengthening effect of nano fluid on the cooling system of internal combustion engine. In addition, it was necessary to carry

Please cite this article as: Haichao Liu, Xiaona Song, Yongwei Gao, 2017, Study on cooling characteristics of water-based carbon nanotube nanofluids for internal combustion engines, Chemical Engineering Transactions, 59, 1075-1080 DOI:10.3303/CET1759180

out nano fluid of engine cooling system based on flow strengthening mechanism. The process flow diagram of preparation of water-based carbon nanotube CNT nanofluids is given in Figure 1 (Rasheed et al., 2016; Nizamani et al., 2017).

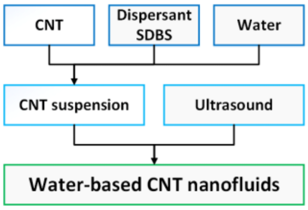

Figure 1: Process flow diagram of preparation of water-based carbon nanotube CNT nanofluids

Once the nanofluids are used as the heat transfer medium for the piston to cool the oil chamber, the gas-liquid two-phase flow becomes the solid-liquid H-phase flow and the heat transfer, whose process is more complicated (Ahammed et al., 2016). Apart from the above problems, we also face with the following difficulties: (1) At present, the numerical simulation of nano-fluid research is mostly based on the traditional solid-liquid two-phase flow or single-phase flow theory. However, the surface effect and the quantum scale effect make the behaviour close to the liquid molecules due to the small size effect of the nanoparticles, which is not the same as the molecules (Azwadi et al., 2016). (2) Under the reciprocating motion condition of the piston, the nanometre fluid is fixed into the solid gas solution with the air, and the mathematical model of the flow and heat transfer of the nanometer fluid is still to be further studied and perfected. (3) The presence of nanoparticles has an additional impact on the wall, and it is necessary to simplify the treatment of nanoparticlesin the process of reciprocating shock, separation and reattachment of the nanofluids, which will result in a violent oscillation of the wall attachment layer (Hussein et al., 2016). (4) When the water-based nanometer fluid is used to cool the piston, it is necessary to distinguish the phase of the nanometer fluid in the numerical simulation process, and the interaction mechanism between the nanometer particles and the wall surface needs further study, (Sekhar et al., 2016). The water-based carbon nanotube nanofluids are studied in this paper, which can artificially reach fluid turbulent flow to improve the cooling performance of internal combustion engines due to the special structure of the wave shaped wave wall. And the test equipment is reduced sharply. The results are easily observed, and the most important thing is to reflect on the flow of nanofluids.

2. Mathematical and physical models of nanofluids

In this section, we firstly introduce the mathematical model of nano-fluid and the tracking model in the CFD numerical simulation, and the mathematical expressions of different models are given in details. In the model, since the nanoparticles are regarded as a cleavage fluid, it is necessary to specify the faint viscosity in solving the conservation equation. The commonly particle viscosity models are based on the gas-solid two-phase flow at high concentrations. However, the large particle sizes may not be suitable for nanofluids such as low concentrations, small particle sizes and Liquid-solid two-phase flow. In this section, the virtual viscosity model which is suitable for the nanoparticles is deduced from the N-S equation of the basic fluid and the nanoparticles. In the subsequent calculation, the empirical formula based water-based fluidized bed is compared with the formula based on molecular motion theory, which highlights the advantages of the new model and provides theoretical support for the numerical simulation. And then we introduce the geometric reconstruction algorithm and the local compressible algorithm based on the limiting factor. The interface between the gas-liquid two-phase flow and the solid-liquid flow is used in the reciprocating oscillation condition.

2.1 Single-phase flow model

The single-phase flow model is a relatively simple continuous model. In the Euler coordinate system, the nanofluids are used as a single-phase fluid to calculate the physical parameters, such as density, viscosity, thermal conductivity, of the nanofluids, and then the empirical formula can be obtained. Compared with the basic fluid, the single-phase flow model only considers the change of the physical properties of the nanofluids, which does not consider the interaction between the nanoparticles and the basic liquid. In this paper, we ignore the phase of the momentum exchange and energy exchange process, but the impact of nano-particles on the flow field is applied into a physical parameter of the change. Finally, the conservation equations for the single-phase flow model are expressed as follows (Sidik et al., 2017).
The quality equation:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\left(\rho V\right)=0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\rho V\right)+\nabla\cdot\left(\rho VV\right)=-\nabla p+\nabla\overline{\overline{\tau}}+\rho g \tag{2}$$

The quality equation:

$$\frac{\partial}{\partial t}\left(\rho E\right)+\nabla\cdot\left(V\left(\rho E+p\right)\right)=\nabla\left(k_{eff}\nabla T+\left(\nabla\overline{\overline{\tau_{eff}}}\cdot V\right)\right) \tag{3}$$

Where ρ is the density of the nanofluids, V is the velocity of the nanofluids, g is the gravitational acceleration, p is the static pressure, $\overline{\overline{\tau}}$ is the stress tensor, E is the total energy, k_{eff} is the effective thermal conductivity of the nanometre and T is the temperature.

2.2 Multiphase flow model

In this paper, the multiphase flow model takes into account the velocity difference between discrete and continuous phases and the interaction between them. And the flow and heat transfer processes of nanofluids are calculated by solving the conservation equation of the mixed phase, the volume fraction equation of the solid phase and the velocity slip. In general, the mixture model is more reasonable than the single-phase flow model, because it takes into account the temperature difference between the base fluid and the solid particles, additionally, and the speed slip is closer to the actual situation. In the conservation equation, the conservation of the physical parameters is the volume mean of each phase, the velocity field and the temperature field, which are no longer shared by the solid-liquid two-phase. In this paper, the conservation equation of the multiphase flow model is shown as follows (Sidik et al., 2017).
The quality equation:

$$\frac{\partial\rho_m}{\partial t}+\nabla\cdot\left(\rho_m V_m\right)=0 \tag{4}$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\rho_m V_m\right)+\nabla\cdot\left(\rho_m V_m V_m\right)=-\nabla p+\nabla\cdot\left[\mu_m\left(\nabla V_m+\nabla V_m^T\right)\right]+\rho_m g+F+\nabla\left[\sum_{k=1}^{n}\alpha_k\rho_k V_{dr,k}V_{dr,k}\right] \tag{5}$$

The quality equation:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\left(\alpha_k\rho_k E_k\right)+\nabla\cdot\sum_{k=1}^{n}\left(\alpha_k V_k\left(\rho_k E_k+p\right)\right)=\nabla\left(k_{eff}\nabla T\right) \tag{6}$$

The multiphase model introduces the concept of algebraic slip and defines the algebraic relation of relative velocity between two phases. On a shorter space length scale, the local balance should be achieved and the relative velocity can be expressed as follows,

$$V_{pq}=\frac{\tau_p}{f_{drag}}\frac{\left(\rho_p-\rho_m\right)}{\rho_p}a \tag{7}$$

Where ρ_k is the density of the k-phase, V_k is the velocity of the k-phase, α_k is the volume fraction of the k-th phase,n is the number of phases, F is the volume force, ρ_m is the average density of the mixed phase, μ_m is the volume average viscosity of the mixed phase, V_m is the average velocity of the sea phase is the velocity of the particle phase, k_{eff} is the effective thermal conductivity, E_k is the total energy for the first phase, and T is the temperature for the temperature, τ_p is the relaxation time, d_p is the particle size of the particle. f_{drag} is the drag force function, ρ_p is the density of the particle phase, a is the acceleration.

2.3 Thermophysical Properties of Nanofluids

The thermal conductivity of nanofluids was measured experimentally before 2003. In recent years, many scholars have successfully established an effective theoretical model to predict the thermal conductivity, density, specific heat capacity and viscosity of nanofluids. The thermo physical properties of the nanofluids used in the numerical simulation are determined by the formulas (8) to (11)
Thermal conductivity is expressed as follows (Solangi et al., 2015),

$$k_{nf}=\frac{\left\{\left(k_p-k_{lr}\right)\phi k_{lr}\left[2\beta_1^3-\beta^3+1\right]+\left(k_p+2k_{lr}\right)\beta^3\left[\phi\beta^3\left(k_{lr}-k_f\right)+k_f\right]\right\}}{\left\{\beta_1^3\left(k_p+2k_{lr}\right)-\left(k_p-k_{lr}\right)\phi\left[\beta_1^3+\beta^3-1\right]\right\}} \tag{8}$$

Density is shown as,

$$\rho_{nf}=\left(1-\phi\right)\rho_f+\phi\rho_p \tag{9}$$

Specific heat capacity is the following equation,

$$\left(c_p\right)_{nf}=\left(1-\phi\right)\left(c_p\right)_f+\phi\left(c_p\right)_p \tag{10}$$

Viscosity is shown as follows,

$$\mu_{nf}=\mu_f\frac{1}{(1-\emptyset)^{2.5}},\beta=1+\gamma,\beta_1=1+\frac{\gamma}{2},\ \gamma=\frac{h}{a},k_{lr}=2k_f \tag{11}$$

Where h is the thickness of the interface layer, a is the particle radius, k is the thermal conductivity, φ is the volume fraction of the nanoparticles, ρ is the density, c is the specific heat capacity, μ is the viscosity, respectively.

3. Cooling characteristics of water-based carbon nanotubes nanofluids in internal combustion engines

Table 1: Main technical parameters of internal combustion engine

Item Name	Index
Model	CA6DE2-23
Type	inline six-cylinder, four-stroke, water-cooled, direct jet type
Bore (mm)	106
Compression ratio	17.5:1
Piston stroke (mm)	125
Calibration power (KW)	180
Calibrated power speed (r·min^{-1})	2300
Maximum torque (N·m)	900
Maximum torque speed (r·min^{-1})	1400

As shown in Table 1, main technical parameters of internal combustion engine are given in details. SEM morphology of water-based carbon nanotube CNT nanofluids with SDBS adding is shown in Figure 2. We can find that the visible carbon nanotubes in the nano-fluid dispersion are better and it do not see the reunion of CNT particles.

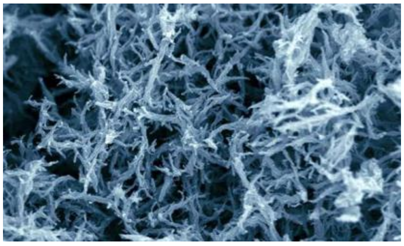

Figure 2: SEM morphology of water-based carbon nanotube CNT nanofluids with SDBS adding

The temperature probe material of cooling performance is the 45 steels with the size 20mm×40mm. And probe thermocouple is chosen as the armoured nickel-chromium - nickel silicon thermocouple, which has the wire diameter φ 0.3mm and response time 0. 1s. And the thermocouple is located in the geometric center of the probe. In this paper, a vertical resistance furnace is used to heat the cooling temperature probe with the temperature control accuracy of± 5 °C. The temperature of the cooling test is placed in a resistance furnace, which is heated to 850 °C for 10 min. Then, the temperature probe is quickly quenched into the nano-fluid, while the initial temperature of the nano-fluid is 25 °C, and the nano-fluid with different CNT content is measured of the cooling characteristics for internal combustion engines.

In this paper, the measured temperature of the cooling curve of the probe is shown in Figure 3 (a), while the water is treated as a reference liquid of different CNT content of nano-fluid quenching medium, and the initial temperature is 25 °C. The differential curve of the temperature probe in the temperature is given in Figure 3 (a).

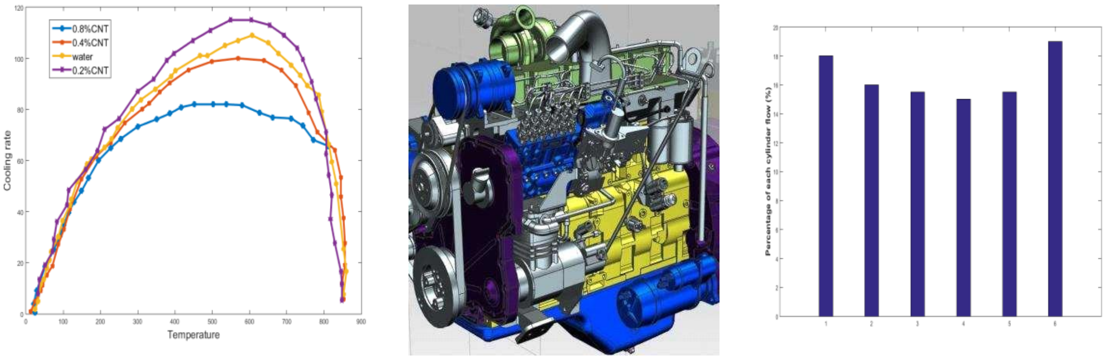

Figure 3: (a) Cooling rate of temperature transmitter overall grid CNT content (b) Inline six cylinder cooling water flow in each cylinder (c) The percentage of total

Table 2: Cooling capacity of temperature probe in different CNT content water based CNT nanofluids

Test temperature	Probe cooling temperature
>800	same
800-400	0.2wt%CNT >water >0.4wt%CNT >0.8wt%CNT
400-300	0.2wt%CNT >0.4wt%CNT >water >0.8wt%CNT
<300	0.2wt%CNT >0.4wt%CNT >water >0.8wt%CNT

As shown in Figure 3 (a), we can find that all curves are almost coincident at all temperatures above 800°C, which indicates that the cooling rate of all quenching media including water is substantially the same. When the probe temperature drops below 800°C, the cooling rate in the nanofluids begins to change. And in Figure 3 (b), we give the inline six cylinder transmitter overall grid. And the Cooling capacity of temperature probe in different CNT content water based CNT nanofluids is given in Table 2. From Figure 3 (c), the percentage of total cooling water flow in each cylinder can be obtained in details. It can be explained that the low content of CNT nanofluids in the study range is better than that of CNTs with high content of CNT under the condition of natural convection, and the heat dissipation capacity of water is higher than that of high CNT of the nanofluids. The cooling rate of water-based carbon nanotubes nanofluids changes with different quenching medium temperatures as shown in Figure 6. It can be seen that the cooling rate of nano-fluid at different temperatures is basically the same at 630°C, and the cooling rate of nanometer fluid decreases with the increase of temperature of nanometer fluid quenching at 630°C. And we find that the cooling performance of nanofluids decreases gradually with the increase of nanometer fluid temperature. At different temperatures of quenching fluid, the cooling rate of nanometer fluid changes little at high temperature and changes greatly at low temperature.

Nano-fluid quenching fluid canbroaden the scope of application of quenching medium, and it will not produce flue gas pollution and avoid the risk of fire without mineral oil, nitrite and other harmful substances, while it can ensure the operator and the safety of the equipment. Due to the presence of nanoparticles, the bursting of the bubbles is accelerated and the stage of the vapour film is shortened. Thus, the different parts of the work piece can enter the boiling stage at the same time and the cooling rate is faster. The main drawbacks of water-based carbon nanotubes nanofluids quenching fluids are: the water-based carbon nanotubes quenching fluid is still mostly better than the water, while the water is seen as a quenching medium. And the cooling rate will be greatly reduced in a high temperature, in addition, the liquid also inherits the shortcoming. The concentration of the changes is more sensitive to the requirements of the concentration of quenching fluid; And the degree of agitation is very strict, while the work-piece quenching area of the degree of mixing should be uniform to ensure the adequate strength, while the uniform mixing is used to ensure that the temperature concentration and cooling uniform. Compared with the quenching oil, quenching liquid is easier to produce pollution and needs careful maintenance.

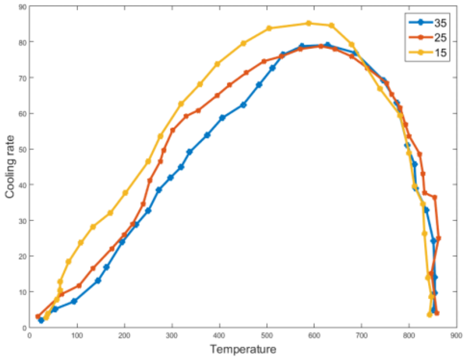

Figure 6: Effect of cooling medium temperature on cooling rate of nanometer fluid

Reference

Ahammed N., Asirvatham A.G., Wongwises S., 2016, Effect of volume concentration and temperature on viscosity and surface tension of graphene-water nanofluid for heat transfer applications, Journal of Thermal Analysis and Calorimetry, 123(2), 1399-1409, DOI: 10.1007/s10973-015-5034-x.

Azwadi C.S.N., Adamu I.M., Jamil M.M., 2016, Preparation methods and thermal performance of hybrid nanofluids, Journal of Advanced Review on Scientific Research, 24(1), 13-23.

Esfe M.H., Afrand M., Rostamian S.H., Toghraie D., 2017, Examination of rheological behavior of MWCNTs/ZnO-SAE40 hybrid nano-lubricants under various temperatures and solid volume fractions, Experimental Thermal and Fluid Science, 80, 384-390.

Hussein A.M., Kadirgama K., Sharma K.V., Ramasamy D., Bakar R.A., 2017, Heat Transfer Enhancement with Nanofluids for Automotive Cooling. Engineering Applications of Nanotechnology, Springer International Publishing. 71-100.

Islam M.R., Shabani B., Rosengarten G., Andrews J., 2015, The potential of using nanofluids in pem fuel cell cooling systems: a review, Renewable & Sustainable Energy Reviews, 48, 523-539, DOI: 10.1016/j.rser.2015.04.018.

Nizamani A.A., Ismail A.R., Junin R., Dayo A.Q., Tunio A.H., Ibupoto Z.H., Sidek M.A.M., 2017, Synthesis of titaniabentonite nanocomposite and its applications in water-based drilling fluids, Chemical Engineering Transactions, 56, 949-954, DOI: 10.3303/CET1756159.

Oliveira G.A., Contreras E.M.C., Filho E.P.B., 2017, Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator, Applied Thermal Engineering, 111, 1450-1456.

Rasheed A.K., Khalid M., Javeed A., Rashmi W., Gupta T.C.S.M., Chan A., Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine, Tribology International, 103, 504-515, DOI: 10.1016/j.triboint.2016.08.007.

Safaei M.R., Shadloo M.S., Goodarzi M.S., Hadjadj A., Goshayeshi H.R., 2016, A survey on experimental and numerical studies of convection heat transfer of nanofluids inside closed conduits, Advances in Mechanical Engineering, 8(10), 1-14, DOI: 10.1177/1687814016673569.

Sekhar S.C., Karuppasamy K., Sathiyamoorthy K., 2017, The Impact of various Nano Additives Blended with Diesel and Biodiesel on DI Diesel Engine Performance, Combustion and Emission Parameters-A Mini-Review, Asian Journal of Research in Social Sciences and Humanities, 7(2), 483-496.

Sidik N.A.C., Muhammad N.A.W.M.Y., Mamat R., 2015, A review on the application of nanofluids in vehicle engine cooling system, International Communications in Heat and Mass Transfer, 68, 85-90, DOI: 10.1016/j.icheatmasstransfer.2015.08.017.

Sidik N.A.C., Samion S., Ghaderian J., 2017, Recent progress on the application of nanofluids in minimum quantity lubrication machining: a review, International Journal of Heat & Mass Transfer, 108, 79-89.

Solangi K.H., Kazi S.N., Luhur M.R., Badarudin A., Amiri A., Sadri R., 2015, A comprehensive review of thermo-physical properties and convective heat transfer to nanofluids, Energy, 89, 1065-1086.