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The numerical investigation of heat transfer enhancement of copper-oil and diamond-oil nanofluids inside the piston cooling gallery

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A B S T R A C T

The current paper added several kinds and amounts of nanoparticles into traditional engine oil to form a new type of cooling medium (nanofluids). Two interface-tracking methods (CLSVOF and Eulerian) were employed to discuss the transient flow and heat transfer of engine oil and nanofluids with different nanoparticles (copper and diamond) and volume concentrations (1%, 2% and 3%). The distributions of oil filling ratio and heat transfer coefficient were investigated at various crank angles. The advantages of nanofluids on cooling down the piston gallery were illustrated by comparing the statues of flow and heat transfer in local surfaces at the same moment.

1. Introduction

Chemical energy is transformed into thermal energy by combustion during the working process of internal combustion engines. In the combustion process, the transient temperature of local gas reaches 2500 K, and the heat flux of chamber components exceeds 100 MW/m^2. Half of the thermal energy passed to the chamber components from the high temperature gas is transferred to the piston [1], which will suffer severe thermal deformation due to decreased material strength if it cannot be properly cooled. Excessive temperature also leads to coking of the lubricating oil and abrasion between components, which compromises engine reliability. Therefore, the piston must be effectively cooled to maintain thermal stress within its safe range and guarantee normal operation.

The most effective method to cool the piston is to devise a cooling gallery inside the piston head, which significantly reduces the heat loading of the whole piston [2–4]. When the piston is running, engine oil is injected into the cooling gallery at high speed from a bottom nozzle. Inside the piston cooling gallery, the engine oil follows the piston reciprocating motion, flowing in the circumferential direction and returning to the crankcase after a 180° travel along the wall. Generally, the low temperature engine oil does not completely fill the cooling gallery, but forms a complicated gas-liquid two phase flow with air, as illustrated in Fig. 1. The reciprocating inertial force of pistons produces a large relative velocity between the engine oil and cooling gallery surfaces, providing a strong cooling effect from oscillation impingement and effectively reducing overall piston heat loading. However, a cooling gallery inside the piston head has a negative effect on piston strength. With constant enhancement of internal combustion engines, it has become more difficult to satisfy the heat transfer requirement by increasing or optimizing the cooling gallery structure. Therefore, it is essential to explore new cooling media with better heat transfer capacities.

The nanofluid is a kind of cooling medium with nanoscale particles of metals, metal oxides or nonmetals stably suspended inside traditional fluids, such as water, oil or alcohol [5]. A large number of investigations on the flow characteristics and heat transfer of nanofluids have shown that the presence of nanoparticles inside the base fluids significantly increases thermal conductivity and heat transfer in both laminar and turbulent states. With increasing nanofluid concentration, heat transfer enhancement significantly increases with relatively small increased pressure drop [6–8]. Nanofluids also have a positive effect on pulsation and oscillation, which further improves heat transfer capacity [9,10]. Multiphase flow with gas, liquid, and nanoparticles influences heat transfer remarkably, which further enhances overall heat transfer in some cases [11–13].

Thus, nanofluids possess unique characteristics of flow and heat transfer during reciprocating motion. If they can be employed as a cooling medium for pistons, much better heat transfer efficiency will be achieved [14,15]. High nanofluid thermal conductivity and heat transfer enhancement induced by microscale convection of nanoparticles can effectively reduce heat flux from the cooling gallery inside the

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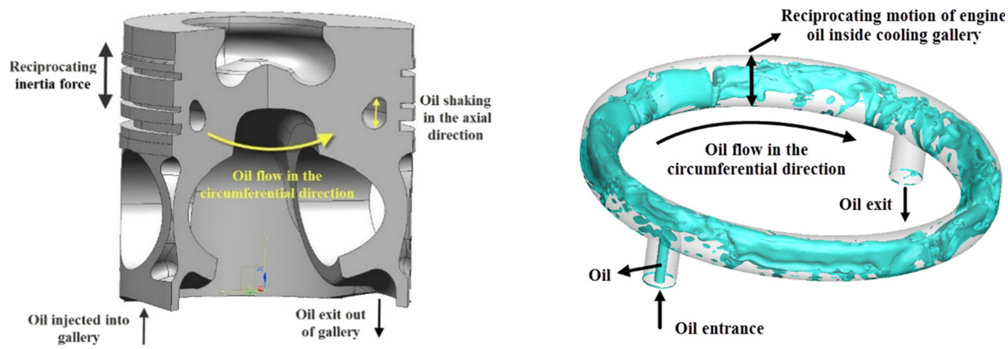

(a) The working process of piston cooling gallery (b) The geometric construction of piston cooling gallery

Fig. 1. The configuration of piston cooling gallery.

piston head. The addition of nanoparticles into engine oil does not increase wear on piston components, but has, in contrast, a positive effect on lubrication, particularly in the case of diamond nanoparticles. The chemical properties of diamond nanoparticles are relatively stable, which results in little chemical pollution on the metal materials. Despite the high cost of artificial diamond nanoparticles [16–18], a very small amount produces a significant improvement in heat transfer efficiency.

The cooling gallery is located deep within the piston head, with quite small space and complicated structure, and faces many problems during the cooling process with traditional engine oil [2,3]. When a nanofluid heat transfer medium is employed, the gas-liquid two phase flow (air and engine oil) becomes gas–liquid–solid three phase flow (air, engine oil, and nanoparticles), leading to more complex flow and heat transfer processes.

(1) Currently, nanofluid numerical simulations are mainly based on traditional theory of liquid-solid two phase or single phase flow [19,20]. Because of small size, surface, and quantum size effects, nanoparticle behavior tends to be quite similar to liquid molecules, but not the same [21,22]. Therefore, nanofluids cannot be treated as a single-phase flow or traditional gas-liquid two phase flow. The physical mechanism of heat transfer enhancement and nanofluid mathematical physical model needs further exploration and improvement.

(2) The heat transfer mechanism of gas-liquid-solid three phase flow formed by air and nanofluids becomes more complicated during piston reciprocating motion [23,24], which makes it more difficult to establish a mathematical physical model. The ideal multiphase model that best describes this phenomenon remains uncertain, particularly for the solid phase (nanoparticles). Whether the nanoparticles can be simplified as a pseudo fluid needs further discussion [25].

(3) The presence of nanoparticles generates additional impinging effect on the heated surfaces [26,27]. The processes of reciprocating impingement, separation, and reattachment of nanofluids lead to an intense oscillation of the stagnation layer in the near-wall region, which destroys its internal structure and enhances heat transfer. It has been indicated that nanoparticles play a role similar to a "heat transfer bridge" in the boundary layer flow field [28,29]. The physical mechanism of heat transfer enhancement within the stagnation layer and interaction mechanisms between nanofluids and the heated wall during reciprocating motion need further discussion.

(4) When nanofluid is used to cool the piston, it is essential to distinguish interfaces of the three phases by numerical simulation. As engine oil and air are immiscible, a sharp interface is suitable. However, if nanoparticles are assumed to be a fluid, sharp interface modeling would also be appropriate for nanoparticles in air [30]. On the other hand, if nanoparticles are stably dispersed within the engine oil, a diffused interface is required. A sharpening scheme would cause undesirable effects on modeling of the diffused interface between the engine oil and nanoparticles [31]. However, a diffusion scheme would not be able to maintain the sharp interface for air bubbles and oil droplets [32]. Thus, within the cooling gallery, there are diffuse and sharp interfaces in different regimes, which require a unique discretization procedure to handle such applications.

Current cooling media for the piston cooling gallery focuses on traditional engine oil, which greatly limits heat transfer efficiency. Some studies have employed nanofluids as the heat transfer medium of the piston cooling gallery. The current paper adds several types and amounts of nanoparticles into traditional engine oil to form a new type of cooling medium (nanofluids). Two interface-tracking methods (CLSVOF and Eulerian) were employed to study transient flow and heat transfer of engine oil and nanofluids with different nanoparticles (copper and diamond) and volume concentrations (1%, 2%, and 3%). The distributions of oil filling ratio and heat transfer coefficient were investigated at various crank angles. The advantages of nanofluids on cooling the piston gallery were illustrated by comparing flow and heat transfer status for local surfaces at the same moment.

2. Mathematical physical model

2.1. Mathematical model

There are currently two common interface tracking methods, VOF multiphase [33,34], and coupled multiphase and level set (CLSVOF) models [35–37]. The model combines VOF and level set advantages, and tracks the interface motion of gas-liquid two phase through a coupled calculation. This method predicts interface curvatures by employing the VOF model to capture the interface and geometric method to solve the level set function, Φ, near the interface. The model effectively reduces the large error of interface curvatures in the VOF phase function and solves mass non-conservation problems during the transport process of the level set method, and is more accurate than either method alone.

In the VOF model, the function F represents the volume fraction of liquid phase within the grid domain, which is used to determine the orientation and location of interface. The function F has the form of:

$$F(\bar{x}, t) = \begin{cases} 1 & \text{(liquid phase)} \\ 0{-}1 & \text{(mixture)} \\ 0 & \text{(gas phase)} \end{cases} \quad (1)$$