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The reciprocating motion characteristics of nanofluid inside the piston cooling gallery

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ABSTRACT

With the peak cylinder pressure in diesel engines steadily increasing, simply extending or modifying the cooling gallery configuration may be insufficient when power rating is above a certain level. The nanofluid with better heat transfer capacity may become a more appropriate option to improve piston cooling performance. Therefore, the current paper employed a high-speed camera to capture the flow patterns of nanofluid and air inside a simplified piston gallery at various crank angles and explored the heat transfer mechanism of solid-gas-liquid three-phase flow (nanoparticles, base fluid and air) during the reciprocating motion. On this basis, three numerical simulation methods (VOF, CLSVOF and Eulerian-Eulerian) were further carried out. The effects of engine speed, nanofluid filling ratio and nanoparticle concentration were discussed. The results revealed that the nanofluid is more appropriate for the piston thermal management and the cooling effect increases with the engine speed and nanoparticle volume fraction.

1. Introduction

During the operation of an internal combustion engine, chemical energy is converted into thermal energy. The local gas temperature in the cylinder may reach as high as 2500 K, and more than 50% of the heat flux inside the chamber components is transferred to the piston [1]. The piston suffers periodic mechanical and thermal loading during its prolonged exposure to the combustion chamber. An excessive piston temperature can cause oxidation or severe degradation, which eventually leads to poor engine performance. At present, cooling is commonly accomplished either by a "cocktail shaking" action using oil in pistons with galleries, or by impingement of oil on the undercrown surface of solid pistons [2]. In the case of spray-cooled pistons, 60–70% of the heat flux is transferred to the ring belt; for pistons with undercrown cooling by oil impingement, 40–50% of the heat flux flows from the combustion bowl to the back surface of the piston crown; and in the case of cooling-gallery pistons, 60–70% of the heat flux is removed by the cooling gallery [3]. The use of a cooling gallery inside the piston head makes it possible to optimize the heat extraction and control the piston temperature effectively [4].

When the engine is running, the cooling oil is injected from an oil jet nozzle into the gallery through an inlet hole, flows around in a circumferential direction, and exits the gallery through an outlet back into the crankcase [5], as illustrated in Fig. 1. In general, the piston gallery is not completely filled with cooling oil. During the sloshing process that occurs, the cooling oil flushes the gallery surface at high velocity under the inertial forces induced by the reciprocating motion of the piston. Air and cooling oil are mixed together to form a gas–liquid two-phase flow inside the piston gallery. This so-called "cocktail shaking" action increases the intensity of turbulence in the oil, enhances the effect of impingement on the gallery surfaces, and significantly reduces the piston temperature. However, the structure of cooling gallery limits the piston strength to some extent. With the peak cylinder pressure in diesel engines steadily increasing, simply extending or modifying the cooling gallery configuration may be insufficient when power rating is above a certain level [6]. The nanofluid with better heat transfer capacity may become a more appropriate option to improve piston cooling performance [7–14]. Therefore, if nanofluid can be used in the engine heat transfer process, especially as the cooling medium of piston gallery, the heat transfer efficiency will be effectively improved.

Owing to the small space in piston galleries and their complicated structure, it is rather difficult experimentally to perform accurate visual observations of the internal cooling oil and study the heat transfer characteristics. With advances in computer capacity and speed, the CFD (Computational Fluid Dynamics) numerical simulations have become an alternate tool to accurately understand the transient flow and heat transfer mechanisms inside the piston gallery [2,3,5,15–20]. However, the previous studies were all based on a quasi-steady-state assumption. The temporal and spatial characteristics of the distribution were partly or completely neglected and only the overall heat transfer

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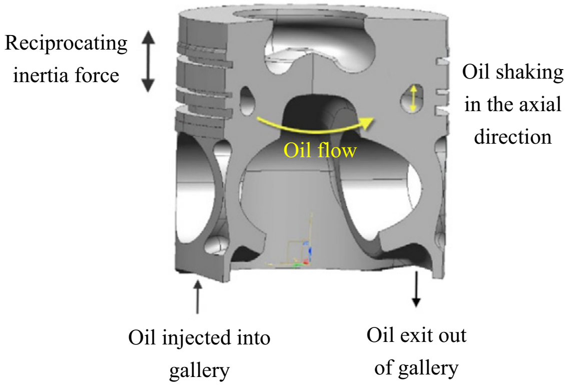
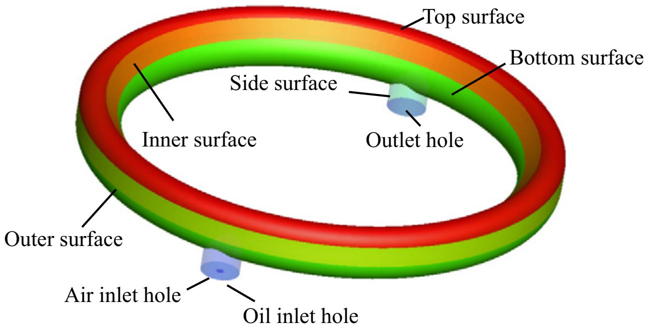


(a) Schematics of piston gallery oil flow



(b) Geometry configuration of piston gallery

Fig. 1. Piston cooling gallery configurations.

coefficient averaged over a cycle could be estimated. What is more, few studies have explored the turbulent flow of cooling oil and the heat transfer mechanism during reciprocating motion. The heat transfer coefficients predicted by different empirical correlations are not consistent with each other [4,21–23], which indicates that the flow pattern may be the determining factor for the heat transfer process under dynamic conditions. So far, the heat transfer medium widely used for piston gallery cooling in previous studies mainly focused on the traditional engine oil and there are almost no reports or discussions on nanofluid for cooling down the piston gallery. When the engine is running, the nanofluid and air forms complicated solid-gas-liquid three-phase flow (nanoparticles, base fluid and air), which significantly improves the heat transfer efficiency in comparison with the gas-liquid two-phase flow.

Therefore, it becomes critical to develop an effective method to achieve a full understanding of the flow characteristics of nanofluid and the effect of their impingement inside the cooling gallery, and this forms the main purpose of the present work. In the current work, we employed a high-speed camera to capture the flow patterns of nanofluid and air inside a simplified piston gallery at various crank angles. The heat transfer mechanisms in solid-gas–liquid three-phase flow during the reciprocating motion was explored. The effects of engine speed ($n = 200$ r/min and $n = 300$ r/min), nanoparticle volume fraction ($\varphi = 3\%$ and $\varphi = 5\%$) and nanofluid filling ratio ($\omega = 40\%$ and $\omega = 60\%$) were also discussed. On this basis, three numerical simulation methods were further carried out to investigate the mixing process of the three-phase turbulent flow and their periodic impinging effect on the wall. The compressive and zonal discretization schemes were introduced into the Eulerian-Eulerian multiphase model and the numerical results were compared with the traditional interface tracking models (VOF and CLSVOF). We also suggested a criterion for judging the heat transfer effect of nanofluid under dynamic conditions.

2. Methodology

2.1. Experimental apparatus

Because of the enclosed construction and opaque material of pistons, it is not possible to capture the motion of the nanofluid and air inside a piston gallery in a real situation. In order to accurately observe the transient flow patterns of a solid-gas-liquid three-phase mixture during the reciprocating motion of a piston, we used a transparent organic glass to build a simplified piston cooling gallery, as depicted in Fig. 2. The piston gallery was simplified to a rectangular cavity instead of a ring structure, as the high-speed camera used was not capable of capturing clearly the motion of the interface inside a ring structure and the flow patterns on opposite sides would overlap seriously with each other. A partition was mounted in the middle of the simplified piston gallery to compare the interface motions between the gas-liquid two-phase flow and the solid-gas-liquid three-phase flow under the same conditions. Also, in general, engine oil can easily cover transparent surfaces because of its large viscosity, and its poor transparency and transmittance would seriously restrict the observation of interface motion inside the piston gallery. Therefore, the deionized water and water-based nanofluid with much better transparency and transmittance was used instead. Inside the simplified piston gallery, the deionized water and air were in the left side, and the SiO_2-water nanofluid and air were in the other side, both with the same size of 120 mm × 40 mm × 40 mm.

The experimental apparatus consisted of an electric motor, a frequency modulator, a diesel engine, a laser source, a simplified piston cooling gallery, a high-speed camera, and a data collection system, as shown in Figs. 3 and 4. The electric motor provided power for the whole system, the frequency modulator controlled the operating speed of the diesel engine, the piston components generated the reciprocating motion, the high-speed camera captured the transient flow patterns of the solid-gas-liquid three-phase mixture, and the data collection system stored the visualization images in a computer. The cylinder head was removed from the engine and the simplified piston cooling gallery (with a size of 240 mm × 40 mm × 40 mm) was fixed to the top of a piston so that it would follow the reciprocating motion. The main technical parameters of the engine are listed in Table 1. In the experiments, we employed an ASTCAM Ultima APX high-speed camera with an image intensifier tube. The frame rate was in the range of 50–20 000 Hz with a maximum resolution of 1024 × 1024. In order to clearly observe the interface motion inside the rectangular cavity, the visualization experiments were conducted in a darkened room with a green laser source on top of the simplified piston cooling gallery.

2.2. Numerical simulation

2.2.1. Geometrical model

In the numerical simulation, our geometric model exactly reflected the same flow region used in the visualization experiment, with the computational domain of 120 mm × 40 mm × 40 mm. The present study mainly focused on the flow characteristic of solid-gas-liquid mixture without considering heat transfer process between wall and fluid. Therefore, it was assumed that the mixture inside the simplified piston gallery were with constant temperature and all the surfaces

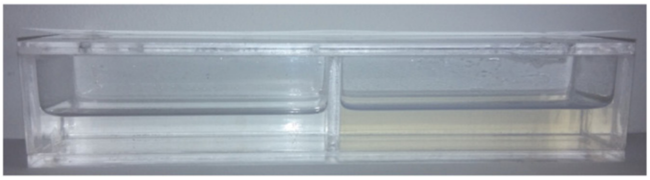


Fig. 2. Simplified piston cooling gallery.