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The gas-liquid two-phase flow in reciprocating enclosure with piston cooling gallery application

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ABSTRACT

With the specific power of diesel engines steadily advancing, heat removal from the piston has become a determining factor to ensure engine reliability and durability of engines. However, piston head complex structure makes it very difficult to accurately capture the flow and heat transfer processes of cooling engine oil within the piston gallery. The current study used high-speed photography to obtain periodic interface motions of gas and liquid phases under dynamic conditions, investigated the influences of engine speed and filling ratio on the interface motion, and derived the mechanism for heat transfer enhancement. Numerical simulations further explored turbulent mixing characteristics of gas-liquid mixture and reciprocating impinging effect on walls under various dynamic conditions. Coupled with a geometric reconstruction scheme, gas and liquid flow patterns were tracked by the Eulerian model, and then compared with results from VOF and CLSVOF models. A rough criterion was proposed to qualitatively estimate heat transfer enhancement of gas-liquid two-phase flow during periodic piston motion.

1. Introduction

When an engine is running, combustion converts fuel into heat flux. Peak temperatures inside the cylinder approach 2500 K, and more than half the thermal energy is absorbed by the piston. Direct contact with the high temperature fuel gas produces intense mechanical and thermal piston loadings, leading to poor internal combustion engine performances. Pistons are one of the most important engine components, and their temperature control and management has become a determining factor for engine reliability and durability. Several methods have been developed to cool piston in engines [1]. More than 60% of thermal energy flows through the piston ring belt for spray-cooled pistons, whereas 40%–50% of heat loading is transferred to the piston crown for impingement-cooled pistons; and > 60% of heat flux is directly transferred to the cooling gallery for gallery-cooled pistons [2,3].

Previous studies have clearly indicated that a cooling gallery located in the piston head is an effective method to reduce piston temperature [4,5]. During engine operation, cooling oil is injected into the piston head through the cooling gallery inlet and returns to the crankcase through the gallery outlet after 180° circumferential travel along the wall (Fig. 1) [6]. Generally speaking, the cooling oil does not completely fill the piston gallery, but forms a two-phase mixture with the air [7]. Under the action of periodic inertial force, low temperature oil impinges the piston gallery at high speed, which significantly increases turbulence of the internal cooling medium [8,9], improves the impinging effect on the high temperature gallery wall [10,11], and reduces the heat loading on the piston. However, the piston head complex structure makes it very difficult to accurately capture the flow and heat transfer processes of cooling engine oil within the piston gallery, and there have been few experimental studies on the piston cooling gallery.

Several piston cooling gallery heat transfer models for have been proposed, but these generally have poor agreement with experimental results or each other [4,12–15]. The models do not consider mechanisms that enhance flow and heat transfer of gas-liquid two-phase flow under piston reciprocating vibration. With the rapid development of computer technology, CFD has become an effective method to model and understand cooling oil flow and heat transfer characteristics inside the piston gallery [1,2,6,16–21].

The cooling gallery is located deeply within the piston head, with quite small space and complicated structure, making it quite difficult to capture the periodic state of gas and liquid phases within the gallery. Most previous studies have employed the quasi steady state hypothesis to predict average heat transfer coefficient(s) through one cycle, and completely ignored heat flux temporal and spatial distributions

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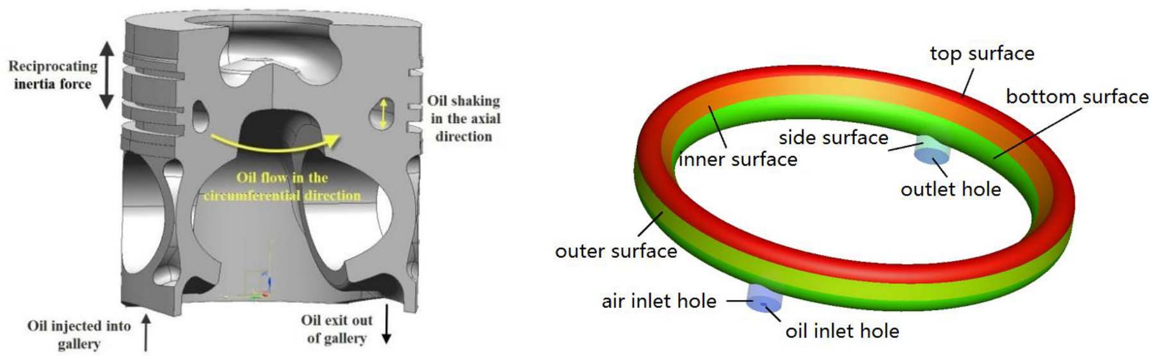

(a) Schematics of piston gallery oil flow (b) Geometry configuration of piston gallery

Fig. 1. Piston cooling gallery configurations.

[4,12–15,22]. Detailed mechanisms for flow and heat transfer enhancement of gas-liquid two-phase flow under piston reciprocating motion have not been considered or discussed. Heat transfer coefficients calculated by various studies are not consistent, indicating that flow patterns may have a critical role in heat transfer during reciprocating motion [3,5]. Therefore, it is critical to explore periodic impingement characteristics of gas-liquid two-phase flow inside the cooling gallery, which was the main purpose of current study.

In previous studies, the authors have employed high-speed photography to obtain periodic interface motions of gas and liquid phases under various dynamic conditions. Based on these findings, the current study conducted further experiments and numerical simulations to further understand flow and heat transfer mechanism under piston reciprocating vibration [23]. The effects of engine speed and filling ratio were also considered. Coupled with a geometric reconstruction scheme, gas and liquid flow patterns were tracked using the Eulerian model, and compared with results from VOF and CLSVOF models. A rough criterion was proposed to qualitatively estimate heat transfer enhancement of gas–liquid two-phase flow during piston periodic motion.

2. Experimental apparatus

The detailed experimental apparatus has been described previously [24], and is not repeated here. It should be noticed that a rectangular cavity was used to simplify the annular piston cooling gallery in this experiment, which means the effects of impinging jet at the oil entrance and the centrifugal force on the flow and heat transfer processes were ignored. Some of the conclusions drawn in the present study may not be appropriate to be used to design a cooling gallery in a piston. In this experimental study, as its not easy to track flow patterns of traditional engine oil inside the piston cooling gallery due to its poor transparency and transmittance, the deionized water was employed instead, since it has significantly better transparency and transmittance. Interface motions of the gas-liquid mixture were captured at various crank angles, engine speeds, and filling ratios.

Bush et al. [12] proposed a reciprocating Reynolds number for pistons based on a series of experiments,

$$Re_B = \frac{2nHDe}{60\nu},\ \nu = \frac{\mu}{\rho} \tag{1}$$

whereRe_B is the reciprocating Reynolds number; De is the gallery equivalent diameter; n is the engine operation speed (rpm), H is the average cross section height; and μ ν, and ρ are the dynamic viscosity, kinematic viscosity, and density, respectively, of the cooling medium.

In the current work, experiments were performed at room temperature (T = 20 °C) and the density and dynamic viscosity of deionized water were 998.2 kg/mPPP^{3}PPP and 0.001004 Pa s, respectively [25]. During actual engine operation, average engine oil temperature inside the piston cooling gallery is about 120 °C [6]. The density and dynamic viscosity of engine oil were assumed to be 829 kg/mPPP^{3}PPP and 0.0103 Pa s, respectively [26]. The reciprocating Reynolds numbers of deionized water and engine oil should be the same to ensure similar flow patterns during reciprocating motion. Therefore, engine speeds for different cooling media can be expressed as

$$\frac{n_{oil}}{n_{water}} = \frac{\rho_{water}\mu_{oil}}{\rho_{oil}\mu_{water}} \approx 12, \tag{2}$$

where n is the engine speed, ρ is the density and μ is the viscosity, respectively.

In the experiments, engine speeds were 200 and 300 rpm using deionized water cooling medium, which corresponds to 2400 and 3600 rpm, respectively, for engine oil cooling medium. Therefore, the experiment and numerical simulation performed here represent a practical application.

3. Numerical simulation model

3.1. Geometric model

The computational domain for the CFD geometry model was 240 × 40 × 40 mm, which was the same size as the flow region in the experimental study. Since the simplified cooling gallery employed in the experiment was built from transparent acrylic glass, it was not practical to place some thermocouples in the critical regions. Therefore, the main purpose of the current research was to investigate flow characteristics of gas-liquid two-phase flow, rather than the heat transfer process. Although the heat transfer process was not considered during piston reciprocating vibration, heat transfer trends can be qualitatively estimated by the distribution of cooling oil at various crank angles.

3.2. Multiphase model

There are currently two common interface tracking methods: VOF [27,28] and CLSVOF [29–31] multiphase models, where CLSVOF combines VOF and Level Set advantages, and tracks gas-liquid two phase interface motion through a coupled calculation. In the CLSVOF model, the interface is first reconstructed via a PLIC scheme from the VOF model and then the interface normal and curvature will be updated by the Level Set function. This method is able to effectively reduce the large error for interface curvatures in the VOF phase function, solves mass non-conservation problems during the Level Set approach transport process, 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 [32,33], which determines the interface orientation and location,