

Simulation and Optimization on Oscillating Cooling Characteristics in High-Enhanced Piston Oil Cooling Gallery

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ABSTRACT

Oscillating cooling characteristics in piston oil cooling gallery of internal combustion engines were simulated by adopting Coupled Level Set Volume of Fluid method and Arbitrary Lagrangian Eulerian dynamic grid technique. The influence relationship of structure parameters and oil filling rate to the average temperature of oil gallery was studied by response surface method. The optimal structure parameters and oil filling rate were acquired by Multi-Objective Genetic Algorithm method. The calculation results show that the average temperature of oil gallery wall reduces with the height of oil cooling gallery raising; the average temperature of oil cooling gallery wall reduces after first decreases with the length of oil gallery top surface increasing; the contribution rate of oil filling rate is greater than oil gallery structure in reducing average temperature of wall; the optimal case reduces average temperature of original machine wall by 8 °C and the error between optimal results and calculating result is less than 1%.

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INTRODUCTION

As the internal combustion engine develops in the highly-intensified, compacted and light weighted direction, piston, one of the worst working conditions of heated components, increasingly suffers terrible double impact of mechanical load and thermal load. Traditional spray cooling and free jet cooling [1] cannot fully meet the new requirement of highly intensified piston cooling. In order to improve heat transfer effect [2], forced oscillating cooling technology in piston oil cooling gallery takes advantage of the oil reciprocating stroke inertia to scour the oil gallery. This can effectively solve the increasingly terrible problem of piston thermal load.

In recent years, researches on two-phase oscillating cooling characteristics in piston oil cooling gallery have been on the increase. Varghese et al. [3] designed oil injection test bed to verify the effect of oil jet distance, jet velocity and oil type on distribution of piston temperature. Wang et al. [4] adopted visual research on stroke characteristic of coolant in oil cooling gallery. Luff et al. [5] analyzed the effect of jet cooling on piston temperature, emission of internal combustion engine and fuel consumption. The related numerical investigation has been one of current research hot spots. Kajiwar et al. [6] explored the effect of different oil filling rate on oscillating cooling in oil gallery. Yi et al. [7] further researched the changing rule of oil filling rate, heat transfer coefficient etc. with crank angle. Sander et al. [8] researched the effect of shape, acceleration and oil filling rate on closed oil cooling gallery. Zhang Wei-zheng et al. [9-10] researched the effect of oil cooling gallery filling rate on the changing rule of average heat transfer coefficient etc. Undoubtedly, these researches strongly pushed forward the development of the research on oscillating cooling in piston oil cooling gallery. However,

with few reports about it, the coupling effects of two major factors, construction and oil filling rate of oil cooling gallery, on piston oscillating cooling have not been fully mastered.

In this paper, by using CFD software SC/Tetra, based on Coupled Level Set Volume of Fluid (CLSVOF) method and Arbitrary Lagrangian Eulerian (ALE) dynamic grid technique, simulation research on oscillating cooling characteristics in highly-intensified piston oil cooling gallery was conducted. The research was focused on the interaction effects and heat transfer mechanism on two-phase oscillating cooling of oil gallery structure parameter and oil filling rate, in the hope of achieving the best Trade-off proposal and providing theoretical basis for the optimal design of highly-intensified piston.

MATHEMATICAL MODEL INTRODUCTION

Governing Equation

In the numerical simulation of oscillating cooling in piston oil cooling gallery, possible heat transfer between oil phase and oil vapor phase was assumedly ignored. It was simplified into a problem of engine oil and air, mutually immiscible vapor-liquid two-phase flow. CLSVOF model was adopted in this research. CLSVOF model, based on VOF model and bringing in Level set method, has higher resolution of tracing moving interface and can captures the motion state of oil and gas at the interface more accurately. CLSVOF multi-phase model uses volume fraction of unit phase to denote each phase. In each control unit, the sum of all phase volume fraction is 1. Function F represents the liquid-phase volume fraction of unit space



in any control unit as shown in Eq. (1). The density of substance in control unit can be calculated in Eq. (2) and other attributes (such as dynamic viscosity) can be calculated in the same way.

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

$$\rho = F\rho_{\text{oil}} + (1 - F)\rho_{\text{air}} \quad (2)$$

Level set method is called level set function method, using phase function to represent phase, which means that phase interface kinetic is regarded as the level set of a phase function Φ ; as long as the function value of the function Φ at one point is figured out, the position of corresponding level set will be obtained. Phase function is shown in Eq. (3).

$$\phi(x, t) = \begin{cases} > 0 & (\text{beyond interface}) \\ = 0 & (\text{interface}) \\ < 0 & (\text{within interface}) \end{cases} \quad (3)$$

The convection transport equation of phase function Φ is that

$$\frac{\partial \phi}{\partial t} + (u \cdot \nabla) \phi = 0 \quad (4)$$

In this equation, u is unit fluid velocity and t is time. Momentum equation is that

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot (\rho u u) = -\nabla p + \nabla \mu [\nabla u + (\nabla u)^T] + \rho g + \nabla \sigma \quad (5)$$

Energy equation is that

$$\frac{\partial}{\partial t}(\rho c_p T) + u \nabla (\rho c_p T) = \nabla \cdot (\kappa \nabla T) \quad (6)$$

In these equations, p , μ , ρ , σ , T , κ , c_p represent pressure, viscosity, density, surface tension, temperature, effective thermal conductivity and heat capacity respectively.

Dynamic Grid Treatment

ALE method is used in dynamic grid treatment. The basic idea is: the computational grid is no longer fixed, being independent from fluid particle, and can move freely relative to the coordinate system. This description can not only keep the viewpoint of Lagrange and Euler, and overcome grid distortion, but also be useful for the free surface flow.

As is shown in Eq. (7), piston stroke equation defines oil gallery as stroke region and approximates oil gallery stroke as sinusoidal stroke whose amplitude controls the displacement of oil gallery stroke and angular frequency decides revolving speed of piston stroke while its initial phase can determine the initial position of oil gallery stroke.

$$S = R(1 - \cos \alpha + R/L \sin(\alpha/2)) \quad (7)$$

In this equation, S is piston displacement. R is crank radius. L is connecting rod length. α is crank angle.

Model Verification

To verify the accuracy of computational mode, experiment result in literature [4] is quoted to simulate vapor-liquid two-phase distribution of deionized water in 120mm×40mm×40mm enclosed gallery. With water as the coolant, the given filling rate, revolving speed and stroke are 60%, 300r/min and 123mm respectively. The stability circulation after ten circulation calculation results are taken. We compared the simulation results and experiment results of top dead center (TDC), 90° crank angle, bottom dead center (BDC) and 270° crank angle, the figure (i) for the experimental results of literature [4]. As shown in Fig. 1, it can be found that local vapor-liquid distribution of simulation is close to experimental results in the progress of oscillating motion, which verified that the mathematical model established in this article has better precision in simulating cavity oscillating flow.

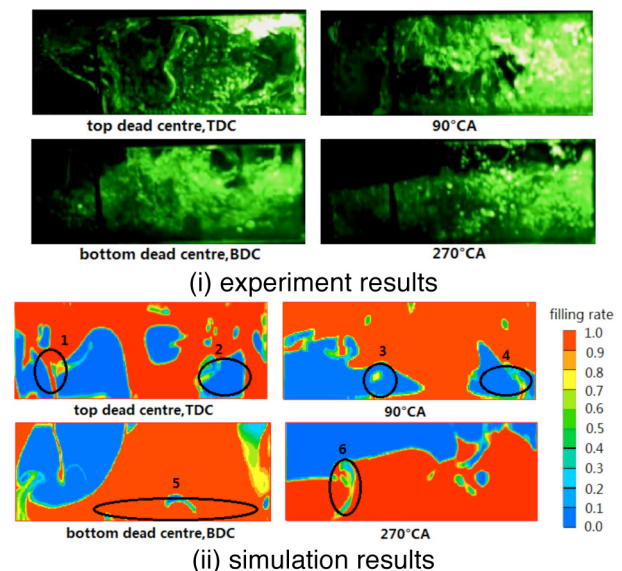


Fig. 1. The comparison between experiment and simulation of oscillating flow in simplified cooling gallery