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Research Paper

Numerical investigation on the oscillating flow and uneven heat transfer processes of the cooling oil inside a piston gallery

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HIGHLIGHTS

- A RDM was proposed to translate constants boundary conditions to varying ones.
- The uneven heat transfer phenomenon of the gallery was investigated.
- The HTC of the TOP region is more uneven than that of other wall regions.
- The more uneven heat transfer of the gallery located closer to the oil inlet passage.

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ABSTRACT

In previous research of achieving high cooling efficiency of engine pistons, the phenomenon of uneven heat transfer has not been investigated or recognized. These issues lead to a greater piston temperature gradient and its effects on engine durability have not been paid sufficient attention. In this research, a piston gallery was classified into four regions and several zones per region to investigate oscillating oil flows and uneven heat transfer distributions with a Relative Displacement Method (RDM). The RDM allows the cooling gallery to be treated as a rigid body, and the original constant boundary conditions could be translated into varying conditions that change as a function of engine crank angle. The relationships are investigated between the heat transfer performance and some factors such as the movement conditions of the air-oil two-phase flow inside the gallery, the instantaneous oil distributions, the relative oil velocity, the instantaneous acceleration and the velocity of the piston. The results reveal that the instantaneous oil charge ratio decreases and the area-weighted heat transfer coefficient increases as the engine speed increases. Different regions exhibit more apparent uneven heat transfer at higher engine speeds, and the top and bottom regions play a dominant role in the overall heat transfer coefficient. When the gallery was positioned closer to the oil inlet passage, the uneven heat transfer is more intense.

1. Introduction

In order to meet the requirements of increasingly more stringent regulations of energy conservation and emissions reduction for automotive engines, many new technologies have been applied, such as multi-valve structures, variable geometry turbochargers, exhaust gas recirculation (EGR), electronic controlled high-pressure fuel injection systems, exhaust aftertreatment devices. On the other hand, in order to ensure high power density and reliability, various piston cooling gallery structures have been widely applied in piston design to provide high cooling efficiency. Increased thermal load due to higher requirements of power density makes piston cooling more challenging.

The pioneer work of the piston cooling gallery can be traced to the 1960s when Bush and London [1] presented some basic design information for "cocktail shaker" cooled pistons. Shortly later, French [2] proposed empirical formulae of the heat transfer of the cooling oil inside galleries through various engine experiments, providing a good foundation of design and analysis for piston galleries. In recent twenty years, in order to meet the requirements of lower emissions and higher power density of internal combustion engines, piston gallery design was received more attention all over the world. Many researchers adopted different methods to intensively study the cooling flow conditions and heat transfer performance of various piston galleries.

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Nomenclature

A_{oil}	cross-sectional area of oil nozzle, m^2
$C_{\varepsilon 1}$	k-ε turbulence model constant, 1.44
$C_{\varepsilon 2}$	k-ε turbulence model constant, 1.92
C_μ	model constant, 0.09
E	energy
E_m	empirical constant, 9.793
h_{Aw}	area-weighted heat transfer coefficient (WHTC)
h_{tw}	time-averaged WHTC
I	turbulence intensity
k	turbulence kinetic energy, m^2/s^2
k_e	effective thermal conductivity, W/(m K)
k_m	constant, 0.4187
L	eddy length scale, m
l	length of connecting rod, m
$\dot{m}_{\beta\alpha}$	mass transfer rate from oil phase to air phase
$\dot{m}_{\alpha\beta}$	mass transfer rate from air phase to oil phase
p_α	pressure of air phase at the control unit, Pa
Q_{oil}	oil flow at the nozzle, m^3/s
R	crank radius, m
r	volume fracture of a phase
R_e	Reynolds number
S	engine stroke, m
T	mass averaged temperature, K
U	velocity vector of a phase
U_n	velocity vector of the nozzle
U_{rel}	relative oil velocity
U_p	velocity of piston, m/s
U^*	dimensionless velocity
y_p	distance from the centroid of the wall-adjacent cell to the wall
y^*	dimensionless distance from the wall

Greek symbols

ε	energy dissipation rate, m^2/s^3
θ	crank angle, °CA
μ	dynamic viscosity, kg m^{-1} s^{-1}
ρ	density of a phase, kg/m^3
σ_k	turbulence model constant, 1.0
σ_ε	turbulence model constant, 1.3
ω	angular speed of the crankshaft, rad/s

Subscripts

α	air phase
β	oil phase

Experimental method has been a main approach in piston cooling research. Bush and London [1] conducted a series of experiments to explore the rules of forced convective heat transfer coefficients of piston galleries. French [2] proposed mathematical expressions of the coefficients based on Bush's results and considered the influence of oil viscosity through engine testing. Jos et al. [3] studied the impact of different oil nozzle arrangements on the cooling performance of an articulated piston, and found that the temperature of the piston could be more effectively reduced by increasing oil injection velocity than increasing oil flow rate. In 1975, Minami et al. [4] developed dimensionless explanations for convective heat transfer based on experiments, and their method was able to use simple and basic plane-surface pistons with various cavity conditions to simulate operating conditions of diesel engines. In 1977, Evan [5] developed a visual simulation test bench to study the mathematical expressions of averaged heat transfer coefficients of a piston gallery in the entire oscillation cycle. Some advanced gallery cooling concepts have been successfully tested and verified by Thiel et al. [6] in an experimental study, and they found that it was possible to significantly reduce piston temperatures via suitable cooling gallery geometry or by using two oil nozzles per cylinder in combination with a compatibly designed cooling gallery without changing the volume flow rate of the cooling oil. In 2008, Robinson and Whelan [7] studied the cooling capacity of different nozzle structures for a water jet impingement plate by using an experiment. In 2010, Torregrosa et al. [8] built a test bench with a controllable heat source and a piston cooling system. In their work, different cooling strategies were used at different engine operating conditions in order to study the improvement of piston cooling by using oil galleries. Their empirical formula was validated by using measured temperatures of two engines. In 2012, Luff et al. [9] modified a Ford 2.4 litre 115 PS light-duty diesel engine to allow solenoid control of the oil feed to the piston cooling jets, enabling them to be switched on or off on demand. With the jets switched off at different speed-load modes, the amplitude of piston temperature increase varied from 23 °C to 88 °C. In 2013, Splitter et al. [10] obtained a similar conclusion by conducting a series experiments. Their results showed that the CO emission of a single-cylinder heavy-duty research diesel engine decreased by a magnitude of 5–10% without a cooling gallery at low-speed conditions, and the engine thermal efficiency increased with increasing temperature of the piston head surfaces. In 2015, Lv et al. [11] explored mechanisms of oscillating flows by using a simplified visible closed gallery to simulate the flow of nanoparticles under different engine speeds.

There is no doubt that using accurate experimental data is the most reliable method in piston cooling research. However, it is very difficult to understand the process of heat transfer and oscillating flows in the gallery only by using experiments due to the quasi-steady-state nature of the experimental data. The space-time distribution characteristics of that process are almost ignored, and only an overall averaged convective heat transfer coefficient can be estimated over an engine cycle in experiments. Therefore, only using experiments is not sufficient for achieving a full understanding of the cooling oil flow and the impingement effect on the piston for the purpose of optimizing piston design [12].

With rapid development of computer hardware and commercial simulation software, it is possible to solve the problems mentioned above. Computational fluid dynamics (CFD) simulation has become an important and effective way to achieve better cooling capacity of piston galleries. As early as 1975, Minami [4] proposed a dimensionless method for numerical calculation based on experimental data, but his method was only able to obtain an averaged heat transfer coefficient of the piston galley. With the development of commercial CFD software, Kajiwara et al. [13] had developed a new 2D approach to calculate the coefficient of heat transfer for the cooling gallery for piston temperature prediction. Compared with the traditional approach of estimating piston temperatures with empirical experience, the accuracy of prediction was improved and validated, allowing engineers to successfully achieve the best cooling condition at the design stage. In 2005, Cheng and Hung [14] studied the flow and heat transfer in different oscillation frequencies using a two-dimensional closed simplified gallery and a compressible fluid model. Their governing equations were expressed in an integral form and discretized on moving grids. Pan et al. [15] had developed a numerical procedure using 3D CFD to simulate a cooling process and estimate the cooling efficiency of a gallery. The heat transfer coefficient of the cooling