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Research Paper

Study of different cooling structures on the thermal status of an Internal Combustion Engine

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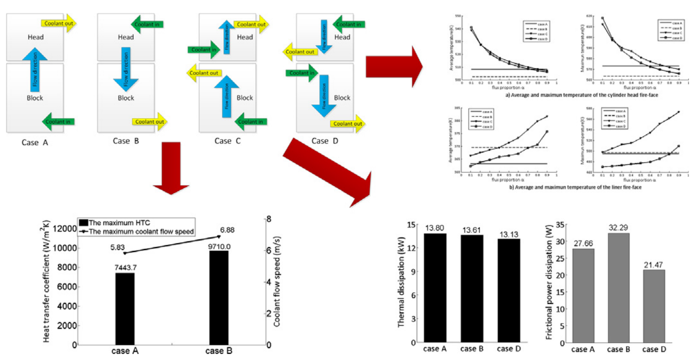
HIGHLIGHTS

- A 3D single cylinder engine model was developed for thermal status analysis.
- Conventional, top-bottom and split cooling structures were investigated.
- The optimal cooling structure was identified and studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Different cooling structures for cylinder head and block and the corresponding thermal status, thermal dissipation and frictional power dissipation were investigated in this study.

In a conventional engine cooling configuration, the coolant flow travels from the block to the head, leading to the coolant temperature of the head being higher than that of block. Furthermore, the over-cooling problem in the block will occur because the cooling system is designed for the cooling requirements of the cylinder head without considering the cooling load of the block.

This paper developed a 3D single cylinder model to analyse the influence of coolant flow direction and split structure cooling for the head and block. The analysis indicated that the top-bottom flow cooling structure can effectively reduce the cylinder head thermal load and slightly increase the temperature of the cylinder liner. The combined split and top-bottom cooling structure is proven as the optimal solution with the advantages of lower thermal and frictional power dissipation compared with that of the conventional cooling structure.

1. Introduction

The growing concerns on energy crisis and environmental problems are raising the research attentions on energy saving and emission reduction technologies for Internal Combustion Engine (ICE) to improve the overall energy efficiency. Diesel engine convers less than 40% of the fuel energy into the effective power from the crankshaft and wasted the remaining fuel energy through the exhaust gas system and cooling system [1–5]. The heated components in ICE such as cylinder head requires to be used under high thermal stress conditions, which will increase the potential of components damage with the increase of combustion intensity [6,7]. The development of alternative and advanced cooling system

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Nomenclature

T	temperature
λ	thermal conductivity
h	convective heat transfer coefficient
θ	rotating angle
k	turbulence kinetic energy
ε	turbulent dissipation rate
c	thermal capacity of solid
t	time
ρ	density
μ	dynamic viscosity
v	kinematic viscosity
F	body force
ϕ	thermal dissipation function
G_k	turbulence kinetic energy induced by velocity difference
G_b	turbulence kinetic energy induced by buoyancy
c_μ, c_1, c_2, c_3	empirical constant
R	cylinder radius
r	radius of r location
S	piston stroke
x	dimensionless radius
D	cylinder bore
u	velocity
H	distance from piston location to TDC
β	dimensionless distance
Q	coolant flux
α	flux proportion
P	energy dissipation
p	pressure
τ	shear stress
σ	Prandtl number

Subscript

w	wall
g	gas
c	coolant
k	turbulence kinetic energy equation
ε	turbulent dissipation rate equation
m	mean value
r	r location
β	dimensionless distance
f	frictional
T	total
H	cylinder head
q	mass flow rate
v	volume flow rate
p	node

with precisely controllable strategies is quite important to replace the conventional engine cooling system.

In conventional engine cooling system, the engine rotational speed determines the coolant pump speed and speed of radiator fan, which means the engine cooling load cannot be adjusted according to the thermal load under different working conditions. Some researchers conducted the investigation on intelligent cooling systems to achieve precisely controlling cooling strategies using smart controlling electrical components to replace the conventional components such as wax thermostat valve, mechanical water pump and radiator fan [8–14]. By adopting smart cooling controlling strategies engine warm-up time and CO_2 emissions can be effectively reduced [8].

In engine operational conditions, the thermal load of the cylinder head is higher than that of the block, but the coolant flow can only travel from the block to the head through the upper hole in traditional cooling system [5], which will lead to temperature of the cylinder head higher than that of the block. On the other hand, the coolant flow rate for ICE is designed based on the thermal limitations of the cylinder head, which requires a larger cooling intensity than that of block part, which will cause over cooling problem on the block. Therefore, advanced cooling system is desirable to avoid the over cooling problem on cylinder liner and potentially reduce the temperature field of the cylinder head. Considering the various cooling requirements of heated components, multiple cooling circuits can effectively control the temperature conditions in separately cooling circuits. Cipollone et al. [15] proposed a novel engine cooling system with two circuits including an HT (high temperature) circuit for the engine, EGR cooler, oil cooler, 1st stage inter-cooler and a LT (low temperature) circuit for the 2nd stage inter-cooler and A/C condenser. The two circuits cooling system can optimize the cooling demands of different heated components in ICE [15,16]. Moreover, the two circuits cooling system can reduce the overall fuel consumption and simplify the front end model of the engine compartment [15,16]. Kang et al. [17] studied on an engine smart cooling system with double loop coolant structure, which indicated the smart cooling system can effectively control the temperature of the cylinder head and block resulting in the reduction of fuel consumption and engine warm up time. Cipollone et al. studied two split coolant structure schemes for head and block cooling [18]. In these schemes, coolant flows from the cylinder head to the block and the valve between the water jackets of the cylinder head and the block was controlled to adjust the coolant flux, which can control the temperature of the cylinder head lower than that of the block with proper flow repartition [18]. For industrial application, a double circuit cooling system was launched in a Ford gasoline engine to independently control the component temperature by thermostat [19]. Results indicated the block temperature can be increased more quickly under a split cooling structure, and the friction between the liner and piston is reduced in cold running conditions [19].

However, the previously conducted researches all studied the mean temperature of the cylinder head and block at different cooling structures with 1D simulation model, which cannot represent the coolant flow conditions under different coolant flow directions or different coolant flux of the head and block cooling system. Furthermore, the temperature distribution and thermal stress of the heated components, thermal dissipation from the coolant and frictional power dissipation of the water jacket require to be further studied to understand the effects of different cooling structures. A 3D engine simulation model is therefore necessary to investigate the effect of different cooling structures on the thermal status of the heated components, thermal dissipation and frictional power dissipation.

In this study, a 3D single cylinder engine model was built to study the temperature and thermal stress field of the cylinder head and liner. Moreover, the frictional power and thermal dissipation for different cooling structures under engine rated condition were analysed and compared in the following sections. Finally, the optimal cooling structure was further studied under various engine power outputs, which can be used as important references to conduct further study on the development of advanced cooling organization strategies for Internal Combustion Engine.