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Effect analysis on boiling heat transfer performance of an internal combustion engine at the shutdown time

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ABSTRACT

In this paper, a liquid-solid coupling simulation of circulated coolant fluid and solid body of an internal combustion engine is carried out using AVL-FIRE software. Contrary to the previous numerical studies, unsteady simulations are performed in the present work. A validation test against experimental data is examined using BDL and Chen correlations. The results show that two correlations give reasonable results for the used setup at engine operating temperature. The effect of pressure, heat transfer coefficient in water jacket and temperature distribution in block and cylinder head is studied. In addition, the influence of engine shutdown on temperature distribution in water jacket, block and cylinder head is investigated. The results demonstrate that the boiling heat flux is zero until the shutdown time, then increases suddenly and reaches a maximum value between the two cylinders.

1. Introduction

Increase of the temperature in hot spots in an engine, such as exhaust valves and piston head, causes burning phenomena in these areas. If the heat transfer from combustion chamber walls is not performed well, the temperature in these areas increases considerably. This sudden increase in the temperature causes the sharp mechanic noise called knock. The thermal efficiency of internal combustion engines enhances if the engine's temperature is kept in a certain range using a cooling system. Generally, when cooling process in the engine cannot keep the engine's temperature in a certain range, not only the performance of the engine parts is affected and the oil lose its lubrication properties, but also combustion and emission performances of an internal combustion engine will be decreased [1–5]. The nucleate boiling occurs in the cooling passages of an internal combustion engine cylinder head. This is divided into subcooled boiling and saturated boiling, depending on the temperature of the bulk fluid. In the subcooled boiling, the fluid temperature is less than the saturation temperature. In saturated boiling, the fluid temperature is equal to the saturation one. Hence, the bubbles are generated on the heated surfaces in the subcooled boiling region. As the local fluid temperature reaches the saturation value, the bubbles are not destroyed and move along with the flow. If the surface temperature increases, the rate of bubble generation increases and the surface is completely covered by a vapor layer results in a sudden reduction of the heat transfer from surface and a significant increase in surface temperature [6]. Bo [7] used a single-phase boiling model to simulate the subcooled boiling in a water passage. They validated their proposed model with Robinson's and Zeitoun's experimental results [8,9]. They employed the model for horizontal and vertical pipes to examine the ability of the model to predict the boiling in the passages of a 6-cylinder engine. You et al. [10] performed the simulations to correct the cylinder head gasket. They enumerated the communication channels between block and cylinder head and changed their diameters in three stages. Dong et al. [11] investigated four boiling models in a water jacket of an internal combustion engine using two models. The characteristics of boiling heat transfer coefficient of a single- and two-phase flow heat transfer in a diesel engine water-jacket are investigated by Mohammadi et al. [12–14]. They used the results of Kang [15,16] to validate the models and concluded that the boiling heat transfer coefficient which is obtained by simulating the Chen single-phase boiling model is close to the results of that obtained from the mixed two-phase flow analysis. Jafarabadi et al. [17] simulated the fluid flow in cooling water-jacket of a diesel engine, taking into account the boiling phenomenon using boiling departure lift-off (BDL) model. Hemmat khanlou et al. [18,19] investigated the heat transfer in water-jacket of EF7-TC high feeding engine with the assumption of boiling phenomenon by AVL-FIRE software. They employed Chen and BDL models and demonstrated that although both models have a good result, the trend of the Chen model is

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closer to the real results. They examined the precise cooling effect in water-jacket by changing the diameter of the holes in the cylinder gasket and closing some of them. By simulating the 3126 Caterpillar diesel engine during engine silencing, AbdulNour et al. [20] examined the maximum external temperature of the engine chamber and the air temperature surrounding the engine when the fan was turned on and off. Measurements of heat transfer to water/ethylene glycol mixtures were reported by Finlay et al. [21] for a range of coolant velocities (0.1–5.5 m/s) and heat fluxes (up to 140 W/cm^2). They indicated that forced convection heat transfer is the dominant mechanism at the highest velocities (3 and 5.5 m/s). The boiling phenomenon is studied in water jacket of an SI engine turbocharger [22], an automotive turbocharger turbine [23], and in an exhaust gas turbocharger system [24].

Also, the orthogonal experimental design (OED) was employed to introduce the combustion models in a liquid-cooled system [25] and to optimize the efficiency of a micro-combustor [26].

In the present work, the effect of engine shutdown and subsequent phenomena on the temperature distribution of block and cylinder head and possible boiling due to stopping fluid movement due to engine and water pump shutdown is studied. In the first 10 s, the engine works in critical conditions (maximum load), then the engine suddenly turns off and all conditions (heat transfer coefficient and fluid temperature) change. To the best of our knowledge, no numerical study exists addressing the thermal performance of an internal combustion engine at the shutdown time unsteadily. The main objective of the present study is to perform unsteady simulation of the boiling heat transfer performance of a spark ignition engine at the shutdown time.

2. Governing equations and mathematical models

The governing equations for thermal exchange between the coolant and engine walls are mass, momentum and energy conservation equations. These equations in their simpler form are based on the following assumptions: i) coolant fluid is incompressible, ii) coolant properties vary with the temperature, iii) uniform flow is considered for inlet section of water jacket, and iv) the radiation effect is neglected. Therefore:

The mass conservation equation is as follows:

$$\nabla.\, \boldsymbol{V} = 0 \tag{1}$$

The momentum conservation equation is expressed as follows:

$$\rho \frac{D\boldsymbol{V}}{Dt} = \rho \boldsymbol{g} - \nabla P + \mu \nabla^2 \boldsymbol{V} \tag{2}$$

The conservation form of the energy equation is as follows:

$$\rho c_v \frac{DT}{Dt} = k \nabla^2 T \tag{3}$$

where D/Dt is the material derivative.

In addition, the material of block and cylinder head is cast iron (k = 55 W/m.K, ρ = 7.92 × 10^3 kg/m^3, and C_p = 456 J/kg.K) and aluminum (k = 220 W/m.K, ρ = 2.707 × 10^3 kg/m^3, and C_p = 896 J/kg.K), respectively. Since water jacket inside the engine has many windings and there are many barriers to flow, the fluid flow is naturally turbulent. Therefore, it is necessary to use a turbulence model with good degree of accuracy and reasonable computational time by comparing the performance of the turbulence models. Here, the turbulence model $k - f - \xi$ developed by Hanjalić et al. [27] is used. The eddy-viscosity parameter is obtained from the following equation:

$$\nu_t = C_\mu \xi \frac{k^2}{\varepsilon} \tag{4}$$

Flow parameters, k, ε, ξ and f are obtained from the following equations:

$$\rho \frac{Dk}{Dt} = \rho (P_k - \varepsilon) + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \tag{5}$$

$$\rho \frac{D\varepsilon}{Dt} = \rho \frac{C_{\varepsilon 1}^{*} P_k - C_{\varepsilon 2}\varepsilon}{T} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right] \tag{6}$$

$$\rho \frac{D\xi}{Dt} = \rho f - \rho \frac{\xi}{k} P_k + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\xi}\right)\frac{\partial \xi}{\partial x_j}\right] \tag{7}$$

$$f - L^2 \frac{\partial^2 f}{\partial x_j \partial x_j} = \left(C_1 + C_2 \frac{P_k}{\xi}\right)\frac{\left(\frac{2}{3} - \xi\right)}{T} \tag{8}$$

2.1. Turbulence time and length scales are

$$T = \max\left(\min\left(\frac{k}{\varepsilon},\ \frac{a}{\sqrt{6}\, C_\mu^{\nu} |S| \xi}\right), C_T\left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{2}}\right) \tag{9}$$

$$L = C_L \max\left(\min\left(\frac{k^{\frac{3}{2}}}{\varepsilon}\right),\ C_\eta \frac{\nu^{\frac{3}{4}}}{\varepsilon^{\frac{1}{4}}}\right) \tag{10}$$

To simulate the engine cooling jacket, most of the numerical simulations did not focus on boiling heat transfer in the engine water jacket unsteadily. The heat transfer mechanism is forced convection before the onset of nucleate boiling. The boiling heat transfer correlation that were employed by the researchers were the correlations of Chen [28] and Rohsenow [29]. These correlations use a super-positioning method where the heat flux consists of forced convection and nucleate boiling. Chen [28] performed experiments to determine heat transfer rate in a vertical flow tube and corrected the proposed relationship of Rohsenow [29]. Chen [28] presented a heat transfer of boiling flow as a sum of two macro (forced convection) and micro (nucleate boiling) mechanisms:

$$h_{total} = h_{mac} + h_{mic} \tag{11}$$

where h_{mac} is the forced convection heat transfer coefficient obtained from the wall function. Also, h_{mic} is the nucleate boiling heat transfer coefficient obtained from the Forster-Zuber equation [28], is as follows:

$$h_{mic} = 0.00122 \times \left(\frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{lg}^{0.24} \rho_g^{0.24}}\right)(T_w - T_{sat})^{0.24}(P_w - P_{sat})^{0.75} S \tag{12}$$

The Forster-Zuber equation is used to calculate the heat transfer coefficient of nucleate boiling. It is possible to correct the nucleate boiling heat transfer coefficient with a suppression factor S due to the flow availability. Two models are proposed for calculating the suppression factor S: Chen and Boundary Departure Lift-off (BDL) models. The total heat flux is also obtained by equation (13):

$$q''_{total} = \varphi h_{mac}(T_w - T_\infty) + S h_{mic}(T_w - T_{sat}) \tag{13}$$

2.2. Chen correlation

Chen model was first used for saturated boiling flow and then developed to be used for nucleate boiling. Chen proposed the correction factor as the following [29]:

$$S_{Chen} = \frac{1}{(Re\varphi^{1.25})^{1.17}} \tag{14}$$

Butterworth modified it in to the following form [30]:

$$S_{Chen} = \frac{1}{1 + 2.53 \times 10^{-6}(Re\, \varphi^{1.25})^{1.17}} \tag{15}$$

In the present work, $S_{Chen}$is defined as a multivalued function [30]: