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Research paper

Experimental study on the heat transfer characteristics of subcooled flow boiling with cast iron heating surface

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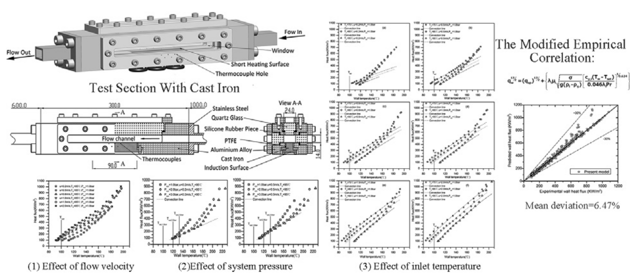
HIGHLIGHTS

- An experimental facility with cast iron was designed to produce boiling phenomenon.
- Some characteristics in flow boiling were obtained under specified conditions.
- Three types of original boiling models were utilized to correlate present data.
- A modified boiling model was developed to adapt to the cast iron heating surface.

GRAPHICAL ABSTRACT



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ABSTRACT

Subcooled boiling is an effective heat transfer form for modern engine cooling systems. The significantly higher heat transfer rate achievable with boiling can keep the temperature in key thermal areas within an acceptable level and optimize thermal management strategies even at high engine loads. In this study, an experimental setup was designed using cast iron as heating block to simulate the flow boiling in engine cooling passage. The heat transfer characteristics were obtained under comprehensive cooling conditions for an engine, where the inlet temperature ranges from 75 to 95 °C, the system pressure ranges from 100 to 300 kPa, and the flow velocity ranges from 0.2 to 2.0 m/s. The experimental results were used to verify the wall heat flux of subcooled flow boiling in the cooling system of diesel engine, which was predicted by three types of empirical boiling models with primitive parameters. The results indicate that the prediction models are not accurate. Based on the experimental results and Franz's correlation, a modified boiling model was developed to adapt to the cast iron heating surface status.

1. Introduction

Cylinder head as a complex part of internal combustion engine (ICE) is directly exposed to hot burning gas and subjects the flame plate to high temperature and thermal load during the operation [1]. Thus, the engine cooling system plays an important role in ensuring normal operation of the machine. As the design of modern engine is shifting to high combustion pressure and high power density output [2], advanced cooling system needs to be more compacted yet less power consumption, and more efficient to keep the temperatures of individual components at an acceptable level [3,4]. The traditional engine cooling systems designed with convection heat transfer, without coolant saturation boiling are not able to meet the cooling requirement under high load conditions

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[5]. Recently, there has been interest in replacing conventional forced convection with nucleate boiling cooling in engine cooling systems under certain conditions or in certain areas. This technology will remove ever increased thermal loads, eliminate potential hot spots in engines, and further optimize the power loss of the coolant pump [6,7]. Additionally, the potential benefits of nucleate boiling cooling are compliant to the thermal management and precision cooling strategies of ICE. Therefore, in order to achieve the nucleate boiling cooling under specified operating conditions, an experimental study on the heat transfer characteristics of subcooled flow boiling in the simulated cooling passage is essential.

In many studies on the subcooled flow boiling in simple channel with global heating, most efforts focused on the high-velocity and high-pressure nuclear reactor systems or work fluid with refrigerant [8–11]. Many theoretical and experimental studies have been conducted in the last three decades for the subcooled flow boiling in a channel of ICE cooling systems. The existence of boiling in engine cooling system was confirmed in 1980s. By comparing the temperature distributions in a running engine at two coolant pressures, an increase in pressure reduced the nucleate boiling and increased metal temperature [12]. A similar conclusion was made later in another study [13]. A rectangular channel thermal flow test rig was set up to study the scientific problems of thermal in ICE cooling galleries [14], and an experiment on the smooth and intermediate as-cast aluminum test pieces was conducted to quantify the effects of cooling passage surface roughness on the nucleate boiling regime. Based on Campbell's work, an extensive array of experimental data was obtained as the basis of the predictive validation, and based on a superposition of convective and boiling heat transfer coefficients (HTCs), the empirical Chen correlation for flow boiling was modified to predict HTCs under flow boiling operating conditions on the rig [15]. A division model with the boiling number (the ratio of a dimensional estimation of the boiling velocity to the bulk flow velocity) was presented [16], and then extended to comprise subcooled boiling of ethylene-glycol/water mixture on the rig [17]. Subcooled flow boiling in a rectangular channel with one-sided heating was experimentally studied [18]. Based on the experimental data, a wall heat transfer model was developed by changing the modification factor for the nucleate boiling component in the Chen's correlation [19] and by introducing two suppression factors accounting for the effects of bubble balance forces [20] and the subcooling of the thermal boundary layer. Because it requires only local input quantities, the model is well suited to computational fluid dynamics (CFD) simulations on geometrically complex coolant flows, where the definition of global length or velocity scales was impractical. A new numerical model without any geometry-dependent parameter was proposed on the division description method [21], which can be incorporated into a CFD package to predict the flow boiling heat transfer in geometrically complex cooling galleries of ICEs. In addition, several studies were carried out to experimentally study the convective boiling of typical engine coolants, and the flow boiling heat transfer was characterized under low heat flux and pressure [22–27].

Consequently, there is a great interest in the understanding of flow boiling heat transfer rates and characteristics in engine cooling applications. However, the subcooled flow boiling heat transfer characteristics are affected by many factors such as micro-scale surface morphology, roughness or contamination, macroscopic flow property, heater materials, and work fluid [4]. Moreover, there is far less knowledge about the characteristics of boiling than single-phase convection, and we generally lack enough experimental data and an appropriate correlation for subcooled flow boiling heat transfer in engine cooling system, particularly with cast iron surfaces. Therefore, this work is aimed to study the heat transfer characteristics of subcooled flow boiling with cast iron which is the most common cylinder head material for diesel engine. Also the development of flow boiling was recorded using a high-speed visualization technique. Three types of empirical boiling correlations with primitive parameters were utilized to predict the heat flux in subcooled flow boiling. Finally, a modified boiling model based on Franz's correlation was proposed to adapt to the cast iron heating surface status.

2. Experimental methods

2.1. Experimental facility

The experimental channel was designed to simulate subcooling boiling under forced flow conditions in the coolant passage of ICEs. A schematic of the experimental setup is shown in Fig. 1. The liquid flows in a closed loop which includes a water storage tank with electric pre-heater and a condenser used for water cooling and steam bubbles eliminating. Both the pre-heater and condenser play a role in thermal equilibrium and control of the bulk fluid temperature. The work fluid of deionized water was circulated by a variable-speed pump and supplied by the electric frequency changer to the pump, and the bypass valve openings were controlled to keep the flow velocity at the prescribed values in test section channel. It was worth mentioning that the minimum subcooling must be limited under high flow rate conditions due to cavitation in the pump. The liquid flowed from electromagnetic flow meter to the test channel with a rectangle cross-section, then to the test section. The liquid leaving the test section returned to the water storage tank which was also served as a deaerator. The flow loop system pressure was created using a N_2 gas accumulator to connect water storage tank with rubber tube. And then the pressure valve of opening would be set up by a PID controller combined with pressure sensor. So, the closed flow loop system was allowed to change the main experimental parameters including the system pressure, liquid subcooling and flow velocity. Besides, the stainless steel material was used for test pipe to avoid the work fluid being polluted with rust, and a layer of 3 cm-thick fiberglass and a layer of foam glass, as an insulation, with the same thickness were coved on the out surfaces of pipes, tank, test duct, and test section to minimize heat losses to the environment.

Fig. 2 shows the details of rectangle flow channel with the size of 24×14 mm and the test section assembly was in horizontal direction with coolant flowing above the short heating surface. In this device, the cast iron specimen was fitted at the bottom of test duct and the dimensions of the bottom short heating surfaces is 90×14 mm. Because of the low thermal conductivity of cast iron, the conventional electric heating tube is difficult to obtain a wide range of heat flux. In present work, a sufficient heat flux to the specimen was provided by a high frequency induction heating device whose radio frequency induction coils were attached to the heater block of induction surface. Five K-type thermocouples, 1.0 mm in diameter, were fitted to the vertical direction of the cast iron specimen, arranging in two rows as shown in Fig. 2(b), where the upper row has three thermocouples and two thermocouples were put in lower row. A high-temperature resistant PTFE material was coated on the surrounding of cast iron specimen to prevent thermal diffusion. Therefore, the heat loss from the sides of the cast iron was considered very small and negligible. At the same time, thermal insulation of asbestos and glass wool were used to minimize heat losses for heater block. In order to reduce the effect of flow disturbances due to the change of flow area from circular to