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Subcooled flow boiling of ethylene–glycol/water mixture in an inclined channel with a hot spot: An experimental study☆

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ABSTRACT

Subcooled flow boiling plays an important role in many industrial systems like Internal Combustion Engines (ICE). The main reason of its extensive application is its high potential of heat removal due to the fluid latent heat. The ethylene–glycol/water mixtures have been used as engine coolants for several decades. In this study, the effects of some parameters such as surface roughness, fluid velocity and surface inclination on the subcooled flow boiling of ethylene–glycol/water mixture with 50–50% volume fraction (WEG50) are investigated experimentally. An experimental test rig with the most resemblance condition to an ICE water jacket is set up and comprehensive data are collected. The setup consists of a 12 mm circular heater that is placed on the lower wall of a 20×30 mm^2 channel and the WEG50 is used as the working fluid.

Based on the experimental data, two new independent empirical correlations are presented to predict the subcooled flow boiling heat transfer inside the horizontal channel with good accuracy. The experimental results show that by increasing the test section surface roughness and fluid velocity the surface heat fluxes increase too. Inclination of the surface in either direction yields higher heat transfer coefficient in comparison to its horizontal position when the surface is smooth but lower for the rough surface.

1. Introduction

Boiling is a process in which heat transfer causes evaporation. Due to the fluid latent heat, large amount of energy is removed from the hot solid surface during this phenomenon. By increasing the wall temperature, the rate and number of bubbles creation increases and consequently the heat transfer coefficient increases. This significant effect of the process has been used in Internal Combustion Engines (ICE) cooling system [1] and some other systems [2]. Considerable fuel consumption and emissions reduction would be expected if the boiling phenomenon is properly used in the cooling system of ICE [3]. Higher heat transfer rate is achievable by using boiling; therefore, it can keep temperature at proper level condition in some critical areas like the exhaust valves. There is evidence that the boiling taking place in some regions of an ICE is a subcooled flow boiling regime since the bulk temperature of the fluid is normally below the saturation point [4,5]. When the boiling develops beyond the nucleate regime, overheating may result damage to the surface. Therefore, an accurate prediction of the flow boiling characteristics is essential for safe operation in ICE.

The simulation of flows as engine coolant application has been carried out in rectangular ducts with a small flat heated area at the bottom surface of the flow channel by many researchers [6–11]. There is evidence that the WEG50 is normally used as the engine coolant flow fluid [9–14].

The solid surface properties have shown to have significant effects on the boiling phenomena. It appears that Bonilla and Perry [15] are the pioneer to study this subject. Tewari et al. [16] studied the effect of surface roughness on the pool boiling heat transfer at sub-atmospheric and atmospheric pressure and concluded that the wall superheat at a given heat flux increase with decrease in saturation pressure. They [16] also found that by increasing the surface roughness the heat transfer coefficient increase too. Torregrosa et al. [14] studied subcooled boiling flow of water/ethylene–glycol mixtures in a rectangular duct with the heating section of 40 mm wide and 300 mm long. In their experiments, the thermal condition was very close to an engine coolant flow with low velocity range (0.1–0.3 m/s) and an empirical model which may be useful for practical engine cooling applications was presented. Yu et al. [13] studied subcooled flow boiling of water and ethylene–glycol/water mixtures with volume ratios of 40/60 and 50/50 in a steel tube. They [13] simulated the heating condition of a cylinder head coolant channel in a heavy-duty vehicle engine and based on the experimental results, the boiling curves and subcooled flow boiling heat transfer coefficients were determined for the tested fluids.

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Nomenclature

C_p	specific heat capacity [J kg^{-1} K^{-1}]
d	diameter of heater [m]
D_h	hydraulic diameter of channel [m]
f	friction factor [−]
h	heat transfer coefficient[W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length of channel [m]
Nu	Nusselt number [−]
Pr	Prandtl number [−]
q''	heat flux [W m^{-2}]
Re	Reynolds number [−]
S	suppression factor
T	temperature [°C]
u	fluid velocity [ms^{-1}]
Greek symbols	
ρ	fluid density [kg m^{-3}]
ε	surface roughness [m]
θ	surface angle of inclination [°]
μ	fluid viscosity [Pa·s]
Subscript	
Al	aluminum
b	bulk
e	entrance
f	fluid
fc	forced convection
fb	flow boiling
nb	nucleate boiling
s	surface
sat	saturation

The surface inclination has also had impact on the boiling process. Class et al. [17] studied the effect of surface condition and the angle of surface orientation on the nucleate and film boiling of liquid hydrogen. They [17] reported that when the smooth surface was changed from horizontal to a vertical position, an upward shifting on the boiling curve was observed. Similar shifting also took place for greased surface. Nishikawa et al. [18] investigated the nucleate pool boiling of water at atmospheric pressure on an inclined copper plate. Their results showed that by increasing the angle of inclination, the heat transfer coefficient under low heat flux conditions increases too. Jung et al. [19] conducted experiments on a flat copper plate for R-11 with angles varying from 0° to 180°. They [19] observed that the bubble agitation mechanism is a strong function of the surface orientation and similar results as of Nishikawa et al. [18] were reported by Jung et al. [19]. Kang [20] investigated pool boiling of water at three inclinations of 0°, 45° and 90° for smooth tubes with average surface roughness of 60.9 and 15.1 nm. He [20] observed that at 45° inclination the bubbles move upward and then depart before getting to the top region of tube perimeter.

The primary goal of this experimental study is to investigate the subcooled flow boiling inside a duct with a hot spot on the bottom surface at different thermo-fluid conditions. This type of duct flow is meant to simulate the most resemblance condition of an ICE water jacket coolant at some critical locations like the valves bridge.

2. Experimental setup

The schematic of the experimental setup used for WEG50 subcooled flow boiling measurements is shown in Fig. 1. The experimental apparatus consists of a reservoir, pump, three pressure gauges, an insulated channel made of Plexiglas, rotameter, two heaters, copper block, controller, some thermocouples, power control and cooling systems.

The test section is a circular surface with a diameter of 12 mm made of aluminum is screwed on the top of a copper block as shown in Fig. 2. Then, it is mounted to the bottom surface of the Plexiglas channel with a thickness of 20 mm. This test section surface is heated by a copper block with length of 12 cm from the bottom with a 1 kW cylindrical heater. Three k-type thermocouples with about 1 mm in diameter of the junction bead, 0.5 mm in wires and accuracy of 0.1 °C are imbedded in the trunk of the aluminum test section to measure the surface temperature and the heat flux as shown in Fig. 3. They are located at specified locations from the boiling surface to determine the boiling surface temperature by extrapolation. This indirect connection of thermocouples to measure the boiling surface temperature is more accurate than direct connection since in an indirect one, thermocouples do not interfere with the boiling process by providing additional nucleation sites. For instance, Das et al. [21] welded all thermocouples on the boiling surface. Since bubbles have a tendency to nucleate on the welded positions, the measured temperature may not be the representative of the actual boiling surface temperature.

Teflon Polytetrafluoro Ethylene (PTFE) with low conductivity compared to aluminum is furnished around the test section as an O-ring seal to prevent any leakage of fluid between the test section and the channel. Three layers of ceramic insulation with thickness of approximately 5 cm are also used to minimize the copper block as well as the test section heat loss. The PTFE surface which is in the channel is greatly polished to minimize the fluid flow perturbation.

Grease (COPASLIP MOLY SLIP) type of oil with high conductivity ($k \approx 4.5$ W/m·K) is applied between the test section and copper block to minimize the contact thermal resistance. The length and cross section of the Plexiglas channel are chosen as 1.2 m and 0.02×0.03 m^2 respectively to ensure a fully developed flow near the test section. The test section is located at distance of 0.9 m from the channel entrance. Two pressure transducers (model: TG-25Ss-PPR) with accuracy of 0.02 bar are used at each end of the channel for the pressure drop measurements. A 50 L capacity insulated tank is used as a reservoir to provide WEG50 to the channel continuously. A multi-speeds pump (model: GRUNDFOS type: UPS32-55) and a rotameter (model: GEC-ELLIOT) with accuracy of 0.1 L/min are used for the fluid circulation and flow measurement respectively. The rotameter was originally calibrated for pure water and recalibrated for WEG50 according to Eq. (1).

$$Q_2 = Q_1 \sqrt{\frac{\rho_1 \left(\rho_f - \rho_2\right)}{\rho_2 \left(\rho_f - \rho_1\right)}} \tag{1}$$

where Q_2 and Q_1 are the volumetric flow rate of the WEG50 and water, ρ_2 and ρ_1 are the density of the WEG50 and water and ρ_f is the float density.

To achieve the most resemblance condition to the engine jacket coolant flow, the fluid pressure and temperature around the test section are set to be 1.4 bar and 80 °C respectively.

A heater and a condenser are immersed in the reservoir to ensure desired inlet temperature as shown in Fig. 1. All the connecting pipes are constructed of 3/4 in (model: DAMPFSCHLAUCH) and insulated with fiberglass with a thickness of approximately 1 cm to minimize heat transfer loss.

The roughness of the test section surface is changed by using different sand papers or grindstones between 15–600 grit (model: Emery Tousa) and is measured by a roughness tester (model: TR200). After each test the fluid flow loop and test section surface are cleaned by distilled water and then the surface roughness is adjusted.

Data acquisition system (model: ADAM 5000/TCP) along with an in-house developed software is used as a controller and data recorder. The

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