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Research Paper

Heat transfer enhancement of an internal subcooled flow boiling over a hot spot

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HIGHLIGHTS

- Experimental investigation of subcooled flow boiling.
- The impact of fluid velocity, surface roughness, and materials on the subcooled flow boiling.
- The boiling heat transfer performance enhancement.
- Addition of nanoparticles on the subcooled flow boiling.
- The impact of mini-channels on the nanofluid subcooled flow boiling.

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ABSTRACT

Using nanofluids is one of the most recent techniques for improving the boiling performance. The present paper investigates the impact of fluid velocity, nanoparticles addition, and surface characteristics, such as roughness, material and topography on the subcooled flow boiling, experimentally. An experimental setup consisting of a Plexiglas channel with the cross section of 20×30 mm^2 and the length of 120 cm was used for this propose. A cylindrical heater with a diameter of 12 mm was located at the bottom surface of the channel. The experiments were conducted with four different heaters which were made of brass (with and without mini-grooves), aluminum and copper. The experimental results showed that the surface heat flux increases with an increase in the surface roughness and velocity. However, the impact of velocity on the heat flux is only observed at lower boiling surface temperatures and opposite trend has been seen for the higher boiling surface temperature. The experiments were also conducted for pure water and water-alumina nanofluids with a concentration of 0.1 and 0.25 vol.%. The nanofluid with the concentration of 0.25 vol.% has better heat transfer performance than the other ones. When the surface material was considered, brass showed a better boiling heat transfer performance than that of the copper and aluminum. The effect of mini-channels (grooves) on the performance of the nanofluid subcooled flow boiling showed that these grooves have enhanced the heat transfer significantly.

1. Introduction

Boiling is defined as a phase change from liquid to vapor state which occurs when the liquid temperature exceeds the saturation temperature at its corresponding saturated pressure. The highest significance of boiling phenomenon is related to the high latent heat of the fluid. This could remove a large amount of heat flux at a relatively low temperature difference between the liquid and the hot surface. The flow boiling is classified as saturated and subcooled flow boiling. The subcooled flow boiling occurs when the bulk temperature is less than that of the saturation temperature of the liquid at its corresponding saturated pressure. While the saturated flow boiling takes place when the temperature is higher. The boiling phenomenon may take place in some regions of an internal combustion engine water jacket is a subcooled flow boiling type. This is the focus of this study.

The rate of the bubbles nucleation increases, by increasing the wall temperature and, consequently, the heat transfer coefficient increases. This significant effect of the boiling has been used in some industrial applications, such as: internal combustion engines (ICEs) cooling system, boilers, air conditioning, and refrigerating systems [1].

The surface properties, such as roughness and material, have a significant impact on the flow boiling heat transfer. Many researchers have investigated the surface roughness impact on the boiling performance [2–5]. Jakob and Fritz [2] investigated the pool boiling and used a surface with 0.016 mm square machined grooves spaced at 0.48 mm and a sandblasted surface. Kandlikar and Spiesman [3] investigated the subcooled flow boiling heat transfer of water over heated surfaces. Their results showed that the heat transfer

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performance depends on the cavity size distributions and number of the cavities rather than just the average roughness indicator. Jabardo et al. [4] investigated nucleate boiling heat transfer coefficient of refrigerants R-123 and R-134a for different materials. Jones and Garimella [5] studied the flow boiling heat transfer in microchannels. They reported that the surface roughness had a little influence on the boiling incipience. They also indicated that by increasing the surface roughness, the heat transfer increases while this increment has not been seen at higher surface roughness. All of the researchers unanimously agreed that the heat transfer performance improves as the surface roughness increases.

The surface material impact on boiling is another parameter that has been studied by many researchers [4,6,7]. Jabardo et al. [4] investigated copper, brass and stainless steel heating surfaces. They observed that brass and stainless steel surfaces have the best and the worst heat transfer performance, respectively. Saeidi et al. [6] investigated the pool boiling with different surface materials experimentally. Their result showed that the aluminum surface has a better performance than the copper surface. Suriyawong and Wongwises [7] studied the effects of the surface roughness and the volume concentration of TiO_2–water nanofluids on nucleate pool boiling heat transfer over a horizontal circular plate made of copper and aluminum experimentally. Their results showed that aluminum has a better performance than copper and the heat transfer coefficient increases by increasing the surface roughness. They also reported that the addition of nano-materials to the base fluid may increase the heat transfer to some volume fraction; then, it starts to decrease for others.

The fluid velocity impact on the flow boiling has been studied by [8,9]. Yu and Sheikholeslami [8] investigated the subcooled flow boiling heat transfer coefficients of water and sugar solutions in an annulus tube. Campbell et al. [9] studied the flow boiling heat transfer in a rectangular duct. They investigated both the velocity and the roughness impact on the flow boiling heat transfer performance and showed that the heat transfer coefficient increases with the fluid velocity increment.

It seems that Yang and Maa [10] were the pioneers in investigating the nanofluid boiling. Prajapati and Rohatgi [11] and Abedini et al. [12] studied the nanofluid subcooled flow boiling at various concentrations, both experimentally and numerically, respectively. Both researchers [11,12] reported that the nanofluid improves the boiling heat transfer performance and this augmentation continues with the concentration increment up to about 4% [12].

Moita et al. [13] and Das et al. [14] studied the impact of surface grooves on the boiling. Moita et al. [13] investigated the pool boiling heat transfer over micro grooved surfaces made of silicon wafers. They indicated that the heat transfer coefficient increased about 10 times for water and 8 times for the dielectric fluid with respect to their corresponding smooth surfaces. Das et al. [14] used several structured surfaces to investigate the performance of the surfaces in nucleate pool boiling. The surfaces finished with a number of either parallel or orthogonal intersecting furrows. Three various structures, such as rectangular, circular, and rounded grooves were also used at the end of the furrows. They observed significant heat transfer enhancement with these micro-channels' surfaces.

Three empirical correlations for the pool boiling heat transfer were presented by Gorenflo [15], Cooper [16] and Rohsenow [17]. Two of them included the surface roughness while the other one considered the surface material. The correlation provided by Rohsenow [17] considered the impact of the surface material on the pool boiling for smooth surfaces. He introduced an empirical constant C_{sf} to account for the effect of the fluid-surface material on the pool boiling. The three correlations were obtained from the experimental data. According to these correlations, the pool boiling heat transfer increases by increasing the surface roughness [15,16] and the brass surface has a better heat transfer performance than that of the copper surface [17].

Boiling phenomenon is utilized in some practical and industrial applications. ICEs cooling system is one of the applications in which subcooled flow boiling may take place in the cooling passages with hot spots. The present study focuses on measuring the influence of the surface roughness and the material, both with and without, some grooves on nanofluids subcooled flow boiling heat transfer performance along with their interactions. This type of flow along with a channel having a hot spot has not been studied in detail, so far.

2. Experimental setup

An experimental setup was designed and manufactured to consider the impact of the fluid velocity, surface characteristics, and the type of fluid on the subcooled flow boiling heat transfer coefficient in a channel with a hot spot. The schematic of the experimental setup is shown in Fig. 1.

The experimental apparatus consists of a channel made of Plexiglas, controller (relay connected to the DC power supply), rotameter, copper block, two heaters, three pressure gauges, pump, four K-type thermocouples, power controller, and cooling system. The test sections are a circular surface with a diameter of 12 mm and they are located at the bottom of the Plexiglas channel as shown in Fig. 2. The test section is made of three different materials, namely copper, aluminum, and brass. The cross section area of the channel is 2×3 cm^2 and its length is 120 cm. The test section surface is heated by a copper block from the bottom with a 1000 W cylindrical heater with three embedded thermocouples as shown in Fig. 3. The test section surface temperature is evaluated by extrapolating the measured three temperatures as shown in Fig. 4. The other thermocouple was used for the measurement of the fluid bulk temperature. The accuracy of these K-type thermocouples with 1 mm junction diameter is 0.1 °C.

Teflon polytetrafluoroethylene (PTFE) with low conductivity compared to copper, brass and aluminum is furnished around the test section as an O-ring seal. The heads and the copper body are insulated by three layers of fiber glass insulation during the test. The thermal conductivity of this insulation and the PTFE is 0.1 W/m.K and 0.25 W/m.K, respectively. Two pressure transducers (model: TG-25Ss- PPR) with the accuracy of 0.02 bar were used at each end of the channel for the pressure drop measurements. The pressure was controlled by a three way connector and valves. To supply the fluid flow into the channel continuously, a 50 L capacity insulated tank was used as a reservoir. A rotameter (model: GEC-ELLIOT) with accuracy of 0.1 L/min was used for the flow rate measurements and a multi-speed pump (model: GRUNDFOS type: UPS32-55) is used for the fluid circulation. In order to provide the most similar condition to the engine water jacket, the fluid pressure and the temperature around the test section were set to 1.2 bar and 80 °C, respectively.

To ensure the desired inlet temperature, a condenser and a heater were immersed in the reservoir tank as shown in Fig. 1. All of the connecting pipes were constructed of 3/4 in (model: DAMPFSCHLAUCH) which have been thermally insulated with fiberglass. The test sections' surface was roughed, using different types of sand papers or grindstones between 15-600-grit (model: Emery Tousa). The average roughness of the test section surface (the averaged value of about 20 different measured points was used) for each test was measured by the roughness tester (model: TR200). A data acquisition system (model: ADAM 5000/TCP) along with an in-house developed software was used to control and record the experimental data. By increasing the input heating power, the fluid moved from the single-phase to the two-phase regime. The curves