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Gas-assisted evaporation and boiling in minichannels

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ABSTRACT

This study experimentally explores the heat transfer characteristics of gas-assisted evaporation and boiling in single or two parallel minichannels under both non-boiling and boiling conditions. The liquid working fluid used is ethanol and the inert gas is helium. Compared to the pure ethanol flow in a minichannel under both non-boiling and boiling conditions, the heat transfer enhancement (HTE) caused by the adjunction of helium is examined. The maximal HTE owing to an inert gas is located at the wall superheat (ΔT_{sat}) of −10 °C (i.e., non-boiling region) in the single minichannel in which the annular flow occurring in most parts of the channel; however, for the boiling region, the HTE is insignificant in the single minichannel, as the flow patterns observed for the studied cases are approximately the same. For the two parallel minichannels, the differences in the mean (effective) wall heat flux between the cases with and without helium become much more evident than those in a single minichannel. Under boiling conditions, primarily an annular flow, accompanied with bubble nucleation at the wall downstream, occurs for the studied cases when helium flow is present; however, extensive bubble nucleation occurs and bubbly flow prevails for the case without helium flow. Owing to the difference in flow pattern, the heat transfer performances for the cases with and without helium are significantly different in the parallel minichannels under this boiling condition. In addition, the HTE significantly increases with an increase in the helium flow rate at a given wall superheat. The maximal HTE, which also occurred at about $\Delta T_{sat} = -10$ °C, is 206% obtained under the conditions of the lowest ethanol flow rate and the highest helium flow rate in the parallel minichannels.

1. Introduction

Most air-conditioning equipment used in businesses and homes utilize a vapor compression refrigeration cycle, which generally has a good cooling capability; however, the operation of the compressor can consume a significant amount of power. As reported in the literature, although refrigeration technology based on vapor compression is currently the most popular, it consumes about 30% of the final energy use globally [1]. Therefore, reducing the energy consumption of air conditioning equipment has become an important issue, particularly in subtropical areas. For example, electricity consumption by air-conditioning systems contributes to 41% of the electricity used in commercial buildings annually [2] and also contributes to about 30–35% of the total electricity consumed during the summer in Taiwan [3]. The absorption refrigeration (AR) cycle is an alternative candidate to a vapor compression system because there is no need to use a compressor, resulting in less energy consumption with the same cooling capacity [4,5]. In addition, the AR cycle can use different types of thermal energy (such as solar, thermal, geothermal, or waste heat) as a driving force, which is another merit of this cycle. The significant feature of the AR cycle is the working fluid, which includes two fluids with a significant difference in their boiling point. The fluid with the lower boiling temperature is called a “refrigerant,” whereas that with the higher boiling temperature is called an “absorbent.” The AR cycle is widely used in fabrication industries to meet a higher requirement of the cooling load, such as in energy- and technology-intensive plants.

However, the pump used for driving the working fluid in an AR system still has certain problems, particularly in a small cooling-capacity system [6]. To resolve the problems occurring in a pump, another pump-less system based on the AR cycle, the so-called diffusion–absorption refrigeration (DAR) system, was developed [7].

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The working fluid and the ability to operate without a pump or expansion valve are major significant differences between AR and DAR systems. There are three fluids used in a typical DAR system: a refrigerant, absorbent, and auxiliary gas [6]. The driving force of a DAR system is introduced through the natural circulation of the refrigerant vapor generated in the generator. An auxiliary or inert gas (such as hydrogen or helium) is used to reduce the partial pressure of the refrigerant, and therefore, to enhance the evaporation of the refrigerant. The preferred inert gas used in a DAR system generally has unfavorable properties in terms of heat transfer, such as a low specific heat and a low density [8]. A DAR system typically consists of a generator, separator, condenser, evaporator, gas heat exchanger, absorber, reservoir, and heat exchanger for the solution [6]; for more detailed descriptions and the working processes of a DAR system, refer to [6].

There have been very few investigations on the detailed characteristics of an evaporator that involves the gas-assisted two-phase flow of evaporation or boiling in a DAR system. For example, Jelinek et al. [9] studied the effects of the evaporator inlet conditions on the performance of a DAR system, and their results demonstrate that the inlet temperature of the evaporator should be as low as possible. However, they did not report the two-phase flow or heat transfer characteristics in the evaporator. Many studies concerning the heat transfer characteristics of a two-phase non-boiling flow (but not in the application of a DAR system) have been conducted. Walsh et al. [10], for example, experimentally investigated the mechanisms of heat and/or mass transfer enhancement in two-phase non-boiling slug flows under a constant wall heat flux. They analyzed the results of the heat transfer characteristics through flow visualizations (using both infrared thermography and high-speed digital cameras). Their results indicate that the slug flow, with regard to the thermal entrance length, might reach its fully developed asymptotic region at a distance of one slug length regardless of the Reynolds number. In addition, they reported that in a fully developed flow region, the Nusselt number can be one order of magnitude higher than that of a single-phase flow while the length of the slug flow approaches that of the channel diameter. Such a heat transfer enhancement might be mainly due to the strong liquid circulation between neighboring slug bubbles [11].

Betz and Attinger [12] experimentally studied the heat transfer characteristics of a segmented flow in microchannel heat sinks in which the air is periodically injected into the water-flow channels using a T-junction. Compared to the results of the single-phase flow, their results show that a segmented flow enhances the heat transfer by 140% or 50%, respectively, at the same flow rate or same pressure drop with the water flow in the channel. Lim et al. [13] conducted an experimental study on the flow visualization and heat transfer characteristics of a Nitrogen–water two-phase flow in a microtube. Their experimental results demonstrated that, compared to the results of a single-phase water flow, the two-phase heat transfer is significantly enhanced by 176%, whereas the corresponding pressure drop only increases by 27%. Similar to the results reported by Walsh et al. [10], Lim et al. [13] also stated that the optimal heat transfer performance is obtained under conditions in which the bubble size approaches the channel diameter, which might result in a minimal increase in the pressure drop. Saisorn et al. [14] also demonstrated that the heat transfer can be enhanced by 80% (for the best case) while adding air into the water-flow channels, and that the heat transfer performance for a short slug flow is better than that for a bubbly flow.

According to the above-mentioned references, the heat transfer performance of a non-boiling two-phase flow in the channels is significantly affected by the flow pattern. The channel size might be another important parameter that affects the heat transfer characteristic for such studies. For example, Choo and Kim [15] investigated the heat transfer characteristics of a non-boiling air–water two-phase flow in different-diameter microchannels. They found that an increase in the gas flow rate is a benefit for the Nusselt number in large channels with diameters of 334 or 506 μm; however, such an increase is harmful to the Nusselt number in small channels with diameters of 140 or 222 μm. This effect of the gas flow rate on the Nusselt number in small channels was also reported by Hetsroni et al. [16]. The effect of the thermal boundary layer on the heat transfer performance in an air–water two-phase flow in a microchannel was studied by Houshmand and Peles [17]. Their results show that the heat transfer can be enhanced significantly, up to 100%, by injecting air into a water flow channel, as compared to a single-phase flow. In addition, they found that the heat transfer enhancement in a bubbly flow is more remarkable under a thick boundary layer.

The present study investigates the heat transfer characteristics of gas-assisted evaporation and boiling in single or parallel minichannels. The liquid working fluid used is ethanol and the inert gas is helium. The thermophysical properties of ethanol are much close to the water than that of typically-used refrigerants. Therefore, the heat transfer performance of the ethanol might be much better than that of refrigerants. Recently, the boiling characteristics of the ethanol or its mixture have been widely studied by many researcher, such as Vasileiadou et al. [18] and Panse and Kandlikar [19]. The reason for the choice of helium is based on the results of Zohar et al. [20], who reported that the coefficient of performance (COP) of a DAR system using helium as an inert gas is up to 40% higher than that using hydrogen. However, to the best of our knowledge, the heat transfer characteristics of a helium–ethanol two-phase flow in a channel with heating have yet to be studied in the literature. Unlike most of the above-mentioned researches [10,12–15], both non-boiling and boiling conditions were applied in the present study. The detailed heat transfer performance and corresponding flow patterns captured by a high-speed digital camera were examined. Compared to the pure ethanol flow in a minichannel under both non-boiling and boiling conditions, the heat transfer enhancement (HTE) occurring from the adjunction of helium (namely, a gas-assisted two-phase flow) was examined.

2. Experiment details

2.1. Experiment setup

Fig. 1 shows the test rig of the experiments, which consists of a test section embedded with a heating module, a power supply, a reservoir of the working fluid, a high-performance liquid chromatography (HPLC) pump (Dionex, HPG-3200P), a low-temperature water bath (KANSIN, RCB411), a helium cylinder, a thermal mass flowmeter (TOKYO KEISO, NM-2100DC), a flow visualization system, a data acquisition system (YOKOGAWA, MX100), and a computer. In the present experiments, the HPLC pump drove the working fluid (i.e., liquid ethanol with a concentration of 99.8%) at a given flow rate through the minichannel, where the ethanol might be evaporated or boiled. In this study, helium as an inert gas was supplied through the gas cylinder, and its flow rate was further controlled using the thermal mass flowmeter. The two-phase mixtures (i.e., ethanol and helium) drained from the test section were cooled to room temperature by a low-temperature water bath, and were then transported to the reservoir where the helium was released into the ambient air owing to its non-condensable nature. Two T-type thermocouples (with a diameter of 1.6 mm) were located at the inlet/outlet of the minichannel to measure