International Journal of Heat and Mass Transfer 121 (2018) 107–118

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

A review of boiling heat transfer and heat pipes behaviour with self-rewetting fluids

Yanxin Hu, Kaixin Huang, Jin Huang *

School of Materials and Energy, Guangdong University of Technology, 510006 Guangzhou, People's Republic of China

A R T I C L E I N F O

Article history:
Received 7 June 2017
Received in revised form 22 November 2017
Accepted 30 December 2017

Keywords:
Self-rewetting fluid
Surface tension
Thermophysical properties
Boiling heat transfer
Heat pipe applications

A B S T R A C T

The self-rewetting fluid is the liquid which have an anomalous surface tension increasing with temperature when the temperature exceeds a certain value. This particular property can cause the subcooled liquid to be drawn towards the heated surface if a dry patch appears, thus making it possible for the self-rewetting fluids to become promising working fluids. This paper presents an overview of the recent developments of the research on boiling heat transfer using self-rewetting fluids. Thermophysical properties, pool and flow boiling experiments and heat pipe applications of self-rewetting fluids have been reported in this paper. It can be found that the use of self-rewetting fluids in a wide range of applications appears promising. However, further detailed and valuable theoretical and numerical investigations are necessary for us to better understand the boiling phenomenon of self-rewetting fluids.

Contents

1. Introduction

Heat transfer enhancement in two phase flow and boiling processes has been one of the most important technical issues in engineering applications, typically boiler plants, high heat flux cooling devices and microstructure heat transfer surfaces [1–6] that have been successfully developed. Convective heat transfer can be enhanced passively by using high efficiency working fluids, changing flow geometry, boundary conditions and the other ways. Nowadays, some researchers focus their attention on improving the heat transfer process by changing the transport properties of the fluids used in the heat transfer devices.

Discovery of new working fluids makes it possible to improve the ability of convective heat transfer in boiling processes. Although the surface tension of most liquids decreases with

* Corresponding author.
E-mail address: huangjiner@gdut.edu.cn (J. Huang).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.158
0017-9310/

increasing temperature, some exceptional behaviour can be found an increase in the surface tension with the increasing temperature. This particular surface tension behavior induces the thermocapillary flow of inverse direction compared to normal fluids, i.e. from the cold to the hot region of the interface. Petre et al. [7] found that the surface tension of dilute aqueous solutions of high carbon alcohols (number of $C \geqslant 4$) increased with the increasing temperature when the temperature exceeded a certain value. This mechanism will provide an additional driving force for the bubble departure, which enhances the boiling heat transfer. Zhang and Chao [8] claimed that the positive surface tension gradient with temperature was the main driving force to enhance heat transfer under microgravity conditions. Therefore, the aqueous solutions of alcohols with a chain length longer than four carbon atoms can be used as ideal working fluids for boiling heat transfer in microgravity based on the previous experiments [9–12].

The conception of self-rewetting fluids was put forward by Abe et al. [13] when they investigated the heat transfer of some dilute aqueous solutions of high carbon alcohols in 2004. Since the boiling point of these components of dilute alcohol solutions is different, alcohol-rich component preferentially evaporates in the course of liquid/vapor phase change, which results in a concentration gradient in the liquid/vapor interface. Consequently, the concentration gradient results in the surface tension gradient. Meanwhile, the temperature gradient that generates in the liquid/vapor interface also results in the surface tension gradient. Marangoni flow due to the concentration gradient, coupled with the thermocapillary flow, therefore induce a rather strong liquid inflow at the three-phase interline of bubble/heater contact area. There is a larger driving force between high temperature area and low temperature area, which makes the liquid flow spontaneously to the high temperature area. Therefore, the expression of self-rewetting fluids comes from such characteristics of spontaneous liquids supply to local dry patches or hot spots by such coupled Marangoni flow considered to cause an increase in the critical flux not only in microgravity conditions but probably also in the normal gravity conditions to some extent.

The aqueous solutions of alcohols with a chain length longer than four carbon atoms can offer a new way of heat transfer enhancement, which is achieved through an anomalous surface tension. Necessary studies need to be performed before wide applications of self-rewetting fluids can be found. In this paper, we present an overview of the literature dealing with the recent development in the study of heat transfer using self-rewetting fluids. Firstly, the experimental investigations of self-rewetting fluids are discussed, which is followed by a review of recent numerical investigations with self-rewetting fluids.

2. Experimental investigations

2.1. Thermophysical properties

Preparation of self-rewetting fluid is the first key step in experimental studies. In order to investigate the solution for preparing self-rewetting fluids, many experimental works have been reported on measuring the thermophysical properties, such as surface tension, temperature gradient, concentration, wettability, thermal conductivity and so on. After taking the thermophysical properties of different liquids into account, self-rewetting fluids were prepared by mixing different fluids with a corresponding ratio. Above all, surface tension is the key factor for heat transfer limitations, since it influences the dynamics associated with Marangoni flow along the gas-liquid interface. For this reason, the surface tension of self-rewetting fluids becomes the research hot pot in heat transfer enhancement field.

Savino et al. [14] measured the surface tension of long-chain alcohol solutions, including water/butanol, water/pentanol, water/hexanol, water/heptanol and water/octanol. Results showed that the temperature corresponding to the minimum of the surface tension increased with increasing Carbon atoms.

Di Francescantonio et al. [15] measured the surface tension of water and alcohol solutions such as 1-butanol, 1-heptanol and 1-octanol using a Dataphysics OCA 15 tensiometer. Results showed that the surface tension decreased with increasing temperature when the alcohol concentration was very low, but a positive surface tension gradient with the temperature could be found when the temperature exceeded a certain value.

Wu [16] studied the thermal performance of butanol, pentanol, hexanol aqueous solutions. Results showed that each alcohol aqueous solution reached the greatest surface tension gradient when each one's concentration was around its saturation concentration. It was also observed that 6% butanol was the best self-rewetting fluid in solute and concentration.

Fumoto et al. [17] measured the surface tension of water, 1-butanol, and 1-pentanol aqueous solution. They observed that pure 1-butanol and pure 1-pentanol showed monotonically decreasing surface tension values with temperature and the surface tension of an aqueous solution decreased gradually, reaching a minimum value at approximately 70 °C and gradually increasing at higher temperature.

Senthilkumar et al. [18] measured the surface tension of butanol, pentanol aqueous solutions in heat pipe. They found that the aqueous solution of *n*-pentanol gave the better results than the aqueous solution of *n*-butanol as it had the better surface tension characteristics.

Hu et al. [19] carried out an experimental study of surface tension of heptanol aqueous solutions (with concentration of 0–0.1 wt %). Results showed that the surface tensions increased with the increasing of temperature when the temperature reached a specific value.

Many researchers had done a lot of experiments not only in aqueous solutions of dibasic alcohols but also in other fluids such as multi-component mixtures to find suitable working fluids. Savino et al. [20] measured the surface tension for liquids including ternary mixtures based on traditional brines, e.g. ethylene glycol (EG), propylene glycol (PG), ammonia and methanol. Results showed that antifreeze solutions used in previous self-rewetting aqueous solutions that exhibited positive surface tension temperature gradient were similar to binary self-rewetting solutions. In addition, they also measured the surface tension for innovative brines (FD-40, FP-40), that the first one was water solution of potassium hydroxide (24%), acetic acid (24%) and other components (6%), the second brine was a water solution of potassium formate (50%) and inhibitors (1%). They found that both FD-40 and FP-40 brines showed a "self-rewetting" behavior with the addition of heptanol or butanol alcohols (0.2 wt% and 5 wt%, respectively). Also, they concluded that the wetting properties of brines increased with the addition of a small concentration of alcohol.

Savino et al. [21] measured the contact angle of butanol (5 wt%)/water, heptanol (0.2 wt%)/water, potassium formate-based brines (FP-40)/butanol (5 wt%), FP-40/heptanol (0.2 wt%). Experimental data indicated that the addition of a small amount of alcohols, in particular butanol and heptanol, improved the metal wettability.

To sum up, we have obtained the available experimental data from different research groups of surface tension. As shown in Fig. 1, the results of surface tension curve ranged with temperature have been plotted for discussing. It has been shown that the surface tension of ordinary fluids linearly decreases with the increasing temperature, and the presented ordinary fluids include water, ethanol, butanol, heptanol, FP40 and so on. While the surface