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Study on boiling heat transfer characteristics of surfactant modified nano-refrigerant

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In order to study the influence of surfactant concentration on the boiling heat transfer characteristics of nano-refrigerants, a two-step method was used to prepare anionic SDBS–Al_2O_3/R141b nano-refrigerant with different concentrations of surfactant SDBS (0 wt. %, 0.1 wt. %, 0.2 wt. %, 0.3 wt. %, 0.4 wt. %), and the variation of the boiling heat transfer coefficient was studied. The results show that the average heat transfer coefficient of the saturated boiling zone shows maximum increase of 30.9 % and 22.8 % when the concentration is 0.2 wt. and 0.3 wt. % SDBS, respectively, which can improve the heat transfer properties of the micro-channel.

Keywords: surfactant SDBS, boiling heat transfer coefficient.

Изучено влияние концентрации поверхностно-активного вещества на характеристики теплопередачи при кипении нанохладагента. Для этой цели использован двухстадийный метод получения анионного нанохладагента SDBS–Al_2O_3/R141b с различными концентрациями сурфактанта SDBS (0 мас.%, 0,1 мас.%, 0,2 мас.%, 0,3 мас.%, 0,4 мас.%). Исследованы изменения коэффициента теплопередачи при кипении. Результаты показывают, что средний коэффициент теплопередачи в насыщенной зоне кипения имеет максимальное увеличение на 30,9 % и 22,8 % при концентрации SDBS, соответственно, 0,2 мас.% и 0,3 мас.%, что может улучшить теплопередающие свойства микроканала.

Дослідження характеристик теплопередачі при кипінні модифікованого сурфактантом нанохладагента. *А.Лі, М.Хао, П.Лю.*

Вивчено вплив концентрації поверхнево-активної речовини на характеристики теплопередачі при кипінні нанохладагента. Для цієї мети використаний двостадійний метод отримання аніонного нанохладагента SDBS–Al_2O_3/R141b з різними концентраціями сурфактанта SDBS (0 мас.%, 0,1 мас.%, 0,2 мас.%, 0,3 мас.%, 0,4 мас.%). Досліджено зміни коефіцієнта теплопередачі при кипінні. Результати показують, що середній коефіцієнт теплопередачі у насиченій зоні кипіння має максимальне збільшення на 30,9 % і 22,8 % при концентрації SDBS, відповідно, 0,2 мас.% і 0,3 мас.%, що може поліпшити властивості мікроканалу, що передають тепло .

1. Introduction

Since high performance of microscale heat transfer technology was put forward, the microscale heat transfer technology has been widely used in electronic industry, solar batteries, fuel cells, medical equipment, heat exchangers, biological engineering, micro thrusters, etc. [1], but there are still a lot of microscale heat transfer problems demanding prompt solution, which is of important research significance for development of highly efficient energy-saving stable heat exchangers [2, 3]. The preparation technology of nanofluids has become quite mature, but the long-term stability of nanofluids remains one of the main limiting conditions for the application of nanofluids. According to DLVO theory, the stability of nanoparticles in suspension depends on the

Table. Main instruments and their measurement errors in the data acquisition system

Measuring parameters/measuring instrument	Instrument model	The manufacturer	Range	Measurement error, %
Heating power/power meter	MS2205	Huayi Instrument	0.01 ~ 600 kW	±3.0
Flow/turbine flowmeter	LWGYD	Shanghai automation instrument company	0 – 250 L/h	0.5
Flow/flow integrator	XSJ/A-H2KB1A2V0	Guangzhou Hanchuan instrument company	0 ~ 250 L/h	0.2
Temperature/K thermocouple	WRNK-291	Shanghai Juntai electric instrument factory	0 ~ 200	0.2
Pressure/pressure sensors	HC3160-HVG4	Guangzhou Hanchuan instrument company	0 ~ 700 kPa	0.5
Temperature/temperature transmitter	MIK-ST-500	Hangzhou Meikong automation company	0 ~ 200	0.2

balance between van der Waals attraction and electrostatic repulsion between particles [4].

When the electrostatic repulsion between suspended particles dominates, the system is stable. At present, the two-step preparation technology is widely used, and the commonly used methods to improve the stability of nanofluids include adding surfactants, surface modification of nanoparticles, and ultrasonic oscillation treatment of nanofluids [5]. Wang et al. [6] compare the characteristics of fresh water with surfactant solution of boiling CHF, boiling point and pressure surge. The measured fluid was an aqueous CTAC solution with the same mass concentration of sodium salicylate (NaSal). The surfactant concentration range is 0 ~ 600 ppm, velocity range is 192 – 406 ml/min, flow channel inlet temperature is 80°C, the outlet pressure is 101.3 kPa, cross section is 6.0×3.5 mm^2. Experimental results show that the CHF value of CTAC/NaSal solution is larger than that of pure water [6]. Bastakoti et al. studied the heat transfer characteristics of PHP with alcohol and surfactant solution. Studies have shown that the surface tension and viscosity of surfactants are two important factors affecting the heat transfer characteristics of PHP [7].

To sum up, the surface modification of nanoparticles with surfactants can be used as an effective method to improve the dispersion stability of nanofluids. Surfactant nano-refrigerant, as an experimental medium for enhancing boiling heat transfer, has important academic significance and application value in the study of the influence of its concentration on boiling phase change heat transfer in micro-channel flow. Therefore, it is necessary to carry out the research on the heat transfer characteristics of surfactant nano-refrigerant. In this paper, anionic SDBS–Al_2O_3/R141b nano-refrigerant with different concentrations (0 wt.%, 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%) of surfactant was prepared by two-step method, and the effects of optimal dispersion concentration, sub-optimal dispersion concentration of surfactant, heat flux, mass flow rate and other parameters on the boiling heat transfer coefficient of surfactant-modified nano-refrigerant in the microchannel were studied.

Domestic and foreign scholars have done a lot of research on new nanofluids. Nanofluids are generally divided into two categories: water-based nanofluids and refrigerant-based nanofluids [2]. Many studies have shown that nano-refrigerant can improve the energy efficiency of heat exchange system. Kumar and other studies have found that the amount of a small, 0.05 % CuO nanoparticle in the household air conditioner and fridge is a good way to increase the boiling heat factor and reduce the power of the compressor [3]. At present, studies on the boiling heat transfer of surfactant nanofluids generally focus on the pool boiling heat transfer or the flow boiling heat transfer of conventional scale bellows and horizontal tubes. Considering that the microchannels have the advantages of compact structure, large specific surface area and uniform wall temperature distribution, as well as the complexity, diversity and randomness in the process of phase change boiling heat transfer, the experimental study on surfactant strengthening the flow boiling heat transfer of nano-refrigerant in the microchannel has a good practical significance, which can provide a reference for further research on the phase change heat transfer strengthening technology of the microchannel [8–10].

2. Experimental

2.1. Experimental materials and instruments

During the operation of the experimental system, the main parameters collected by the data acquisition system include the flow rate of the experimental working medium, the power of the electric heating plate, the inlet and outlet pressure, the inlet and outlet temperature, and the wall temperature at 8 temperature measuring points. The main characteristics and measurement errors of each data acquisition instrument are introduced respectively, as shown in Table, which can provide a basis for subsequent experimental data processing and experimental error analysis.

2.2. Preparation of experimental working medium

The refrigerant used in this paper is R141b, the nanoparticle is Al_2O_3 with a particle size of 20 nm, the surfactant is sodium dodecyl benzene sulfonate (SDBS), and the chemical formula of SDBS is $C_{18}H_{29}NaO_3S$. R141b chemical formula is CH_3CCl_2F. There are two reasons for choosing refrigerant R141b, one of which is the standard of R141b boiling point can reach 32.06°C, and it is easy to carry out the flow boiling heat transfer experiment. Second, the basic characteristics of R141b are similar to common refrigerants such as R22, R410a and R134a [8]. Al_2O_3 nanoparticles with a diameter of 20 nm were purchased from Shanghai Aladdin biochemical technology co., LTD., with a purity of 99.5 %. The preparation process is as follows:

(1) place a clean vial of silin on the electronic balance of sydoris and press the "reset" button of the electronic balance;

(2) for the need of an experiment and the the quality of the experiment one requires the quality of the R141b, to add the refrigerant R141b to the drop of a pipe vector cup, until the electronic balance count is consistent with the calculated mass of Mr. And then the "return to zero" button on the electronic balance;

(3) calculate the mass mn of the corresponding nanoparticle according to the wn concentration of the nanoparticle, then add the corresponding amount of nanoparticle with the medicine spoon until the number of the electronic balance and the calculated mass mn are consistent, then press the "return to zero" button of the electronic balance;

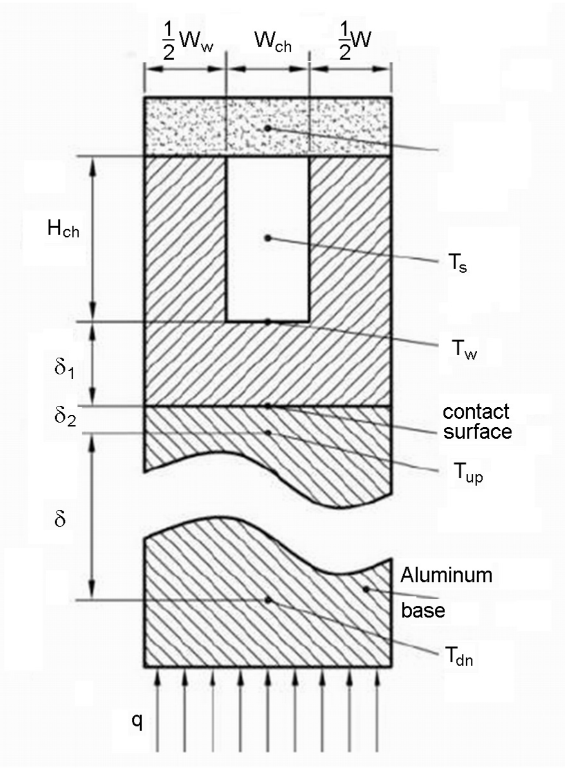


Fig. 1. Schematic diagram of cross section of rectangular micro-channel of unit.

(4) Calculate the mass m_s of the corresponding surfactant according to the required surfactant concentration C, and then add the corresponding amount of surfactant with the medicine spoon until the number shown in the electronic balance is consistent with the calculated mass m_s. Take out the bottle, seal the bottle mouth, use high temperature and high pressure resistant bottle to ensure good sealing performance, and stick the label;

(5) repeat (1)–(3), to get a different concentration of the lab work, and to have a label of the sileen in a kq5200 digital ultrasonic washer with an ice cube, ultrasonicate for 30 min.

Before conducting the flow boiling heat transfer experiment of each working medium, it is necessary to calibrate the thermocouple, check the air tightness of the experimental system, pump out the vacuum and fill the experimental working medium, which plays a crucial role in the stable and safe operation of the above experimental system [9].

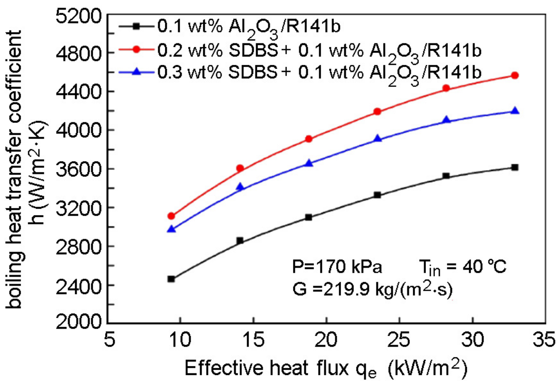
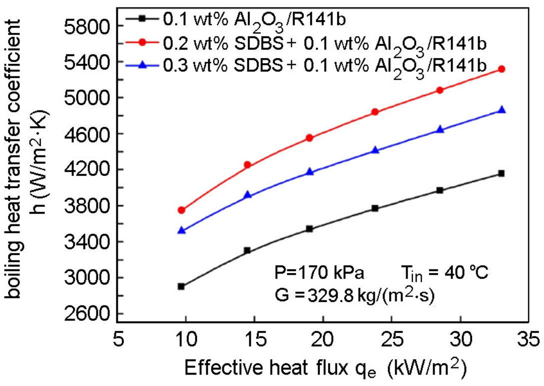
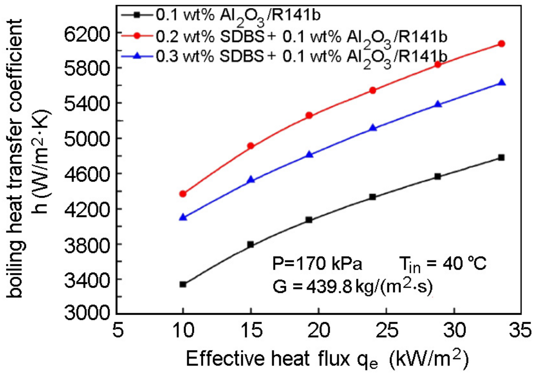


Fig. 2 a). $G = 219.9$ kg/m^2·s.



b) $G = 329.8$ kg/m^2·s.



c) $G = 439.8$ kg/m^2·s.

Fig 2. The influence of surfactant concentration on the boiling heat transfer characteristics of nano-refrigerants

2.3. Saturated boiling heat transfer coefficient h

The expression of saturated boiling heat transfer coefficient h is shown in equation (1):

$$h = \frac{qe(W_{ch} + W_w)}{(T_w - T)(W_{ch} + 2\eta H_{ch})}, \quad (1)$$

$$\tanh\frac{\left(\sqrt{\frac{2h}{\lambda W_w}} H_{ch}\right)}{\left(\sqrt{\frac{2h}{\lambda W_w}} H_{ch}\right)}, \quad (2)$$

where $q(e)$ — average effective heat flux in the experimental section of the micro channel, kW/m^2; H — flow boiling heat transfer coefficient, kW/m^2); W_w — the side wall width of the channel is twice, as shown in Fig. 1; W_{ch} — channel width, as shown in Fig. 1; H_{ch} — depth in the channel, as shown in Fig. 1; T_w — micro channel, at the bottom of the wall temperature; T — micro channels in the experiment the temperature of the working medium, °C, in saturated boiling stage, $T = T_s$; η — vertical fin efficiency; λ — coefficient of thermal conductivity of aluminum, the paper values of 237 w/(m·K) [10].

3. Results and discussion

In order to explore the change of thermal performance of the micro-channel heat exchanger based on surfactant modified nano-refrigerant under variable working conditions, it is one of the key points to find out the saturated boiling heat transfer coefficient of the micro-channel heat exchanger under various working conditions when the heat transfer area, inlet temperature of the experimental working medium, saturation temperature of the experimental working medium and types of the experimental working medium are known. Figures 2–4 respectively show the microchannel flow boiling heat transfer coefficient based on a surfactant modified nano-refrigerant. Fig 2 (a-c) show the variation curves of flow boiling heat transfer coefficient and heat flux in the saturated boiling zone of anionic surfactant SDBS with mass flow rate of $G = 219.9$ kg/(m^2·s), $G = 329.8$ kg/(m^2·s) and $G = 439.8$ kg/(m^2·s), respectively.

It can be seen from Fig. 2 that at low mass flow rate, the boiling heat transfer coefficient of SDBS nanorefrigerant at different concentrations is approximately correlated positively with the heat flow density. Under the condition of the same heat flux, the boiling heat transfer coefficient of the pure nano-refrigerant is lower than that of the surfactant nano-refrigerant with the concentration of C being 0.2 wt. % and 0.3 wt. %, while the boiling heat transfer coefficient of the nano-refrigerant with the surfactant concentration of C being 0.2 wt. % and 0.3 wt. % is relatively close under the condition of the same heat flux. For example, at low heat flux $q_e = 9.4$ kW/m^2, the boiling heat transfer coefficient of pure nanorefrigerant is 2458.7 W/(m^2·K), while the boiling heat transfer coefficient of 0.3 wt. % SDBS–Al_2O_3/R141b and 0.2 wt. % SDBS–Al_2O_3/R141b are 3111.4 W/(m^2·K) and 2970.386 W/(m^2·K), respectively. It is clear that the dispersing performance of 0.2 wt. SDBS–Al_2O_3/R141b is up to 26.5 % higher than the pure nano-refrigerant, which is a fraction of the amount of heat, and that's the difference between the two different levels of SDBS–Al_2O_3/R141b, and two different levels of SDBS–Al_2O_3/R141b, which is more than 0.3 wt. %. In addition, with the increase of the effective thermal flow density, the distance between the two different concentrations of SDBS boiling hot lines, the increase rate of the boiling heat coefficient of the surface of the surfactant, the suboptimal dispersal of the surfactant is decreasing, and the optimal concentration of the SDBS has the ability to enhance the boiling heat coefficient of the nano refrigerant. For example, when q_e= 32.9 kW/m^2, the 0.3 wt. % SDBS–Al_2O_3/R141b is only 16.06 % higher than the pure nano-refrigerant, which is still up to 26.3 %, and 2 wt. %, Al_2O_3/R141b, which is still up to 26.3 %, and the concentration of 0.2 wt. % of the surfactant is 8.8 % higher than the 0.3 wt %. So, in the case of the low mass rate, the optimal concentration of 0.2 wt. % SDBS means that the boiling heat coefficient of the pure nano-refrigerant is better than the concentration of the boiling heat transfer of the pure nano-refrigerant, which is better than the concentration of the boiling heat transfer of the pure nano-refrigerant, and as the heat flux density goes up, the increase of the ratio is always more stable, and the increase of the latter is going to go down.

When the mass flow rate G = 329.8 kg/(m^2·s), and the thermal flow density q_e range is 9.7 ~ 33 kW/m^2, as shown in Fig. 2b, the boiling heat transfer coefficient of 0.2 wt. % SDBS–0.1 wt % Al_2O_3/R141b and 0.3 wt. % SDBS–0.1 wt % Al_2O_3/R141b increases by 29.2 % ~ 27.9 % and 21.2 % ~ 16.8 %, respectively, compared with the pure nano refrigerant. In Fig. 2c, at the higher mass flow rate of G = 439.8 kg/(m^2·s), the heat flow density ranges from 10 to 33.5 kW/m^2, and the boiling heat wave of the three concentrations of the surfactant nano-refrigerant is consistent with the low mass flow rate. Compared with pure nano-refrigerants, the boiling heat transfer coefficient of nano-refrigerants containing 0.2 wt. % SDBS and 0.3 wt. % SDBS increased by 30.9 % – 27.1 % and 22.8 % – 17.8 %, respectively.

The experimental results show that: (1) Under the same mass flow rate, the boiling heat transfer coefficient of the pure nano-refrigerant can be increased by the surfactant SDBS nano-refrigerant with different concentrations, and it is found that the effect of 0.2 wt. % is better than 0.3 wt. %. (2) At the three levels of mass flow, the boiling heat curve at the various surfactant concentrations in SDBS–Al_2O_3/R141b, which is consistent with the changing tendency of the thermal flux density, both of which is in the lower thermal flux density, and the concentration of 0.2 wt. and 0.3 wt. % is closer to each other, which means that the enhanced effect of the two works better. With the increase of heat flux, the enhancement effect of 0.3 wt. % decreased slightly, and the interval between 0.2 wt. % and 0.3 wt. % increased. (3) With the increase in the mass flow rate, the enhancement effect of SDBS was slightly increased. In the process of flow boiling heat transfer experiment, the micro channel at the bottom of the experimental section will deposit a small amount of surfactant and nanoparticles, and the deposition can make the micro channel heat transfer surface hydrophilicity enhanced, contact Angle decreased. So, heat transfer surface roughness increases slightly, vaporization core density increases, bubble out diameter decreases, and the bubble from the frequency is to speed up. In addition, surfactant molecules gather on the heated surface to form an excess layer, which reduces the surface energy between the liquid and the heated surface and increases the density of bubble nucleation point. However, the particle size of the agglomerated particles in the surfactant nano-refrigerant is smaller than that of the deposited particles in the pure nano-refrigerant, so the above experimental results show that the boiling heat transfer coefficient of the surfactant-modified nano-refrigerant is larger than that of the pure nano-refrigerant.

4. Conclusions

In summary, the optimal dispersion concentration of each surfactant within the range of 0 – 0.4 wt. % was 0.2 wt. % SDBS and 0.3 wt. % SDBS. SDBS–Al_2O_3/R141b, an experimental working medium, can increase the flow boiling heat transfer coefficient, and the flow boiling heat transfer in the micro-channel with surfactant nano-refrigerant as the experimental working medium can occur at the lower heat flow density. The dispersing experiments of nano-refrigerant and the boiling heat transfer experiment of micro-channel flow were carried out with different concentration of surfactant. The experimental results show that the surfactant with the best dispersing concentration and the smallest molecular weight is the most favorable for the boiling heat transfer of the nano-refrigerant. However, the ionic nature of the surfactant was not considered. If an electric field is applied to the micro-channels, whether the surfactant nano-refrigerant can further improve the boiling heat transfer characteristics needs to be further studied.

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