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Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid

Hao Peng [a,b], Guoliang Ding [a,*], Haitao Hu [a]

[a] Institute of Refrigeration and Cryogenics, Shanghai Jiaotong University, 800 Dongchuan Road, Shanghai 200240, China
[b] Key Laboratory of Microgravity (National Microgravity Laboratory)/CAS Institute of Mechanics, Chinese Academy of Sciences (CAS), 15 Beisihuan Xilu, Beijing 100190, China

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ABSTRACT

Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid was investigated experimentally. Three types of surfactants including Sodium Dodecyl Sulfate (SDS), Cetyltrimethyl Ammonium Bromide (CTAB) and Sorbitan Monooleate (Span-80) were used in the experiments. The refrigerant-based nanofluid was formed from Cu nanoparticles and refrigerant R113. The test surface is horizontal with the average roughness of 1.6 μm. Test conditions include a saturation pressure of 101.3 kPa, heat fluxes from 10 to 80 kW m^{-2}, surfactant concentrations from 0 to 5000 ppm (parts per million by weight), and nanoparticle concentrations from 0 to 1.0 wt.%. The experimental results indicate that the presence of surfactant enhances the nucleate pool boiling heat transfer of refrigerant-based nanofluid on most conditions, but deteriorates the nucleate pool boiling heat transfer at high surfactant concentrations. The ratio of nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant to that without surfactant (defined as surfactant enhancement ratio, *SER*) are in the ranges of 1.12–1.67, 0.94–1.39, and 0.85–1.29 for SDS, CTAB and Span-80, respectively, and the values of *SER* are in the order of SDS > CTAB > Span-80, which is opposite to the order of surfactant density values. The *SER* increases with the increase of surfactant concentration and then decreases, presenting the maximum values at 2000, 500 and 1000 ppm for SDS, CTAB and Span-80, respectively. At a fixed surfactant concentration, the *SER* increases with the decrease of nanoparticle concentration. A nucleate pool boiling heat transfer correlation for refrigerant-based nanofluid with surfactant is proposed, and it agrees with 92% of the experimental data within a deviation of ±25%.

1. Introduction

Refrigerant-based nanofluid is one kind of nanofluids, in which the host fluid is conventional pure refrigerant. Experimental studies showed that the refrigerant-based nanofluid has higher thermal conductivity than the host refrigerant [1], and the refrigeration system using refrigerant-based nanofluid has better performance than that using conventional pure refrigerant [2–4]. However, the aggregation and sedimentation of nanoparticles in the refrigerant-based nanofluid may reduce the stability of refrigerant-based nanofluid and limit the application of refrigerant-based nanofluid in the refrigeration system. In order to stabilize the nanoparticles in the refrigerant-based nanofluid, one effective way is adding the surfactant into the refrigerant-based nanofluid. The presence of surfactant additives may have effects on the boiling heat transfer characteristics and then the overall performance of evaporators in the refrigeration systems because the surfactant additives change the thermophysical properties of working fluids including surface tension, viscosity, etc. The nucleate pool boiling heat transfer is the basic type of boiling heat transfer of refrigerant-based nanofluid in the evaporator. Therefore, the effect of surfactant additives on the nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid must be known for evaluating the overall performance of the evaporator.

Until now, the researches related to the effect of surfactant on the nucleate pool boiling heat transfer are focused on pure water [5–11], organic fluids [12,13], water–organic fluid mixtures [14,15] or water-based nanofluid [16,17], and there is no published research on refrigerant-based nanofluid. For the effect of surfactant on the nucleate pool boiling heat transfer of pure water, organic fluids or water-organic fluid mixtures, most of the researches indicated that the presence of surfactant enhances the nucleate pool boiling heat transfer [6–11,13–15], but some researches indicated that the surfactant deteriorates the nucleate pool boiling heat transfer or has little effect on the nucleate pool boiling heat transfer [5,12]. For the effect of surfactant on the nucleate pool boiling heat transfer of water-based nanofluid, the research reported by Chopkar et al. [16] showed that the presence of surfactant deteriorates the nucleate pool boiling heat transfer, but the research

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[*] Corresponding author. Tel.: +86 21 34206378; fax: +86 21 34206814.
E-mail address: glding@sjtu.edu.cn (G. Ding).

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Nomenclature

a_1, a_2	coefficients in Eq. (3)
C	surfactant concentration
C_p	isobaric specific heat (J kg^{-1} K^{-1})
d_p	nanoparticle diameter (m)
D_b	bubble departure diameter (m)
h	nucleate pool boiling heat transfer coefficient (W m^{-2} K^{-1})
M	molecular weight
m_1, m_2, m_3, m_4, m_5	coefficients in Eqs. (8) and (9)
NER	nanoparticle enhancement ratio
n_1, n_2	coefficients in Eqs. (8) and (9)
q	heat flux (W m^{-2})
R_a	heating surface roughness (m)
SER	surfactant enhancement ratio
T	temperature (°C)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β	contact angle (°)
λ	thermal conductivity (W m^{-1} K^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
ω	nanoparticle concentration

Subscripts

c	copper
f	saturated liquid, fluid
g	saturated vapor
n	nanoparticle
s	surfactant
sat	saturation
w	test surface

reported by Kathiravan et al. [17] showed that the presence of surfactant enhances the nucleate pool boiling heat transfer. The existing researches on the nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid without surfactant showed that the presence of nanoparticles has effect on the nucleate pool boiling heat transfer and the effect is related to the nanoparticle concentration [18], resulting in the difference between the effect of surfactant on the nucleate pool boiling heat transfer of refrigerant-based nanofluid and those on pure water, organic fluids or water-organic fluid mixtures. The thermophysical properties of refrigerant are different from those of water, causing that the research related to the effect of surfactant on the nucleate pool boiling heat transfer of water-based nanofluid may not be extended to refrigerant-based nanofluid. Therefore, it is necessary to investigate the effect of surfactant on the nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid.

The purpose of this paper is to experimentally investigate the effect of surfactant on the nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid, and to propose a correlation for predicting the nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant.

2. Preparation and characterization of refrigerant-based nanofluid with surfactant

The refrigerant-based nanofluid used in the present study is Cu-R113 nanofluid. Cu nanoparticle is one kind of the commonly used metal nanoparticles in nanofluid [19–23]. R113 is chosen as the host refrigerant, just as Peng et al. [24] did. R113 is in liquid state at atmospheric pressure and room temperature while the widely used refrigerants (e.g. R410A) are in vapor state, so it is much easier to prepare nanofluids based on R113 than those based on the widely used refrigerants.

Cu nanoparticles with average diameter of 20 nm are produced by hydrogen direct current arc plasma evaporation method, and the TEM (transmission electron microscope) photograph of Cu nanoparticles is shown in Fig. 1. The properties of nanoparticle and liquid-phase refrigerant are listed in Table 1.

Three types of surfactants including Sodium Dodecyl Sulfate (SDS), Cetyltrimethyl Ammonium Bromide (CTAB) and Sorbitan Monooleate (Span-80) are used in the experiments, and they are anionic, cationic and nonionic surfactants, respectively. The surfactants used in the experiments are miscible with R113. The physical and chemical properties of these three surfactants are listed in Table 2. In order to investigate the effects of surfactant concentration and nanoparticle concentration on the nucleate pool boiling heat transfer, for Cu-R113 nanofluid with each type of surfactant, the surfactant concentrations (C) cover 200, 500, 1000, 2000 and 5000 ppm (parts per million by weight), and the nanoparticle concentrations (ω) cover 0.1, 0.5 and 1.0 wt.%.

Cu-R113 nanofluids with surfactants are prepared by the following steps: (1) weighing the required mass of Cu nanoparticles and surfactants by a digital electronic balance with a measurement range of 10 mg to 210 g and a maximum error of 0.1 mg; (2) putting the Cu nanoparticles and surfactants into the weighed R113 to form the Cu-R113 nanofluids with surfactants; (3) vibrating the Cu-R113 nanofluids with surfactants by an ultrasonic processor for 1 h to disperse the nanoparticles evenly. Experimental observation shows that the even dispersion of Cu nanoparticles in the Cu-R113 nanofluids with surfactants can be kept for more than 24 h. The duration of the experiment for each sample of Cu-R113 nanofluid with surfactant is less than 4 h which is shorter than 24 h. For the time duration same to the nucleate boiling experiment for each sample, the stability tests using the spectrophotom-

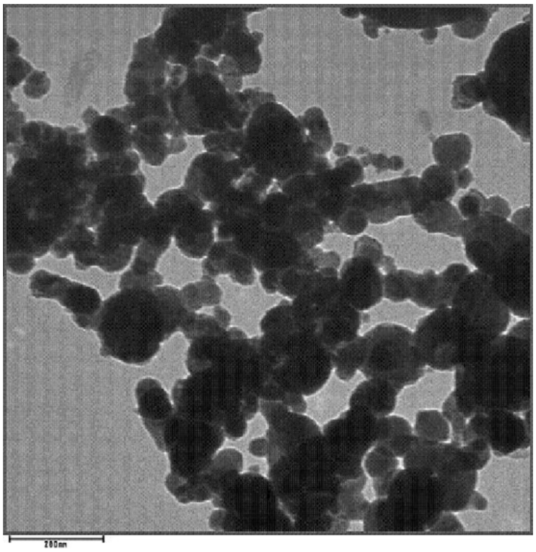


Fig. 1. TEM photographs of Cu nanoparticles.

Table 1
The properties of nanoparticle and liquid-phase refrigerant.

	Thermal conductivity ($W m^{-1} K^{-1}$)	Isobaric specific heat ($J kg^{-1} K^{-1}$)	Dynamic viscosity (Pa s)	Density ($kg m^{-3}$)
Cu	398	385	–	8920
R113	0.06363	940.4	0.0005	1508

Table 2
Physical and chemical properties of these surfactants.

Surfactant name	SDS	CTAB	Span-80
Chemical formula	C12H25SO4Na	C19H42NBr	C24H44O6
Ionic nature	Anionic	Cationic	Nonionic
Form	White powder	White powder	Pale yellow oily liquid
Molecular weight	288.3	364.5	428.6

eter showed that three types of surfactants have same effect on the dispersion stability of Cu-R113 nanofluids, and the prepared Cu-R113 nanofluids with surfactants can maintain good uniformity in the experiment.

3. Nucleate pool boiling experiments

3.1. Experimental setup

Similar to that used by Peng et al. [24], the experimental setup used for testing the nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid with surfactant is composed of three parts (i.e., a test section, a boiling apparatus and a condensation loop), as schematically shown in Fig. 2.

The test section is fabricated by a copper block. Five calibrated K-type thermocouples with the precision of ± 0.1 °C at 95% confidence level are inserted into five 1.0 mm diameter holes in the top part of the copper block in order to obtain the temperature gradient of the test surface accurately, and then to determine the heat flux and the test surface temperature. The top surface of the copper block is horizontal, and is used as the test surface for pool boiling heat transfer experiments. This surface is circular with a diameter of 20.0 mm. The average roughness (R_a) of the test surface is measured by a contact stylus instrument, and the value of R_a is 1.6 μm.

The boiling apparatus mainly consists of a boiling chamber, an electrical heating wire and a charge device for refrigerant-based nanofluid with surfactant. The bottom of the boiling chamber is a copper plate with a circular hole at the center. The copper block is linked with the copper plate by a Teflon ring ensuring the test surface exposed in the pool liquid. The Teflon ring has very low thermal conductivity (about 0.23 $W m^{-1}K^{-1}$), and epoxy glue is filled between the copper block and Teflon ring for seal, resulting in negligible nucleation on the contact between copper block and Teflon ring in the experiments. The maximum relative deviation of the heat fluxes between the central point and the edge of the test surface is less than 8%, so the one-dimensional heat conduction in the copper block can be extrapolated to the test surface. The electrical heating wire is used as an auxiliary heater to maintain the nucleate boiling of the test fluid and to control the saturation pressure. The liquid temperature is measured by a calibrated K-type thermocouple with the precision of ±0.1 °C at 95% confidence level, and the pressure inside the boiling chamber is measured by a pressure transducer with the precision of ±0.1 kPa. According to the measured liquid temperature and the pressure inside the boiling chamber, it can be confirmed that no subcooled boiling occurs for pure refrigerant. As the concentrations of surfactants and nanoparticles in the refrigerant-based nanofluid with

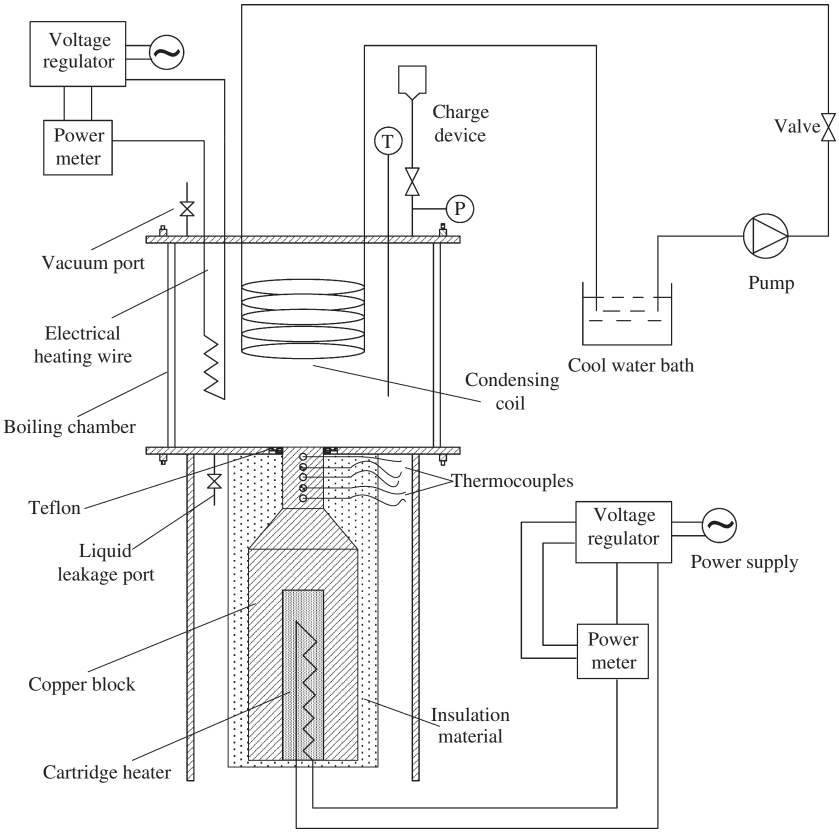


Fig. 2. Schematic diagram of experimental setup.

Table 3
Test conditions.

Test fluid	Surfactant	Heat flux (kW m^{-2})	Saturation pressure (kPa)	Nanoparticle concentration ω (wt.%)	Surfactant concentration C (ppm)	Number of experimental data
Pure R113	–	10, 20, 30, 40, 50, 60, 70, 80	101.3	–	–	8
Cu-R113 nanofluid without surfactant	–	10, 20, 30, 40, 50, 60, 70, 80	101.3	0.1, 0.5, 1.0	–	24
Pure R113 with surfactants	SDS, CTAB, Span-80	10, 20, 30, 40, 50, 60, 70, 80	101.3	–	200, 500, 1000, 2000, 5000	120
Cu-R113 nanofluid with surfactants	SDS, CTAB, Span-80	10, 20, 30, 40, 50, 60, 70, 80	101.3	0.1, 0.5, 1.0	200, 500, 1000, 2000, 5000	360

surfactant are low, it can be considered that the saturated liquid temperature for refrigerant-based nanofluid with surfactant is equal to that of pure refrigerant.

The condensation loop mainly consists of a condensing coil, a pump, a cool water bath and a valve. The mass flow rate of the cool water is controlled by adjusting the opening of the valve.

The saturation pressure is controlled by adjusting the heating power of the electrical heating wire connected to the boiling chamber or adjusting the mass flow rate of the cool water in the condensation loop. The heat flux is controlled by adjusting the heating power to the cartridge heater in the copper block.

3.2. Experimental procedure

The nucleate pool boiling heat transfer characteristics of refrigerant-based nanofluid with surfactant is tested at the heat flux ranging from 10 to 80 kW m^{-2}, and the saturation pressure of 101.3 kPa. Before each experiment, the boiling chamber is vacuumized to remove the air firstly, and then the test fluid is charged into the boiling chamber and heated to the saturation pressure. The measurement starts from the lowest heat flux (10 kW m^{-2}) at a fixed saturation pressure. If the temperature variation of copper block is smaller than 1 °C in 10 min, the heat transfer process can be considered to reach a steady state. After that, the five temperatures on the cooper block, the liquid temperature, and the heating power to the copper block are recorded. Then the heat flux is increased by the increment of 10 kW m^{-2}, and the above procedure is repeated. After each experiment, pure R113 is injected into the boiling chamber to remove the nanoparticles and surfactants from the boiling chamber and the test surface. The test surface and the trim heater are cleaned by acetone to remove the sticking nanoparticles, ensuring no change of the test surface characteristics and no reintroduction of nanoparticles from heater.

3.3. Test conditions

Test conditions are tabulated in Table 3. Total 512 experimental data are recorded, including eight experimental data of pure R113, 24 experimental data of Cu-R113 nanofluid without surfactant, 120 experimental data of pure R113 with surfactants, and 360 experimental data of Cu-R113 nanofluid with surfactants. All signals of temperature, pressure are collected by a data acquisition system and transmitted to a computer after the system reaches a steady state.

3.4. Data reduction and uncertainties

The nucleate pool boiling heat transfer coefficient, h, can be calculated as:

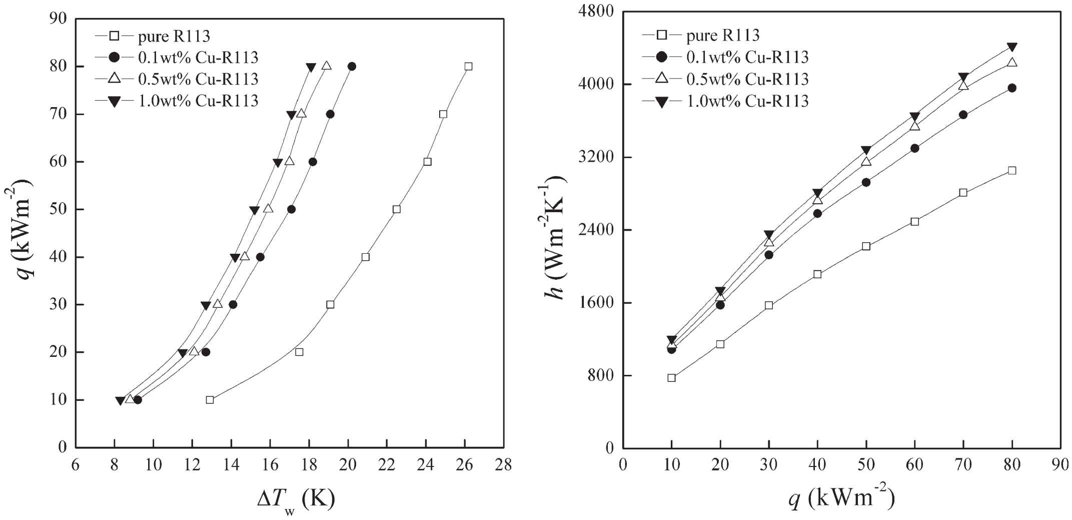
$$h = q/(T_w - T_{sat}) \tag{1}$$

where, q is the heat flux, T_w is the test surface temperature, and T_{sat} is the saturated liquid temperature.

The heat flux, q, is calculated by Eqs. (2) and (3) based on the one-dimensional heat conduction equation:

$$q = -\lambda_c \left.\frac{dT}{dz}\right|_w \tag{2}$$

$$T = a_1 + a_2 z \tag{3}$$



(a) Boiling curves (heat flux vs. excess temperature)

(b) Heat transfer coefficients vs. heat flux

Fig. 3. Nucleate pool boiling heat transfer of pure R113 and Cu-R113 nanofluids.

where, λ_c is the copper thermal conductivity, z is the coordinate perpendicular to the test surface, a_1 and a_2 are constants correlated based on the measured five temperatures on the copper block.

The test surface temperature, T_w, is calculated as:

$$T_w = (a_1 + a_2 z)|_{z=0} = a_1 \tag{4}$$

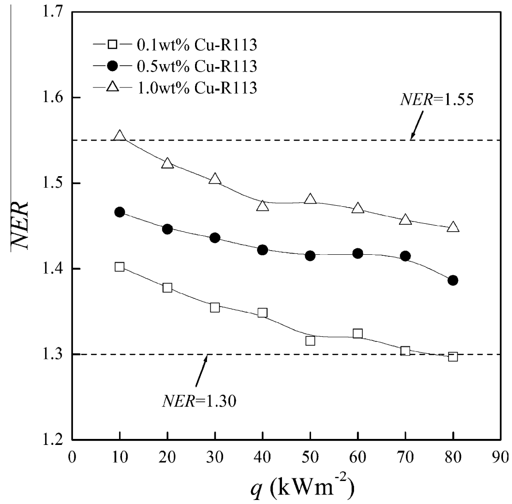


Fig. 4. Nanoparticle enhancement ratio (*NER*) at different nanoparticle concentrations.

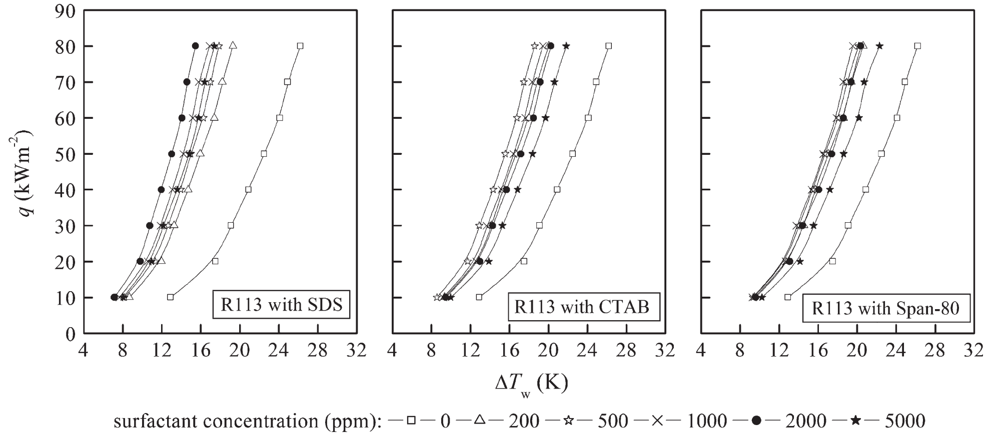
In the present study, the differences among the measured saturated liquid temperatures (T_{sat}) in different positions are less than 0.2 °C. Therefore, it can be considered that the saturated liquid temperatures liquid temperature is almost homogeneous outside the thermal boundary layer.

The relative uncertainties of heat flux and nucleate pool boiling heat transfer coefficient are estimated to be smaller than 8.9% and 9.2%, respectively. The confidence levels for the uncertainties of the heat flux and heat transfer coefficient measurements are 95%. Tests under several conditions were repeated for three times, and it shows that the differences among the three testing results under each condition are less than 5%.

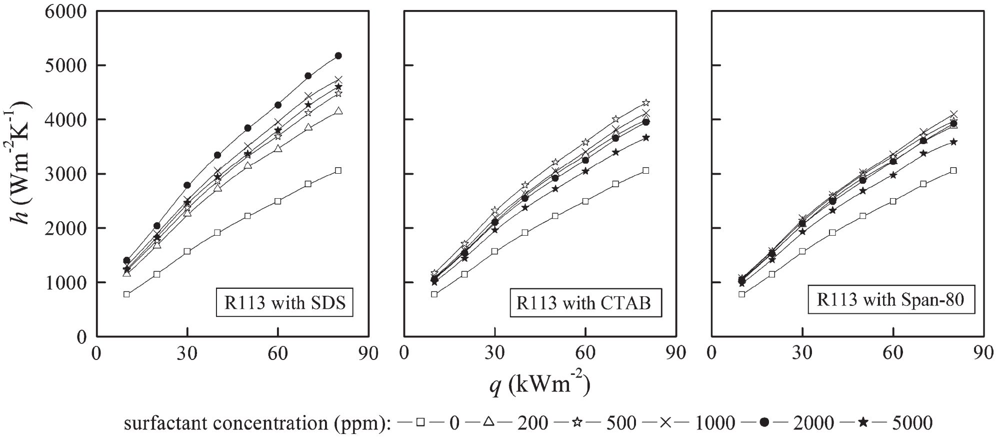
4. Results and discussion

4.1. Nucleate pool boiling heat transfer coefficients of Cu-R113 nanofluid without surfactant

The boiling curves and the nucleate pool boiling heat transfer coefficients of pure R113 as well as Cu-R113 nanofluids with three nanoparticle concentrations of 0.1 wt.%, 0.5 wt.% and 1.0 wt.% are shown in Fig. 3a and b, respectively. It can be seen that the nucleate pool boiling heat transfer coefficient of Cu-R113 nanofluid is larger than that of pure R113. The maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at the highest nanoparticle concentration, and it can reach 55.4% under the



(a) Boiling curves (heat flux vs. excess temperature)



(b) Heat transfer coefficients vs. heat flux

Fig. 5. Nucleate pool boiling heat transfer of pure R113 with surfactants.

present experimental conditions. The possible reasons for the nucleate pool boiling heat transfer enhancement are as follows.

(1) The heating surface characteristics are changed due to the interaction between nanoparticles and heating surface.

According to the principle proposed by Prakash et al. [25], when the ratio of heating surface roughness to nanoparticle diameter (R_a/d_p) is much larger than 1, the number of nucleation sites greatly increase. R_a/d_p in the present study is 80, so the interaction between nanoparticles and heating surface causes the increase of the active nucleation site density, which leads to the enhancement of the nucleate pool boiling heat transfer.

(2) The thermophysical properties are changed due to the presence of nanoparticles.

The thermal conductivity of Cu nanoparticle (398 W m^{-1}·K^{-1}) is four orders of magnitude higher than that of R113 (0.064 W m^{-1}·K^{-1}), so the thermal conductivity of Cu-R113 nanofluid is larger than that of pure R113, causing the enhancement of micro-layer evaporation [26], which leads to the enhancement of the nucleate pool boiling heat transfer.

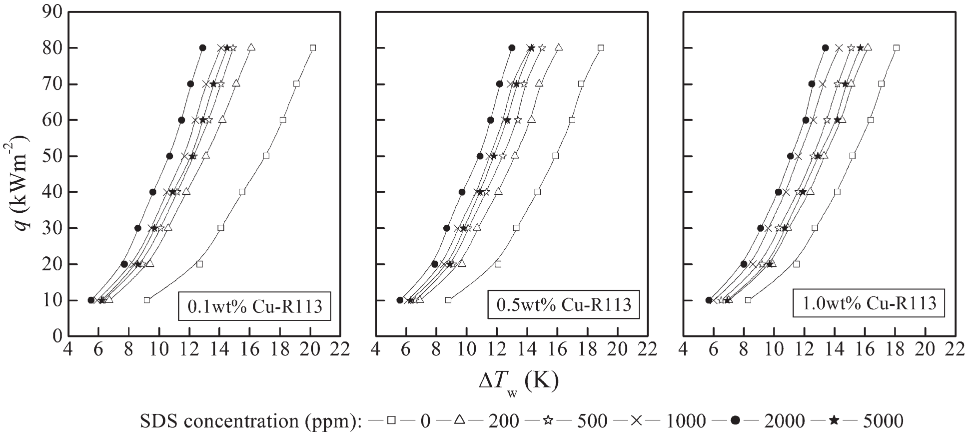
In order to analyze the effect of nanaoparticles on the nucleate pool boiling heat transfer coefficient quantitatively, nanoparticle enhancement ratio, *NER*, is defined in this paper, as shown in Eq. (5):

$$NER = h_{r,n}/h_r \quad (5)$$

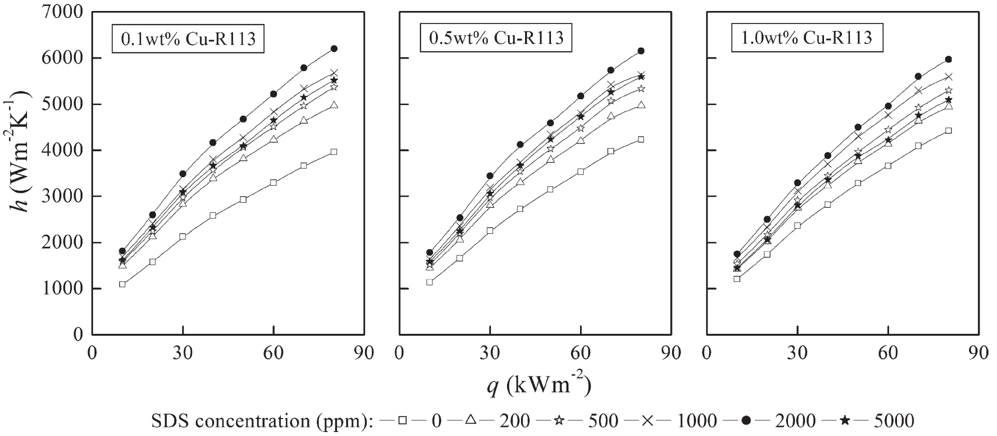
where $h_{r,n}$ and h_r are the nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid and that of pure refrigerant, respectively.

Fig. 4 shows the nanoparticle enhancement ratio (*NER*) at nanoparticle concentrations of 0.1 wt.%, 0.5 wt.% and 1.0 wt.%, respectively. From Fig. 4, it can be seen that *NER* is in range of 1.30–1.55, and increases with the increase of nanoparticle concentration. The possible reasons for this phenomenon are as follows. (1) The interaction between nanoparticles and heating surface increases with the increase of nanoparticle concentration, causing the larger increase of the active nucleation site density, which leads to *NER* increasing with the increase of nanoparticle concentration. (2) The thermal conductivity of Cu-R113 nanofluid increases with the increase of nanoparticle concentration, causing the larger enhancement of micro-layer evaporation, which leads to *NER* increasing with the increase of nanoparticle concentration.

When comparing the present experimental data of Cu-R113 nanofluid with the experimental data of TiO_2–water nanofluid presented by Suriyawong and Wongwises [27] as well as the experimental data of TiO_2-R141b nanofluid presented by Trisaksri and Wongwises [18], it can be found that the nanoparticle type and concentration, the surface roughness and material, and the host fluid type have effects on the nucleate pool boiling heat transfer.



(a) Boiling curves (heat flux vs. excess temperature)



(b) Heat transfer coefficients vs. heat flux

Fig. 6. Nucleate pool boiling heat transfer of Cu-R113 nanofluid with anionic surfactant (SDS).

4.2. Nucleate pool boiling heat transfer coefficients of pure R113 with surfactant

The boiling curves and the nucleate pool boiling heat transfer coefficients of pure R113 with surfactants are shown in Fig. 5 a and b, respectively. It can be seen from Fig. 5a that the addition of surfactant enhances the nucleate pool boiling heat transfer of pure refrigerant, shifting the boiling curve to the left. From Fig. 5b, it can be seen that for different type of surfactants, the maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at different surfactant concentration. For pure R113 with SDS, the maximum enhancement occurs at SDS concentration (C_{SDS}) of 2000 ppm. For pure R113 with CTAB, the maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at CTAB concentration (C_{CTAB}) of 500 ppm. For pure R113 with Span-80, the maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at Span-80 concentration ($C_{\mathrm{Span\text{-}80}}$) of 1000 ppm.

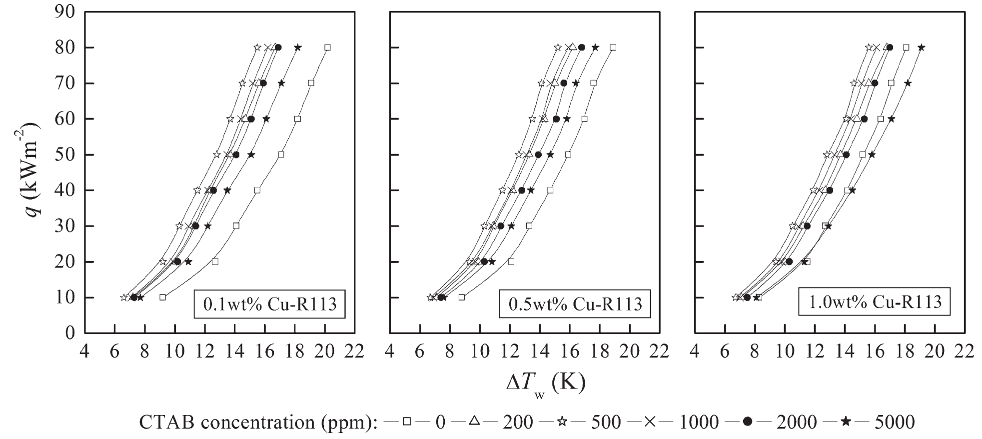
From Fig. 5, it can be concluded that the surfactant concentration and the surfactant type have effects on the nucleate pool boiling heat transfer coefficient of pure refrigerant. These effects will be quantitatively analyzed in Section 4.4.

4.3. Nucleate pool boiling heat transfer coefficients of Cu-R113 nanofluid with surfactant

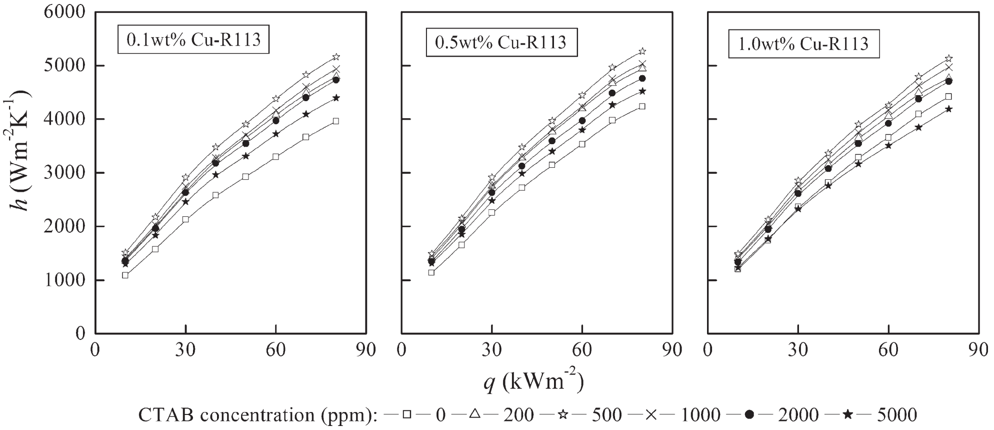
The boiling curves and the nucleate pool boiling heat transfer coefficients of Cu-R113 nanofluid with anionic surfactant (SDS) are shown in Fig. 6a and b, respectively. Experimental conditions cover three nanoparticle concentrations (i.e., 0.1 wt.%, 0.5 wt.% and 1.0 wt.%). It can be seen that the Cu-R113 nanofluid with SDS has larger nucleate pool boiling heat transfer coefficient than that without SDS at each nanoparticle concentration. The maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at SDS concentration (C_{SDS}) of 2000 ppm.

The boiling curves and the nucleate pool boiling heat transfer coefficients of Cu-R113 nanofluid with cationic surfactant (CTAB) are shown in Fig. 7a and b, respectively. Experimental conditions cover three nanoparticle concentrations (i.e., 0.1 wt.%, 0.5 wt.% and 1.0 wt.%). It can be seen that the Cu-R113 nanofluid with CTAB has larger nucleate pool boiling heat transfer coefficient than that without CTAB under the experimental conditions except at nanoparticle concentration (ω) of 1.0 wt.% and CTAB concentration (C_{CTAB}) of 5000 ppm. The maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at C_{CTAB} of 500 ppm.

The boiling curves and the nucleate pool boiling heat transfer coefficients of Cu-R113 nanofluid with nonionic surfactant (Span-80) are shown in Fig. 8a and b, respectively. Experimental conditions cover three nanoparticle concentrations (i.e., 0.1 wt.%, 0.5 wt.% and 1.0 wt.%). It can be seen that the Cu-R113 nanofluid with Span-80 has larger nucleate pool boiling heat transfer coefficient than that without Span-80 under the experimental conditions except at nanoparticle concentration (ω) of 1.0 wt.% and Span-80 concentration ($C_{\mathrm{Span\text{-}80}}$) of 5000 ppm. The maximum enhancement of the nucleate pool boiling heat transfer coefficient occurs at $C_{\mathrm{Span\text{-}80}}$ of 1000 ppm.

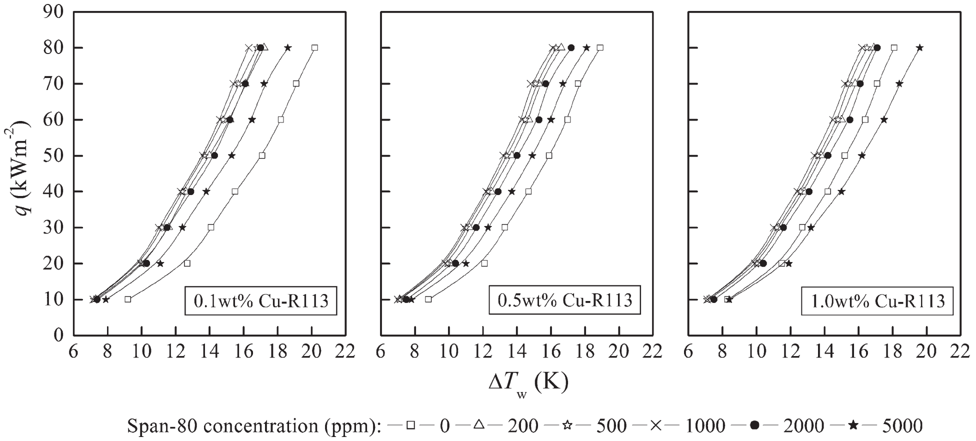


(a) Boiling curves (heat flux vs. excess temperature)

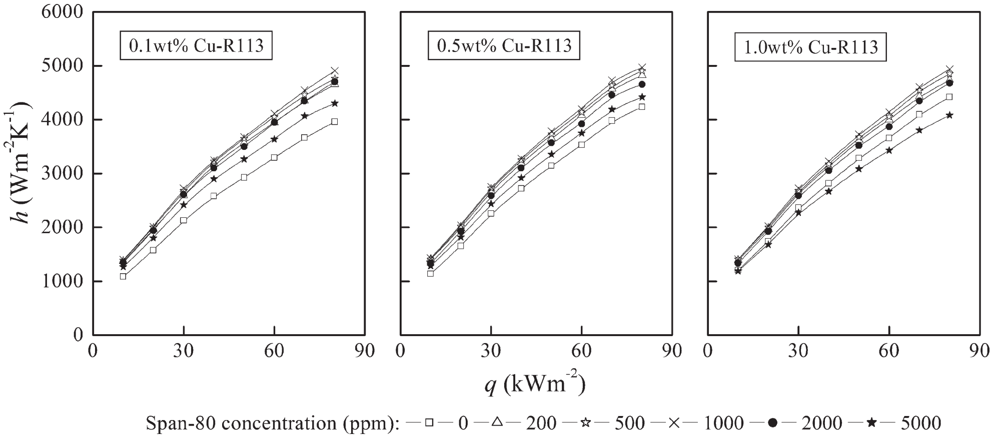


(b) Heat transfer coefficients vs. heat flux

Fig. 7. Nucleate pool boiling heat transfer of Cu-R113 nanofluid with cationic surfactant (CTAB).



(a) Boiling curves (heat flux vs. excess temperature)



(b) Heat transfer coefficients vs. heat flux

Fig. 8. Nucleate pool boiling heat transfer of Cu-R113 nanofluid with nonionic surfactant (Span-80).

From Figs. 6–8, it can be concluded that the surfactant concentration and the surfactant have effects on the nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid. These effects will be quantitatively analyzed in the following section.

4.4. Effects of surfactant on the nucleate pool boiling heat transfer of pure refrigerant and refrigerant-based nanofluid

In order to analyze the effect of surfactant on the nucleate pool boiling heat transfer coefficient quantitatively, surfactant enhancement ratio, *SER*, is defined in this paper, as shown in Eq. (6):

$$SER = h_{f,s}/h_f \tag{6}$$

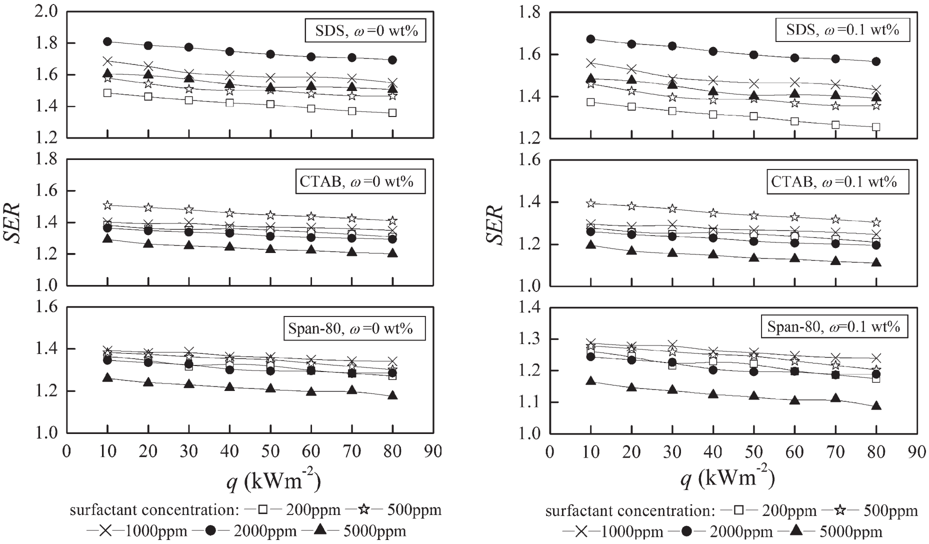
where $h_{f,s}$ and h_f are the nucleate pool boiling heat transfer coefficient of fluid with surfactant and that of fluid without surfactant, respectively. The fluids in the present study include pure R113 and Cu-R113 nanofluid.

Fig. 9a–d show the surfactant enhancement ratio (*SER*) for three types of surfactants (i.e., SDS, CTAB, Span-80) at nanoparticle concentration (ω) of 0 wt.%, 0.1 wt.%, 0.5 wt.% and 1.0 wt.%, respectively. It can be seen from Fig. 9a that *SER* at ω of 0 wt.% (i.e., the fluid is pure R113) are in the ranges of 1.36–1.81, 1.20–1.51, and 1.18–1.39 for SDS, CTAB and Span-80, respectively. Fig. 9b shows *SER* at ω of 0.1 wt.% are in the ranges of 1.25–1.67, 1.11–1.39, and 1.09–1.29 for SDS, CTAB and Span-80, respectively. Fig. 9c shows *SER* at ω of 0.5 wt.% are in the ranges of 1.17–1.57, 1.07–1.31, and 1.04–1.26 for SDS, CTAB and Span-80, respectively. Fig. 9d shows *SER* at ω of 1.0 wt.% are in the ranges of 1.12–1.46, 0.94–1.24, and 0.85–1.17 for SDS, CTAB and Span-80, respectively.

In order to isolate the effects of surfactant and the nanoparticles on the nucleate pool boiling heat transfer, the effect of surfactant on the nucleate pool boiling heat transfer of pure refrigerant are firstly analyzed as follows.

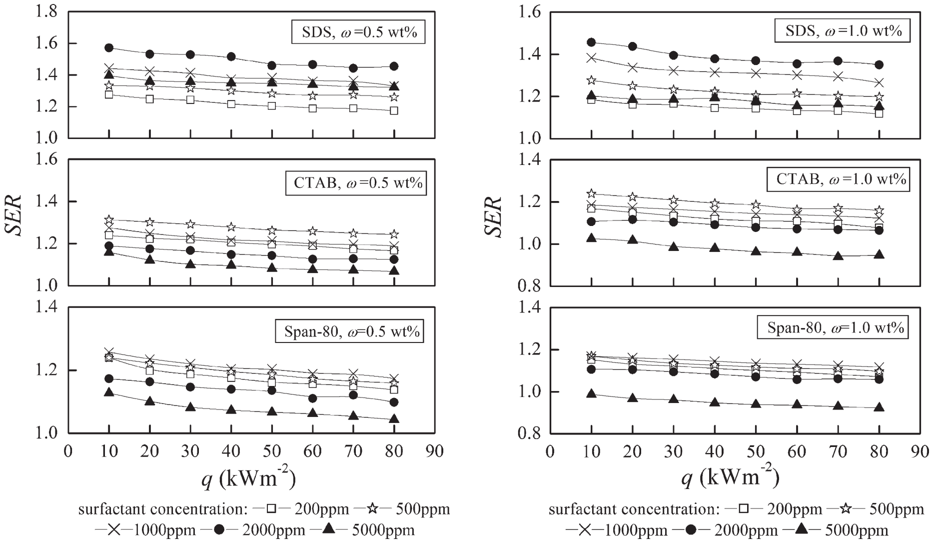
From Fig. 9a, it can be seen that for pure R113, the value of *SER* increases with the increase of surfactant concentration and then decreases, presenting the maximum values at 2000 ppm, 500 ppm and 1000 ppm for SDS, CTAB and Span-80, respectively.

There are following three enhancement factors of surfactant on the nucleate pool boiling heat transfer of pure refrigerant. (1) The surfactants can be absorbed by the liquid–vapor interface and form an orientation-arrange molecular layer, decreasing the surface tension especially at low surfactant concentration [6]. The decrease of surface tension causes the decrease of the superheat degree of the bubble nucleation, the decrease of bubble departure diameter, and the increase of bubble departure frequency. (2) The surfactants accumulate at the heating surface and form the excess layer, reducing the surface-energy between the liquid and the heating surface [13], thus the active nucleation sites increase. (3) The surfactants may aggregate in the fluid and form the large particles [28]. The interaction between these hot particles and bubbles may induce the secondary nucleation on the bubbles [29]. However, the surfactants increase the viscosity especially at high surfactant concentration, causing reduced micro-convection near the heating surface [28], which may lead to the deterioration of the



(a) ω= 0 wt% (pure R113)

(b) ω= 0.1 wt%



(c) ω= 0.5 wt%

(d) ω= 1.0 wt%

Fig. 9. Surfactant enhancement ratio (*SER*) for three types of surfactants (i.e., SDS, CTAB, Span-80) at different nanoparticle concentrations: (a) 0 wt.%; (b) 0.1 wt.%; (c) 0.5 wt.%; (d) 1.0 wt.%.

nucleate pool boiling heat transfer. The conjunct role of three enhancement factors and one deterioration factor determines the influence of surfactant on the nucleate pool boiling heat transfer of pure refrigerant. For SDS, at surfactant concentration lower than 2000 ppm, the enhancement factors dominate; while at surfactant concentration higher than 2000 ppm, the deterioration factor dominates. For CTAB, at surfactant concentration lower than 500 ppm, the enhancement factors dominate; while at surfactant concentration higher than 500 ppm, the deterioration factor dominates. For Span-80, at surfactant concentration lower than 1000 ppm, the enhancement factors dominate; while at surfactant concentration higher than 1000 ppm, the deterioration factor dominates. Therefore, for each type of surfactant, there exists an optimal surfactant concentration to obtain the maximal *SER* as well as the highest enhancement effect of surfactant on the nucleate pool boiling. Under the experimental conditions, 2000 ppm, 500 ppm and 1000 ppm are the optimal concentrations for SDS, CTAB and Span-80, respectively.

From Fig. 9b–d, it can be seen that for Cu-R113 nanofluid, the value of *SER* also increases with the increase of surfactant concentration and then decreases, presenting the maximum values at 2000 ppm, 500 ppm and 1000 ppm for SDS, CTAB and Span-80, respectively. The presence of nanoparticles does not change the tendency of *SER* changed with the surfactant concentration. From Fig. 9, it can be seen that the value of *SER* increases with the decrease of nanoparticle concentration (ω) for fixed surfactant type and surfactant concentration (*C*), and reaches the maximum value at ω of 0 wt.% (i.e., the fluid is pure R113). The possible reasons for this phenomenon are as follows. (1) The decrease of nanoparticle concentration weakens the interaction between surfactant molecules and nanoparticles, thus the diffusion velocities of surfactant molecules increase and a larger number of surfactant molecules accumulate on the growing bubble surface, which reduces the surface tension faster. (2) The faster reduction of the surface tension causes the decrease of bubble departure diameter and the increase of bubble departure frequency to be more obvious, which leads to *SER* increasing with the decrease of nanoparticle concentration.

From Fig. 9, it can be seen that the values of *SER* are in the order of SDS > CTAB > Span-80 at fixed surfactant concentration (*C*) and nanoparticle concentration (ω). For example, on the condition of

C = 2000 ppm and ω = 0.1 wt.%, the *SER* for SDS is averagely 31.8% larger than that for CTAB, and is averagely 33.4% larger than that for Span-80. The order of the *SER* values for SDS, CTAB, and Span-80 is opposite to the order of the density values for SDS, CTAB and Span-80, meaning that the surfactant with smaller density gives more enhancement of the nucleate pool boiling heat transfer. The possible reason for this phenomenon is as follows. The diffusion velocities of surfactant molecules increase with the decrease of surfactant density, causing a larger number of surfactant molecules approach and accumulate on the growing bubble surface and reduces the surface tension faster [10], which leads to the larger decrease of bubble departure diameter and the larger increase of bubble departure frequency. Therefore, the *SER* increases with the decrease of surfactant density.

5. Nucleate pool boiling heat transfer correlation for refrigerant-based nanofluid with surfactant

As there is no published literature on nucleate pool boiling heat transfer correlation for refrigerant-based nanofluid with surfactant, the development of a new correlation is needed. The surfactant concentration, the nanoparticle concentration and the surfactant type are three important factors influencing the nucleate pool boiling heat transfer, and should be reflected in the new correlation.

The nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant ($h_{\mathrm{r,n,s}}$) can be obtained by using surfactant enhancement ratio (*SER*) and nanoparticle enhancement ratio (*NER*) to correct the nucleate pool boiling heat transfer coefficient of pure refrigerant (h_{r}). In order to reflect the influences of surfactant concentration, nanoparticle concentration and surfactant type on the nucleate pool boiling heat transfer, the *SER* should be expressed as the function of the surfactant concentration, the nanoparticle concentration, the molecular weight of surfactant and the heat flux; while the *NER* should be expressed as the function of the nanoparticle concentration and thermophysical properties. The nucleate pool boiling heat transfer coefficient of pure refrigerant (h_{r}) can be calculated by Stephan and Abdelsalam correlation [30] which is widely used in the prediction of nucleate boiling heat transfer coefficient of refrigerant.

In the new correlation, the nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant, $h_{\mathrm{r,n,s}}$, is expressed as Eq. (7).

$$h_{\mathrm{r,n,s}} = SER \cdot NER \cdot h_{\mathrm{r}} \tag{7}$$

where *SER*, *NER* and h_{r} can be calculated by Eqs. (8)–(10), respectively.

$$SER = \exp\left[(m_1C^2 + m_2C)\frac{m_3}{(qM\omega)^{n_1}}\right] \tag{8}$$

$$NER = 1 + \omega^{n_2}\left[m_4\frac{\lambda_{\mathrm{n}}}{\lambda_{\mathrm{r,f}}} + m_5\frac{(\rho C_p)_{\mathrm{n}}}{(\rho C_p)_{\mathrm{r,f}}}\right] \tag{9}$$

$$h_{\mathrm{r}} = 207\frac{\lambda_{\mathrm{r,f}}}{D_{\mathrm{b}}}\left(\frac{qD_{\mathrm{b}}}{\lambda_{\mathrm{r,f}}T_{\mathrm{sat}}}\right)^{0.745}\left(\frac{\rho_{\mathrm{r,g}}}{\rho_{\mathrm{r,f}}}\right)^{0.581}\left(\frac{\nu_{\mathrm{r,f}}}{\alpha_{\mathrm{r,f}}}\right)^{0.533} \tag{10}$$

In Eqs. (8)-(10), $C_{p\mathrm{r,f}}$, $\lambda_{\mathrm{r,f}}$ $\nu_{\mathrm{r,f}}$ $\alpha_{\mathrm{r,f}}$ are the isobaric specific heat, the thermal conductivity, the kinematic viscosity, and the thermal diffusivity of pure refrigerant, respectively; $\rho_{\mathrm{r,g}}$ and $\rho_{\mathrm{r,f}}$ are the vapor and liquid densities of pure refrigerant, respectively; $C_{p\mathrm{n}}$, λ_{n}, ρ_{n} are the isobaric specific heat, the thermal conductivity and the density of nanoparticle, respectively; M is the molecular weight of surfactant; D_{b} is the bubble departure diameter, an is defined as $D_{\mathrm{b}} = 0.0146\beta[2\sigma/g(\rho_{\mathrm{r,f}} - \rho_{\mathrm{r,g}})]^{0.5}$ with a contact angle, β, of 35°; q is the heat flux; T_{sat} is the saturated liquid temperature.

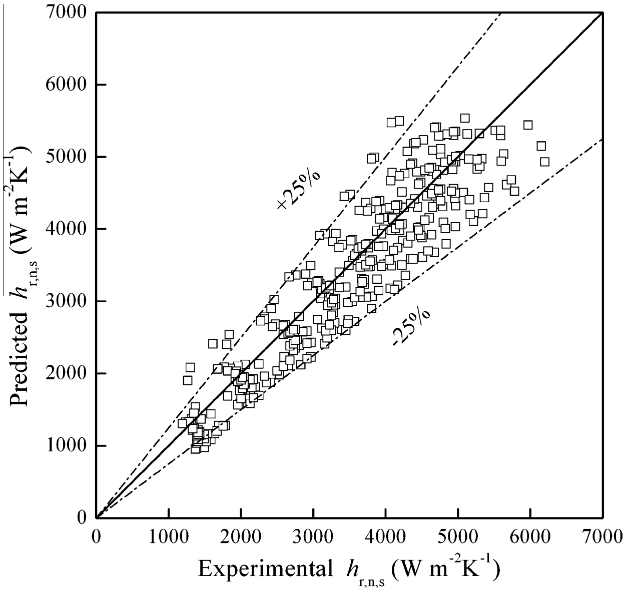


Fig. 10. Comparison of the predicted values of the new correlation with the experimental data of Cu-R113 nanofluid with surfactant.

The seven coefficients of m_1, m_2, m_3, m_4, m_5, n_1 and n_2 in Eqs. (8) and (9) are fitted based on 360 experimental data of Cu-R113 nanofluid with three different types of surfactants (i.e., SDS, CTAB and Span-80) in this study, covering the surfactant concentrations from 200 to 5000 ppm, and the nanoparticle concentrations from 0.1 to 1.0 wt.%. By nonlinear programming solution method, the seven coefficients of m_1, m_2, m_3, m_4, m_5, n_1 and n_2 can be determined as -2691, 27.1, 3517, 0.5, −1290, 0.69 and 0.25, respectively. Therefore, the nucleate pool boiling heat transfer correlation for refrigerant-based nanofluid with surfactant is expressed Eq. (11).

$$\begin{aligned} h_{\mathrm{r}} &= 207\frac{\lambda_{\mathrm{r,f}}}{D_{\mathrm{b}}}\left(\frac{qD_{\mathrm{b}}}{\lambda_{\mathrm{r,f}}T_{\mathrm{sat}}}\right)^{0.745}\left(\frac{\rho_{\mathrm{r,g}}}{\rho_{\mathrm{r,f}}}\right)^{0.581}\left(\frac{\nu_{\mathrm{r,f}}}{\alpha_{\mathrm{r,f}}}\right)^{0.533} \\ &\quad \times \exp\left[(-2691C^2 + 27.1C)\frac{3517}{(qM\omega)^{0.69}}\right] \\ &\quad \times \left\{1 + \omega^{0.25}\left[0.5\frac{\lambda_{\mathrm{n}}}{\lambda_{\mathrm{r,f}}} - 1290\frac{(\rho C_p)_{\mathrm{n}}}{(\rho C_p)_{\mathrm{r,f}}}\right]\right\} \end{aligned} \tag{11}$$

Fig. 10 shows the comparison of the predicted values of the new correlation with the experimental data of Cu-R113 nanofluid with surfactant. From Fig. 10, it can be seen that the predicted values agree with 92% of the experimental data within a deviation of ± 25%. The thermophysical properties of refrigerant and nanoparticles, and the molecular weight of surfactant are reflected in the new correlation, so the new correlation can be used to other kinds of refrigerant-based nanofluids with or without surfactants. But this nucleate pool boiling heat transfer correlation was verified only by Cu-R113 nanofluids with three different types of surfactants in the present study, and more verifications are needed in the future in order to ensure the accuracy of this correlation for other kinds of refrigerant-based nanofluids with or without surfactants.

6. Conclusions

Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid is investigated experimentally, and some conclusions are obtained.

(1) The presence of surfactant enhances the nucleate pool boiling heat transfer of Cu-R113 nanofluid on most conditions, but deteriorates the nucleate pool boiling heat transfer at high surfactant concentrations. The ratio of nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant to that without surfactant, *SER*, are in the ranges of 1.12–1.67, 0.94–1.39, and 0.85–1.29 for SDS, CTAB and Span-80, respectively.

(2) For each type of surfactant, the *SER* increases with the increase of surfactant concentration and then decreases, presenting the maximum value at the optimal concentration. Under the experimental conditions, the optimal concentrations for SDS, CTAB and Span-80 are 2000 ppm, 500 ppm and 1000 ppm, respectively. At a fixed surfactant concentration, the *SER* increases with the decrease of nanoparticle concentration.

(3) The values of *SER* are in the order of SDS > CTAB > Span-80, which is opposite to the order of their density values, meaning that the surfactant with smaller density gives more enhancement of the nucleate pool boiling heat transfer.

(4) A correlation for predicting the nucleate pool boiling heat transfer coefficient of refrigerant-based nanofluid with surfactant is proposed, and the predicted values can agree with 92% of the experimental data within a deviation of ±25%.

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