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# AN EXPERIMENTAL STUDY OF THE EFFECT OF NANOPARTICLE ADDITIVES TO THE REFRIGERANT R141B ON THE POOL BOILING PROCESS

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***Наведено результати експериментального дослідження внутрішніх характеристик процесу кипіння у вільному об'ємі холодоагенту R141b, розчину R141b/поверхнево-активна речовина Span-80 і нанофлюїду R141b/Span-80/наночастинки TiO$_2$ на поверхнях з нержавкої сталі й тефлону.***

***Виміри відривного діаметра бульбашок, частоти відриву бульбашок та густини центрів зародкоутворення проведено при атмосферному тиску в діапазоні густини теплового потоку від 3,0 до 7,5 кВт·м$^{-2}$.***

***Дослідження показали, що відривний діаметр бульбашок при кипінні нанофлюїду на поверхні нержавкої сталі становить 0,7 мм, на тефлоновій поверхні – 0,45 мм. При цьому добавки наночастинок до розчину R141b/Span-80 призводять до зменшення відривного діаметра бульбашок на тефлоновій поверхні. На поверхні нержавкої сталі спостерігався протилежний ефект.***

***Показано, що добавки наночастинок TiO2 до розчину R141b/Span-80 у 2–8 разів зменшують кількість активних центрів зародкоутворення. Цей ефект залежить від густини теплового потоку та типу поверхні кипіння.***

***Виявлено, що при кипінні R141b і R141b/Span-80 зі збільшенням густини теплового потоку зростає різниця між значеннями густини активних центрів зародкоутворення на тефлоновій поверхні й на поверхні нержавкої сталі.***

***При густині теплового потоку 7,5 кВт·м$^{-2}$ кількість активних центрів зародкоутворення на тефлоновій поверхні нижча у 2 рази, ніж на поверхні нержавкої сталі. При кипінні нанофлюїду в дослідженому діапазоні густини теплового потоку тип поверхні не позначається на кількості активних центрів зародкоутворення і частоті відриву бульбашок.***

***За результатами дослідження встановлено, що частота відриву бульбашок при кипінні холодоагенту R141b і розчину R141b/Span-80 на тефлоновій поверхні у 1,5–2 рази нижча, ніж на поверхні нержавкої сталі.***

***Отримані експериментальні дані можуть бути використані для прогнозування коефіцієнта тепловіддачі при кипінні розчину R141b/Span-80 і нанофлюїду R141b/Span-80/TiO$_2$***

***Ключові слова: нанофлюїд, відривний діаметр, частота відриву бульбашки, густина центрів зародкоутворення***

## 1. Introduction

Recently, an influence of nanoparticles on the heat exchange characteristics both in forced convection of working fluids or coolants [1–5] and in phase transition [6–19] has attracted close attention of researchers.

Concerning heat transfer with phase change, the additives of nanoparticles to the base liquid usually have a strong effect on the nucleate pool boiling process. However, there are many problems in the interpretation of the effects of nanoparticles on pool boiling processes, both quantitative and qualitative. All kinds of effects due to the presence of the nanoparticles have been reported: increase of the heat transfer coefficient (HTC) [1, 2, 4–9, 19], no effect for the HTC [3, 10–12], or deterioration of the HTC [5, 13–19].

Nucleate boiling is the most complex heat transfer process, and invariably empirical correlations or correlations having a mechanistic basis have been proposed in the literature [20, 21]. The correlations serve a useful purpose in their application to estimate the heat exchange parameters in engineering systems. However, because of their limited range of applicability, they can rarely be applied with confidence to new situations [21].

Numerous studies have shown the impossibility to evaluate the HTC of nanofluids in pool boiling using traditional models. Mechanistic models grounded on basic principles can alleviate this problem [21]. Mechanism-Based Correlations are the most physically reasonable models for predicting the nucleate boiling process. These models take into account the internal characteristics of the boiling process such as the vapor bubble departure diameter, the vapor bubble departure frequency and the nucleation site density.

It should be mentioned that some models, which are widely used in practice, despite the fact that they take into account the internal characteristics of the boiling process, cannot be attributed to the Mechanism-Based Correlations. These models include Stephan and Abdelsalam model [22] (that takes into account only the bubble departure diameter), Tolubinskiy model [23] (that takes into account the product of the bubble departure diameter and bubble departure frequency). The true Mechanism-Based Correlations are Mikic and Rohsenow model [24], Benjamin and Balakrishnan model [25], RPI model [26] (that take into account the bubble departure diameter, bubble departure frequency and active nucleation sites per unit area). The widespread use of these models in practice is limited by the lack of reliable information about the internal characteristics of the boiling process. The attempts of development of correlations or models to predict these characteristics have had limited success.

Whereas the number of studies devoted to investigating the influence of nanoparticles on the internal characteristics of pool boiling, their number is very limited [19, 26–29].

Thus, the nucleate pool boiling process should be characterized by several internal boiling characteristics, such as the bubble departure diameter, bubble departure frequency and nucleation site density [23, 30].

The disadvantages of many papers devoted to the study of boiling of nanofluids are the absence of detail studies of the internal characteristics of the process and not always the presence of information on the stability of nanofluids. The mentioned above are the reason why the analysis and generalization of the results are difficult.

In terms of the foregoing, for the development of physically based models for prediction of HTC in nanofluids boiling, the new data on the effect of nanoparticles on the internal characteristics of the boiling process is relevant.

Herewith, the study of the colloidal stability of nanofluids and effect of characteristics of heating surfaces (in particular, wettability) on the boiling process seems to be important.

This information is necessary to assess the prospects of nanofluids application as working fluids of refrigeration machines with the purpose of their energy efficiency increase.

## 2. Literature review and problem statement

The experimental data for many studies on the pool boiling of nanofluids are summarized in reviews [31, 32].

The most detailed studies of the internal boiling characteristics for water/diamond (0.01 vol. %) and water/$SiO_2$ (0.1 vol. %) nanofluids were presented in the paper [26]. The effect of nanoparticles on the bubble departure diameter, their frequency and nucleation site density was determined. Moreover, the authors used the obtained experimental data for the internal boiling characteristics directly to insert into the RPI (Rensselaer Polytechnic Institute) model [26, 33]. As a result, an excellent qualitative and good quantitative agreement between experimental and calculated boiling curves for pure water [33] and nanofluids [26] was obtained.

In the paper [34], the authors carried out an experimental investigation for the nucleate pool boiling heat transfer of water/$TiO_2$ and water/CuO nanofluids (0.001, 0.01 and 0.2 mass %). The performed visualization showed that the additives of nanoparticles to the base fluid increase the number of nucleation sites and decrease the bubble departure diameter. In the work [35], the authors experimentally studied the effect of wettability on the pool boiling HTC for nanofluids containing moderately hydrophilic and strongly hydrophilic silica nanoparticles. It was shown that moderately hydrophilic nanoparticles can be adsorbed at the bubbles interfaces and, therefore, this leads to the reduction of the bubble departure diameter. On the other hand, for strongly hydrophilic nanoparticles the reduction of the bubble diameter was not observed.

The paper [36] is devoted to the study of the CuO nanoparticles influence (0.1, 0.2 and 0.5 mass %) on the R113 refrigerant boiling process characteristics inside a smooth tube. Surface-active substances (surfactants) in this study were not used, and the consideration to the stability of the obtained nanofluid was not given. An increase in HTC was obtained, the maximum of HTC increasing was 29.7 % relative to the HTC for pure refrigerant.

In subsequent investigations, the same authors [8] measured HTC of pool boiling of nanofluid R113/Cu/surfactant nanoparticles. Nanofluids were prepared using various surfactants (anionic, cationic and nonionic) by nature. The concentration of nanoparticles was from 0 to 1.0 % by weight. HTC was determined at atmospheric pressure, different values of the heat flux density and different concentrations of surfactants in both pure refrigerant and in the refrigerant with nanoparticles. It was shown in [8] that the presence of all considered surfactants at the optimum concentration promotes an increase in boiling HTC, compared to the same value for pure R113. At the same time, an increase in the concentration of all types of surfactants in the nanofluid leads initially to an intensification of the heat transfer process during boiling, but at high surfactant concentrations, the value of the HTC starts decreasing.

From the analysis of the work [8], it can be concluded that the increase in boiling HTC is affected both by the addition of surfactants and by the presence of nanoparticles, and the contribution of these two admixtures to the base material is not additive. The disadvantage of the work is the fact that the stability of the samples and the size of the nanoparticles were not assessed in any way, since the use of different surfactants should influence the dispersed composition and stability of nanofluids.

The intensity of heat transfer during pool boiling of nanofluid R141b/$TiO_2$ (without surfactants) was studied in the work [18] under different values of the heat flux density and several values of the excess pressure. The concentration of nanoparticles in the refrigerant was 0.01, 0.03 and 0.05 % vol. It is shown that with an increase of the concentration of nanoparticles, the HTC decreased, and at higher values of the heat flux density, this effect was more significant.

In the work [37], the authors studied the heat transfer coefficient in boiling of R141b/$TiO_2$/cationic surfactant nanofluid inside the pipe. The concentration of nanoparticles was 0.01 and 0.03 % by volume, the surfactant concentration was not specified. An increase of the heat transfer coefficient proportional to the concentration is shown.

The process of pool boiling of the R134a/$Al_2O_3$ nanoparticles nanofluid was experimentally investigated in the work [38]. The concentration of nanoparticles varied from 0.01 to 0.5 % by volume. It is shown that the heat transfer coefficient in the presence of nanoparticles increases significantly (al-most twice at a concentration of 0.25 % by volume), but with a further increasing in the concentration of nanoparticles, the value of the HTC starts decreasing. The obtained effect is explained both by an increase in the thermal conductivity of the nanofluid in comparison with the base liquid and by a decrease in its surface tension, which leads to a decrease in the bubble departure diameter and an increase in the number of active evaporation centers. At the same time, the authors of [38] explain the decrease in HTC with an increase in the concentration of nanoparticles by the active settling of particles on the heating surface and its insulation, which leads to a decrease of overheating and decrease in the HTC.

In the paper [39], an experimental investigation of the pool boiling heat transfer coefficient of a low-finned U-tube immersed in $TiO_2$/R141b nanofluid is presented.

The heat transfer performance of the nanofluids with particle loadings of 0.0001, 0.001 and 0.01 vol % was found to be reduced by around 10, 20 and 50 %, respectively, compared to that of pure R141b refrigerant. This result is explained by the formation of the $TiO_2$ nano-sorption layer on the U-tube surface. After ultrasonic surface treatment, the heat transfer coefficient of 0.0001 vol % nanofluid was around 30 % higher than that of pure R141b refrigerant.

In the work [40], the boiling heat transfer coefficient of the R141b/surfactant SDBS solution and the Cu/R141b/SDAB surfactant nanofluid (concentrations of nanoparticles 0.008, 0.015 and 0.05 % by vol.) was experimentally studied. It is shown that for the nanofluid the heat transfer coefficient (in comparison with pure refrigerant) increases in proportion to the concentration of nanoparticles. And for refrigerant/surfactant solutions and for nanofluids with the same concentration of surfactants, the differences in HTC are insignificant. In addition, an interesting result was obtained in [40]: the boiling HTC of pure R141b on the surface initially coated with settled nanoparticles is higher compared to clean surface.

Thus, as it can see from reviewed papers, the influence of nanoparticle additives on the internal characteristics of boiling and on the HTC seems to be ambiguous. There is a need in future studies, in which the special emphasis should be given to ensuring the colloidal stability of nanofluids and estimation of the effect of characteristics of heating surfaces on boiling intensity.

## 3. The aim and objectives of the study

The aim of this work is to evaluate the effect of nanoparticle additives on the internal characteristics of the boiling process of the refrigerant R141b on the heater surfaces made of stainless steel and teflon at the heat flux densities that are characteristic for the evaporators of refrigeration systems.

To achieve the set aims, the following objectives were to be accomplished:

– to create an experimental setup for the study of the internal characteristics (bubble departure diameter and frequency) of pool boiling processes of pure liquids, solutions and nanofluids;

– to study the influence of additives of the surfactant Span-80 on the colloidal stability of the system R141b/Span-80/$TiO_2$ nanoparticles;

– to study the influence of additives of the surfactant Span-80 and $TiO_2$ nanoparticles on the internal characteristics of pool boiling processes during pool boiling of the refrigerant R141b;

– to analyze the experimentally evaluated internal characteristics of the boiling process of the refrigerant R141b, solution R141b/Span-80 and nanofluid R141b/Span-80/$TiO_2$ at different heat fluxes on the heater surfaces made of stainless steel and teflon.

## 4. Materials and methods used in the study of the pool boiling process for the refrigerant R141b, solution R141b/Span-80 and nanofluid R141b/Span-80/$TiO_2$

### 4. 1. Objects of study and their preparation

The refrigerant R141b, CAS № 1717-00-6 (manufactured by Zhejiang MR Refrigerant Co. Ltd, China) was used as the base fluid for nanofluid preparation. $TiO_2$ nanoparticles were used as the additives. According to the manufacturer's information, the size of the nanoparticles in the powder does not exceed 25 nm, CAS № 1317-70-0 (Sigma-Aldrich).

The material of nanoparticles ($TiO_2$) was chosen because of its chemical stability, well-developed technology of their production and low cost. The refrigerant R141b was chosen as the base model substance for several reasons. Firstly, this refrigerant is liquid at ambient temperature and atmospheric pressure, so it is convenient for nanofluid preparation and for studying its boiling processes. Secondly, the refrigerant R141b and widely used refrigerants (R134a, R410A and others) belong to the same group of hydrohalocarbons. Therefore, the obtained patterns of the boiling process of the model system R141b/nanoparticles can be extended to the hydrofluorocarbon refrigerants, which are widely used in chemical and refrigeration industries, as well as in air conditioning systems.

The preparation of the colloidally stable system R141b/$TiO_2$ nanoparticles without the use of surfactants was not succeeded in the present study. This information also is presented in the paper [41]. This fact contradicts the information given in [18], where the authors report on the stability of the nanofluid of R141b/$TiO_2$ nanoparticle without the use of any surfactants.

Thus, in the presented work and in the previous study [41], the existence of the colloidally stable system R141b/$TiO_2$ nanoparticles only with the presence of surfactants has been established. The type and concentration of the surfactant – Span-80 that provides the best colloidal stability was estimated during special studies, for example, [41].

It should be taken into account that not only nanoparticles, but also surfactant additives will contribute to the change in thermophysical properties of the base fluid and internal characteristics of the boiling process [8, 42]. Therefore, the research objects of this work are:

– the refrigerant R141b without nanoparticle and surfactant additives – R141b;

– solution of the refrigerant R141b and Span-80 surfactant (0.1 wt.%) – R141b/Surf;

– nanofluid consisting of the refrigerant R141b, Span-80 surfactant (0.1 wt.%) and $TiO_2$ nanoparticles (0.1 wt.%) – R141b/Surf./$TiO_2$.

A two-step method of the nanofluid preparation was applied. It consisted of the following stages:

– sonication of the mixture of nanoparticles, surfactants and refrigerants;

– mechanical dispersion;

– repeated sonication.

The Codison CD 4800 bath with a frequency of 42 kHz and a power of 0.07 kW was used for sonication of the mixture for 30 minutes. The bead mill filled with balls of $ZrO_2$ with a diameter of 2 mm was used for mechanical dispersion for 12 hours.

The photos of the samples in the sealed optical cells with the optical path length of 4.05 mm are shown in Fig. 1.

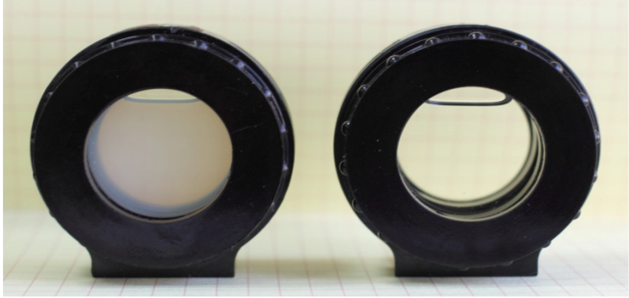


Fig. 1. The snapshot of samples of nanofluid of R141b/Surf./$TiO_2$ (99.80/0.10/0.10 wt. %) (with a surfactant) in comparison with pure R141b in hermetic optical cells in 1 hour after preparation

Stability of the nanofluid in time was checked by measuring the average size of nanoparticles in R141b by the spectral turbidity method. Practical realization of this method consisted in the measuring of the optical density of the nanorefrigerant sample in the optical cell depending on the transmitted light wavelength (wavelength range $\lambda$=500–700 nm). For this purpose, the Shimadzu UV-120-02 spectrophotometer was used. Preliminary studies given in [41] showed the good colloidal stability of the nanofluid for 3 months.

### 4. 2. Experimental facility and experimental procedure

The scheme of the experimental setup for the investigation of the boiling process is presented in Fig. 2.

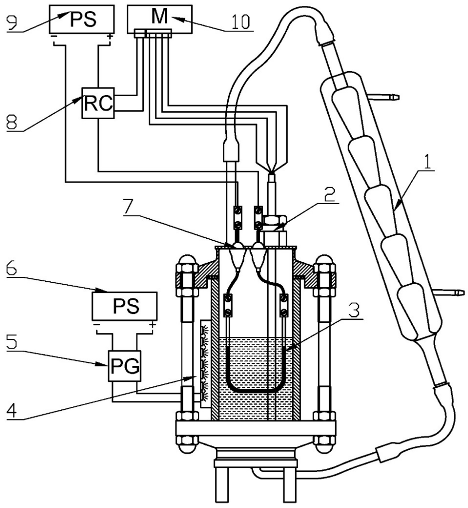


Fig. 2. Facility for the study of the internal characteristics of the boiling nanofluids: 1 – Condenser; 2 – Resistance thermometer; 3 – Heater; 4 – Light source for creating a stroboscopic effect; 5 – Pulse generator; 6, 9 – Power supply; 7 – Hermetic electric connector; 8 – Resistance coil; 10 – Multimeter

The boiling of the research objects was performed on a heater 3 placed into the optical cell. The image of the optical cell is presented in Fig. 3.

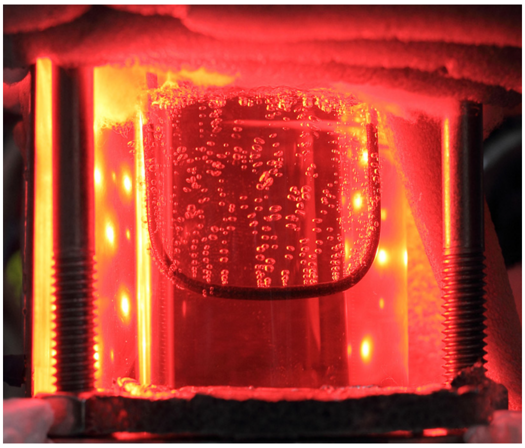


Fig. 3. The snapshot of the experimental cell for the study of the internal characteristics of the pool boiling process at atmospheric pressure

The thin-walled stainless steel capillary with a diameter of 2.00 mm was used on the first stage of the study. The same capillary covered with a thin layer of teflon with a diameter of 2.05 mm was used on the second stage of the study. For the heat supply, a stabilized power supply BVP Electronics Power Supply 30V 50A was used. The uncertainty of measuring the power supplied to the heater was 0.01 W.

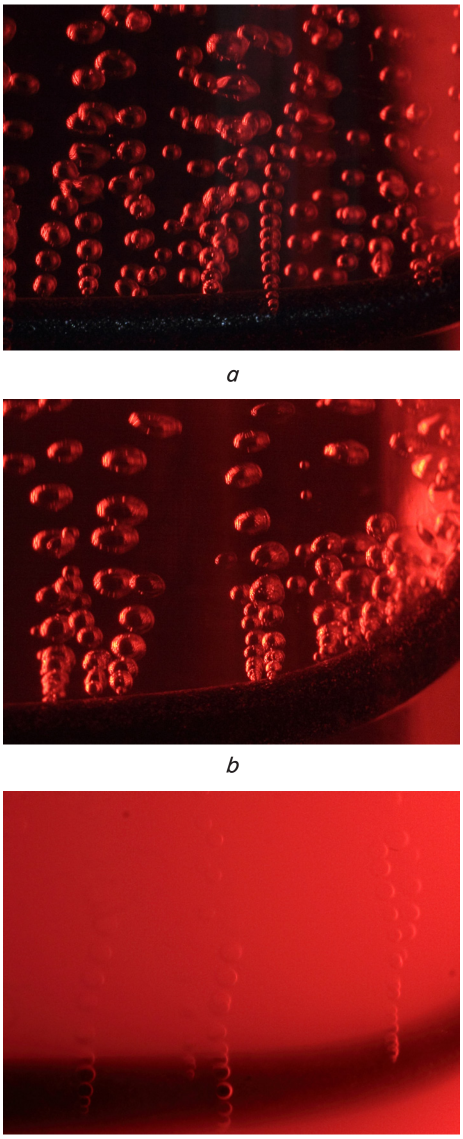
The platinum resistance thermometer 2 was used for measuring the temperature of the liquid during boiling. The balanced method with the application of the digital multimeter 10 (Rigol 3064) and reference resistant coil 8 of precision class 0.01 was used for thermometer resistance measurement. The uncertainty of temperature measuring was not more than 0.05 K.

The camera Canon EOS 1100D and the stroboscope for the lighting of the measurement cell were applied for the photography of the boiling process. It should be noted that the use of a stroboscopic effect allows obtaining digital images of fast processes at high resolution, which is much higher than the images taken by high-speed cameras of the low price range. The disadvantage of this technique is the layering of images of the rising bubbles on each other.

The light source in the stroboscope was the set of 10 light emitting diodes (1 W) with a peak wavelength of 650 nm. The camera and the light source of the stroboscope were located at an angle of 90°. The optical cell where the boiling process was performed was isolated from other light sources during the experiments. The duration of the light emission was 0.3 ms and the intervals between flashes were 2.4–5.0 ms.

As an example, Fig. 4 shows the images of the boiling process of the research objects on the teflon surface under atmospheric pressure and at a heat flux density of $6.60\pm0.03$ kW·m$^{-2}$.

The use of the stroboscopic effect when fixing an image on a camera's matrix allowed estimating the frequency of the vapor bubbles departure when processing the graphic objects. These data have been obtained by processing the snapshots of boiling liquid using the AutoCAD. The mean bubble departure diameter and the mean bubble departure frequency were calculated from 100–160 bubbles.



a

b

c

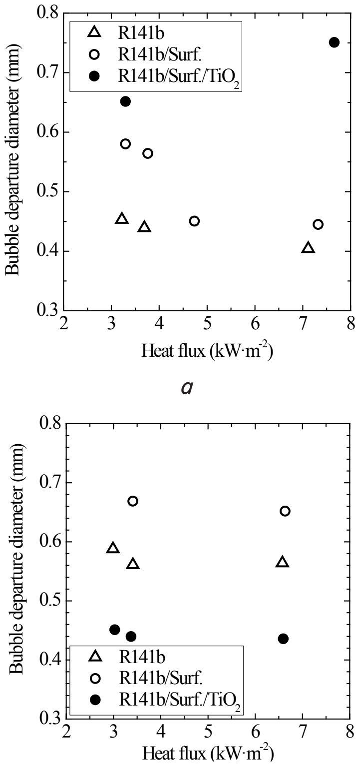
Fig. 4. Visualization of the pool boiling process on the teflon surface at a heat flux density of 6.60±0.03 kW·m$^{-2}$: *a* – R141b; *b* – R141b/Surf.; *c* – R141b/Surf./TiO$_2$

## 5. The results of the study of the boiling process of R141b, solution of R141b/Span-80 and nanofluid R141b/Span-80/TiO$_2$

The internal boiling characteristics (bubble departure diameter, bubble departure frequency and nucleation site density) were studied experimentally under atmospheric pressure in the range of heat fluxes from 3.0 to 7.5 kW·m$^{-2}$. Such an interval of the heat flux densities is characteristic for evaporators of refrigeration systems [43].

The dependences of the mean bubble departure diameter, mean bubble departure frequency and nucleation site density on the heat flux density at $P$=0.1013 MPa for the research objects are shown in Fig. 5–7.

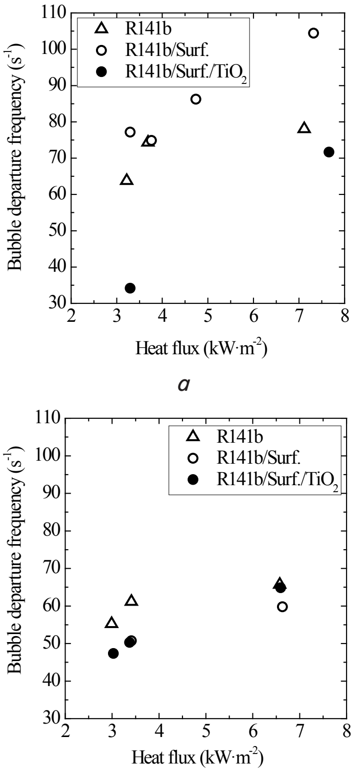
As can be seen from the information in Fig. 5–7, even small additives of surfactants and nanoparticles led to the significant variation of the internal characteristics of boiling of the refrigerant R141b. The wettability of heater surfaces substantially affects the boiling intensity.



a

b

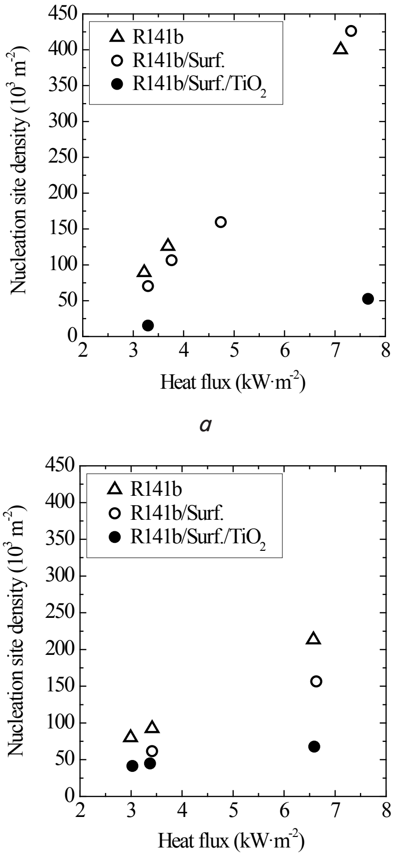
Fig. 5. Dependence of the mean bubble departure diameter on the heat flux density of pure R141b, R141b/Surf. and R141b/Surf./TiO$_2$: *a* – on stainless steel surface; *b* – on teflon surface



a

b

Fig. 6. Dependence of the mean bubble departure frequency on the heat flux density of pure R141b, R141b/Surf. and R141b/Surf./TiO$_2$: *a* – on stainless steel surface; *b* – on teflon surface



*a*

*b*

Fig. 7. Dependence of the nucleation site density on the heat flux density of pure R141b, R141b/Surf. and R141b/Surf./TiO$_2$: *a* — on stainless steel surface; *b* — on teflon surface

## 6. Discussion of the study results of the boiling process of R141b, solution R141b/Span-80 and nanofluid R141b/Span-80/TiO$_2$

It can be mentioned that the advantage of the conducted study is the presence of an important stage – obtaining of a stable nanofluid. This circumstance ensures the reliability and adequacy of the obtained information.

As it follows from the obtained experimental results, the number of nucleation sites during boiling of the R141b and solution of R141b/Surf. on the teflon surface is significantly lower compared with the stainless steel surface. The most probable reason for this is the differences in surface roughness.

At the same time, the number of nucleation sites during boiling of the nanofluid both on the stainless steel and teflon surfaces was comparable. Herewith, the nanoparticle additives led to a decrease in the number of nucleation sites by 2–8 times compared with boiling of the solution of R141b/Surf. Probably, the number of active nucleation sites in the boiling of the nanofluids decreases because the small cavities were filled with nanoparticles [31].

It should be noted the greatest bubble departure frequency was observed in boiling of pure R141b and solution of R141b/Surf. on the stainless steel surface.

An interesting result describing the effect of nanoparticle additives on the bubble departure diameter was obtained. The bubble departure diameter in boiling of the nanofluid on the stainless steel surface is greater than in boiling of pure R141b. In contrast, in boiling of the nanofluid on the teflon surface, the bubble departure diameter is significantly lower than for pure R141b.

As indicated in the paper [19], the information about the internal characteristics of the boiling process allows obtaining an appropriate correlation based on the RPI model [26] for the estimation of the HTC for pure substances and nanofluids. Thus, the obtained experimental information can be used for the development of the physically based models of predicting the HTC in nanofluids boiling. However, carrying out a more weight study is needed to solve this task. Thus, the information about thermophysical properties of nanofluids, first of all, density, surface tension and viscosity, is needed to increase the validity level of calculation models.

The above disadvantages can be eliminated by carrying out an additional investigation in a wide range of pressures with using the setup described in the paper [19]. Also, the measurement of thermophysical properties for the considered objects of study is planned to perform.

## 7. Conclusions

1. The created experimental setup allows investigating the internal characteristics of the pool boiling process of pure fluids, solutions and nanofluids at atmospheric pressure and heat fluxes up to 7.5 kW·m$^{-2}$. The information about the vapor bubble departure diameter, the vapor bubble departure frequency and the nucleation site density can be obtained with using the stroboscopic effect.

The expanded uncertainty of measurements was not more than 0.05 K for temperature and not more than 0.01 W for the power supplied to the heater.

2. It was determined that the system R141b/TiO$_2$ nanoparticles remains stable only in the presence of the surfactant. As a surfactant, it is recommended to use the agent Span-80 at a concentration in a solution equal to 0.1 mass %.

3. The experimental study of processes of pool boiling of the refrigerant R141b, solution R141b/Span-80 and nanofluid R141b/Span-80/TiO$_2$ at heat fluxes from 3.0 to 7.5 kW·m$^{-2}$ has been performed. The obtained experimental information allows estimating the effect of the surfactant Span-80 and nanoparticles TiO$_2$ on the internal characteristics of pool boiling processes for the refrigerant R141b.

4. As a result of the performed analysis of the experimental information, the features of influences of both surfactant and nanoparticle additives and the type of heater surfaces on the internal characteristics of pool boiling of the refrigerant R141b have been determined.

The additives of surfactants to the refrigerant lead to an increase in the vapor bubble departure diameter and the vapor bubble departure frequency but slightly affected the nucleation site density.

The additives of TiO$_2$ nanoparticles to the solution R141b/Span-80 lead to a decrease in the number of nucleation sites by 2–8 times. This effect depends on the heat flux and type of heaters surface.

The study showed that the vapor bubble departure diameter in the nanofluid boiling on the stainless steel surface is 0.7 mm and on the teflon surface – 0.45 mm. Besides, the additives of nanoparticles to the solution of R141b/Span-80 lead to a decrease in the vapor bubble departure diameter in boiling on the teflone surfaces. The opposite effect was detected in boiling on the stainless steel surface.

It was found that the rise of the heat flux leads to an increase in the difference between the magnitudes of nucleation site density for the teflon and stainless steel surfaces in boiling of R141b and R141b/Span-80. The number of nucleation sites on the teflon surface is 2 times lower compared with boiling on the stainless steel surface at a heat flux of 7.5 kW·m$^{-2}$. The type of surfaces does not affect the number of nucleation sites and vapor bubble departure frequency in nanofluid boiling in the entire investigated range of heat fluxes.

Based on the results of the study, it was found that the vapor bubble departure frequency in boiling of R141b and solution R141b/Span-80 on the teflon surface is 1.5–2 times lower compared with boiling on the stainless steel surface.

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