Critical heat flux and dynamics of boiling in nanofluids at stepwise heat release

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Abstract. In this paper results of an experimental study on critical heat flux and dynamics of boiling crisis onset in nanofluids at stepwise heat generation are presented. Freon R21 with three types of nanoparticles - SiO₂, Cu and Al₂O₃ was used as test fluid. Critical heat fluxes and temperatures of boiling initiation were obtained. It was shown that the addition of nanoparticles increased CHF at stepwise heat generation by up to 21%. Under conditions of the experiment transition to film boiling occurred via evaporation fronts. Data on propagation velocity and structure of evaporation fronts were obtained; the spectral analysis of fluctuations of the evaporation front interface was carried out. The characteristic frequencies and amplitudes of interface fluctuations were determined depending on the velocity of evaporation front propagation. It was shown that the addition of nano-sized particles significantly affects development of interface instability and increases the front velocity.

1. Introduction

Boiling is one of the most effective ways to remove heat from a surface, thus it is widely used in various technical applications. But increasing requirements for miniaturization and performance of heat equipment stimulate researchers to look for new methods to improve boiling heat transfer and increase critical heat flux. During the last two decades one of the promising trends in boiling heat transfer enhancement is usage of nanofluids. The addition of nanoparticles can significantly increase both the heat transfer coefficient and CHF [1]. However, the obtained results are often contradictory and depend on many factors, so the practical use of nanofluids needs further systematic research. In addition, there is a necessity in the experiments to be carried out in nanofluids under non-stationary heat release which simulate different emergency processes (depressurization of devices, removal of rods in nuclear power plants, etc.). Under such conditions interphase boundary of a vapor bubble can lose hydrodynamic stability [2, 3]. At presence of overheated wall it leads to initiation of self-sustaining evaporation front in the layer of metastable liquid near the heater and transition to film boiling at much lower heat fluxes than critical heat flux at quasi-stationary heating. There are papers dedicated to experimental and theoretical investigation of evaporation fronts in pure fluids [4-8], but at present only few studies were made with nanofluids [9-10]. The available works demonstrate an increase in non-stationary CHF when adding nanoparticles.

In present work experimental study of boiling crisis in nanofluids at stepwise heat generation was performed. Freon R21 was used as base fluids, and three types of nanoparticles, SiO₂, Al₂O₃ and Cu were used to prepare nanofluids. Critical heat fluxes and temperatures of boiling initiation were measured, and dynamics of evaporation front propagation was studied.
2. Experimental setup and procedure
Experiments were carried out in Freon R21 at reduced pressures \( \frac{P}{P_c} = 0.037 \) (0.193 MPa). For experimental studies of heat transfer and transient dynamics at non-stationary heat release under free convection the setup, shown schematically in figure 1, was developed.

On bed 1, the frame 2 with refill tank 3 and working chamber 4, housing the working section 10, is hinged. The working chamber is a sealed cylindrical stainless steel vessel. The inner diameter of the chamber is 250 mm, and the height of the workspace is 250 mm. The working chamber is equipped with four windows 5. The bellows 6 with an adjusting screw 7 allows creating the required pressure (up to 0.4 MPa) in the working chamber at the closed valve 8. To set the desired temperature of liquid in the bottom of the chamber, heat exchanger 9 was located.

![Figure 1. Scheme of experimental setup.](image)

The working section was made of the stainless steel tube with outer diameter of 3 mm, wall thickness of 0.5 mm and length of 50 mm. A thin-film platinum thermometer was installed inside the tube to measure the temperature in the quasi-stationary regimes. The tube ends were hermetically sealed. The tube was heated by electric current from controllable current source. In experiments with non-stationary heat release the rectangular current pulse of 420 A was supplied to the working section. Since thermal inertia in the section was rather high, at the times of the evaporation front development (about 50 ms) wall temperature was growing with almost a constant rate of 2180 K/s. Temperature of the heater was determined by the current pulse duration. After current was turned off, the wall temperature remained almost constant at the times of the evaporation front propagation. Numerical calculation using thermal conductivity equations has shown that for the time of front passage (much lesser than the time of convection development) the wall temperature before the front dropped no more than by 0.2 K. Thus in each experiment, the propagation of self-sustained evaporation front was investigated at the pre-set constant wall temperature.

The working section temperature until the moment of vapor phase emergence was measured using temperature dependence of the heater resistance. For this purpose, two conductors of 0.05-mm diameter were welded in the middle of the tube to measure the voltage drop in the region of 30-mm length. In each measurement, calibration was performed by the temperature of undisturbed fluid. This technique allowed measuring the average temperature of the working section with an error less than \( \pm 1.5 \) K. After the vapor phase formation, the wall temperature was determined numerically based on the equations of non-stationary thermal conductivity. This approach is valid under conditions of our experiments since the times of the evaporation front propagation (about 30 ms) were much less than the time of convection development (about 200 ms). Comparison of the temperature measured using heater resistance and obtained from numerical solution showed excellent agreement of the experiment and calculations.
Visual observations of vapor phase formation and propagation on the heating surface were performed using a high-speed digital video camera Phantom v7.0. The shooting rate was 25,000 frames per second with the exposure of 26 microseconds. When analyzing the results of high-speed digital video-shooting, the line of the interfacial boundary was determined on each frame using specially developed software. The obtained data was used to study dynamic properties of evaporation front boundary.

Three types of nano-additives were used. The first type is Tarkosil-T20 SiO$_2$ particles with average diameter of 20 nm, specific surface area 140 m$^2$/g, 0.003% vol, produced by electron beam evaporation method. The second type is Al$_2$O$_3$ particles with diameter of 50 nm, specific surface area 30 m$^2$/g, 0.001% vol. The third type is passivated Cu particles with diameter of 80 nm, specific surface area 14 m$^2$/g, 0.0013% vol. Al$_2$O$_3$ and Cu nanoparticles were produced using electric explosion of wire. Nanofluids preparation procedure was as follows. The powder was loaded into the working volume, and then vacuum exhaust, filling with fluid and mixing were performed.

3. Experimental results

3.1. Critical heat flux
In experiments to determine critical heat flux, rectangular current impulses with magnitude of 420 A were supplied, starting with the short impulse duration and, thus, low wall overheat. After each impulse, we waited for the system to return in the initial state. If vapor phase was not registered for 5 attempts, we supposed that evaporation front initiation doesn’t occur at the adjusted wall overheat, and the impulse duration was increased by 1 ms, which corresponds to wall overheat increase by 2 K.

Figure 2 shows the dependence of the heat flux density $q$, transmitted by the wall to the fluid, on the temperature of the wall overheating $\Delta T$. The value of $q$ was obtained from the numerical solution of the heat equation. Vertical lines mark the minimum wall overheats, at which the evaporation front propagation was recorded. In pure Freon R21, the minimal overheat is 41 K and corresponding heat flux density is 0.159 MW/m$^2$. It is 3 times less than CHF in Freon R21 at quasi-stationary heat release. In R21+Al$_2$O$_3$ nanofluid no difference from pure fluid was observed. In R21 + Cu nanofluid minimal overheat of front initiation was increased by 7 K, and corresponding heat flux was 0.172 MW/m$^2$. In R21 + SiO$_2$ nanofluid, minimal wall overheat was higher by 18 K and heat flux was 0.192 MW/m$^2$.

Thus, the addition of nanoparticles has led up to 18 K increase in minimal wall overheat required to evaporation front initiation, which is equivalent to a 21% increase in non-stationary CHF.

![Figure 2.](image-url)
3.2. Evaporation front
As was mentioned before, at nonstationary heat release emergence of a single vapor bubble leads to initiation of self-sustaining evaporation front in the layer of metastable liquid near the heater wall (Figure 3). Interphase boundary has perturbations on two scales: large-scaled waves with wavelength 1.5-2 mm, which is close to capillary length in Freon R21 (about 1.7 mm), and small-scaled perturbations with size 100-200 $\mu$m. In previous works it was shown that these perturbations are caused by development of hydrodynamic instability, and they can increase heat transfer through the interphase boundary, which leads to increase in evaporation rate and front velocity [2, 3].

![Figure 3. Development of the evaporation front in pure Freon R21. Time from the beginning of heating: (a) – 28 ms; (b) – 29.4 ms; (c) – 32.8 ms.](image)

Figure 4 shows dependence of the front velocity on the wall overheat. At low overheats ($\Delta T < 60$ K) the slope of the experimental data is relatively small, and there is no difference in velocity for pure fluid and nanofluids. At higher overheats ($\Delta T > 65$ K), corresponding to the development of the hydrodynamic instability, slope of the experimental data increases. Front velocity in nanofluids is higher compare to the base fluid by 25% on an average, but there is no clear distinction between fluid with different nanoparticles.

To investigate large-scaled pulsations of the front interface, we used the dependence of $x$ coordinate on time over one of the heater generatrices, i.e. for the fixed value of $y$-coordinate. The linear trend, complying with the distance run at constant speed $V_{fr}$, was deducted from the resulting dependence. The fast Fourier transformation was applied to the remained coordinate deviations from the path at a constant velocity. In all the spectra, the pronounced peak of main harmonic was observed. Using the amplitude and frequency of the main harmonic, we determined the characteristic velocity pulsations and acceleration of the interface.

Dependences of frequency and amplitude of the main harmonic on average velocity are shown in figures 5 and 6. In pure liquid, the frequency of the main harmonic increases with a rise of the average velocity. The amplitude doesn’t show any clearly distinguishable trend in studied range of velocities. In $\text{SiO}_2$ and $\text{Al}_2\text{O}_3$ nanofluids the similar tendency is observed, but fluctuation frequencies decrease in comparison with pure liquid. The Cu nanofluid was too opaque to perform spectral analysis, thus corresponding data is not presented.
Figure 4. Evaporation front velocity vs wall overheat.

The amplitude value of interface acceleration, defined as the product of main harmonic amplitude on the square of angular frequency, can be estimated from the obtained data. These values, normalized to gravity acceleration, are shown in figure 7. In pure liquid, acceleration can reach values up to 160 g at high wall overheats. In nanofluids, interface acceleration was several times lower than in the pure liquid.

Figure 5. Interface oscillation frequencies.

Figure 6. Interface oscillation amplitudes.
4. Conclusions

Addition of nanoparticles provided up to 21% increase in CHF under non-stationary heat release. Wall overheat corresponding to boiling initiation also increased by up to 18 K. Temperature of heterogeneous nucleation depends on the surface roughness, and all types of nanofluids caused visible modification of the heater surface. But effect on the temperature of boiling onset at stepwise heat release significantly differs for different nanoparticle types. Detailed analysis of the surface is needed to explain such results.

Addition of nanoparticles also increases the velocity of evaporation front by 25% at high wall overheat. Experiments show that nanoparticles changed parameters of interface pulsations. It is shown in [4] that interface acceleration affects significantly the small-scaled instability development and intensification of heat transfer through the interface. A decrease in acceleration at presence of nanoparticles gives an opportunity for instability development in wider range of front velocities and interface perturbation scales, which can explain increased front velocity.

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