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Experimental study of thermo-hydraulic characteristics of natural circulation loop at water and FC-72 boiling under atmospheric pressure.

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Abstract. The results of experimental study of thermo and hydraulic characteristics of flow boiling of water and FC-72 in natural circulation loop under atmospheric pressure are presented. The experimental data have been obtained in the range of wall heat flux densities (6 – 70) kW/m$^2$ for water and (4.6 – 30) kW/m$^2$ for FC-72. These two liquids differ substantially in thermophysical properties so it makes it possible to extend the range of reduced pressures almost for an order of magnitude without changing the technical parameters of experimental setup. An additional information for the analysis of flow pattern influence on onset of instability and unstable circulation mechanism have been obtained as the result. The flow up tube of the loop had inner diameter 9.1 mm and consisted of two section – heated one 98 diameters length (that is 65 % of total tube length) and upper adiabatic section with length 48 diameters. Different circulation regimes were realized in experiments: mixed regimes with single phase and boiling zones in the heated part of the tube and boiling regimes along the full length of the heated section. The experimental data on circulation velocity (flow rate) and wall temperature distributions (including pulsating components of temperature and velocity) are presented in dependence on wall heat flux density and liquid subcooling at the inlet to the heated zone. At water experiments autooscillating regimes of boiling flows were observed within the whole range of inlet liquid subcoolings up to saturation temperature and at all wall heat flux densities from lowest one (10 kW/m$^2$) to somewhat upper limiting value of 64 kW/m$^2$. At higher heat fluxes the two-phase boiling flow was stable not only in saturation inlet liquid temperature but also at low subcoolings. In FC-72 experiments the flow was stable at all realized heat flux densities within the range of inlet liquid subcoolings (2 – 20) °C.

1. Introduction

Natural circulation loops have many industrial applications such as solar heaters, geothermal systems, nuclear power plants, electrical machine rotor cooling, gas turbine blade cooling, and electronic device cooling. In recent years natural circulation loops, which operates at low pressures are an object of heightened interest of the designers of new technologies. After Fukusima accident (2011, Japan) natural circulation loops became to be considered as the main type of passive safety cooling systems in accidental regimes under the conditions of absence of electrical power supply sources. Natural circulation loop being the base of passive core cooling system does not need for its operation electrical power supply and direct human intervention.
Hydrodynamical and heat transfer processes in natural circulation boiling are sufficiently well studied for high pressures typical for power industry. But as practice has shown the existing engineering methods for calculating heat and hydrodynamic characteristics of loops being developed for high regime parameters are not suitable for systems operating at low pressures (nearatmospheric and lower) [1].

As it is known the flow rate in natural circulation loops is not held as the external parameter, but it is the result of the balance between the buoyancy induced driving force and total hydraulic losses. The circulation velocity is governed by heat flux put into loop, working liquid properties, loop geometry, pressure and loop filling level with working liquid. Practically only heat flux density in heated section, pressure, liquid temperature at the inlet to the heated zone and partially filling liquid level can be considered as external operating regime parameters. Their combination determines the two-phase flow pattern, void fraction, circulation velocity and circulation stability and temperature regime as the result. Great differences between specific volumes of vapour and liquid for water at atmospheric pressure (up to 1600 times) predetermine very intensive change of void fraction along the flow up section, this leads to two-phase flow pattern change even at little change of flow quality. As pressure decreases the initial temperature difference necessary for boiling onset increases, besides the streamwise coordinate of boiling incipience depends upon flow velocity. More over loop operating at low pressures is characterized by low hydrodynamic stability.

As it has been already mentioned above for reliable design works the engineering methods for calculating heat and hydrodynamic characteristics of low pressures loops must be modified with the account of specific features of boiling process and two-phase flow patterns at low pressures. The correct determining of streamwise position of boiling incipience for low pressures is more urgent problem than for high ones. Besides the flow velocity range of unstable circulation regimes in the loop for low pressures is essentially wider. The quantitative criteria for predicting the limits of stable operating of natural circulation loops do not exist for today. The instructive results are published in [2, 3]. In [2] the different types of pressure and flow rate oscillations were investigated experimentally in two channel steam-water loop at pressure of 0.16 MPa, in [3] the numerical simulation of the like loop (but with less height of flow up section and at pressure of 0.125 MPa) were carried out. It must be noted that the reliable methods for calculating velocity circulation, friction hydraulic losses, boundaries of two-phase flow patterns change are not suggested yet for today.

2. Experimental apparatus and procedure

Present experimental data have been obtained in the loop, a schematic diagram of which is shown in Figure 1. The flow up (heated) and flow down legs of the loop are joined to the separator-condenser at the top of the loop. One of the structural features of the loop is large aspect ratio between the down leg cross sectional area and that of the heated leg. This detail of construction made it possible to substantially reduce pressure losses in flow down line (down comer). Cooling heat exchanger and two electrical heaters are installed on the down comer. These members are used for maintaining a specified inlet temperature.

The flow up section was a thin wall stainless steel tube with inner diameter $d=9.1$ mm and total length of 150 $d$. The tube consisted from two sections. Lower section 98$d$ long was electrically heated and the upper section 48$d$ long was adiabatic (draught section).

Experiments were performed at atmospheric pressure. Heat flux density, inlet flow temperature, longitudinal wall temperature distributions and flow rate have been measured at each experimental run. Besides the videorecording of the vapour-liquid jet at outlet cross-section of the flow up tube have been carried out.

The wall temperature of the heated tube was measured by chromium-alumel thermocouples which hot junctions have been point-welded in 20 cross-sections to the outer surface of the tube. The technique afforded to form thermocouple junctions less than 0.2 mm in dimension. Besides the wall thickness of the heated tubes did not exceed 0.45 mm. Thus the thermal response time of the test
section was sufficiently small and we could record temperature fluctuations (which in some regimes were very intensive).

![Experimental setup](image)

Temperature recordings were realized with data acquisition system, which affords high-frequency sampling of measured quantities. The frequency of thermocouples sample was 100 Hz. It was enough to obtain practically simultaneous temperature records for the total heated length.

The flow rate in the loop was measured with ultrasonic flow meter FLUXUS F601 with the error of 0.01 m/s. The pressure transducer AIR of 0.2% accuracy class was used for pressure measuring in the separator-condenser chamber. Temperature measurements are in error by 0.2 °C, heat flux density measuring error is 2%.

Present data have been obtained for the loop fully filled with the working liquid up to outlet of flow up tube section to separator.

3. Experimental results

The effect of the heat flux and liquid temperature at the inlet to the heated section on thermo-hydraulic characteristics of the low pressures loop was one of the tasks of present work. The experimental data on circulation velocity and temperature distributions along the heated section have been obtained at pressure in separator chamber of 100 kPa within the range of heat flux densities \((6.0 - 70)\ kW/m^2\) for water and within the range of \((10 - 30)\ kW/m^2\) for FC-72.

One of the key factors leading to the hydrodynamic flow instability in vapour generating tube of the loop is liquid subcooling to the saturation temperature at the inlet to the heated zone. Under such conditions the boiling onset takes place at some distance from the inlet depending on the subcooling level. So two flow regimes are realized in heated section: single phase convection and flow boiling. The length of the above flow zones depend upon inlet liquid subcooling level and wall heat flux density. At previous experiments with water at atmospheric pressure for total length heating of flow up tube \((L_1/d=142)\) the hydrodynamic instability was observed for the regimes of liquid subcoolings at
the inlet to the heated zone. This instability was characterized by low frequency autooscillations of flow rate, pressure and wall temperature [4].

The results obtained for partial length heating of flow up section of the loop are discussed in present paper. For subcooled inlet liquid two kinds of circulation regimes have been realized, they are mixed circulation regime with single phase convection along some distance from the heating inlet and flow boiling along the rest of the heated zone and flow boiling along the total heated portion of the flow up tube.

Typical time records of wall temperature and circulation velocity for water flow for seven cross-sections for different inlet liquid subcoolings and the same wall heat flux density of $q = 45 \text{ kW/m}^2$ are shown in figure 2. The data presented in figure 2 correspond to inlet liquid temperatures $T_{in} = (35, 65, 91) \degree C$. The two upper rows A and B of plots in figures 2, a)-c) are the wall temperature time records, the row B showing the fragments of row A in more large scale. The row C of plots in figures 2, a)-c) are corresponding time records of circulation velocity. First of all it is seen that wall temperature time records have explicitly pronounced low frequency regular dominated periodic component, its amplitude and frequency for $q =$ idem depending on the inlet liquid subcooling.

**Figure 2.** Time records of wall temperature and circulation velocity for water flow at $q = 45 \text{ kW/m}^2$ and different inlet liquid subcoolings.
As inlet liquid subcooling decreases the frequency of the periodic component increases and its amplitude decreases. For the time records for rows A, B, in figures 2, a)-c) at the change of the inlet liquid temperature $T_{in}$ from $35^\circ C$ to $91^\circ C$ the averaged wall temperature oscillation frequency increased from $f = 0.009$ Hz to $f = 0.235$ Hz with the approximately twice amplitude decreasing. The maximal amplitudes of wall temperature oscillations have been observed as a rule in near inlet part of the tube where the single-phase convection regime is being realized. Such a tendency is typical for all circulation regimes with liquid inlet subcooling. The analysis of wall temperature time records leads to a conclusion that at single-phase convection zone there takes place a substantial flow velocity difference for the stages of wall temperature increase (heating rate) and temperature decrease (cooling rate). For example wall cooling rate for the regime of $q = 45$ kW/m$^2$, $T_{in} = 63$ °C is almost by an order of magnitude higher than heating rate. This tendency remained the same in the case of minimum subcooling ($T_{in} = 91$ °C).

As it is seen from row of plots C in figure 2,a)-c) the amplitude of circulation velocity oscillations also changes with inlet liquid subcooling. The higher the subcooling level the greater the difference between amplitude and averaged velocity values. The periods of circulation velocity oscillations correlate with periods of wall temperature oscillations. As it is seen from plots C in figure 2,a)-b) in circulation regimes with relatively low heat fluxes but sufficient enough for boiling incipience one can observe a reverse flows in the loop, the flow rate decreases down to zero value and flow changes its direction. One can also make a conclusion about the existence of reverse flows from the time records of bulk liquid temperature measured at the inlet to the heated section (see the record 1 of the A-plots in figure 2,a)). Short-time periodic temperature spikes on the $T(t)$ record are induced by the portion of heated liquid brought by the front of periodically occurring reverse flow from the heated section. The cause of this phenomenon is connected to the decrease of liquid level in down comer at the very moment of dynamic flow rate increase at boiling onset. The increase in circulation velocity leads to wall cooling and wall temperature decreases. This in turn stops the boiling process, flow becomes single-phase, driving force decreases and flow rate decreases as the result. The levelling of hydrostatic pressures in loop bends induces liquid to flow in opposite direction, this in turn leads to restoring the liquid level in down comer.

For low inlet liquid subcoolings that is for the inlet temperatures close to saturation temperature at wall heat flux densities lower than 60 kW/m$^2$ the boiling flow is unstable with wall temperature fluctuation in near harmonic mode. Wall temperature time records behaviour together with averaged longitudinal temperature distributions give one a possibility to get quantitative information on the longitudinal position of boiling incipience and to determine boundaries of unstable circulation regimes. For example for the regime with $q = 45$kW/m$^2$ and $T_{in} = 91^\circ C$ the single-phase convection region occupies almost two third parts of total length of the heated section. Boiling in this regime is characterized by instability and periodically is changed by single-phase convection.

In mixed circulation regimes (with single-phase convection region) a strong instability has been observed. Usually liquid is subcooled at the inlet to the heated sections in these regimes and single-phase convection region exists even at relatively high wall heat densities. At regime parameters of the experiments the steam water flow had mainly slug-emulsion pattern. Visual observations and videorecording of two-phase jet pattern at the outlet cross-section of flow up tube have shown that flow pattern is extremely nonuniform and the flow itself is of pulsating behaviour.

At $q = 64$ kW/m$^2$ and $T_{in} = 97$ °C (see figure 3,a)-b)) the two-phase flow behaviour essentially differed from described above. The amplitudes of wall temperature oscillations were by an order of magnitude less (1–1.5°C) then for lower wall heat fluxes both for saturated and subcooled liquids. The frequency of wall temperature oscillations was about $f = 1.25$ Hz and circulation regime was characterized as relatively stable. There is practically no single-phase convection region in this regime and wall heat flux density value is enough for stable boiling. According to estimates at the half length zone of the heated section the flow quality $\chi$ is equal to 0.0088 but volume flow rate quality achieves so high values ($\beta = 0.935$) that set-up of annular steam-water flow pattern is quite probable. As a whole, as it follows from the analysis if wall temperature time records, with wall heat flux density
increase and inlet liquid subcooling decrease the oscillation frequency of temperature and flow rate increases, their amplitude decreases and the circulation stabilizes.

![Temperature-Time Records](image1)

**Figure 3.** Wall temperature time records for water flow at different wall heat flux densities

![Circulation Velocity Time Records](image2)

**Figure 4.** Circulation velocity time records at water boiling

In stable circulation regimes the amplitude of wall temperature oscillations decreases by an order of magnitude remaining at the “noise” level (1 – 2 °C) character to the stable flow vapour generating process. The amplitude decrease of circulation velocity oscillations also takes place to the values of 10 – 20 % from averaged flow velocity.

The oscillation mode, having been observed in the experiments, are caused by onset of liquid boiling in the tube that is by the flow regime change from single phase convection to two-phase flow.
under the conditions of substantially long portion of the tube with single-phase flow. When boiling onsets the generated vapour bubbles lead to the void fraction increase and hence to the increase of driving force and circulation velocity (flow rate) in the loop. The flow rate increasing leads to the wall cooling, the wall temperature decreases and boiling stops. The flow returns to single-phase mode, the flow rate decreases, wall temperature starts to increase, and it again induces boiling. So the process repeats oneself. The vapour bubbles, generated at boiling, coalesce into vapour slugs, which, moving upward, partially push off the liquid from the channel. It leads to the balance break of hydrostatic levels in flow up tube and in down comer of the loop, the balance break induces the reverse flows.

Experiments for FC-72 have been carried out within the range of wall heat flux densities \((4.6 - 30)\,\text{kW/m}^2\) at the inlet liquid temperatures \((40 - 54)\,\text{°C}\). The reduced pressures for water and FC-72 at atmospheric pressure differs by an order of magnitude \((p/p_{cr,\text{water}} = 0.00475)\) and \((p/p_{cr,\text{FC-72}} = 0.054)\). This made it possible to widen pressure range in investigations without any regime or structural changes of the experimental setup.

The thermophysical properties of water and FC-72 are essentially different (see table 1), this gives one an opportunity to widen the amount of possible two-phase flow patterns to be realized in heated section and to get additional information for revealing the effect of flow pattern on mechanism of circulation instability and the conditions of its occurring.

**Table 1.** Thermophysical properties of water and FC-72 at saturation conditions under atmospheric pressure

| Parameter               | Water | FC-72 |
|-------------------------|-------|-------|
| Saturation temperature, °C | 100   | 56.6  |
| Liquid density, kg/m³   | 958.4 | 1594  |
| Vapour density, kg/m³   | 0.59  | 13.13 |
| Latent heat, kJ/kg      | 2257.90 | 95.02 |
| Surface tension, N/m    | 0.0589 | 0.00841 |
| Liquid dynamic viscosity, Pa·s | 0.000279 | 0.000436 |

The main results for FC-72 have been obtained for boiling regimes. Typical time records of circulation velocity and wall temperature at different cross-sections for three wall heat flux densities \((16; 24; 30)\,\text{kW/m}^2\) at inlet temperatures \(T_{in} = (4254)\,\text{°C}\) are shown in figure 5. As it follows from all of the obtained data the wall temperature fluctuations are of very little intensity or are not observed at all. At the same time circulation velocity remains to be in oscillating mode, but the amplitude of velocity fluctuations is not high and does not exceed 10% from the averaged velocity value.

Figure 6 presents the ensemble averaged experimental longitudinal wall temperature distributions at different wall heat fluxes and inlet liquid temperatures for water and FC-72. At high liquid subcoolings the length of single-phase flow can be essentially high. For example at \(\Delta T=65\,\text{°C}\) and \(q=45\,\text{kW/m}^2\) (plot 2 in figure 6,a) the single-phase convection regime occupies more than two third parts of the heated section and only at the end of it boiling process takes place.

The plots 1, 3, 4 in figure 6,a) correspond to the regimes of unstable circulation. At attentive glance on these plots one can notice that averaged wall temperatures are very close to the saturation temperature, that is the wall overheat necessary for boiling incipience have not been achieved (the necessary \(\Delta T\) value for water at atmospheric pressure is \(\Delta T = 5 - 7\,\text{°C}\)). This fact can lead to a conclusion that no boiling took place in these regimes. But in reality it is not so. On the wall temperature time records (see figures 2 and 3, plot row B) it is clearly seen that the records have time intervals with temperatures essentially higher than it is necessary for boiling startup and short time boiling regime takes place. After some time boiling stops and a sudden temperature drop, which follows by temperature increase, occurs along the total heated tube length. So in reality a time change stages of boiling and single phase convection takes place. The mechanism of this phenomenon has been discussed above.
a) $q=16\text{kW/m}^2 T_{in} = 42^\circ\text{C}$, b) $q = 24\text{kW/m}^2 T_{in} = 53^\circ\text{C}$, c) $q = 30\text{kW/m}^2 T_{in} = 54^\circ\text{C}$; A and B rows – time temperature records, B row – fragments of A-records in larger scale; C row – time records of circulation velocity; wall thermocouples distance from the inlet: 1 – 0 mm, 2 – 74.0mm, 3 – 214.0mm, 4 – 353.0mm, 5 – 495.0mm, 6 – 670.0mm, 7 – 811.0mm

**Figure 5.** Time records of wall temperature and circulation velocity for FC-72 flow.

Plot 5 in figure 6,a) for water and plots 1 – 3 in figure 6,b) for FC-72 correspond to the stable circulation mode. As it is seen wall temperature for water practically does not change with tube length. For FC-72 flow boiling a somewhat temperature decrease with length takes place.

**Figure 6.** Measured ensemble-averaged wall temperature distributions along the heated section for water and FC-72 boiling flows.
4. Conclusions
A new experimental data of heat and hydraulic characteristics of low pressures natural circulation loop for two different liquids – water and C\textsubscript{6}F\textsubscript{14} (FC-72) – have been presented.

The effect of wall heat flux density and working liquid subcooling at the inlet to the heated section on the stability of circulation in the loop have been investigated.

In water experiments in cases of single-phase convection and flow boiling in heated tube a strong flow instability have been observed. These regimes are characterized by periodic ejections of liquid from the flow up tube, low frequency autooscillations of flow rate and heated wall temperature which amplitudes in some cases reached significant values. The frequency range of autooscillations was 0.08 – 0.5 Hz. The periods of liquid ejections from the flow up tube correlate with the periods of wall temperature and flow rate oscillations. The flow stability took place at steady boiling at heat flux densities equal or more than 65 kW/m\textsuperscript{2} and working liquid temperatures close to saturated one.

In the experiments with FC-72 the flow remained stable within the whole range of realized regime parameters, flow rate and heated wall temperature oscillations practically have not been registered by measuring system and uniformly dispersed two-phase jet was observed at the outlet section of flow up tube.

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