Experimental studies of non-stationary thermo-hydraulic processes at freon R113 boiling

O O Milman1,2, P A Ananyev2, M O Korlyakova3 and V O Miloserdov2

1Kaluga State University named after K.E. Tsiolkovsky, 26 Stepana Razina st., Kaluga, 248023, Russian Federation
2Scientific Production Company Turbocon, 43 Komsomolskaia roshcha st., Kaluga, 248010, Russian Federation
3Bauman Moscow State Technical University (Kaluga Branch), 2 Bazhenova st., Kaluga, 248000, Russian Federation

E-mail: turbocon@kaluga.ru

Abstract. An experimental unit has been created to study the processes of boiling and condensation in a closed loop. Experimental studies of non-stationary thermo-hydraulic processes at freon R 113 boiling have been carried out inside tubes of low pressure natural circulation systems. Key factors have been identified affecting auto-oscillations characteristics: filling level of the loop, pressure, heat flux density, geometric characteristics of the evaporating elements. Four characteristic modes of operation of such units have been found out. Thermo-hydraulic auto-oscillations at high thermal loads have been studied. Process parameters and conditions under which there is no thermo-hydraulic instability have been determined. The phenomenon of thermo-hydraulic resonance has been detected. The influence of the heating method on the instability characteristics has been revealed.

1. Introduction
Power plants using the natural circulation (NC) of the coolant are highly reliable and are characterized by low energy cost. Most often, to ensure the required level of heat transfer, two-phase coolant systems are used, which complicates the design and development of such a system due to the nature of operation of the NC closed loop. Self-regulation of the heat transfer mode and the lack of pumps in the system make the above mentioned units attractive in a number of technical applications: power plants [1–4], and cooling of miniature electronic devices [5–6]. Due to the strong non-linearity of the processes and low driving pressures, systems with NC are more unstable in comparison with systems with forced circulation of a coolant. The observed types of instabilities are described in a sufficient detail in the following papers [7–9].

In the process of the creating power equipment for low temperature heat sources, the low-pressure NC systems have been studied, the basic element of which is a steam generating section of the vertical tubes, heated by the condensed steam or hot water. Studies were conducted in an area that is characterized by a number of features: the method to heat steam generating tubes, low value of the driving head (less than 20 kPa), low level of pressure and saturation temperatures (70 ÷ 100 °C) of the boiling heat carriers. It should be noted that in the pressure range of less than 2 MPa and low circulation speed, the flow structure of the steam-liquid mixture undergoes a change and the projectile becomes the dominant mode.
The main part of the experiments was carried out on an experimental unit (EU), where the influence of the heat carrier type, its saturation temperature, underheating at the entrance into the steam generating channels, the filling level of the loop with the heat carrier, the structural elements of the NC loop, and the state of the heating steam were studied.

2. **Experimental unit**

EU scheme (figure 1a) is a natural circulation closed loop with a steam generator (SG) 1 incorporated therein with vertical tubes of stainless steel. The design of the SG is shown in figure 1b. Diameter of tubes is $6 \times 1 \text{ mm}$ (internal diameter $4 \text{ mm}$), distance between tube sheets is $L=1.52 \text{ m}$, and number of tubes is 101. The arrangement of tubes in the bundle is chessboard and is according to an equilateral triangle with a step of 8 mm (figure 1b). Bundle width is 5 rows, depth is 21 rows, internal heat exchange surface is 1.93 m$^2$. For even distribution of heating steam flow over the tube bundle height, a distribution grid is used.

![Figure 1. Experimental unit (a) and heat exchanger with steam generating tubes (b), 1 – heat exchanger with steam generating tubes, 2 – condenser evaporator, 3 – outlet tube, 4 – overflow pipe, 5 – tube-in-tube heat exchanger, 6 – observation columns, 7 – humidifier, 8 – pump, 9 – pump, 10 – vacuum pump, 11 – water jet ejector, ─── ─── ─── hot steam, ─── ─── hot water, ─── ─── steam-liquid mixture, ─── cold water, 8 – thermometer, U – thermocouple, Ω – manometer, Ω – pressure sensor, Ψ – flow meter washer, Ω – flow nozzle, Ω – valve.](image-url)
Heat is supplied into the SG tubes by feeding heating steam to the intertubular space of the steam generator 1 through a nozzle with a supercritical pressure drop. This excluded the influence of pressure fluctuations on the steam flow rate down flow from the nozzle. Suction of steam-air mixture occurred through the diaphragm with a supercritical pressure drop. Thus, thermo-hydraulic phenomena in the condensation cavity of the heating steam have been defined by processes of the heating steam supplied to the tubes from the condensing heating steam and its retraction from the steam generating surface by the boiling steam carrier. The steam formed during the boiling of the heat carrier condensed in the auxiliary condenser 2, and its condensate was drained into the outlet tube. A shell-and-tube heat exchanger with vertical tubes from stainless steel with a diameter of 10×2 mm (inner diameter 6 mm) and length of 1 m was used as an auxiliary condenser. The number of tubes is 127, the arrangement is chessboard and by an equilateral triangle with a step of 13 mm. Internal heat exchange surface is 2.4 m², external surface is 4 m². The heat released during condensation of the heat carrier steam is removed by water flowing in the intertubular space.

So that a liquid layer is not formed above the heat exchanger, a simple louvered separator was installed at the exit from it. Draining the coolant from the separator was carried out over the overflow tube. Heat carrier extruded during boiling from steam generating tubes, redistributing along the NC loop. One portion of it entered the outlet section, the other in the form of a film was "smeared" on the surface of the condenser of the evaporator 2 and the walls of the loop. The levels of the liquid coolant in the outlet and overflow tubes, its emissions from the steam generating tubes were monitored using observation columns. On the outlet section there were two heat exchangers 5 of the "tube in tube" type for heating or cooling the coolant and measuring its flow rate by the calorimetric method. To level the temperature field of the coolant for the heat exchangers 5, the mixers were installed. The diameter of the steam path of the NC loop was \( d_s = 100 \) mm, the length was \( L_s = 3 \) m, the diameter of the water path was \( d_w = 50 \) mm, the length was \( L_w = 3.2 \) m. A vacuum pump 10 was used to vacuumize the NC closed loop before it was filled with the coolant, and a water ejector 11 was used to suck the steam-air mixture of the heating steam. For pumping water through a steam condenser 2 the circulation pump 8 was applied. Overheating of steam was changed using the humidifier 7.

3. Research technique

The most important points in conducting experiments using a closed NC loop are: the method of filling it with coolant and determining the heat load removed during liquid boiling, depending on the regime and design factors. The liquid used for filling the loop was freon R113, the parameters of which are shown in Table 1.

| Temperature, °C | T_s at 760 mmHg, °C | T_cr, °C | \( p_c \times 10^{-5} \), Pa | \( p_s \times 10^{-5} \), Pa | \( p_{\phi'} \), kg/m³ | \( p_{\phi''} \), kg/m³ | \( r_s \), kJ/kg |
|----------------|---------------------|----------|--------------------------|--------------------------|----------------|----------------|------------|
| 70             | 47.7                | 214.1    | 34.15                    | 2.014                    | 1451           | 14.18          | 136.8      |
| 100            | 47.7                | 214.1    | 34.15                    | 4.421                    | 1380           | 30.0           | 126.1      |

Before filling the loop with a coolant, it was vacuumized. Checking the presence of air using such a method of filling the loop with freon R113 by chromatograph showed that the mass fraction of non-condensable gases did not exceed 0.1 %.

The occurrence of thermo-hydraulic instability in the loop was determined by the appearance of periodic fluctuations in the liquid level in the outlet tube with amplitude of at least 25 mm, both with increasing heat load and reducing it. To record pressure fluctuations in the experiments, the pressure sensors were used; to measure the temperature, a calibrated thermocouple was used.

Experimental data obtained in the experiments in most cases can be represented as a dependence of period and fluctuations amplitude of the average heat flux density \( \dot{q} = Q / F_s = f(\bar{T}_c, h_b, ...) \) under
various conditions (pressure, temperature, filling level), where $Q$ is the total amount of heat removed by the coolant; $F_S$ is the surface of the steam generating area.

This method of presentation is convenient for comparing experimental data obtained on units with different numbers and surfaces of steam generating tubes, as well as for the cases when the distribution of heat flux density $\dot{q}$ along the height of the channel and the circulation rate of the coolant are not the decisive parameters.

4. Test results

Basic experimental unit mode is characterized by intense fluctuations of temperatures and pressures both within the NC loop and the cavity of the heating steam condensation. It exists until the maximum thermal loads $\dot{q}_e$ are reached [10]. The presence of this type of thermo-hydraulic instability limits the increase in thermal load on the heat exchanger. Therefore, the main part of the experiments was devoted to the study of thermo-hydraulic auto-oscillations in the field of high thermal loads, the determination of process parameters and conditions under which this thermo-hydraulic instability is absent.

When using freon R113 as a coolant, the experiments carried out at the EU without an overflow tube in the pressure range $100 \leq \bar{p}_e \leq 260$ kPa ($\bar{p}_e/p_{cr} < 0.1$) showed that the work of the EU at $\dot{q} > 0.4\dot{q}_e$ is accompanied by fluctuations of $p_c$ with an amplitude from 0.5 to 2 kPa and fluctuations of $p_s$ from 0.5 to 1.5 kPa. Amplitude of the level fluctuations in the outlet tube did not exceed 250 mm.

With the increase in $\dot{q}$ and $\bar{p}_e$ the oscillation period was reduced (figure 2), change in $p_s$ was lagged in the phase from $p_c$ approximately by $180^\circ$ (figure 3).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2}
\caption{Dependence of the period of auto-oscillations on $\dot{q}$ and $\bar{p}_e$ when boiling freon R113 in EU tubes, a) $162 \leq \bar{p}_e \leq 173$ kPa; b) $24 < \dot{q} < 30 \cdot 10^3$ kW/m$^2$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3}
\caption{Oscillograms of pressure fluctuations $p_s$ and $p_c$ at boiling of freon R113 in EU pipes, $h_0/L = 0.79$, $\bar{p}_e = 160$ kPa; $\dot{q} = 28.6 \cdot 10^3$ kW/m$^2$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4}
\caption{Oscillograms of pressure fluctuations $p_s$ and $p_c$ at boiling of freon R113 in EU pipes, $h_0/L = 0.79$, $\bar{p}_e = 160$ kPa; $\dot{q} = 28.6 \cdot 10^3$ kW/m$^2$.}
\end{figure}

During freon R113 boiling at $\bar{p}_e < 1.1$ MPa ($\bar{p}_e/p_{cr} < 0.3$) the operation mode with intense fluctuations in temperature and pressure exists in a wide range of thermal loads $0.5\dot{q}_e \leq \dot{q} \leq \dot{q}_e$. Figure 4
shows waveforms of pressure $p_s$ and $p_c$ when the heat load changes from $0.5\tilde{q}$ to $\tilde{q}$, for the first initial filling level, $h_0=1.28$ m. The instability arising inside the loop at $\tilde{q}=0.5q_*$ and $p_c=0.78$ MPa is not transferred to the condensation cavity of the heating steam (figure 4a), i.e. it does not lead to fluctuations of $T_s$ and $p_s$. When the heat load increases to $\tilde{q}=(0.6+0.7)\tilde{q}$, the intensity of the oscillations increases, pressure oscillations $p_s$ arise. The oscillation frequency increases with the growth of $\tilde{q}$ and $p_c$ (figure 4b). Oscillation amplitude $p_c$ in the studied range of operating parameters did not exceed 0.4 kPa. There were almost no fluid level fluctuations at the tube outlet. At $\tilde{q}>0.9q_*$ oscillations and maximum load were achieved in a non pulsating mode ($\tilde{q}=53.3\cdot10^3$ kW/m$^2$; $p_c=0.78$ MPa). It is necessary to note that the fluctuations of pressure and temperature at $p_c>1.1$ MPa in the studied range of thermal loads were not observed. Figure 4f shows the dependence of the oscillation period on heat load $\tilde{q}$ with the relative height of the liquid column in the outlet tube $h_0/L = 0.83$; $p_c = 0.6–0.85$ MPa.

![Figure 4. Oscillograms of fluctuations $p_s$, $p_c$ at boiling of freon R113 in EU tubes ($h_0 = 1.28$ m), a) $\tilde{q} = 25.6\cdot10^3$ kW/m$^2$, $p_c = 0.55$ MPa; b) $\tilde{q} = 37.7\cdot10^3$ kW/m$^2$, $p_c = 0.7$ MPa; c) $\tilde{q} = 49.3\cdot10^3$ kW/m$^2$, $p_c = 0.75$ MPa; d) $\tilde{q} = 51.7\cdot10^3$ kW/m$^2$, $p_c = 0.78$ MPa; e) $\tilde{q} = 53.5\cdot10^3$ kW/m$^2$, $p_c = 0.78$ MPa; f) - dependence of oscillation period $\tau$ on $\tilde{q}$.](image)

In the experiments when flooding steam-generating tubes with condensate to the height $h_c$ from the side of the heating steam, it was found that with a decrease in $(L-h_c)/d$ amplitude of $p_c$ and $p_s$ oscillations decreases, and at $(L-h_c)/d<200$ there is no visible instability in the loop. Figure 5 shows a waveform of the pressure $p_c$ recorded during continuous increase in the part of tubes flooded with condensate, at constant heat load $Q_\Sigma=Q_\Sigma^*$. The $Q_\Sigma$ stable level when reducing the length of the tubes
heated by steam \((L-h_c)\) was maintained by increasing the temperature pressure between the heating environment and the boiling heat carrier.

![Figure 5](image)

**Figure 5.** Changing the amplitude of \(p_c\) oscillations for freon R113 with the gradual flooding of the steam generating tubes of the EU with heating steam condensate at \(h_0/L = 0.79, \bar{p}_c = 185\) kPa, \(\bar{q} = 24\times10^3\) kW/m\(^2\), \(r = 0\) at \((L-h_c) = 1.52\) m, \(\tau = 36\) s at \((L-h_c) = 0.76\) m.

The experiment with a decrease in \((L-h_c)\) allows us to conclude: reducing the length of the steam generating channels leads to stabilization of boiling processes. It was also established in the experiments that the stability range of the EU operation at \(\bar{q}\), close to \(\bar{q}_c\), expanded with the increase in the NC loop initial filling level.

**Conclusions**

The stability range of the heat exchange systems operation in the studied range of regime and design parameters expands both with increasing pressure more than 1.1 MPa and the filling level of the NC closed loop with the coolant freon R113 at 0.8 from \(L\), as well as with reducing the length of the steam generating tubes (due to flooding).

Experimental study of instability with heat loads close to the limit confirmed that the cause of its occurrence is the projectile flow regime.

**Acknowledgments**

Scientific research is carried out with the financial support of the state represented by the Ministry of Education and Science of Russia; unique identifier of the applied scientific research and experimental development (project) RFMEF157917X0148.

**References**

[1] Lisowski D D, Omotowa O, Muci M A, Tokuhiro A, Anderson M H, and Corradini M L 2014 *Int.J. of Multiphase Flow* **60** 135–48

[2] Bakhmetyev A M 2009 *Atomic Energy* **106** (3) 148–52

[3] Subki M H, Aritomi M, Watanabe N, Chung M K and Kikura H 2004 *Int. J. Series B Fluids and Therm. Eng.* **47** (2) 277–86

[4] Marcel C P, Rohde M and Van Der Hagen T H J J 2010 *Exp. Therm. Fluid Sci* **34** 879–92

[5] Tuma P E and Mortazavi P E 2006 *Electronic Cooling* **12** (1) 26–32

[6] Mukherjee S and Mudawar I 2003 *IEEE Trans.Comp.Packag.Technoc* **26** (1) 99–109

[7] Kakac S and Kakac B 2008 *Int. J. Heat Mass Transfer* **51** (3–4) 399–433

[8] Nayak A and Vijayan P 2008 *Sci. and Technol. of nuclear installations* **1** 15.

[9] Bhattacharyya S, Basu D and Das P 2012 *Heat Trans. Eng.* **33** (4–5) 461–82

[10] Leontyev A I, Milman O O and Fedorov V A 1985 *J. Eng. Phys.* **48** (4) 460–5