Experimental study of the structure of vapor phase during boiling of R134a on heat exchange surfaces of heat pump

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Abstract. The heat supply by means of heat pumps is considered now as a rational method of local heating which can lead to economy of primary fuel. At use of low-potential heat, for example, the heat of a ground (5 … 18 °C) or ground waters (8 … 10 °C) only small depressing of temperature of these sources (on 3 … 5 °C) is possible that demands application of heat exchangers with intensified heatmass transfer surfaces. In thermal laboratory of TOT department the 200 W experimental installation has been developed for research of process of boiling of freon R134a. The principle of action of the installation consists in realisation of reverse thermodynamic cycle and consecutive natural measurement of characteristics of elements of surfaces of heat exchangers of real installations at boiling points of freon from -10 °C to +10 °C and condensing temperatures from 15 °C to 50 °C. The evaporator casing has optical windows for control of process of boiling of freon on ribbed on technology of distorting cut tubes. Temperature measurement in characteristic points of a cycle is provided by copper-constantan thermocouples which by means of ADT are connected to the computer that allows treat results of measurements in a real time mode. The structure of a two-phase flow investigated by means of the optical procedure based on laser technique.

1. Introduction

One of effective actions for a fuel economy and environment protection is use of the heatpumping unit (HPU) transforming natural low-potential warmth and thermal waste to the warmth of higher temperature suitable, in particular, for heat supply.

Rapid progress in the field of heat power and refrigerating mechanical engineering has led now to the fact that heat supply by means of thermal pumps represents a rational method of central heating which can lead to a considerable fuel economy.

When using low-potential warmth, for example, warmth of soil (5 … 18 °C) or subsoil waters (8 … 10 °C) only small decrease of temperature of these sources is possible (on 3 … 5 °C) that demands application of metal-consuming extended surfaces in the heat exchangers. Similar problems arise also in the power generating sets of small power using renewable raw materials in a direct thermodynamic freon cycle. Effective operation of such devices requires application of the intensified heat-exchange surfaces.

Heat pumping unit (HPU) includes the following main components (figure 1a): 1 – Electric engine; 2 – Compressor; 3 – Condenser; 4 – Throttle; 5 – Evaporator.

The operation principle of heat pumping installation consists in use of warmth of phase change of low-boiling liquids. The compressor squeezes coolant vapor, increasing its parameters (pressure and
temperature) to the set level (process a-b in figure 1b). Further the working medium comes to the condenser where being condensed (cooled-condensed-cooled) on a working surface (process of b-c), gives energy to heated liquid. To return a working medium to an initial (gaseous) state, the flow is choked (process c-d). After that freon gets to the evaporator where boiling, takes away heat from the cooled liquid (process d-a). The cycle comes to the end. Heat transferred to the heated liquid is actually the energy which is "taken away" in the evaporator plus the energy consumed from network for operation of the compressor.

![Diagram](image)

**Figure 1.** HPU main components. a) Scheme HPU; b) Ts-diagram and thermodynamic cycle of HPU.

### 2. Description of experimental installation

The 200 W experimental installation “TN-300” [1] has been developed for a research of process of boiling of R134a freon in thermal laboratory of theoretical basis of thermal-technique (TOT) department of NRU “MPEI” (figure 2). The operation principle of the “TN-300” is put into implementations of the reverse thermodynamic cycle and natural measurement of characteristics of elements of surfaces of heat exchangers of real installations. The schematic diagram of “TN-300” is presented on figure 3.

“TN-300” is intended for a process research boiling of freon in large volume on the tubes ribbed on technology of the “deforming cutting” (DR). The main part of “TN-300” is the refrigerator on working medium freon R134a. For ensuring the set refrigerating capacity (from 100 to 300 W) at freon boiling temperatures from -10°C to +10°C the THB 1340Y compressor of producer L’ Unite Hermetique (France) has been chosen.

The main experimental part of “TN-300” is the evaporator 1. The casing of the evaporator is made in the form of a pipe with a diameter of 50/43,5 of stainless steel 12X10H and 1000 mm long. In end faces of a casing are welded in with some shift concerning a casing axis special valves for fixing and sealing of the studied samples 2 - DR-tubes of different modification (figure 4a). The casing of the evaporator has optical windows for control of the evaporating freon. Freon refill (950 g of R134a) provides immersion of the studied sample on 8-10 mm from the upper end of ribs. The casing of the evaporator is isolated by cryogenic heat insulation with layer thickness not less than 25 mm. The closed water contour via the thermostat with the pump provides a water flow through the evaporator up to 50 g/s and with temperatures from 0,5 °C to 15 °C. On an entrance (on freon) of the evaporator the throttle valve is installed which allows to establish the necessary saturation temperature of freon more accurate.
Figure 2. “TN-300” installation for research of processes of boiling in elements of heat pumping unit.

Figure 3. Schematic diagram of “TN-300”
Figure 4. Test section: a) DR – tube, b) scheme of thermocouples sites

For definition of a mass flow rate of freon the flowmeter 3 calorimetric type is designed and established on the inhaustung compressor line. Freon vapors (dry saturated steam) pass on interpipe space, then go to an internal ceramic tube with the heating spiral from a nichrome wire with a resistance of 15,2 kOhm. Such design allows to remove heat losses from the central heating element on the periphery, in a circumambient. The body of a flowmeter is closed by isolation.

Entrance and differential thermocouples through special valves are entered directly into a gas flow that gives to device high sensitivity on the electric power given on a spiral. Further freon vapors on the inhaustung contour through receiver 7 get to compressor 6. The compressor has bypass line with throttle valve Tr.2 which allow to reduce evaporator refrigerating capacity several times from nominal and to install at the given saturation temperature in evaporator a different heat loads.

The condenser 5 with water cooling from thermostat 4 allows to establish the chosen condensing temperature (pressure, respectively) in the range of temperatures from 15°C to 50 °C that gives additional flexibility to change the value of work of a cycle and to manage a heat loads in evaporator.

For pressure monitoring in evaporator and condenser manometers exemplary accuracy rating 0,4 were used.

Measurement was made by copper - constantan thermocouples (figure 4b). The output signal from thermocouples was sent to analog digitizer which output signal transferred to computer allowed to process results of measurement in real time during the experiment by means of specially developed software.

Thermocouples were installed directly in a gas flow, or liquids. The measurement of water temperatures on an entrance to evaporator (t1), by the differential thermocouple (Δt2) - cooling of water after passing via evaporator, freon saturation temperature in evaporator (t4) were taken so.

Temperature of a tube outer surface was taken by the differential thermocouple (Δt4) which one end was soldered in a cross-cut in a surface at the rib basis in middle section of a tube (since temperature longwise of a tube changed a little, but no more, than on 1,5 °C), and other end was directly put in liquid. Actually, thus average value of boiling film coefficient of freon was measured.

The evaporator is set to the given temperature by adjustment of water mass flow rate through the studied tube and selection of the corresponding condensing temperature in condenser 5 by means of water from the thermostat 4 (from +15°C to +50°C) within several degrees, and more precisely (to the tenth shares of degree) the mode is set by means of Tr1 throttle valve. At stabilization of temperature in the evaporator within 15 minutes measurements of other values are performed.

On a calorimetric flowmeter the power of 1 - 2 W loads from a source of a direct current, the freon overheat (by several degrees) from temperature of dry saturated steam is measured; heat capacity C_p (on the known temperature and pressure) is calculated on an equation of state for R134a.

After fixing of all measurements on the first mode (the maximum heat load) the Tr2 throttle valve on a bypass contour is slightly opened and experiment with an evaporation mode for new level of temperature is repeated.
3. Analysis of characteristics of the two-phase flow

The structure of a two-phase flow was investigated by means of the optical technique described in [2]. Important information on medium in which the laser beam extends can be received, analyzing the weakening of radiation intensity in relation to intensity of the laser beam generated by the laser. This weakening, first of all is connected with index of refraction and a microstructure of optical non-uniformities. In the latter case, the following complex of microphysical characteristics means:

- Aggregate state of optical non-uniformities;
- Ranges of distribution of optical non-uniformities by size;
- Volume concentration.

In case of research of interphase boundary, the listed characteristics should be carried to a boundary of the phases and areas directly adjacent to it. Weakening of radiation in the scattering environments under the certain conditions is described by the theory of single dispersion of Mi [3]. Theory is based on the following restrictions:

- It is necessary that the falling and scattering radiation have identical wavelength;
- Scattering is considered by means of independent particles, it is supposed that the interfential phenomena are absent.

It is considered that the influence of multiple scattering have no significant effect, i.e. intensity of weakening and scattering of \( n \) particles is in \( n \) times more of the corresponding characteristics of separately taken particle.

For the quantitative characteristic of weakening of a parallel beam of monochromatic radiation in the scattering environment the volume coefficient of weakening \( \alpha \) is equal to the sum of volume scattering factors \( \alpha_p \) and absorption \( \alpha_n \):

\[
\alpha = \alpha_p + \alpha_n
\] (1)

Due to abovementioned assumptions each of coefficients \( \alpha, \alpha_p, \alpha_n \) can be expressed through the sum of the corresponding coefficients for one particle:

\[
\alpha = \sum_{i=1}^{N} K_i ; \alpha_p = \sum_{i=1}^{N} K_{pi} ; \alpha_n = \sum_{i=1}^{N} K_{ni},
\]

where \( K_i, K_{pi}, K_{ni} \) - coefficients of weakening, scattering and absorption of \( i \)-th particle, respectively; \( N \) – number of particles in unit volume.

Thus, having defined characteristics of weakening of radiation for one particle, having made operation of summing for all particles of scattering volume, we define integral characteristics of the scattering environment. In Mi [3] work the strict solution of a task on scattering and absorption of electro-magnetic radiation by a diffusive sphere is for the first time received. The received analytical expressions have the form of an infinite weakly convergent series. From the practical point of view two limit cases have interest: when the radius of particles is much less than the wavelength; and when the radius of particles is much more than the wavelength of the probing radiation.

In the first limit case we have so-called Rayleigh scattering:

\[
Q(x, m) \cong 4\left(\frac{m^2 - 1}{m^2 + 1}\right)x^4
\] (2)

where \( Q(x, m) \) - the factor of efficiency of weakening numerically equal to the relation of the weakened energy to the energy falling on geometrical cross-section of a particle;

\( x \) - relative size of a particle, \( x = \frac{2\pi a}{\lambda} \), i.e. in relation to the wavelength of the probing radiation;
\( m \) - complex index of refraction of substance of a particle.

In the second limit case, a case of big particles, it is possible to consider approximately that \( Q(x, m) \approx 2 \).

Due to the fact that the factor of efficiency of scattering represents the relation of radiation energy scattered by a particle to total energy which falls on geometrical cross-section of a particle, values \( Q(x, m) > 1 \) can seem strange. The answer to this question is the fact that the electromagnetic field undergoes perturbation in the field of space which size exceeds the geometrical size of a particle, otherwise boundary conditions on its surface would not be met [4].

Volume coefficient of weakening \( \alpha \) is connected with intensity of the radiation passing through a layer \( I(R) \) and the radiation falling on a layer \( I_0 \) ratio:

\[
I(R) = I_0 \exp\left[-\int_0^R \alpha(R) dR\right]
\]

where \( R \) - path length of a laser beam in the scattering environment.

The last ratio expresses itself Buger's law [5].

It is possible to evaluate a particle size order in a limit case of big particles with equal radius. Then from [4]:

\[
Q \approx 2 \int_0^\infty f(a) da = 1
\]

and the volume coefficient of weakening will be proportional to the product of concentration of particles on their effective section. At the densest packing of particles in scattering volume:

\[
N \sim \frac{1}{\frac{4}{3} \pi a^3}; \quad \alpha \sim \frac{1}{\frac{4}{3} \pi a^3}; \quad 2\pi a^2 \approx \frac{3}{2} \frac{1}{\alpha},
\]

from where

\[
a = \frac{3}{2} \frac{1}{\alpha}
\]

4. Results of experiments

In experiments the ratio \( J/J_0 \) was defined, where \( J \) - power of scattered radiation, \( J_0 \) - power of the probing radiation.

Proceeding from a ratio \( J = J_0 \exp(-aR) \), where \( R \) - the characteristic size of the scattering layer, one can make evaluation of the extent of optical non-uniformities. In the made experiments \( J/J_0 = 1/10 \div 1/1000 \). As \( R \) the diameter of the evaporation origin was undertook \( d_e = 0.5mm \).

At these parameters we receive \( a \approx 0.1mm \).

In addition to integral characteristics of the laser beam which has passed through the studied volume of working fluid the high-frequency fluctuations (to 100 kHz) caused by modulation by optical non-uniformities were fixed. For the analysis of high-frequency fluctuations the technique of [6] was used. The timing signal is presented on figure 5. Results of experimental data are presented in the form of phase portraits of fluctuations of intensity of the modulated laser beam (figure 7). For calculation of
timing scale of Taylor the autocorrelated functions of process of fluctuations were constructed and presented on figure 6.

Figure 5. A timing signal of fluctuations of the modulated laser beam.

Figure 6. Autocorrelated function of a signal. (tau = 0.00687c)

Figure 7. A phase portrait of fluctuations of intensity of the modulated laser beam.
5. Conclusion
The structure of a two-phase flow investigated by means of the optical procedure based on laser technik. Weakening of intensity of laser radiance first of all is bound to index of refraction and a microstructure optical inequalities, and at performance of certain conditions is described by the theory of unitary dispersion of \( \text{Mi} \). In experiments the interrelation of power of a scattered radiation to power of probing radiance was defined that has allowed to evaluate the dimensions of optical inequalities. Besides integrated characteristics of a laser beam high-frequency fluctuations (up to 100 kHz), invoked by modulation of optical inequalities were fixed. For calculation of time scale of Taylor autocorrelation functions of process of fluctuations are constructed. Results of experimental researches are presented in the form of phase portraits of fluctuations of intensity of the modulated laser beam. Phase portrait has a periodic attractor. Frequencies associated with operation of the power equipment and vapor phase are selected. It is determined that the forced oscillations of the coolant lead to heat transfer enhancement.

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