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WATER HEAT PUMP OPERATION UNDER CONDITIONS OF ICE FORMATION ON THE EVAPORATOR PIPE SURFACE

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Abstract: *We experimentally investigated the conditions and characteristics of ice formation on pipe surface of a heat pump evaporator which appears when using cold water (at a temperature lower than 280 K) as a low-grade energy source. During operation of such heat pump, we registered ice thicknesses, temperature of water in evaporator, and temperature of evaporation from pipe wall. The results allow us to make a conclusion on the possible use of water heat pump in practical applications under the conditions of partial ice coverage of evaporator surface at water heating in the condenser up to 313 K. It was experimentally shown that when initial water temperature in evaporator is decreased by 6 K, the maximum thickness of ice formed on the evaporator surface is increased by 30%. The ice formed on the evaporator, after reaching the maximum temperature of water in the condenser, completely melts over time. The relationship between Nusselt number and the natural convection heat exchange characteristics at phase change has been established.*

Keywords*: water heat pump, temperature, ice, evaporator, heat transfer during phase transitions, convection.*

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Introduction

Heat pumps which use low-grade water energy source can provide the necessary heat load with high performance coefficient (2–4) [1]. Water heat exchange loop generates a significant part of the required heat load for the building. The systems based on heat pumps with water loop work quite effectively even under partial load conditions [2].

Water temperature of deep water bodies in cold seasons is higher than the ambient air temperature [3]. Therefore, thermal potential of energy sources for water heat pumps is higher than that for air heat pumps [4].

Nowadays, use of ground heat pumps increased dramatically [5], but their installation and maintenance have significant difficulties [6]. Besides this, such pumps have negative impact on soil temperature after a long operation period [7]. The low value of soil thermal conductivity is another disadvantage for this types of heat pumps [8]. All these problems can be avoided by the use of water as an energy source. But in this case, at low water temperatures, an ice may form on the evaporator pipe surface, which reduces the heat pump efficiency [9] in general.

The heat exchange process between the surface of spiral freon pipe of heat pump evaporator and water of low-potential heat source was studied in details by Zu S., Ni L., Yau W.

[10, 11]. But in experimental scheme [11] it was assumed that the surface temperature of evaporator pipe is higher than 273 K. Consequently, there has been no ice on the evaporator wall. And in these cases it has been concluded that the influence of vertical and horizontal pitch between the evaporator pipes on the intensity of heat transfer can be neglected.

It has been established that ice formation on evaporator pipe leads to an uneven temperature distribution in the liquid volume, which surrounds the pipes, and significantly reduces the heat transfer rate [12]. The results in [12] allow defining the heat pump temperature work range with full or partial ice coverage. For example, an ice layer with a thickness of 0.003 m reduces the heat flux between water and freon by 40 % [13]. Maintaining the water temperature at 277 K causes a natural convection current which increases the ice growth rate by 10–50 % (depending on the evaporator container height).

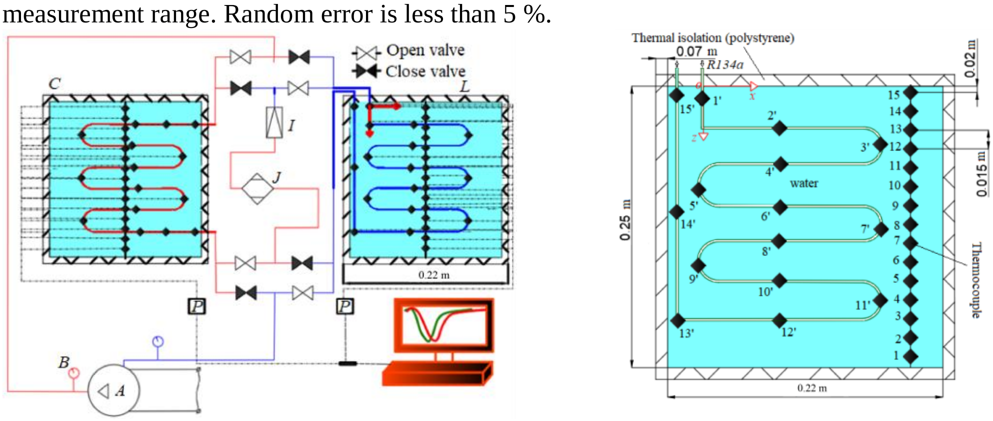
The purpose of this research is to study the working characteristics of heat pump under the conditions of ice formation on the evaporator pipe when using cold water as a low-grade energy source and to check the operation possibility of heat pump in the successive ice formation and melting cycles.

Experimental Facilities and Procedure Description

A series of experiments was conducted at water heat pump (HP) (fig.1) using the method described in [14]. Water temperature was measured at various vertical coordinates around the evaporator pipe using 15 thermocouples which were fixed with a step of 0,0154 m between every two of them. Also, 15 thermocouples were installed on the evaporator pipe wall surface with a distance of 0,23 m between each other by freon flow direction (fig. 1).

Thermocouples of Chromel/Alumel type with a junction point size of 0,001 m are connected to analog-to-digital converter and after that through a network adapter to a personal computer. A software is developed in the environment of National Instruments LabVIEW to record the real-time temperatures. The ice layer thickness formed on the surface of evaporator pipe is measured using a digital vernier caliper.

The temperature of water bodies which are used as energy source for heat pumps during the cold season is higher than the air temperature [15]. It has been established that the average water temperature in a lake varies in the range of 275–286 K for air temperature between 263–277 K [15]. In our experiments water around heat pump evaporator pipe has initial temperature (T_0^E) 280 K in the first stage and 286 K in the sond one. For all cases, water initial temperature around the condenser pipe is 291 K in average. Freon pressure in evaporator pipe is 0,2 MPa and its flow rate is 0,002 kg/s. Under identical conditions, every experiment is repeated three times. The total relative systematic error of all temperature measurements does not not exceed 4,6 % for the whole measurement range. Random error is less than 5 %.



a) *b*)

Fig. 1. The schematic diagram of experimental heat pump setup (*a*) and thermocouple installation points (*b*): *a*): *A* – compressor; *B* – manometer; *C* – condenser; *J* – filter; *I* – capillary pipe; *L* – evaporator; *P* – analog-to-digital converter; *b*) – the black squares represent the temperature measuring points

Experimental Results and Discussion:

In a few minutes after launching the experimental stand, we noticed a sharp decrease of wall temperature at the evaporator entrance ($T_{1'}$) down to 258 K (fig. 2.). With the course of time, (τ~1000 s) $T_{1'}$ begins to grow up due to the increase in water temperature around the condenser pipe. Also, when the heat pump panel is turned on the thermocouples 2'–5 ' registered a decrease in the evaporator wall temperature. Freon is evaporated and its vapour is heated in the evaporator pipe by absorbing energy from the water heat source. After 10000 s from the initial operating moment, the pipe wall temperature at the evaporator inlet exceedes 273 K, and as a result, the ice formed on the pipe starts to melt. Also, in the experimental procedure, the change in water temperature around the evaporator at various vertical levels is recorded (fig. 3.). The initial increase in water temperature in the first 600 s can be explained that freon temperature has the ambient value at the beginning of the experiment. After 600 s freon temperature increases along the evaporator pipe which causes a gradual cooling and freezing of water around its surface. The thermocouple 1, which is located close to the lower part of the evaporator, registers the lowest temperature in the first 6000 s compared with the readings of thermocouples 2–5 which are located higher (fig. 3)

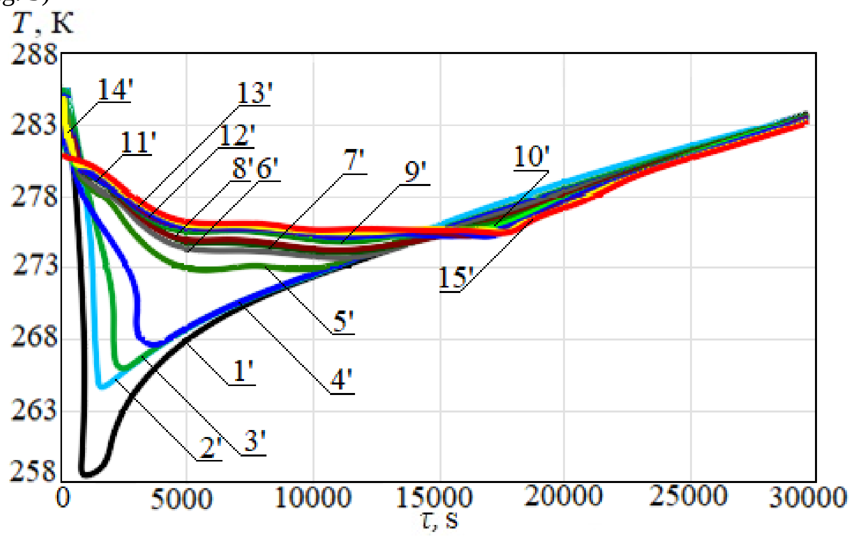


Fig. 2. The evaporator surface temperature change with time (T_0^E = 286 K):
1', 15' – Thermocouples located on the surface of the evaporator pipe at the inlet and outlet respectively; *2' –14'* – Thermocouples located on the surface of the evaporator pipe at a distance of 0,230 m from each other

In time interval from 6000 to 10000 s, the water temperature in the lower part of the evaporator is about 277 K, and in the upper parts, it ranges from 274 to 276 K. This can be explained that the water has a maximum density at a temperature value of 277 K.

For working time higher than 11000 s, the water temperature in the evaporator starts to increase due to the growth in freon temperature in the evaporator because water in the condenser is already heated and it is not able to cool down freon to the liquid phase which affects its characteristics at the capillary pipe outlet.

The water temperature changes around the condenser pipe at various heights is shown in fig. 4. The water temperature increases from 291 to 308 K in a time period of 6000 s. Water heated up to these temperatures can be used in local heating systems “warm floor”. But such heating will be effective only when the ambient air temperatures are not lower than 283–290 K. If after 6000 s, this water is not cooled by using it in the heating system, its temperature will continue to increase to 313 K in the upper part of the condenser container. Under these conditions, freon is not cooled enough to finish its condenation process. After 11000–12000 s, freon temperature at the exit of the capillary pipe increases exceeds 273 K which causes the melting of ice on the evaporator wall (fig. 5, 6).

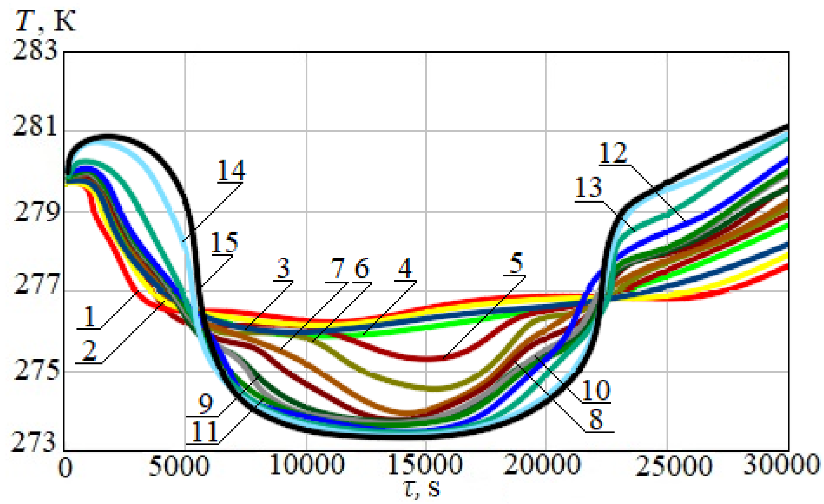


Fig. 3. The change in water temperature around the evaporator pipe with time at various vertical coordinates ($T_0^E = 286$ K): *1* – Thermocouple at the lower part of the evaporator; *15* – Thermocouple located close to water surface; *2–14* – Thermocouples located at various vertical coordinates on the evaporator with a distance of 0,0154 m from each other

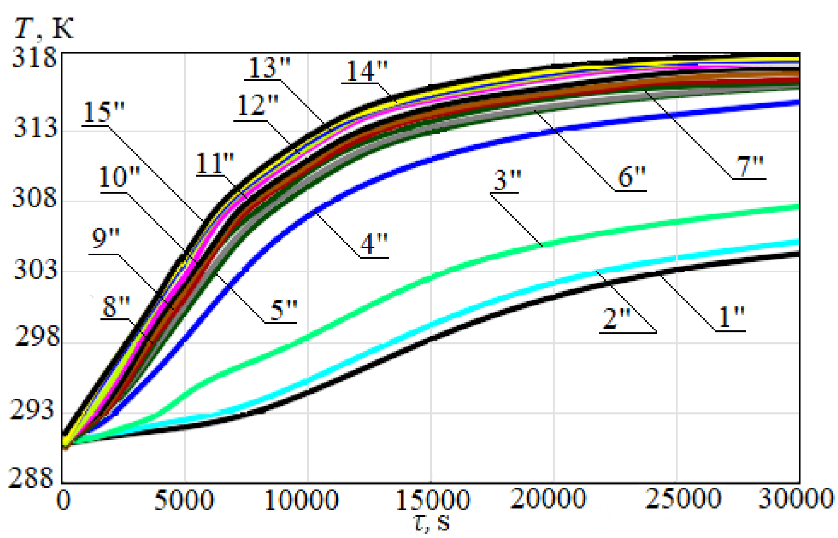


Рис. 4. The change of water temperature around the condenser pipe in time at various vertical coordinates ($T_0^E = 286$ K): *1"* – Thermocouple located close to the lower part of the condenser; *15"* – Thermocouple located close to the water surface in the condenser; *2"–14"* – Thermocouples at various vertical coordinates in the water around the condenser pipe with a distance of 0,0154 m between each other

The ice which is formed in the first 8000 s, totally melts in the next 5000 s. And in this stage, the heat pump warms up the water from 291 to 313 K.

Basing on the experimental results, it can be concluded that for initial water temperature around the evaporator of 286 K, the thicknesses of ice in measuring points on the evaporator pipe surface are lower by 0,0024 m comparing to their values for an initial temperature 280 K. and the necessary time to remove the ice melting is 4000 s.

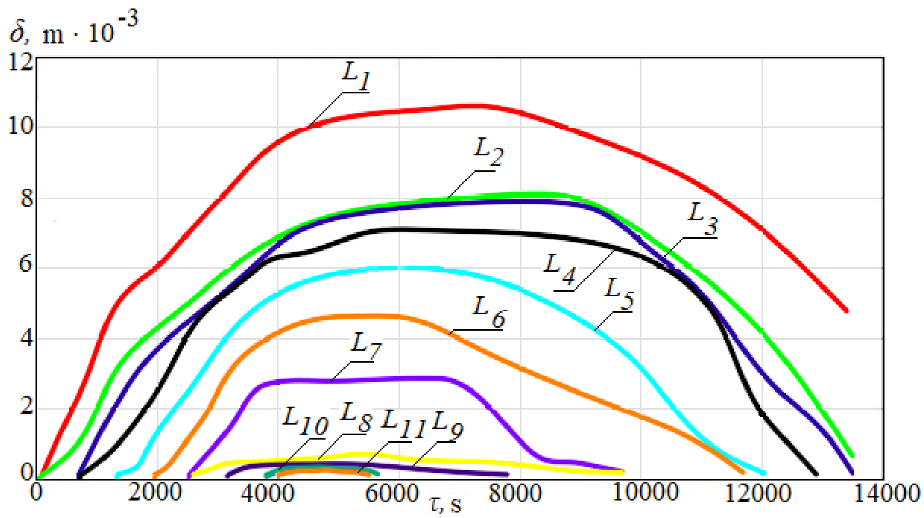


Fig. 5. The formed ice thickness change in time in various points along the evaporator pipe (the coordinates of ice thickness measuring points are given in the table, $T_0^E = 286$ K)

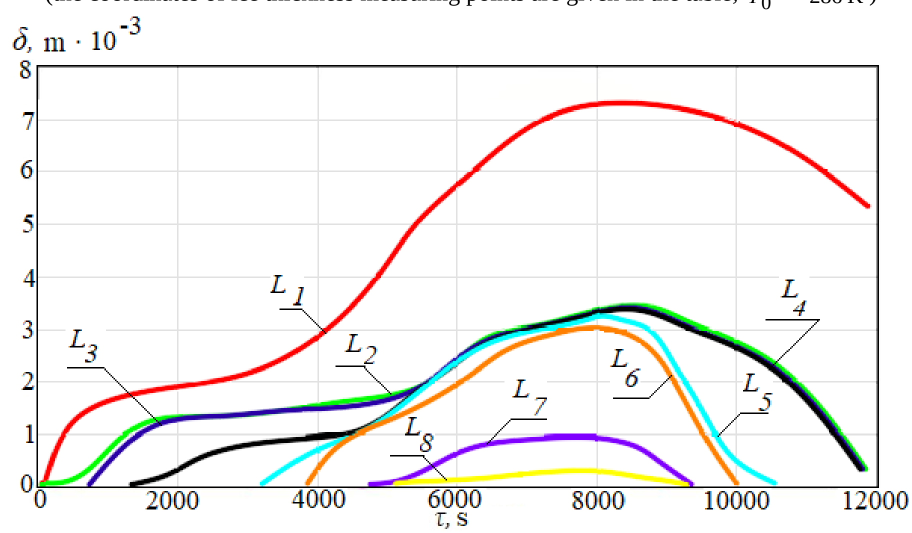


Fig. 6. The formed ice thickness change in time in various points along the evaporator pipe length (the coordinates of ice thickness measuring points are given in the table, $T_0^E = 286$ K)

Table

The coordinates of the ice thickness measuring points

Measuring point		L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}
The distance from the evaporator start point, m		0	0,11	0,26	0,44	0,59	0,77	0,92	1,11	1,25	1,43	1,58
Cartesian coordinates, m	*x*	0	0.11	0,11	-0,07	-0,07	0,11	0,11	-0,07	-0,07	0,1	0,11
	y	0	0	0,14	0,14	0	0	0,14	0,14	0	0	0,14
	z	0	0,04	0,04	0,04	0,04	0.09	0,09	0,09	0,09	0,1	0,13

The experimental results show that the formed ice on the evaporator pipe surface of the water heat pump which operates in the conditions of the cold seasons (autumn, winter, spring) significantly reduces its efficiency during a working time period equals to two hours. The ice is removed in 2–3 houres. After the full melting of ice, the working cycle is repeated again. The working efficiency of the heat pump unit decreases significantly when water around the condenser reaches its maximum temperature (313 K).

Analysis of the obtained water temperature values in the condenser and the evaporator for the heat pump experimental panel, showed the possibility to use this method to heat up water in the condenser to a temperature of 313 K which is enough for the heating system “warm floor” [16, 17]. But, under these working conditions, freon temperature in the evaporator decreases to values lower than 273 K, which causes an ice formation on its surface. When water in the condenser is heated to a maximum value (313 K), freon is partially condensed, and as a result, the temperature of the evaporator pipe wall becomes higher than the water freezing point. And the formed ice melts. The necessary time for ice to melt increases by 4 % for every decrease in the initial water temperature around the evaporator pipe for 1 K. When the ice is removed, the heat pump can be used again to heat up water from 291 to 313 K.

The obtained results can be used to develop the design of the evaporator, which operates in the conditions of ice formation on its surface. The thickness of ice layer formed on the evaporator pipe increases by 4 % for every 1 K decrease in water temperature in the evaporator.

To heat up water from 291 K to a higher temperature of 313 K, two heat pumps can be used. When one of them operates in a heating mode, the other one works in ice melting mode to keep water temperature equal to 313 K in the floor heating coil.

Conclusions

The research results prove the suggestion to use water heat pump station in mode of ice formation on the evaporator pipe surface when water temperature in evaporator corresponds to temperature of water surfaces in different Russian regions in the cold period of the year “autumn - winter - spring” to provide the heating system "warm floor" with hot water.

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