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STUDY OF CONDENSATE FORMATION AND FREEZING IN HEAT EXCHANGERS OF AIR-SOURCE HEAT PUMP SYSTEMS

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ABSTRACT

This article is devoted to the study of condensate formation and freezing in the heat exchangers utilizing low-grade heat of atmospheric air and prepared according to the results of theoretical and experimental research. The article presents the results of numerical experiments carried out by JSC "INSOLAR-ENERGO" during elaboration of technical solutions on protection of heat exchangers from freezing the moisture, which is condensed on heat exchange surfaces while recovering low-grade air heat in the heat pump systems. The purpose of the calculations is simulation of the condensation of moisture in the humid air flow during its cooling for heat recovery. The results presented in this article can be extended on heat pump systems that use low-grade air heat, for example for space heating or snow melting, and on exhaust air heat recovery in ventilation systems of buildings.

Keywords: condensation, phase transition, heat exchanger, de-frostation, heat pump system, energy efficiency, thermal conditions.

INTRODUCTION

The problem of condensation and subsequent freezing of moisture on surfaces of heat exchangers for air heat recovery cooled to subzero temperatures is one of the major technical obstacles to the widespread use of air-source heat pump systems in countries with cold climate. Technical problems are associated with frost formation and icing of heat exchange surfaces, and as a consequence - with a sharp decline in the efficiency of heat exchangers.

Similar problems are observed in the recuperative heat exchangers that use low-grade heat of exhaust air in ventilation systems. These problems are characteristic for air-source heat pump systems in their use almost on the entire territory of Russia. According to (G.I. Sultan, E. A. ElShafieea, M. G. Safana, M. A. Elraouf, 2012) the coefficient of performance decreasing with time for a range from (10-15%) due to the frost layer blockage and so degrading heat transfer process and so increasing the average compressor work done, and paper (Da Silva D.L., 2012) demonstrates that the frost layer growth reduces the air free flow area by 70%, which increases the air pressure drop and reduces the fan air flow rate.

As a rule, the problem of frost formation and icing of heat exchange surfaces are solved during their defrosting due to periodic heating of icy surface and cleaning it from frost and ice (Vasilyev G.P., Timofeev N.A., 2010, Vasilyev G.P., 2002). However, this technology requires significant energy costs.

An alternative way to protect the heat transfer surfaces from freezing is protection by chemical means, by application of a special composition on the heat exchange surface. The principle of operation of all anti-icing compositions based on their increased hydrophobicity, in other words, they do not collect water and its vapor on their surface. All known inventions, for example the Patent (Patent 2162872) and work (Shulzhenko Y. P., 1993), concerning the problem of creating an anti-icing coatings, as a main ingredient propose the use of silicon compounds as least wetting substances. Deicing compositions may contain succinic acid or succinic anhydride and a neutralizing base, in particular sodium hydroxide, potassium hydroxide or ammonium hydroxide. When mixed with water, de-icing compounds form salts of succinic acid in the reaction, which quickly release heat sufficient to melt the ice on the surface. In other cases, the anti-icing compositions also contain a glycol, which inhibits the re-formation of ice on the cleaned surface. Nowadays it is possible to spray propylene glycol based de-icing fluid on the surfaces to be protected. The next options for de-icing are: chemical composition - a solution of the alcohol with glycerol in a ratio of 10 to 1, and spraying Teflon coating on the heat exchange surface.

Numerical experiments

Authors of this article have conducted a series of studies aimed at determination of areas of heat exchanger, which are most likely influenced by appearance of condensation and its subsequent freezing during heat recovery of saturated air. Studies have been carried out on computer models. The purpose was to simulate condensation of moisture in the air flow during its cooling in the process of heat recovery.

For modelling and conducting of numerical experiments software system ANSYS 11.0 was used.

The calculations were done for the experimental model simulating two air channels exchanging heat through heat-conducting wall. General view of the model is shown on Figure-1.

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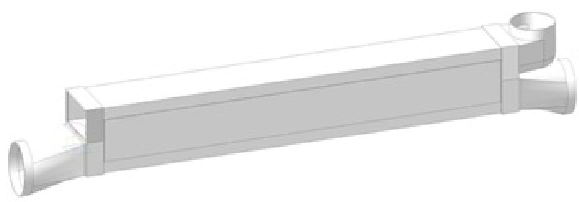

Figure 1. General view of the experimental model.

When conducting numerical experiments, calculation model presented in Figure-2 was used, representing only a half of the model divided by XY plane at the middle of the model.

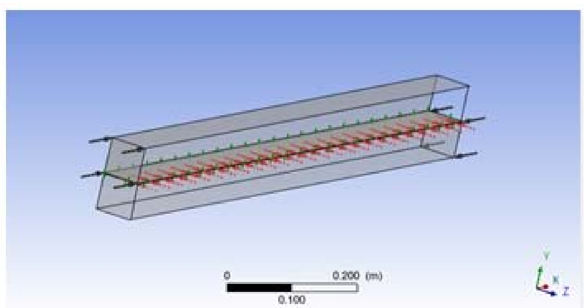

Figure 2. Experimental model for numerical experiments.

Length - 1 m (along axis X). Height of each area of cold and warm air flow (along axis Y) - 0.059 m. Width of 0.06 m was taken (along axis Z) and conditions of symmetry were provided on its boundary. Plate thickness is 0.002 m.

For hydro-gas-dynamic calculations program module ANSYS CFX was used.The calculations were carried out using the SST turbulence model until the residuals not exceeding 10^{-4}.

The boundary conditions.

Warm air enters the heat exchanger (top channel, indicated with arrows) along axis X: flow rate of 3.85 m/s (calculated on the basis of volumetric flow of the fan); air temperature 23 ˚C. Static pressure of the cooled air at the outlet of heat exchanger - 1 atm.

Cold air enters the heat exchanger (bottom channel, indicated with arrows) along axis X (counter flow with warm air): flow rate of 3.85 m/s (calculated on the basis of volumetric flow of the fan); air temperature has been changing and was taken as minus 3,1 ˚C (the average winter temperature in Moscow), minus 15 ˚C, minus 28 ˚C. Static pressure of the cold air at the outlet of heat exchanger - 1 atm.

Plate between cold and warm air flow is made of polymer. All other walls are considered to be thermally insulated.

In order to reduce the computational domain in the XY plane, symmetry conditions of flow were provided.

After that task was solved, temperature distribution on the plate from the warm air side have been obtained, which further was used as boundary condition for solving the problem of moisture condensation. Calculation results are given in Figures-3 and 4.

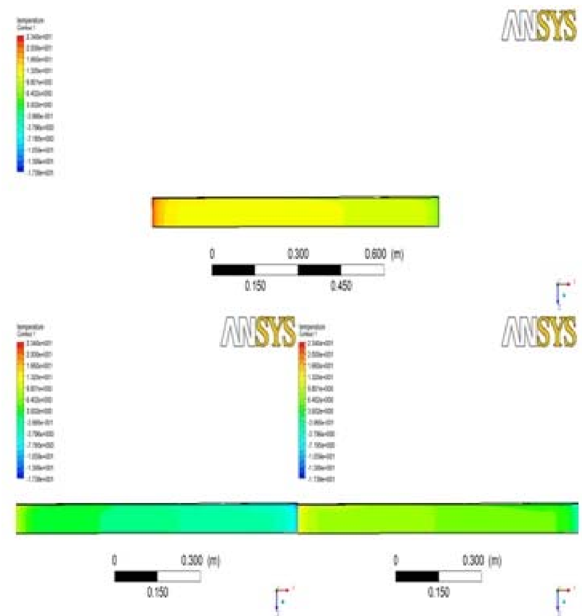

Figure-3. Temperature distribution on a PVC plate from warm air side for the three cold air temperatures: minus 3 ^{0}C (top); minus 15 ^{0}C (lower right); minus 28 ^{0}C(lower left).

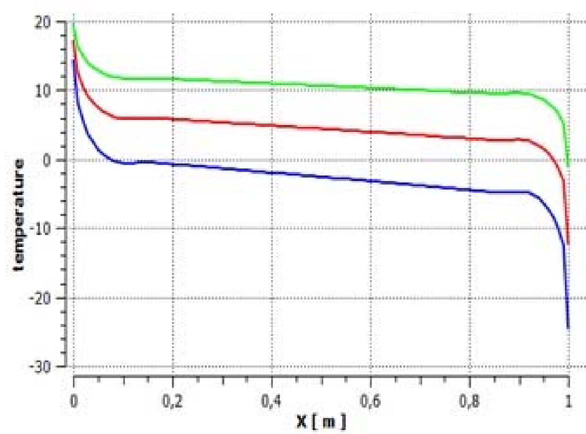

Figure 4. Graph of behavior of a cross-section average temperature along axis X. Green line – cold air temperature of minus 3 ^{0}C; red line of mi nus 15 ^{0}C; blue line of minus 28 ^{0}C.

Further, as a calculation model to assess the moisture condensation only the area of warm air flow was taken, and the previously obtained temperature distributions were given as a boundary temperature condition of the corresponding wall. The experimental

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model for numerical experiments to assess the moisture condensation is shown in Figure-5. Force of gravity is directed down the axis Y.

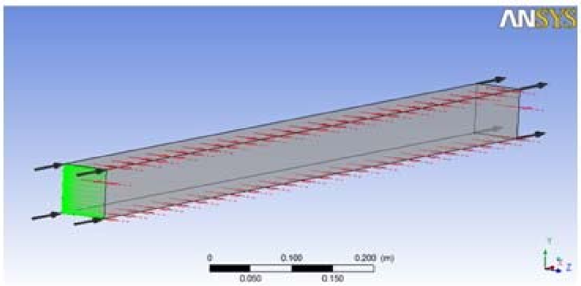

Figure-5. The experimental model for numerical experiments to assess the moisture condensation.

To simulate the condensation of liquid on the wall, mathematical model of multiphase flow «Droplets with Phase Change» has been chosen, wherein the carrier phase was considered to be gas (more precisely, the saturated steam), and the secondary phase - liquid droplets.

Especially important is the choice of the correct time step for providing stability condition. In this case it is chosen between 10^{-6} s and $5*10^{-5}$ s. As a result of this choice, and assuming the length of area to be considered (1 m), each calculation lasted for more than a day.

Boundary conditions accepted for numerical experiments to assess the moisture condensation.

Warm air at entrance. Flow rate of 3.85 m/s; temperature 23 ^{0}C. Relative moisture content by weight was taken 60% and was converted into a volumetric liquid fraction of total volumetric flow. Static pressure is 1 atm.

The bottom wall (plane XZ) - a three-dimensional temperature distribution obtained in previous calculations for three different temperatures of cold air supply.

All other walls are considered to be thermally insulated.

In the XY plane, symmetry condition of flow is provided.

Figures-6 through 8 present the contours of the phase distribution at the outlet section of the heat exchanger.

Moisture grew evenly to the end of the area while displacing gas. Phase transition was at a maximum near the wall and in the end of the area.

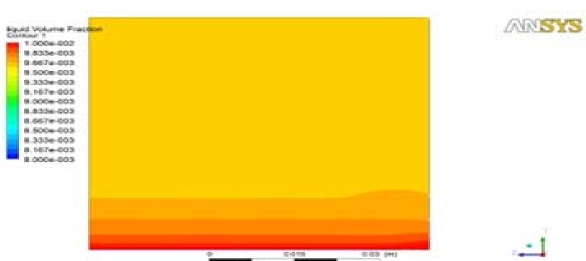

Figure-6. Volumetric fraction of fluid in the outlet section.

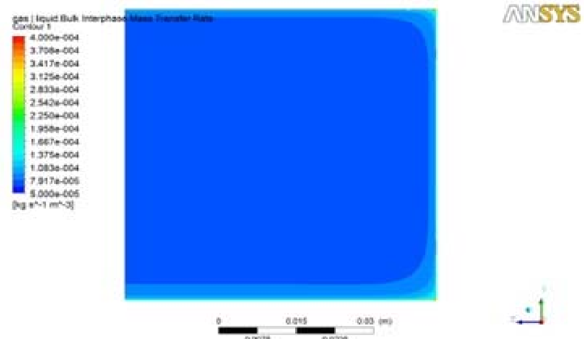

Figure-7. Gas-to-liquid phase transition rate in the outlet section area.

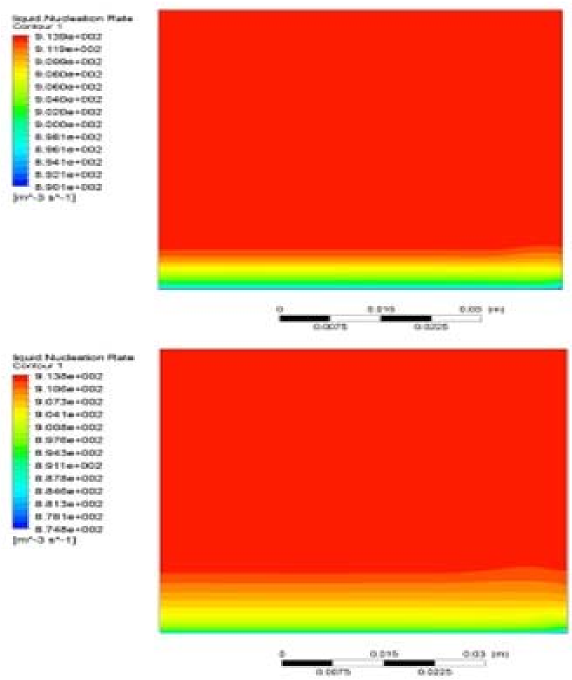

Figure-8. Liquid formation rate by volume unit. Left - cross-section in the middle (x = 0.5 m); right - the outlet section (x = 1 m).

Figure-6 shows that thickness of the condensate layer increases closer to the wall (to the right), while in the middle area (where there is a symmetrical flow condition) fluid is concentrated more uniformly, and Figure-7 illustrates that maximum rate of condensation is in the lower right corner of the area. Respectively, a major amount of liquid shall be accumulated there. Average condensation rate values as per discharge area for each numerical experiment carried out is given in Table-1. Figure 8 confirms that near the walls liquid is no longer formed, as it has been accumulated there. Intensive formation takes place in the middle of computational domain (of heat exchanger), where the saturated steam is.

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It is noticeable that closer to the heat exchanger output area, film thickness of the condensed liquid increases.

Table-1. Simulation results of moisture condensation.

Material	Cold air temperature	Moisture content (relative, by weight)	Max. rate of gas-to-liquid phase transition, kg $m^{-3}s^{-1}$
PVC	-3.1°C	30%	0.00038
		60%	0.00043
		80%	0.00044
	-15°C	30%	0.00085
		60%	0.001
		80%	0.00114
	-28°C	30%	0.00088
		60%	0.00098
		80%	0.00112

These calculations provide a detailed study of the formation of droplets of water vapor condensate while recovering air flow heat. The calculations revealed the most "condensate-dangerous" areas of heat exchanger, which are most likely influenced by appearance of condensation and its subsequent freezing.

In addition to the calculation results an experiment was carried out to choose a way to protect heat exchanging surface from condensate.

EXPERIMENTAL STUDY

Practically, the experimental model copied the geometric dimensions of the experimental model shown in Figure 1 and consisted of two air channels (for warm air and cold air), separated with a plate of material being tested, so that the sample plate was positioned horizontally, in parallel to the movement of air in channels caused by fans. The model was equipped with sensors, fixing surface temperature of the test materials, as well as air temperatures at inlet and outlet of each channel.

When conducting experimental studies on condensate formation, three samples of thermally conductive wall separating the flows of warm and cold air in the heat exchanger were tested.

- sample 1 - Teflon-coated polycarbonate (PC);
- sample 2 – PC without coating;
- sample 3 – PVC without coating.

Photo of the samples is shown in Figure-9, and photo of the test facility is shown in Figure-10.

Figure-9. The three samples of thermally conductive wall to be tested. From left to right: Sample 1 - Teflon-coated PC, Sample 2 - PC without coating, Sample 3 PVC without coating.

Figure-10. Photo of the test facility.

During the experimental study the samples were placed inside the experimental model and blown with air according to the scheme shown in Figure-11.

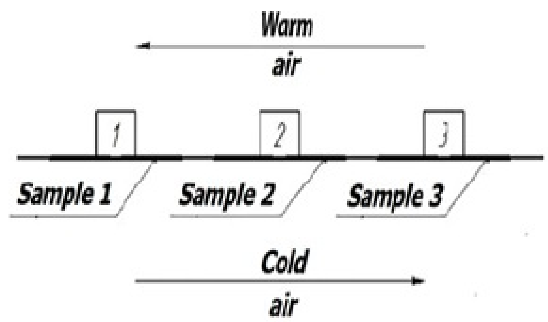

Figure 11. Air flow scheme for the experimental study.

Condensate formation on the surface of the test samples was controlled visually and photographed. Photos of test samples are shown in Figure-12.

Sample 1.

Sample 2.

Sample 3.

Figure-12. Photos of the samples with droplets of condensed moisture.

Provided Figures depicture following results:

1. Condensate is formed on all test samples at both steps.

2. During the condensate formation, trend towards increasing the droplet size in direction of the warm air flow can be observed. This fact is in good agreement with the results of numerical experiments.

3. Condensed moisture tends to the walls of a channel in accordance with calculation results.

4. Presence of the Teflon coating causes a change in the size and shape of condensate droplets with the decrease of their contact surface with the sample (see Figure 12 samples 1 and 2). At the same time, as it is stated in (Jang-Seok Lee, Sung Jhee, Jin-Koo Park, Jung-Soo Kim, Kwan Soo Lee, 2005), the frost growth on the surface that has a relatively large contact angle goes faster. In this work we consider not desublimational way of frosting but condensation with later freezing, so this effect was not discussed here.

It is important, that presence of a thin Teflon coating does not substantially affect thermal resistance of heat exchange surface, but can help removing condensed moisture from heat exchange surface with air flow since the contact angle becomes larger and contact surface of droplet and heat exchange surface decreases. If the velocity of air will be sufficient to blow droplets out of heat exchanger, it will reduce risk of freezing.

CONCLUSIONS

Research described in the article represents a detailed study of the formation of droplets of condensate while recovering air flow heat. The calculations revealed the most "condensate-dangerous" areas of heat exchanger, which are most likely influenced by appearance of condensation and its subsequent freezing.

Experimental studies have shown, that during the condensate formation, trend towards increasing the droplet size in direction of the warm air flow can be observed, while condensate tends to the walls of a channel. These facts are in good agreement with the results of numerical experiments.

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REFERENCES

[1] G.I. Sultan, E. A. ElShafieea, M. G. Safana and M. A. Elraouf. 2012. «Frost Formation and Heat Transfer over Flat Plate Evaporator», Journal of Engineering and Computer Sciences, Qassim University, Vol. 5, No. 1, pp. 49-71 (January 2012/Safar 1433H).

[2] Da Silva D.L. 2012. «Frost Formation on Fan-Supplied Tube-Fin Evaporators: A Visual and Numerical Analysis», International Refrigeration and Air Conditioning Conference. Paper 1164.

[3] Vasilyev G.P. and Timofeev N. A. 2010. «The energy potential of air emissions of residential buildings in Moscow» AVOK: Ventilation, heating, air conditioning, heat supply and building thermal physics. No. 1. S. 24-32.

[4] Vasilyev G.P. «Results of field investigations of the thermal regime of the experimental energy-efficient building» Building materials, equipment, technologies of XXI century». No. 6. C.

[5] Aleskovskaya E. C. Dubinsky J. A.; Tokarev. Patent 2162872 RF IPC C09K3/18. Hydrophobic anti-icing composition.

[6] Polymer roofing and waterproofing materials. Edited Shulzhenko Y. P. - M., VNIINM, (1993).

[7] Jang-Seok Lee, Sung Jhee, Jin-Koo Park, Jung-Soo Kim, Kwan Soo Lee. 2005. «Frost formation on thermally conductive plastic plain plate», Proceedings of Fifth International Conference on Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology.