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3-D MODELING OF WATER FLOW AND COOLING DOWN WITHIN THE TEMPERATURE RANGE CLOSE TO INVERSION POINT

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Abstract: *The research and simulation of heat transfer during water refrigeration in the experimental section close to the vertical pipe which is cooled down considering abnormal character of water density change from the temperature in close to inversion point (+4°C) section were investigated. The graphs of water temperature velocity distribution throughout the height of experimental section were constructed and analyzed. The results obtained allow estimating the impact of water temperature that is closely situated to inversion point on the dynamics of water ice melting and generation as well as on the form factors of cold accumulators. Such software and analytical research will allow increasing effectiveness and efficiency at the heat and bulk transfer equipment engineering.*

Keywords: *computer modeling, boundary conditions, heat transfer, cold accumulators, water ice, ice melting, Ansys.*

1. Introduction

The modern computational experiment is important at the stage of scientific research for solving various linear and nonlinear, stationary and non-stationary tree-dimensional problems. Information, received by numerical calculations, allows understanding the observed physical effects but, in certain circumstances the only possible solution is to replace the real experiment by the computerized one. Due to the further progress in computing technique development, it is expectative that in the nearest future the role of the computer modeling will increase especially at the stage of new industrial samples creation as well as in the research of complex effects and processes. Currently, the computational fluid dynamics packages, heat transfer, durability and electrodynamics for engineering calculations are widespread.

The problem that is being dealt with belongs to the extremely complex problems of mutual interconnected and mutually influencing problems of heat transfer and hydrodynamics. When dealing with the water moving slowly near a cooled down surface one should expect that significantly changing density of water will strongly affect the velocity distribution in the layers adjacent to the surface. The problem becomes more aggravated in case of water, since the density of water changes abnormally within the temperature range 0...+10°C, having its extremum value at the temperature of 4°C. Therefore there will be reverse buoyancy in respect of layers. It is obvious that an analytical calculation of hydrodynamics of such flows is impossible and yet the prognostic calculations of velocity distribution in the said region are extremely helpful, since the local velocity of water determines the onset of water crystallization (ice generation). The last is extremely important at a stage of ice accumulators designing. Application of 3-D computerized simulation of the process mentioned above look extremely promising on the problem on hand.

2. Formulation of the problem

The complex and internally interrelated heat and mass transfer problems that arise at the study of ice generation on the vertical cooled surface that is streamlined by water are significantly nonlinear physical problems. In this case, the liquid has a noticeable extremum of density at 4°C, Fig. 1. It significantly affects the water flow, close to the surface with the temperature of 0°C or lower, since the adjacent layers have reverse buoyancy. It is obvious, that such difficult phenomenon is a problem for direct experiment or computer 3-D simulation.

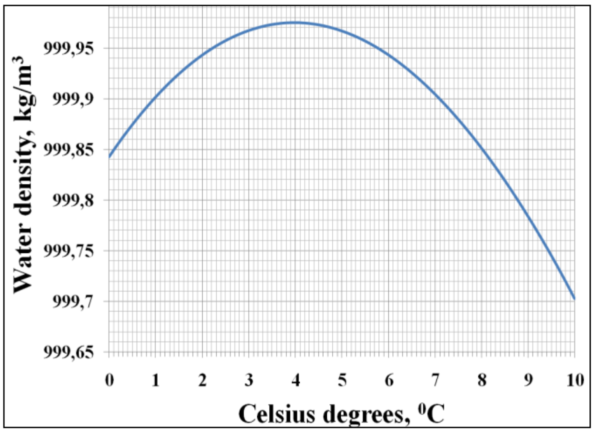

Fig. 1. Correlation of water density from the temperature

The initial stage of studying into the processes of ice generation and melting at the vertical cylindrical surface, the modeling of water cooling down on the 3-D model in the research section was carried out. It is clear that within the temperature range +10…0°C a crucial density change of water takes place.

3. Experimental rig

The ice melting and generation research was held at the experimental stand, which is shown in the Fig. 2.

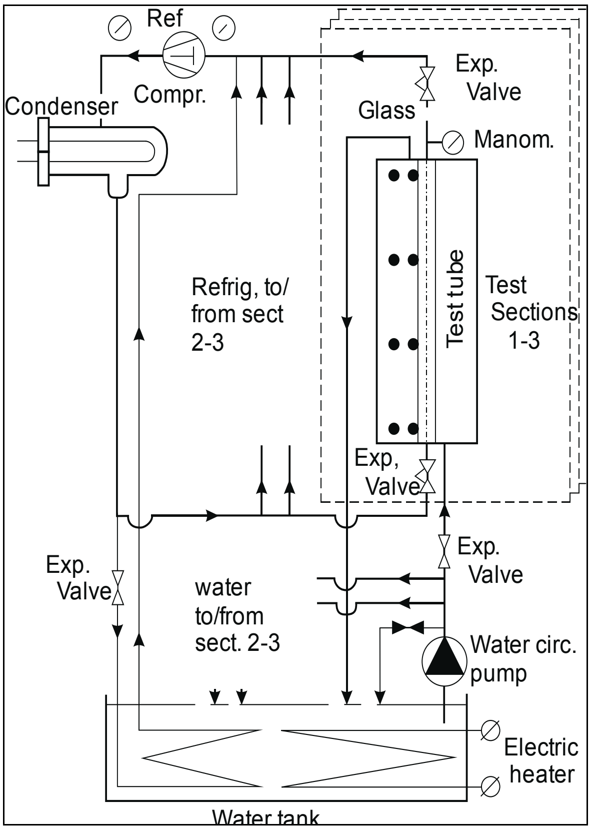

Fig. 2. Experimental rig

The rig consists of three similar blocks (Test sections 1-3). The main part of a section is a test copper tube 290 mm height, 10 mm outer diameter, 1 mm wall thickness. Each tube is mounted inside of water jacket of 180 mm diameter. A water circulation contour consists of a pump, water piping, water tank, measurement and control systems including regulation and stop valves. Circulating water was fed in parallel and supplied from the bottom of the jackets and removed from the upper part, so that an upward flow of water inside all jackets took place. The flow rate of water was controlled by a rotameter, adjusted and kept constant during every experimental run by precision needle valves, and precisely measured by the volumetric method. The water flow rate could be maintained individually for each test unit. A given temperature at the entry to the jackets has been maintained by switching on/off of a cooling coil or electric heater in the water tank. The test tubes were hooked up to the refrigeration contour in parallel on the refrigerant. The refrigeration unit has been equipped with all necessary systems allowing control, measurements and regulation of the evaporation pressure (evaporation temperature) inside each test tube and condensation pressure in the condenser. Time rate of ice layer thickness formed during the experiments was measured by means visual technique. Photographs of the test sections of pipes covered with ice were taken from the front of the transparent water jackets. Immediately before the experiments, an adjustment session had been carried out including testing of different lighting techniques and light sources, and calibration procedures which aimed at the determination of the best measurement arrangements [1-3]. For detailed study of the processes that take place close to the cooling surface, 3-D model of the research section was built.

3. 3-D model creation

Geometrical model of the research area is built in the Ansys software package. The core of the geometrical model is the area of coaxial cylinder, within which the water flows. Four inlet and outlet pips for water are located at the bottom and in the top of cylinder respectively. Cooled cylindrical surface is modeled along the central axis, Fig. 3.

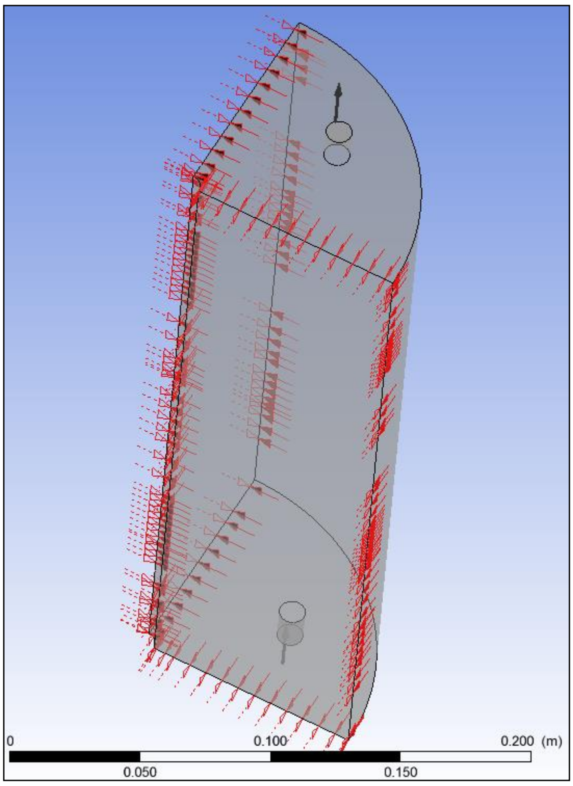

Fig. 3. Geometrical model of experimental (research section)

To provide the most accurate calculation at a reasonable number of integrations, the research section was generated as a 90° sector, since the whole section is a symmetrical one. A special attention was paid to the accuracy mesh creation. This enabled to generate 500000 nodes mesh in the sector which is equal to 2 million nodes for whole cylinder. For forming the boundary layer in the mesh and more accurate calculations, a special inflation limit was used, Fig. 4. [4-7] To avoid possible ice-coating at the wall surface which is cooling, the temperature of inner cylinder has been programmed as a surface with 0°C. The water temperature varied within +10 to +40°C. The SST (Shear-Stress-Transport) turbulence model was chosen, as it effectively combines the stability and accuracy of the standard *k-w* model in the boundary regions and *k-e* model in the flow core [8-10].

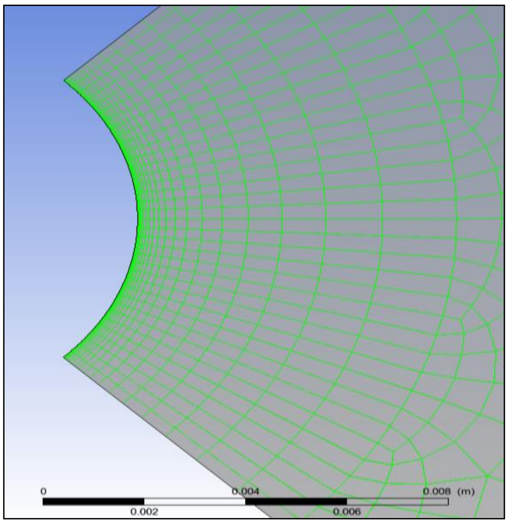

Fig. 4. The inflation limit in the boundary layer (cooling wall is a coolant)

In order to reach the convergence of calculation results, the following physical properties of cooled water were introduced into the program model: the water density and heat capacity variation in the vicinity of the inversion point with the temperature increment of 1°C within a whole interval of experimental temperature change. The results of such program are given in Fig. 5. Calculations were carried out in the CFX-Solver manager. The accuracy of obtained results is demonstrated by the convergence calculated equations and systems and exceeds 1520 iterations. Obtained results have been imported to the CFD-Post. Vectorial images of liquid flow inside the research section, temperature and velocity profiles are shown in the Fig. 6-7. This information allows estimating the influence of regime parameters on the process of water cooling.

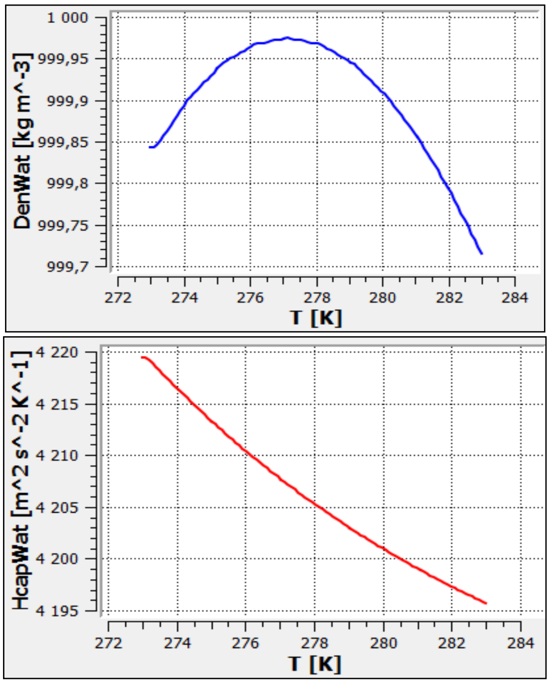

Fig. 5. Water density and heat capacity in the vicinity of inversion point

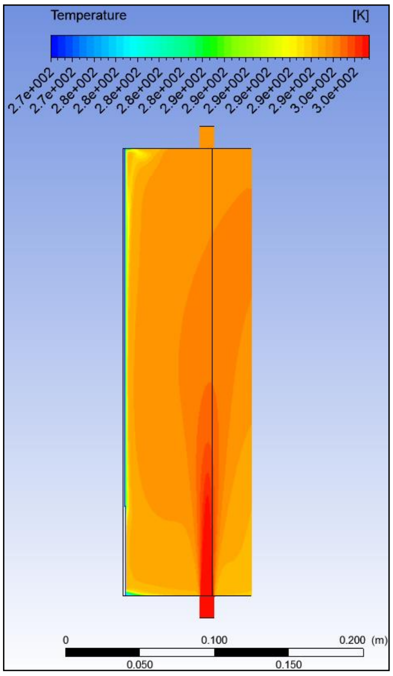

Fig. 6. The profile of temperature distribution in research section

Thus, from the data given in Fig. 7, show that the intense cooling of water takes place at the bottom point of the experimental section, Fig. 6. This can be explained by the existence of vortex in the adjacent to the wall layers which is cooled and by the effect of water density abnormality, which causes the downflow of layers with the temperature of 4°C. The noticeable impact of vortex tributaries on the cooling down cooper surface is presented in the Fig. 7.

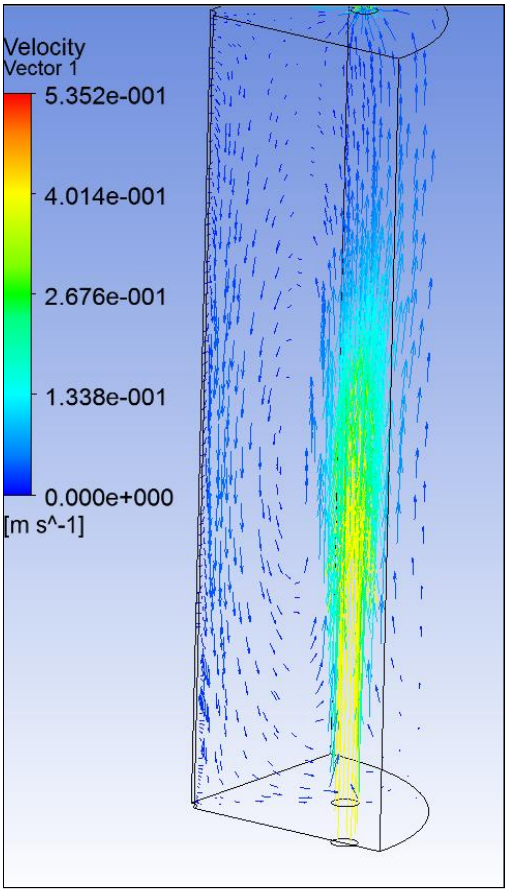

Fig. 7. The vector of velocities in the research section volume

For the more precise analyses of obtained results, the several lines in the middle of research section were positioned. The given approach allowed to built a graph of velocity distribution in the layer of 1...2 mm close to the cooled wall. The data are given in the Fig. 8-9. Water velocity distribution on the ascending and descending flows, i.e. a swirls formation is present.

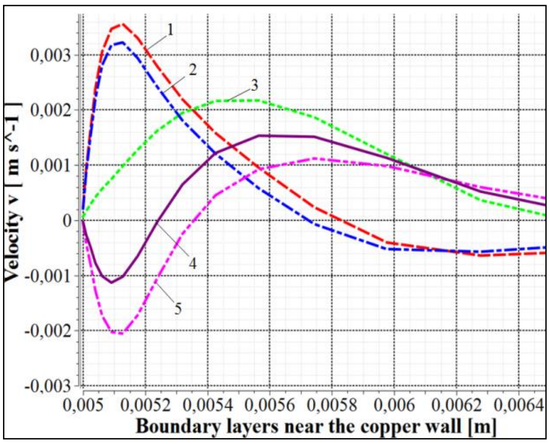

Fig. 8. Water velocity distribution throughout the high of experimental section in the boundary layer: 1, 2, 3, 4, 5 – velocity throughout the height of experimental section 0.1 m; 0.15 m; 0.06 m; 0.058 m; 0.059 m consequently

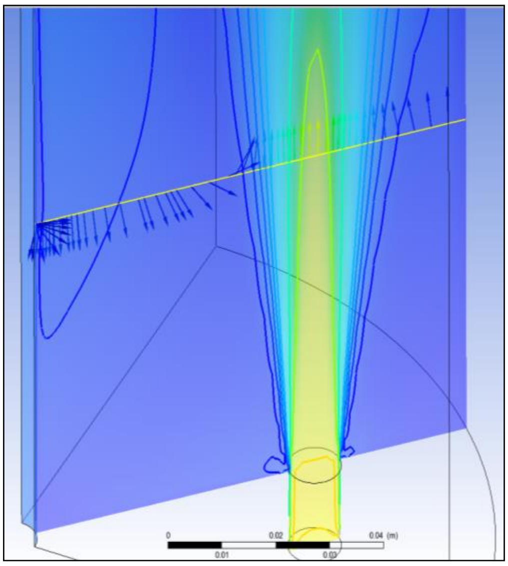

Fig. 9. Velocity vector in high 0.06 m of research area

It can be explained by abnormal water density redistribution. The layers of liquid that are closely situated to the cuprum surface are cooling lower than 4 °C. In this conditions water density decreases. As the result of these layers mixing with the layers whose temperature is 4°C, the local water layers mixing exactly in the boundary layer is happening (cuprum wall is a coolant). The fall of water velocity to its minimal value in the research section on the high of 6 mm is also shown in the graph. Exactly at this high the velocity of the water layer approaches 0°C, so the conditions of ice generation is this very place looks more favorable, since the local shear stress on the wall is 0°C. The obtained results are proven by full-scale experiment. Experimental photographs show clearly the conical shape of the ice, Fig. 10.

Fig.10. Ice generation with clear conical shape

The forming of obliquity at the intensity subcooling of boundary layer which is close to cuprum surface, on the 6 mm high occurs.

4. Conclusions

1.The results obtained of 3-D modeling of water flowing over and cooling down in the vicinity of cooled pipe show that the extremal character of water density change close to the inversion point, significantly affects the velocity distribution in the boundary layer.
2. The effect of reverse buoyancy causes appearing of zero velocity region on the cooled down surface which corresponds to the flow cross section at which the inverse water buoyancy compensates the momentum.
3. The inception of crystallization starts at the zero velocity cross section which is proven by the results of photo fixing of ice generation of the cooled.

5. References

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