IRSTI 29.17.23; 28.17.23 https://doi.org/10.26577/phst202512111

Modeling of thermal distribution on cryosurface for low temperatures

O.D. Vorobyova [1,2*], D.Yu. Sokolov [1,2] and Ye.S. Korshikov [1]

[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[2]Almaty Technological University, Almaty, Kazakhstan
*e-mail: olga.vorobyova842@gmail.com
(*Received April 21, 2025; received in revised form May 30, 2025; accepted June 02, 2025*)

In this work, the temperature distribution on a cryosurface operating at low temperatures (in the range from 300 K to 80 K) was thoroughly studied. This type of cryogenic cooling surface is specifically designed for experimental processes that involve the controlled deposition and subsequent cooling of various inorganic compounds. Such processes are essential for conducting detailed investigations into the physicochemical properties, morphology, and structure of these materials under cryogenic conditions. The temperature distribution was analyzed through numerical simulation, which included modeling the cooling process of the cryopanel surface down to cryogenic temperatures using the finite element method. Liquid nitrogen was selected as the working coolant due to its availability, low boiling point, and high efficiency in achieving the required cooling rate. The simulation results revealed the temperature gradient both within the volume and on the surface of the cryopanel. Additionally, the influence of the thermal conductivity of different structural materials–aluminum and stainless steel–on the cooling efficiency was examined. The desired cryosurface temperature range (80–90 K) was successfully reached within 1800 seconds, using a nitrogen flow through a coiled pipe of 6 mm in diameter.

Key words: cryosurface, computer modelling, thermal distribution, low temperatures, thermal conductivity.
PACS number(s): 64.60.−i; 78.20.Bh

1 Introduction

Cryosurfaces play an important role for cooling and further work with samples in the low temperature range. Computer simulation is one of the most modern and relevant methods for studying the heat transfer processes of cryopanels when interacting with the environment and materials of various compositions applied to the surface of the substrate. This will solve several problems related to:

1) the development of an effective heat exchanger and the study of its heat transfer properties;

2) creating an autonomous system for maintaining temperatures of varying accuracy under conditions of thermal energy balance on the surface of the cryopanel.

In this regard, it is relevant to study the influence of heat transfer processes before achieving optimal temperature operating conditions on the surface of the cryopanel.

Cooling of the coil to cryogenic temperatures is achieved by supplying a cryogenic liquid (in this case, liquid nitrogen with a temperature of 77 K is considered). The use of cryogenic liquids is widespread in modern scientific, medical and food industries [1].

Another challenge in cryogenic cooling is to define and understand the cooling process and the thermal characteristics that affect it with subsequent heat transfer. Therefore, research continues on this topic [2-3].

Rapid progress has been made in the past two decades. In 2007, the authors of [4] analyzed experimental data on the cooling of a horizontal pipe and the heat flux formed in it. They were able to show the transitional regimes from creep to cooling, including visualization of the data obtained during the analysis [4]. In 2012, a similar study was conducted in [5], but in a vertical pipe. They determined the heat flux and heat transfer features with separation of boiling zones and transition flows of the cryogenic liquid flow. Further research in the field of cryogenic liquid cooling contributed more data and investigated the influence of various flow parameters on the cooling process.

These data allowed more accurate modeling of both the cooling process itself and the flow pattern. In 2015, experiments were conducted on cooling lines with liquid nitrogen (LN_2) in horizontal and inclined pipes. The influence of pipe length and mass flow on cooling time and heat flux was investigated [6]. In 2015, Darr et al. conducted in-line cooling experiments with LN_2 in a vertical tube of approximately 0.5 m length and simulated the cooling process using a one-dimensional homogeneous model [7].

In 2016, they further expanded the mass flow range of the experiments and improved the film boiling correlations by taking into account the flow directions [8]. Darr's research has provided many important updates to the investigation of cryogenic line cooling. However, the applicability of the proposed correlations needs to be investigated, especially for a tube that is much longer than the studied one.

This leads to the following issues for calculating temperature using computer modeling:

1) There is always high ambiguity and uncertainty in the data when using cryogenic characteristics in the study.

2) These high uncertainties will lead to significant scatter of results when attempting to develop a cryogenic model that describes the relationship with the experimental data.

For two-phase flows, experimental data and analytical models can be related using computational fluid dynamics (CFD) models.

Such studies for two-phase flow have successfully developed both analytical models [9-11] and CFD models [12-14]. This formed the basis for the experimental validation of models for predicting the behavior of two-phase flow of cryogenic liquids and flow visualization methods [16-17].

Considering that the main attention is paid to the research of heat exchangers at high temperature [18-20], a model of a cooling heat exchanger was developed in this work. This study presents a the temperature distribution of a cryosurface at low temperatures from 80 to 300 K. Determining the thermal efficiency of the cryosurface will improve the design of cryopanels. The model was developed using the finite element method; temperature-time dependencies were obtained when the surface was cooled to cryotemperatures.

2 Methodology

2.1 Methods

In this work, the finite element method (FEM) was used, which can be a minimization function or described by partial differential equations in the form of a set of finite volumes (Fig. 1).

Features of FEM:

1) Using simple approximating elements, one can achieve any accuracy of piecewise approximation of physical fields on finite elements.

2) Locality of approximation leads to systems of sparse equations for the discretized problem. This helps to solve problems with a very large number of nodal unknowns.

The main stages of the finite element method are described below.

The modeling program (in this work, the COMSOL Multiphysics software package) generates a finite element mesh based on the geometry. The mesh description consists of several arrays of system equation solvers, the main ones being the nodal coordinates and the connections between the elements.

2.2 Equations.

To solve the global system of equations for the entire solution domain, it is necessary to combine the equations of local elements. Element connections are used for the assembly process. Before solving, boundary conditions (which are not taken into account in the element equations) must be entered. Before solving a system of equations, boundary conditions must be specified.

Heat removal from the surface of the cryopane is ensured by convection of the gaseous coolant flow and is described by the general heat conduction equation and the Navier-Stokes equation.

The general equation of thermal conductivity for any solid [21]:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot q = Q \quad (1)$$

The general equation of thermal conductivity for a liquid (in this case, liquid nitrogen) [21]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \cdot u \cdot \nabla T + (\nabla \cdot q) = 0 \quad (2)$$

where

ρ – density,

u – velocity vector,

p – pressure,

τ – viscous stress tensor,

C_p – specific heat capacity,

T – absolute temperature,

q – heat flux vector,

Accordingly, the principle of energy conservation is the equation of heat transfer in continuous media from the first law of thermodynamics. These equations in integral and local forms at the nodes of the model grid are applicable to various heat transfer equations that can be solved in COMSOL Multiphysics software package [21-22].

3 Results and discussion

This study presents computer modeling of a cryopanel (300x300x20 mm) with a channel of 6 mm in diameter. Liquid nitrogen enters the cryopanel channel at a speed of 50 mm/s and a temperature of 80 K. In this configuration, we consider the flow to be laminar. We consider the walls of the heat exchanger to be insulated and their initial temperature is set to room temperature.

Figure 2 shows the simulation results for the first 800 seconds of liquid nitrogen flow. As can be seen from the figure, the temperature distribution on the surface is uneven. After 800 seconds, only the channel is cooled, but not the surface. Then the temperature equalizes and the difference between the ends of the cryopanel becomes no more than 0.16 K.

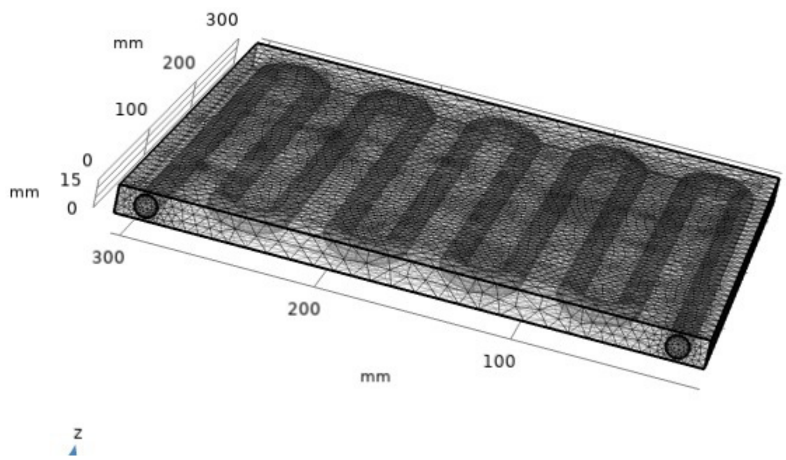


Figure 1 – Image of the calculation grid for the cryopanel volume.

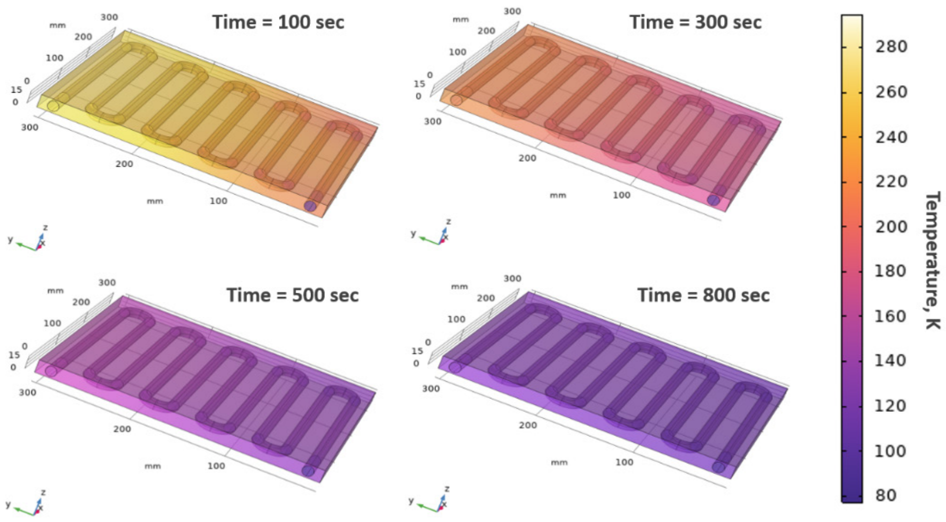
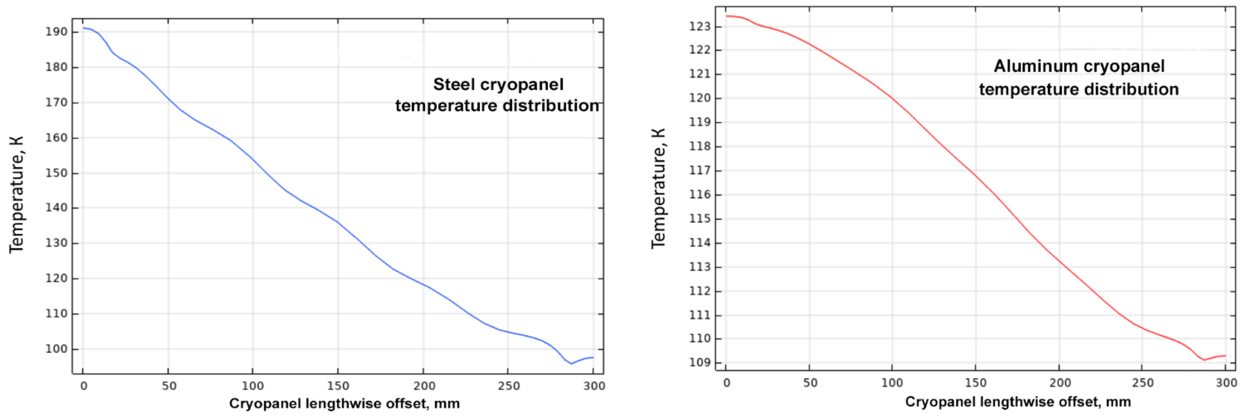


Figure 2 – Time distribution of volumetric temperature in a cryopanel.

Comparing aluminum and steel cryopanels, the results showed that the temperature distribution cannot be compared between two panels if one does not define the same time schedule. When one considers aluminum and steel, where the thermal conductivity coefficient is 235 W/(m·K) for aluminum and 45 W/(m·K) for steel, it is almost obvious that the relative cooling efficiency will be much different (Fig. 3). After 800 seconds, the average temperature difference between the ends of the steel cryopanel was more than 100 K (Fig. 3a), and for the aluminum cryopanel it was 14 K (Fig. 3b). Thus, in this case, based on the modeling results, preference is given to the aluminum cryopanel in terms of thermal conductivity.



a) b)

Figure 3 – An average temperature distribution along the cryopanel surface 800 second later: a) aluminum cryopanel; b) steel cryopanel.

Next, Figure 4 shows the total time spent on cooling the cryopanel. To reach the optimum operating temperature (around 80 K), the aluminum panel took 1850 seconds. The steel panel cooled down more slowly, taking 3000 seconds. Comparing the cooling rate of the entire cryopanel it's shown that the aluminum panel is 43% more efficient due to its high thermal conductivity.

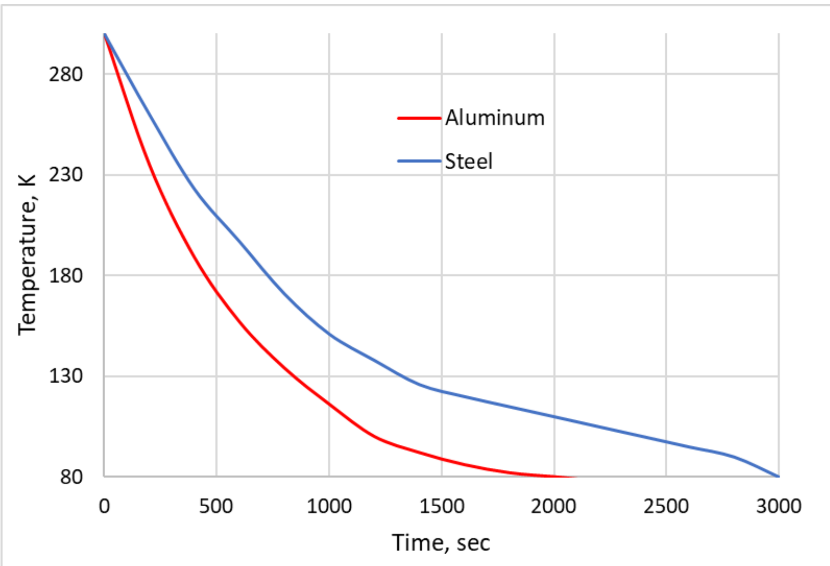


Figure 4 – Comparison of the average temperature of the cryosurface made of steel and aluminum for the 3000 seconds.

4 Conclusions

This work presents a variant of computer modeling of cryogenic surfaces. These surfaces are used in scientific research and food industries. Such types of heat exchangers as cryopanels require preliminary assessments of their efficiency to ensure optimal operating conditions. In this study it's demonstrated that the aluminum cryopanel is 43% more efficient than the steel one, that is in respect of the whole cryopanel surface. When one considers the aluminum and steel, where the thermal conductivity coefficient is 4 times to other it is almost obvious that the relative cooling efficiency will be much different

During the work, the process of cryosurface cooling from room temperature to 80 K was studied. After analyzing the distribution of the average temperature over the volume of the cryosurface, it was found that the coil through which liquid nitrogen flows cools the surface unevenly. This requires additional time to complete cooling of the working surface of the cryopanel. Only 800 seconds after the start of cooling, the temperature of 80 K is reached only along the inner surface of the channel. At the same time, the temperature of the cryosurface equalizes to values of about 80 K only 1850 seconds after the start of cooling. Thus, the configuration of coils throughout the volume that conduct liquid nitrogen affects the achievement of optimal working low temperatures. To improve the indicators for the cooling time, it is recommended to change the coil configuration, and an assessment of the optimal channel diameter is required.

The model allowed us to evaluate the efficiency of materials and the geometry of the pipeline tubes during the design of universal cryogenic surfaces. The results of this study can contribute to the further development of cryogenic technologies in this area.

Acknowledgments. These studies have been carried out with the financial support of the Ministry of Science and Higher Education of the Republic of Kazakhstan under grant №AP19576644.

References

1. Sokolov D.Y., Yerezhep D., Vorobyova O., Ramos M.A., Shinbayeva A. Optical studies of thin films of cryocondensed mixtures of water and admixture of nitrogen and argon // Materials. – 2022. – Vol. 15. – P. 7441-7459. https://doi.org/10.3390/ma15217441

2. Wang B. et al. Potential applications of cryogenic technologies to plant genetic improvement and pathogen eradication // Biotechnology advances. – 2014. – Vol 32. Is.3. – P. 583-595. https://doi.org/10.1016/j.biotechadv.2014.03.003

3. Rutkuniene Z. LES modeling gas particle dispersion and thermal characteristics in a reacting turbulent low // Phys. Sci. Technol. – 2024. – Vol. 11. Is. 1-2. – P. 76-84. https://doi.org/10.26577/phst2024v11i1a9

4. Yuan K., Ji Y., Chung J.N. Cryogenic chilldown process under low flow rates // Int. J. Heat Mass Transf. – 2007. – Vol. 50. Is.19–20. – P. 4011–4022. https://doi.org/10.1016/j.ijheatmasstransfer.2007.01.034

5. Hu H., Chung J.N., Amber S.H. An experimental study on flow patterns and heat transfer characteristics during cryogenic chilldown in a vertical pipe // Cryogenics (Guildf). – 2012. – Vol. 52. Is. 4–6. –P. 268–275. https://doi.org/10.1016/j.cryogenics.2012.01.033

6. Johnson J., Shine S.R. Transient cryogenic chill down process in horizontal and inclined pipes // Cryogenics (Guildf), – 2015. – Vol. 71. – P. 7–17. https://doi.org/10.1016/j.cryogenics.2015.05.003

7. Darr S.R. et al. An experimental study on terrestrial cryogenic tube chilldown II. Effect of flow direction with respect to gravity and new correlation set // Int. J. Heat Mass Transf.– 2016. – Vol. 103. – P. 1243–1260. https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.019

8. Yang J. et al. Numerical study of transient conjugate heat transfer of the cryosupersonic air-quenching based on a Mach-weighted pressure-based method // International Journal of Heat and Mass Transfer. – 2019. – Vol. 134. – P. 586-599. https://doi.org/10.1016/j.ijheatmasstransfer.2019.01.064

9. Ganesan V. et al. Universal critical heat flux (CHF) correlations for cryogenic flow boiling in uniformly heated tubes // Int. J. Heat Mass Transf.– 2021.– Vol. 166. – P. 120678. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120678

10. Devahdhanush V.S., Mudawar I. Review of critical heat flux (CHF) in jet impingement boiling // Int. J. Heat Mass Transf. –2021. – Vol. 169. – P. 120893. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120893

11. Cai C. et al. Assessment of void fraction models and correlations for subcooled boiling in vertical upflow in a circular tube // Int. J. Heat Mass Transf. 2021.– Vol. 171. – P. 121060. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121060

12. Devahdhanush V.S. et al. Assessing advantages and disadvantages of macro- and micro-channel flow boiling for high-heat-flux thermal management using computational and theoretical/empirical methods // Int. J. Heat Mass Transf. – 2021. – Vol. 169. – P. 120787. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120787

13. Ferreira J., Kaviany M. Geometric-confinement suppression of flow-boiling instability using perforated wick: Part I CHF and conductance enhancement //Int. J. Heat Mass Transf.– 2020. – Vol. 159. –P. 120080. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120080

14. O'Neill L.E., Mudawar I. Review of two-phase flow instabilities in macro- and micro-channel systems // Int. J. Heat Mass Transf.– 2020. – Vol. 157. – P. 119738. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119738

15. Kim Y.J. et al. Flow boiling CHF experiment with sudden expansion tubes // Int. Commun. Heat Mass Transf. – 2020. – Vol. 114.– P. 104557. https://doi.org/10.1016/j.icheatmasstransfer.2020.104557

16. Lee H.et al. Experimental and computational investigation of vertical downflow condensation // Int. J. Heat Mass Transf. – 2015. – Vol. 85. – P. 865–879. https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.037

17. Lee J., O'Neill L.E., Mudawar I. 3D computational investigation and experimental validation of effect of shear-lift on twophase flow and heat transfer characteristics of highly subcooled flow boiling in vertical upflow // Int. J. Heat Mass Transf. – 2020. – Vol. 150. – P. 119291. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119291

18. Dzhus A.V., Subbotin S.O., Pulina T.V. and Snizhnoi G.V. Modeling the resistance of plate-like heat exchangers made of 06khn28mdt alloy (analogous to aisi904l steel) to crevice corrosion in recycled water enterprises // Phys. Sci. Technol. – 2024. – Vol. 11. Is. 3-4. – P. 58-66 https://doi.org/10.26577/phst2024v11i2b07

19. Abdullayev J. Sh., Sapaev I. B. Modeling and calibration of electrical features of p-n junctions based on Si and GaAs // Phys. Sci. Technol. – 2024. – Vol. 11. Is. 3-4 – P. 39-48. https://doi.org/10.26577/phst2024v11i2b05

20. Dzhus A., Snizhnoi G. Prediction the durability of heat exchangers made of 06KhN28MDT alloy (analogous to AISI904L steel) to crevice corrosion during their operation in recycled water // Phys. Sci. Technol. – 2023. – Vol. 10. Is. 3-4. – P. 57-67. https://doi.org/10.26577/phst.2023.v10.i2.07

21. Hodzhaeva M., Golikov O., Sokolov D., Yerezhep D. Research of the temperature dynamics change of a universal cryogenic surface using the finite element method // Recent Contributions to Physics. – 2022. – Vol. 1. Is. 80. – P. 66–74. https://doi. org/10.26577/rcph.2022.v80.i1.08 (In Russian)

22. Tazhenova M.S., Sultan R.R., Katpayeva K.A. Numerical study of thermophysical characteristics of a cryogenic surface // Phys. Sci. Technol. –2023. – Vol. 10. Is. 1-2. – P. 4-12. https://doi.org/10.26577/phst.2023.v10.i1.01

Information about authors:

Vorobyova Olga is a 3rd year PhD student at al-Farabi Kazakh National University (Almaty, Kazakhstan), Research Fellow of the scientific project at Almaty Technological University (Almaty, Kazakhstan), e-mail: olga.vorobyova842@gmail.com

Sokolov Dmitriy, PhD is an Associate Professor at al-Farabi Kazakh National University (Almaty, Kazakhstan), Head of the scientific project at Almaty Technological University (Almaty, Kazakhstan), e-mail: yasnyisokol@gmail.com

Korshikov Yevgeniy, PhD is a Senior lecturer at al-Farabi Kazakh National University (Almaty, Kazakhstan), e-mail: e.s.korshikov@ physics.kz