MATEC Web of Conferences **108**, 11003 (2017) DOI: 10.1051/matecconf/201710811003
ICMAA 2017

Numerical Modelling of Evaporation Process in Cryogenic Systems

A.A. Shimanov , D.A. Uglanov, D.V. Sarmin and A. B. Tsapkova

Samara National Research University, Heat engineering and heat engines Department, Samara, Russia

Abstract. This article deals with a problem of evaporation numerical modeling in cryogenic systems of constant volume. Particularly, a method of nitrogen evaporation modeling in cryogenic fueling tank was considered. User-defined functions of nitrogen thermodynamic properties in temperature range of 70...400 K and pressure range of 0.1...30 MPa. The result of this research is calculation algorithm which allows to model processes of phase change in cryogenic systems with constant volume. A comparison obtained between results of numerical modeling with experimental and analytical data is presented. Deviation of results from experimental data is 5-10%.

1 Introduction

A wide range of optical-electronic devices and systems, which require a cryogenic temperatures for its normal operation, is used onboard of aircrafts. Refrigerations systems vary in mass, consumed power, dimensions, durability cold capacity and temperature.

One of the type of onboard refrigeration systems for keeping temperature in aircraft is throttle refrig system. This refrigeration system is based on Joule-Thomson effect. Such refrigeration systems can provide refrigeration on temperature level 20-100 K with cold working fluid flow rate 0.1-1.5 kg per hour (depending on working fluid type). High pressure gas is required for throttle refrigeration system operation. Launder containing moist consuming fluid and filter are installed in high pressure line for removal of undesired примесей and moisture. Throttle refrigeration systems can be divided on systems with open and closed cycle. Throttle system with closed cycle includes compressor, evaporator and condenser which significantly increases mass of system and decreases its durability. Another disadvantage is high consumed power.

In open throttle systems gas from high-pressure tank passes from the throttle and cools an object of refrigeration. These systems utilize cryogenic working fluid in both critical and supercritical conditions as well s liquid working fluid in some special cases. Main advantages of these systems are simplicity, durability, reasonable economic efficiency and small energy consuming. Disadvantages are significant mass of high-pressure tank (including mass of working fluid) and change of the throttling temperature due to decrease of working fluid pressure in tank. In systems with open cycle (tank systems), mass of the fueled gas and working fluid parameters determine their exploitation properties and realistic characteristics. It is a reason why creation of new type of tank able to operate as a part of onboard refrigeration system with improved characteristics (improvement must be achieved by advantages of tank) is important task [1].

2 Problem

Cryogenic fueling tank (CFT), which is developed in Samara National Research University and can be used as element of onboard throttle refrigeration system, has a new functional properties such as increased lifetime and utilizing of both liquid and gaseous working fluids.

Tank design scheme is presented on figure 1. Cryogenic volume (Dewar) is located inside the high-pressure tank. Cryogenic working fluid is filled inside the Dewar. Gas chamber is created between Dewar and tank inner wall which serves as a heat insulation. Relation of the Dewar and inner volume dimensions is selected in such manner that if cryogenic working fluid is fully gasified i.e. gas will embrace entire tank volume, it will corresponds to a nominal pressure and nominal fueling mass of gaseous product.

Optimal point to start CFT is a mass of fueled working fluid. Considering mass of working fluid in liquid condition, volume of the CFT is calculated and then Dewar is selected. Considering final pressure in all volume of CFT, volume of CFT itself, containing both Dewar and screen insulation, is selected. Dependently on final parameters of temperature and pressure of single-phase working fluid in all volume of CFT both heat insulation and number of screens is selected.

To increase a lifetime of throttle system of onboard energy plant or decrease of mass and dimensions of existing system, it is suggested to use given tank during partial gasification of cryogenic product. It is necessary to know accurate duration and intensity of evaporation for this purpose. Complexity of the task is caused by the fact that considered thermodynamic system “gas chamber-liquid” is not in equilibrium. Gas chamber as subsystem is open (i.e. with changing mass of working fluid) and heat transfer is executed by heat conductivity through multilayer gas wall with counter gas flow rate varying along the radius. All of these processes are not stationary.

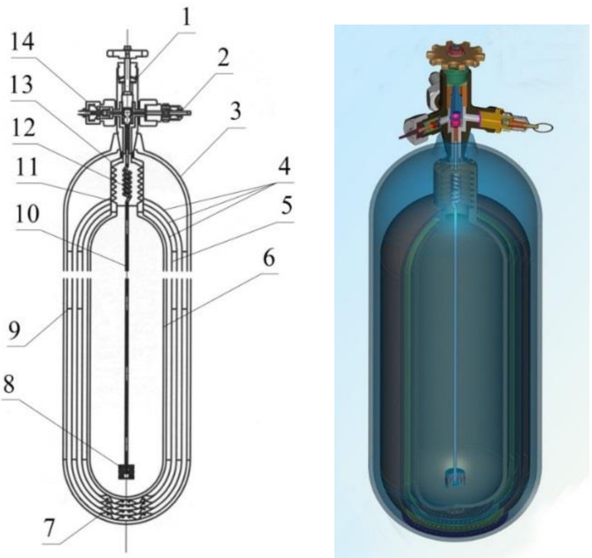


Figure 1. Reservoir with cryogenic filling:
1 – shutoff valve; 2 – safety valve; 3 – reservoir; 4 – insulation; 5 – insulation of internal reservoir; 6 – internal reservoir; 7 – bucking spacer plates; 8 – filter; 9 – radial spacer plates; 10 – barrel; 11 – filling pipe; 12 – coil; 13 – bellows; 14 – flow nipple

A process of cold energy distribution along the tank design elements starts after filling of inner volume by cryogenic fluid. Obviously, in case where there is no outside heat fluxes finite temperature condition of tank is determined by relation of total enthalpy of tank warm wall and cold energy of cryogenic working fluid. If amount of heat determined by enthalpy of wall is enough for evaporation of fueled mass of cryogenic working fluid, the task is converged to a solution of energy equations but process dynamic and duration of full evaporation are determined from the heat transfer equations. Conditions on boundaries of gas volume on every time step corresponds to a first-type boundary conditions. It is necessary to consider changes of gas and liquid heat and thermodynamic properties on every time step of the calculation.

In case of heat fluxes to external surface of the tank on every time step of the calculation, the heat transfer task is solved with third-type boundary condition from external side and first-type boundary conditions from the side of the liquid. In both cases, the processes which occur inside the tank are next.

Liquid starts to evaporate and evaporated part of cryogenic working fluid is distributed along the layers of gas chamber. Pressure in initial moment of time can even decrease which will promote further liquid evaporation. However, after sometime pressure may increase and evaporation will stop. Features of the initial processes and further cryogenic working fluid behavior will be caused by relation of liquid and gas phases volumes. Thus, if specific volume of two-phase mixture in isochoric process is higher than critical one, liquid will continuosly evaporate until full transfer to a condition of dry saturated vapor.

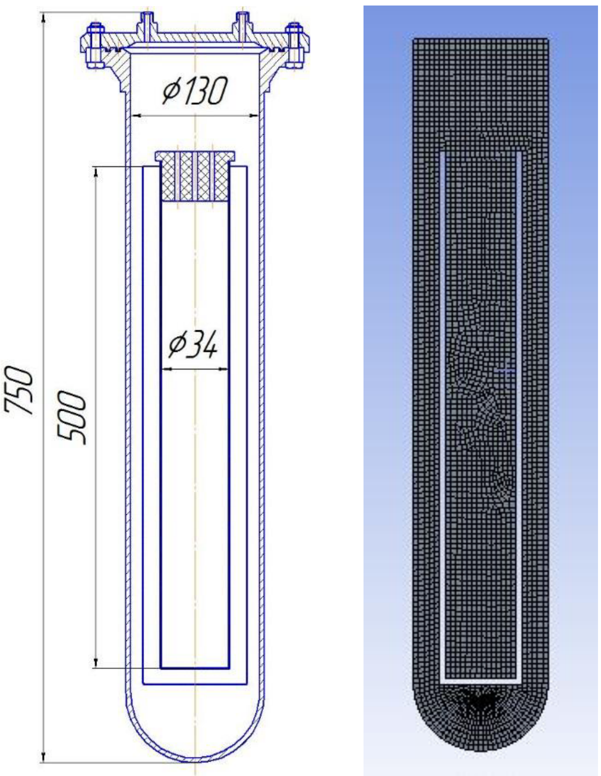
Provided discussion is based on analysis of so called classic two-phase systems were temperature and pressure of saturated vapor and liquid are equal. But in described case where temperature in the gas chamber significantly differs from the temperature of the liquid, the only condition which can be called equilibrium is condition of vapor and liquid in inner volume of tank.

Thus, Clapeyron-Clausius equation is not applicable for such thermodynamic system (entire tank) and analytical solution will not be correct.

Algorithm of this problem solution was suggested in works [1,2].

3 Numerical modeling

To increase accuracy and velocity of different cryogenic processes calculations it was suggested to use numerical modeling. Numerical modeling of the heat processes in cryogenic fueling tank was carried out by ANSYS Fluent software. 2D model was used to increase the calculation speed. CFT 2-D model was created by geometric parameters of tank which was used in the experiment [2] (figure 2) in ANSYS Design Modeler. For the numerical simulation a geometric model of CFT has been simplified. Then model was meshed by ANSYS Meshing module. Figure 2b shows a section of the CFT with applied mesh.



a)　　b)

Figure 2. Model of the CFT with applied finite-element mesh.

Nitrogen was used as a working fluid with phase change in this task. Model Volume of Fluid (VOF) [3, 4, 5] was used for modeling of two-phase condition. The methods and results of evaporation modeling with constant pressure are presented in [6, 7, 8, 9]. The main difficulty of the CFT modeling is the fact the nitrogen evaporation takes place in constant volume [10, 11]. Pressure inside the tank is increased from fueling pressure 0.1 MPa up to 1.2 MPa and temperature increases from 77 K to environment temperature during the process of nitrogen evaporation. Thermodynamic properties and nitrogen evaporation temperature during the gasification will significantly change. Option "floating operating pressure" was used for calculation pressure rise from the integral mass balance, separately from the solution of the pressure correction equation. This option can only be operated by using the ideal gas model.

User-Defined Functions (UDF) were written to describe thermodynamic properties which depend on temperature and pressure (specific heat, heat conductivity, viscosity, density) of liquid and gaseous phase. These functions allows to determine and calculate complicated process of heat-and-mass transfer between nitrogen phases in temperature range of 70 K to 400 K and pressure range from 0.1 to 30 MPa.

Function, which describes evaporation temperature inside the tank dependency on pressure inside the tank, was derivated:

$$T_{sat} = 11{,}546 \cdot ln(P) - 53{,}844 \quad (1)$$

Temperature of phase change become constant when pressure inside the tank reaches the value of critical pressure.

According to experimental data [1], Dewar chamber is filled by liquid nitrogen in initial moment of time with mass of 0.25 kg, temperature 77 K and pressure 0.1 MPa. This amount of nitrogen corresponds to one-third filling of tank. Temperature of external wall is set equal to 293 K. Temperature of inner wall is set variable corresponding to calculation results [1,2]. In initial moment of time temperature of the Dewar inner wall is set 2 K higher than evaporation temperature for given pressure. Time Step Size in initial moment of time is set less than 0.001 second due to complexity of heat-and-mass change process and solution stability. After evaporation stabilization time step size can be increased up to 0.01 sec.

4 Results

Figure 3 shows intermediate results of gasification process calculation. Nitrogen evaporation and transformation to a vapor is clearly seen as well as phase division line. Volume boiling takes place in CFT Dewar where vapor phase occurs directly in the volume of liquid as separate vapor bubbles. Thus, it can be stated that mechanism of phase change in the constant volume evaporation is bubble boiling.

At the initial time gasification process occurs in stages (Figure 4). When the liquid reaches the boiling point, the liquid mass is evaporated, and the CFT pressure increases. Boiling point increases and the boiling process is stopped. The process is repeated until the critical boiling point (126.25 K). As can be seen from the Figure 4 the intensity of the boiling with the course of time is reduced. This is due to the decrease of the temperature gradient between the CFT wall and the nitrogen in CFT. On reaching a critical temperature of the boiling process is stabilized.

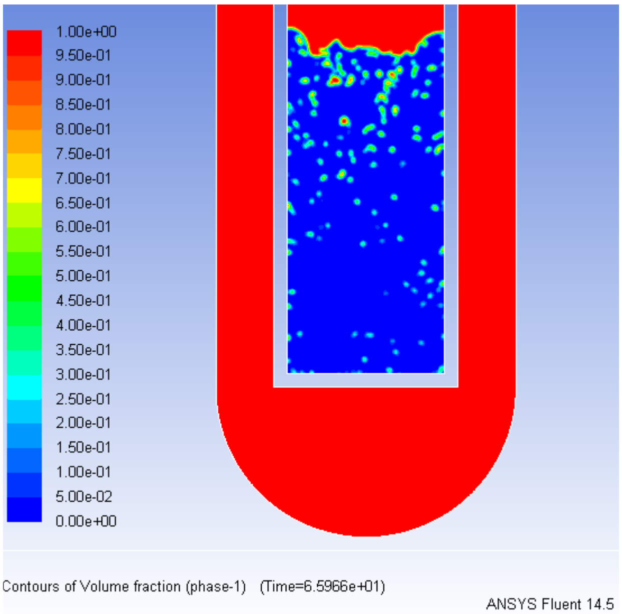


Figure 3. Nitrogen evaporation boundary.

A comparison of the calculation and experimental results dependencies [1,2] with the results of numerical modelling is presented on figure 5. As it can be seen from the plot, pressure rises quicker on the initial stage of the gasification (up to 0.9 MPa for 30 minutes). It is connected with intensive nitrogen transfer from liquid state to a gaseous one. Then pressure of the gas mass inside the tank increases due to increase of the evaporated mass of the gas. This causes boiling point "higher" and slowdown gasification process. 1440 hours of real time was spent on modeling of 3300 second of gasification process.

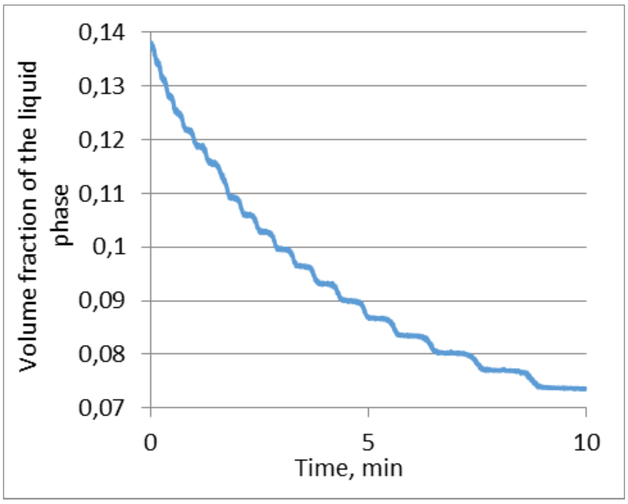


Figure 4. Volume fraction of the liquid phase depending on time.

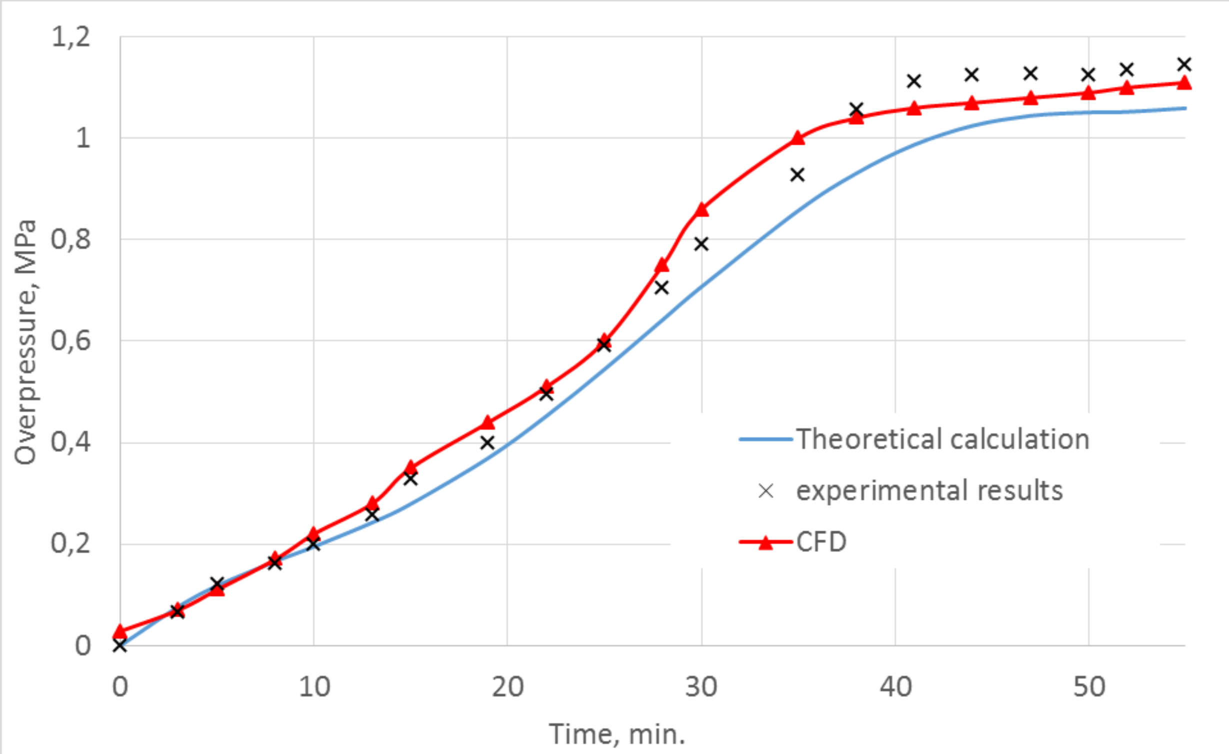


Figure 5. Comparison of the results of numerical modelling with experimental and analytical calculations.

5 Conclusions

The result of this research is calculation algorithm which allows to model processes of phase change in cryogenic systems with constant volume.

Algorithm is based on integration of the equation which describe thermodynamic properties of nitrogen depending on condition parameters in ANSYS Fluent software.

Method is verified by comparison of numerical calculation results with the results of experimental and analytical research carried out earlier. Deviation of results from experimental data is 5-10% which allows to make a conclusion that given method is suitable for modelling of heat processes in various cryogenic systems. Better results can be obtained by increase of thermodynamic properties number which are described in user-defined function.

This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the implementation of the Program ‘‘Research and development on priority directions of scientific-technological complex of Russia for 2014–2020.

References

1. A.I. Dovgyallo, S.O. Nekrasova, D.V. Sarmin, D.A. Uglanov, Appl. Phys., **4**, 54-59 (2013)
2. E.V. Blagin, A.I. Dovgyallo, S.O. Nekrasova, D.V. Sarmin, D.A. Uglanov, Applied Thermal Engineering, **101**, 537-544 (2016)
3. Y. Liu, T. Olewski, L.N. Véchot, Journal of Loss Prevention in the Process Industries, **35**, 125-134 (2015)
4. A. Hens, G.Biswas, S. De., Physics of Fluids, **26**, 012105 (2014)
5. X. Li, R. Wang, R. Huang, Y. Shi, Applied Thermal Engineering, **26**, 2425-2432 (2006)
6. M.H. Yuan, Y.H. Yang, T.S. Li, Z.H. Hu, International Journal of Heat and Mass Transfer, **51**, 1646-1657 (2008)
7. ANSYS Fluent Theory Guide, Ansys Inc.(2014)
8. J.H. Lee, Y.J. Kim, S. Hwang, Ocean Engineering, 2015, **106**, 77–86 (2015)
9. M. Ahammad, Y. Liu, T. Olewski, L.N. Véchot, M.S. Mannan, Industrial and Engineering Chemistry Research, **55**, 7548-7557 (2016)
10. Z. Xu, Y. Zhang, B. Li, J. Huang, International Journal of Heat and Mass Transfer, **101**, 614-619 (2016)
11. B. Fadhl, L.C. Wrobel, H. Jouhara, Applied Thermal Engineering, **60**, 122-131 (2013)