Injection of high-speed cryogenic liquid jets in a vacuum

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Abstract. The purpose of the present work is to numerically calculate cooling of thin deuterium jets to create units for receiving high-speed cryogenic monodisperse targets. The model of cryogenic jet outflow into the low pressure area has been created. Using PHOENICS software the temperature change of the surface and the interior of a jet over time for various external parameters has been investigated by the numerical method. The dependences of temperature changes of liquid deuterium jets have been obtained along the jet surface and along the radius depending on the jet diameter, velocity, initial jet temperature and pressure in the working chamber of units for receiving cryogenic monodisperse targets. The principal possibility of creating high-speed cryogenic monodisperse targets is shown. According to the calculations, at injection of thin liquid Deuterium jets with a speed of up to 100 m s⁻¹ into the working chamber with low pressure, the jets do not have time to freeze at a distance of up to 1 mm. The results of numerical calculations can be used to develop units for receiving high-speed cryogenic monodisperse targets.

1. Introduction

Development of accelerating equipment allowed receiving high-energy beams of elementary particles. The interaction of such beams with cryogenic monodisperse targets will provide unique opportunities for nuclear structure studies. The cryogenic monodisperse target is considered as the most perspective target for future experiment "PANDA" [1, 2]. "PANDA" experiment will address important questions of strong interaction within the project of the new European accelerator FAIR (Facility for Antiproton and Ion Research) in Darmstadt (Germany). The physical program of an experiment implies a research of fundamental problems of nuclear physics and the finding of new extreme states of matter.

In general, cryogenic monodisperse targets are flows of solid identical granules with small sizes produced of preliquefied gas. The dispersion of granules by size and speed does not exceed 0.1%.

The cryogenic monodisperse targets have the following unique properties:
1. Small size of monodisperse targets: diameter of 10 – 100 µm. Targets can be received from liquid hydrogen or its isotopes;
2. High luminosity of targets allows reducing experimental time and increasing statistical reliability of registration of new elementary particles;
3. Registration of scattering particles formed as a result of target nucleus disintegration is possible at an angle of 4π.
4. Reusability of a target: a target after interaction with a beam can be replaced by a new target.

The operation principle of the unit producing cryogenic monodisperse targets is presented in [3-5] and in figure 1.
Figure 1. The operation principle and possible unit of a cryogenic monodisperse target for the study of extreme matter forms: left – principle of operation, right – possible unit of the target.

A cryogenic liquid jet flows from the droplet generator into the first vacuum chamber, where the pressure is maintained equal to the triple point pressure for prevention of fast freezing of the overflowing jet. The liquid jet is exposed to a special disturbance created on the surface and breaks down into identical droplets, which, through the first vacuum sluice, enter the second vacuum chamber. The Rayleigh–Weber theory is taken as the theoretical basis of the target production [6]. In second chamber, due to intensive evaporation, the droplets are cooled, freeze, and turn into solid granules. The solid granules flow through the system of sluices are accelerated; and enter the working chamber, where they interact with the accelerating beam or laser beam. Several low-pressure chambers separated by sluices are used to reduce gas flow into the working chamber and to increase the granules speed. The granules enter the cooling trap and precipitate on its walls after interaction with high-energy beam.

The sluices (especially the first sluice connecting the triple point chamber to other vacuum chambers) exert the strongest influence on the flow stability [4,7,8]. Considerably reducing pressure in the first chamber or removing the first sluice and, at once directing the droplets into the second vacuum chamber, we can simplify the construction of the unit and reduce its size. The most important thing is that the liquid jet does not freeze.
The purpose of this work is to determine the relation between jet parameters and pressure in the first chamber, necessary for steady monodisperse disintegration of liquid Deuterium jets without their freezing. The model of cryogenic jet outflow into the low pressure area has been created. Using PHOENICS software the temperature change of the surface and the interior of a jet over time for various external parameters has been investigated by the numerical method.

2. The mathematical model of cryogenic liquid jet outflow into the low pressure area

The model implies that jet cooling is due substance evaporation from the surface. The evaporation of molecules from the jet surface is realized under the Hertz – Knudsen law. The reverse flow of molecules heats a jet and slows down evaporation. However the impact of this process on the jet temperature can be neglected since its contribution at evaporation to a vacuum does not exceed 5-10%.

The assumptions in the mathematical model are as follows:

– the flow is steady;
– the liquid velocity is rather small in comparison with acoustic velocity both in a jet and in the environment, therefore the approach of incompressible liquid is used;
– the liquid flow is laminar;
– liquid properties are constant regardless of temperature;
– the ambient medium is a strongly rarefied gas, so friction on the jet surface may be neglected;
– the liquid temperature determines non-equilibrium condition of the jet surface with rather intense evaporation;
– jet cooling occurs without a phase change.

Under the described assumptions, the equations of mathematical model can be written down as follows:

- continuity equation:

  \[ \text{div}(\vec{u}) = 0, \quad (1) \]

- Navier – Stokes equation with account for an axial symmetry in a cylindrical coordinate system:

  \[
  \rho \left( \vec{u} \cdot \nabla \right) \vec{u}_r = -\frac{\partial P}{\partial r} + \frac{\mu}{\rho} \left( \Delta u_r - \frac{u_r}{r^2} \right),
  \]

  \[
  \rho \left( \vec{u} \cdot \nabla \right) \vec{u}_z = -\frac{\partial P}{\partial z} + \frac{\mu}{\rho} \Delta u_z,
  \quad (2)
  \]

- energy equation:

  \[
  \rho C_p \left( \vec{u} \cdot \nabla \right) T = \lambda \Delta T,
  \quad (3)
  \]

where: \( \vec{u} \) is the velocity vector of a jet, \( u_r \) is the jet velocity on the radius \( r \), \( u_z \) is the jet velocity on axis \( z \), \( \mu \) is the viscosity coefficient, \( T \) is the jet temperature, \( \rho \) is the liquid density, \( P \) is the pressure in the working chamber, \( C_p \) is the heat capacity, and \( \lambda \) is the heat conductivity.

The system of equations (1) - (3) has the following boundary conditions:

- at an input to the working vacuum chamber the distribution of velocity and temperature of liquid jet is set:

  \[ \text{at } z = 0, \ u_r = 0, \ u_z = u_0(r), \ T = T_0; \quad (4) \]

- the symmetry conditions are set on the axis of symmetry:
at \( r = 0 \), \( \frac{\partial u_r}{\partial r} = 0 \), \( u_z = 0 \), \( \frac{\partial T}{\partial r} = 0 \); \hfill (5)

- on a jet surface at \( r = R(z) \) the zero tangent tension and the conditions of evaporation are set:

\[
\mu \left( \frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} \right) = 0, \quad -\lambda \frac{\partial T}{\partial r} = \chi \cdot j(T), \hfill (6)
\]

where: \( \chi \) is the the latent heat of evaporation; \( u_0 \) and \( T_0 \) is the speed and initial temperature of a jet at an input to the working chamber; \( R \) is the jet radius, \( \lambda \) is the heat conductivity, and \( j(T) \) is the the mass flow.

The mass flow in (6) can be calculated using different models.

In our case the generalized Hertz–Knudsen is used:

\[
j(T) = P_s(T_{surf}) \frac{M}{2\pi R_g T_{surf}} \frac{1}{v^2} - P_{ext} \frac{M}{2\pi R_g T_{ext}} \frac{1}{v^2}, \hfill (7)
\]

where: \( P_s(T_{surf}) \) is the saturation pressure on a jet surface; \( P_{ext} \) is the external pressure in the working chamber, \( T_{surf} \) is the temperature of surface, \( T_{ext} \) is the external temperature in the working chamber (see figure 1); \( M \) is the molecule mass of liquid, and \( R_g \) is the universal gas constant.

Thus, the closed system of equations with the corresponding initial and boundary conditions is received.

3. Calculation results

Using PHOENICS software [9] the dependences of temperature changes of liquid Deuterium jets along the jet surface and along the radius depending on the jet diameter, velocity, initial jet temperature and pressure in the working chamber are investigated by the numerical method.

The finite-difference approximation at a solution of motion equations was made by the method of control volume using the SIMPLEST method [9] to relate pressure and velocity. Calculations were carried out for Deuterium jets with initial temperature of 20 K. The thermophysical properties of Deuterium were taken from works [10,11].

Some calculation results for temperature changes in liquid Deuterium jets are presented in figures 2 - 5. It is shown that freezing of Deuterium jets does not occur instantly. The time of full freezing essentially depends on the jet diameter and on the velocity of outflow into the working chamber. According to the calculations, at the input of thin liquid Deuterium jets with a speed up to 100 ms\(^{-1}\) into the working chamber with low pressure, at a distance of up to 1 mm the jets do not have time to freeze and can be broken into monodisperse drops. Drops are cooled due to evaporation and turn into granules.
Figure 2. Temperature change of the surface and the interior of Deuterium jet with diameter of $10 \mu m$ and outflow velocity of $100 \text{ ms}^{-1}$ in the working chamber with pressure of $50 \text{ mbar}$.

Figure 3. Temperature change on the axis of the Deuterium jet with diameter of $10 \mu m$ and different outflow velocity in the working chamber with pressure of $50 \text{ mbar}$.

Figure 4. Temperature change on the axis of the Deuterium jet with diameter of $50 \mu m$ and different outflow velocity in the working chamber with pressure of $50 \text{ mbar}$.
Figure 5. Temperature change on the axis of Deuterium jet with diameter of 20 µm at the outflow velocity of 100 ms\(^{-1}\) in the working chamber with different pressure.

4. Conclusion

The model of the cryogenic liquid jet outflow into low pressure area has been developed to determine the parameters of steady monodisperse disintegration of liquid cryogenic jets. Using PHOENICS software [9] the dependences of temperature changes of liquid Deuterium jets along the jet surface and along the radius depending on the jet diameter, velocity, initial jet temperature and pressure in the working chamber have been investigated by the numerical method.

It may be inferred from the received results, that freezing of Deuterium jets does not occur instantly at thin cryogenic jets input into vacuum, and jets remain liquid for the time interval. The time of full freezing essentially depends on jet diameter and velocity of outflow into the working chamber. According to the calculations, at the input of thin liquid Deuterium jets with a speed up to 100 ms\(^{-1}\) into the working chamber with low pressure, at a distance of up to 1 mm the jets do not have time to freeze.

The program for determination of parameters of steady monodisperse disintegration of liquid cryogenic jets and results of numerical calculations can be used to create units for receiving high-speed cryogenic monodisperse targets.

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