Cooling of streams of hydrogen and deuterium in relation to units for receiving cryogenic monodisperse targets

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Abstract. The purpose of work is development of the model and carrying out numerical calculations of cooling of thin jets from hydrogen and deuterium as applicable to installations for receiving cryogenic monodisperse targets. For this purpose the model of the expiration of a cryogenic jet to the low pressure area is created, the change of surface temperature and an internal jet part at different external parameters with respect to time is investigated through numerical solutions in PHOENICS software. Dependences of temperature change of liquid jets from hydrogen and deuterium along jet surface and on radius depending on jet diameter, speed, initial jet temperature and pressure in the working chamber of installations for receiving cryogenic monodisperse targets are carried out. The basic possibility of creation of high-speed cryogenic monodisperse targets is shown. According to calculations, at input of thin liquid jets of hydrogen or deuterium with a speed up to 100 m/s in the working chamber with low pressure, jets at distance up to 1 mm do not manage to freeze and can be broken into monodisperse drops. Drops are cooled and become granules due to evaporation. The developed model, the program for determination of parameters of steady monodisperse disintegration of liquid cryogenic jets and results of numerical calculations can be used during creation of installations for receiving high-speed cryogenic monodisperse targets.

1. Introduction
Development of the accelerating equipment made possible receiving the high-energy beams of elementary particles. The interaction of such beams with cryogenic monodisperse targets will successful in solving a number of fundamental problems of nuclear physics. The cryogenic monodisperse target is considered as the most perspective target for future experiment "PANDA" [1-3]. "PANDA" is the unique experiment within the project of the new European FAIR accelerator in Darmstadt (Germany).

The physical program of an experiment is directed to a research of fundamental problems of nuclear physics, finding of new extreme states of matter.

In general, cryogenic monodisperse targets are the flow of solid identical granules (targets) with small sizes produced of preliquefied gas, with dispersion of granules by the sizes and speed which are not exceeding 0.1%.

The cryogenic monodisperse targets have the following unique properties:
1. The small size of monodisperse targets – diameter is from 10μm to 100 μm. Targets can be received from liquid hydrogen or its isotopes;
2. The high luminosity of targets allows to reduce experimental time and to increase statistical reliability of registration of new elementary particles;
3. A possibility of registration of particles scattering which are formed as a result of disintegration of target nucleus in angle $4\pi$.

4. Reusability of a target. The place of a target after interaction with a beam is taken by a new target.

The principle of operation of the installation producing cryogenic monodisperse targets is presented in [4-7] and in figure 1.

A liquid cryoagent 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 expiring jet.

The liquid jet is exposed to a special disturbance created on a surface and breaks down into identical droplets in this camera. The Rayleigh–Weber theory is taken as the theoretical basis of the target production [9]. As pressure in the vacuum chamber is low pressure about drops surface, liquid intensively evaporates. As a result the droplets are cooled, freeze and turn into solid granules. The solid granules flow through the system of sluices and additional vacuum chambers are accelerated and enter the working chamber, where they interact with the accelerating beam or laser beam. In order to reduce gas in leakage into the working chamber and to increase the granule velocity, several low-pressure chambers separated by sluices are used.

Upon interaction with the high-energy beam, the granules enter the cooling trap and precipitate on its walls.
Drawing data from [10-15] the sluices and especially the first sluice connecting the triple point camera to other vacuum chambers, exert the strongest influence on the target-flow stability. If considerably to reduce pressure in the first camera or to remove the first sluice and, to direct the droplets at once into the second vacuum chamber, we can simplify the construction of the installation and reduce its sizes. It is important that liquid cryogenic jet didn't freeze.

The purpose of this work is definition of the communication between jet parameters and pressure in the first camera that necessary for steady monodisperse disintegration of liquid jets from hydrogen and deuterium without their freezing.

For implementation of this purpose the model of the expiration of a cryogenic jet to the low pressure area is created, the change of surface temperature and an internal jet part at different external parameters with respect to time is investigated through numerical solutions in PHOENICS software.

2. The mathematical model of cryogenic liquid expiration into low pressure area

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

There are the following assumptions in the mathematical model:
– flow is steady;
– liquid speed is rather small in comparison with acoustic speed, both in a jet and in the environment therefore approach of incompressible liquid is used;
– liquid flow is laminar;
– liquid properties are constant which are not depending on temperature;
– environment which is rather rarefied therefore friction on jet surface can be neglected;
– jet surface is in a no equilibrium state due liquid temperature therefore there is rather intensive evaporation from a jet surface;
– cooling of a jet happens without phase transition.

Under the described assumptions, the equation of mathematical model can be written down as follows:
- continuity equation:

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

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

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

\[ \rho (\vec{u} \cdot \nabla) u_z = \frac{\partial P}{\partial z} + \frac{\mu}{\rho} \Delta u_z, \]  

- energy equation:

\[ \rho C_p (\vec{u} \cdot \nabla) T = \lambda \Delta T. \]

where: \( \vec{u} \) – a speed vector of a jet, \( u_r \) – jet speed on the radius, \( u_z \) – jet speed on axis z, \( \mu \) – coefficient of dynamic viscosity, \( T \) – jet temperature, \( \rho \) – liquid density, \( P \) – pressure in the working chamber, \( C_p \) – heat capacity, \( \lambda \) – heat conductivity.
The system of equations (1) - (3) has the following boundary conditions:

- on an input in the working vacuum chamber distribution of speed and temperature of liquid is set:

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

(4)

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

\[
\text{at } r = 0 \quad \frac{\partial u_z}{\partial r} = 0 , \quad u_r = 0 , \quad \frac{\partial T}{\partial r} = 0 ;
\]  

(5)

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

\[
\frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} = 0 , \quad -\chi \frac{\partial T}{\partial r} = \chi \cdot j(T),
\]  

(6)

where: \( \chi \) – the latent heat of evaporation; \( u_0 \) and \( T_0 \) - the speed and initial temperature of a jet on an input in the working chamber; \( R \) – jet radius.

The mass flow in (6) can be calculated using different models. In our case the Hertz–Knudsen model is used:

\[
j(T) = \left[ P_s(T) - P \right] \left( \frac{M}{2\pi R_g T} \right)^{\frac{1}{2}},
\]  

(7)

where: \( P_s(T) \) – saturation pressure on a jet surface; \( P \) – pressure in the working chamber (see figure 1); \( M \) – molecule mass of liquid, \( R_g \) – universal gas constant.

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

3. Calculation results

In software PHOENICS [16] the numerical calculations of temperature change of liquid jets of hydrogen and deuterium over length of a jet and on radius depending on jet diameter, speed, initial jet temperature and pressure in the working chamber were carried out. The finite-difference approximation at a solution of motion equations was made by method of control volume using the SIMPLEST method [16] for communication of pressure and speed. Calculations were carried out for jets of hydrogen and deuterium with an initial temperature of 20 K. The heat-physical properties of hydrogen and deuterium are taken from works [17-19].

Results of some calculations of temperature change liquid jets from hydrogen are presented in figures 2 - 5, and results for deuterium jets - in figures 6 - 9.

Calculation results states that freezing of jets of hydrogen and deuterium does not happen instantly. Time of full freezing essentially depends on jet diameter and speed of its expiration in the working chamber. According to calculations the thin liquid jets of hydrogen or deuterium with velocities higher 100 ms\(^{-1}\) into the working chamber are not frozen within a distance up to 1 mm and can be broken down monodisperse droplets. The droplets are cooled due to evaporation turn into granules.

Besides, follows from results of numerical calculations, at identical external parameters freezing of jets from deuterium happens for bigger time, than freezing of hydrogen jets. The received result can be explained with difference of heat-physical properties of hydrogen and deuterium.
Figure 2. Temperature change of the surface and internal part of 10 μm of hydrogen jet with expiration speed of 100 ms$^{-1}$ in the working chamber with pressure of 50 mbar

Figure 3. Temperature change of the internal part of hydrogen jet with diameter of 10 μm with different expiration speed in the working chamber with pressure of 50 mbar

Figure 4. Temperature change of the internal part of hydrogen jet with diameter of 50 μm with different expiration speed in the working chamber with pressure of 50 mbar
Figure 5. Temperature change of the internal part of hydrogen jet with diameter of 20 μm with expiration speed of 100 ms$^{-1}$ in the working chamber with different pressure.

Figure 6. Temperature change of surface and internal part of 10 μm of deuterium jet with expiration speed of 100 ms$^{-1}$ in the working chamber with pressure of 50 mbar.

Figure 7. Temperature change of the internal part of deuterium jet with diameter of 10 μm with different expiration speed in the working chamber with pressure of 50 mbar.
Figure 8. Temperature change of the internal part of deuterium jet with diameter of 50 μm with different expiration speed in the working chamber with pressure of 50 mbar

Figure 9. Temperature change of the internal part of deuterium jet with diameter of 20 mkm at the expiration speed of 100 ms⁻¹ in the working chamber with different pressure

4. Conclusion
The model of the expiration of cryogenic jet to the low pressure area is developed for determination of parameters of steady monodisperse disintegration of liquid cryogenic jets. In software PHOENICS the dependences of temperature change of liquid jets of hydrogen and deuterium along jet surface and on radius depending on jet diameter, speed, initial jet temperature and pressure in the working chamber received for installations for receiving cryogenic monodisperse targets due the numerical method.

Follows from the received results that at input of thin cryogenic jets into vacuum they do not freeze at once, and for some time remain liquid. Time of full freezing essentially depends on jet diameter and speed of its expiration in the working chamber. According to calculations the thin liquid jets of hydrogen or deuterium with velocities higher 100 ms⁻¹ into the working chamber are not frozen within a distance up to 1 mm and can be broken down monodisperse droplets. The droplets are cooled due to evaporation turn into granules.

Besides, follows from results of numerical calculations, at identical external parameters freezing of jets from deuterium happens for bigger time, than freezing of hydrogen jets.
The received result can be explained with difference of heat-physical properties of hydrogen and deuterium.

The developed model, the program for determination of parameters of steady monodisperse disintegration of liquid cryogenic jets and results of numerical calculations can be used during creation of installations for receiving high-speed cryogenic monodisperse targets.

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