HEAT-PHYSICAL PROBLEMS OF CRYOGENIC CORPUSCULAR TARGETS

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In order to solve heat-physical problems in producing cryogenic corpuscular targets, the special mathematical model is developed. In developing mathematical model the following physical processes and the phenomena were considered: capillary disintegration of jets from the liquid cryogen, convective heat exchange with environment, acceleration of drops in a gas stream, radiation heat exchange, cooling and freezing of drops. The model allows to define the general parameters of cryogenic corpuscular targets (temperature, speed, deviation from vertical) since the moment of reception of monodisperse drops of liquid cryogenic agent till the moment of reception of solid granules. Results of calculations on offered mathematical model were used at creation of a prototype of a cryogenic corpuscular target for spectrometer PANDA. Work was supported by grant RFBR 12-08-01170-a and grant MPEI.

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INTRODUCTION

Cryogenic corpuscular targets are monodisperse drops, or the solid monodisperse granules received at condensation of inert gases. The sizes of targets lie in the range of 10…1000 μm.

In high-energy physics the cryogenic corpuscular targets are applied to interaction research with proton beams of high luminosity [1]. Example of the physical program would be the experimental investigations within the FAIR project in Darmstadt, Germany. Experiments are supposed to be made on an anti-proton beam of an accumulative ring (HESR) with energy to 15 GeV.

The major element for realization of the physical program is the internal target. The detector PANDA placed in a ring HESR is a detector for registration of interactions on an internal target. The single target corresponding to all requirements of the detector PANDA is the cryogenic corpuscular target.

In laser technologies the cryogenic corpuscular targets are used for studying of laser acceleration of the charged particles (electrons, protons and heavy ions) [2]. Applications of laser acceleration will allow: to create the compact sources of protons for a radiography; will give the chance to make isotopes and to develop new methods in nuclear medicine; will allow to make experiments in nuclear physics on super-short periods.

Cryogenic corpuscular targets [3] have the following properties that distinguish them from targets of other types: high luminosity; renewability of a target; the small sizes of particles (diameter of granules doesn't exceed several tens microns); stability of sizes and movement trajectories – the dispersion in diameters and movement trajectories of granules doesn't exceed the fraction of a millimeter.

The theoretical basic for installations on receiving targets is Rayleigh's theory [4]. According to this theory the jet breaks up to drops with the minimum dispersion on the speed and the sizes (monodisperse drops) at a certain relationship between a jet speed, jet diameter and frequency of external excitation.

For monodisperse disintegration of cryogenic jets it is necessary to satisfy the following conditions in addition: to eliminate external vibrations from the cooling system; the liquid jet should be laminar; the temperature gradient at liquefaction of gas and formation of a liquid jet should be minimum [5, 6].

The operation of the installation on receiving cryogenic corpuscular targets is shown in Fig. 1. Constructional target elements are: the cryostat; the generator of spherical monodisperse drops; system of vacuum chambers and sluices; a trap.

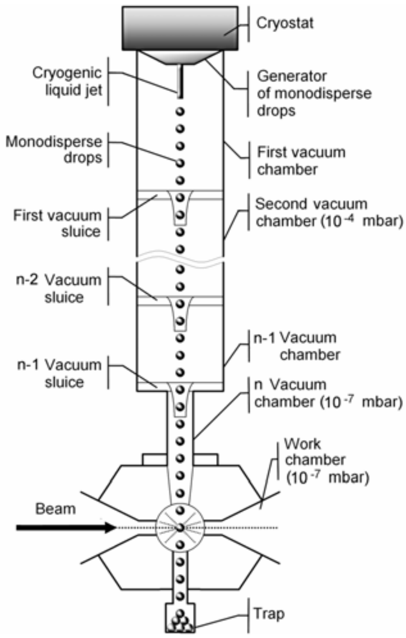

Fig. 1. Layout of the installation on receiving cryogenic corpuscular targets

The installation operates as following. The cryogenic liquid jet follows from the drops generator to the vacuum chamber. The jet breaks up to identical drops in response to external excitation imposed on the fluid jet. Due to intensive evaporation in the vacuum chamber take place cooling of drops, drops freeze and become solid granules.

Monodisperse solid granules through the system of locks (sluices) arrive in the working chamber where there is an interaction to a laser radiation. Sluices provide the minimum leaking in the working chamber. For reduction of leaking it is possible to use two and more vacuum chambers separated among themselves by sluices.

The special mathematical model is developed for the solution of heat-physical problems of producing cryogenic corpuscular targets.

1. MATHEMATICAL SIMULATION OF THE PROCESSES IN PRODUCING CRYOGENIC CORPUSCULAR TARGETS

By development of a mathematical model the following physical processes and the phenomena were considered: the capillary disintegration of jets from the liquid cryogen, the heat exchange with environment, the interaction of drops with gas flow in the sluice.

Previous work showed that the capillary disintegration of jets from the liquid cryogen differs from disintegration of normal liquids a little. Therefore for simulation of capillary disintegration were used the results of the linear Rayleigh`s theory.

There are the heat exchange connected to evaporation, convective and radiation in simulating processes of heat exchange of drops with environment. For cooling as the result of the evaporation in case of a free-molecular mode, i.e. Kn>>1 (Knudsen number), the mass flow from a drop surface was defined by the use of Hertz-Knudsen formula. And for cooling as the result of the evaporation in case of a continuous mode, i.e. Kn<<1, the mass flow from a drop surface is define by the use of Labuntsov-Kryukov formula for intensive evaporation.

The model of the sluice with an exponential profile was used in simulating of the drops interaction with gas flow. Such sluice allows to receive a gas current with the smallest pressure gradient along the sluice.

Using a mathematical model the program for calculation of drops parameters in different chambers was created. The program consists of one head program and nine subprograms.

From head part of the program takes place the recourse to different subprograms. The block-diagram of the program is shown in Fig. 2.

Calculation of heat-physical parameters of drops and granules happens as follows:

1. At first it is necessary to select gas from which we receive cryogenic corpuscular targets. Having addressed to the appropriate table of properties, it is possible to calculate the change of parameters of the drops received from any gases, for example, deuterium, argon, krypton or xenon.

2. After that, File 1 opens where the initial parameters of drops (for appropriate gas) and systems are read.

3. File 2 and File 3 open in turn, where necessary properties of solid, liquid and gaseous nitrogen or hydrogen are read.

4. The File res.dat and File res.xls open, in which results will be output afterwards.

5. It is determined the ordinal number of the chamber, which the drop moves, by:

a) If it is the first chamber, the subprogram Subroutine.8 calculates the length of not broken up part of the jet L_j at the chamber entrance*,* and then Subroutine 1 considers the temperature change dT/dx and radius change dR/dx of a drop when it is passing chamber.

b) If the chamber is not the first, the check proceeds:

- if it is the second chamber, it means that the drop moves in the vacuum sluice; thus there is an appeal to subprograms of Subroutine 6 and Subroutine 7 which calculate the sluice geometry and drop parameters in the sluice respectively;

- if is the chamber is not the first and not the second, it means that the drop moves in the subsequent chambers, and temperature change dT/dx and change radius on length dR/dx is calculated according to subprogram Subroutine1.

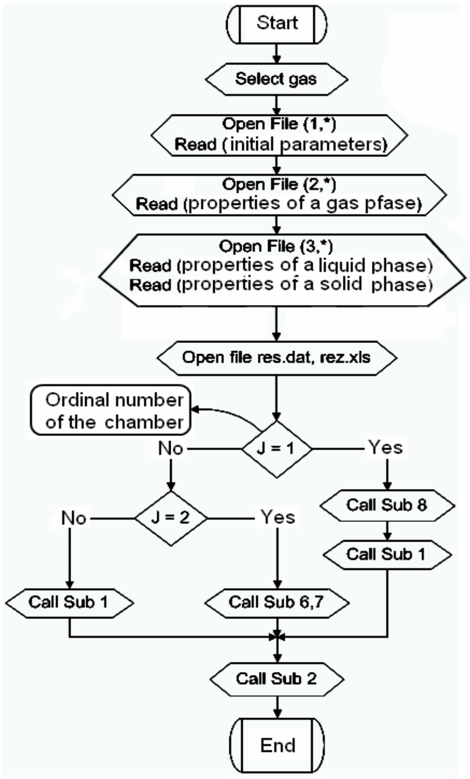

Fig. 2. Block-diagram of the program

6. Referring to the subprogram Subroutine 2, it is reporting to the user about errors if they exist.

7. The program is complete. After its completion in the files res.dat and res.xls all necessary results will be output. By these results the dependences diagrams of required parameters from coordinate in each chamber are plotted further.

Thus, having set on an input by initial parameters of drops and geometry of constructional elements of installation it is possible to define: T temperature, radius R, evaporation percent, and mass flow from a target surface in any chamber of the installation.

2. THE RESULTS OF CALCULATIONS OF HEAT-PHYSICAL TARGETS CHARACTERISTICS

The program was used for determination of heat-physical characteristics of targets from hydrogen and nitrogen in different chambers of installation on receiving targets for the detector PANDA. It is supposed that installation will consist of four chambers and one sluice located between the first and second chambers. Main geometrical characteristics of chambers: the first chamber (the chamber of triple point) has 5 cm length; the sluice between the first and second chambers has length of 10 cm and average diameter 300 μm; the second and third chambers have length of 30 cm.

Following are some results of calculations of heat-physical characteristics of cryogenic corpuscular targets from hydrogen for each chamber of the installation.

2.1. THE FIRST CHAMBER (CHAMBER OF TRIPLE POINT)

In the first chamber the process of formation of the identical hydrogen drops is carried out. There is suggested to support the jet parameters near triple point in order to avoid the premature freezing of a jet before disintegration it on the drops. For the jet with the diameter of 30 µm (drops diameter $D \approx 50$ µm) and the initial jet speed of vj = 11 m/s the length of not broken up part of the jet $Lj \approx 2{,}8$ mm.

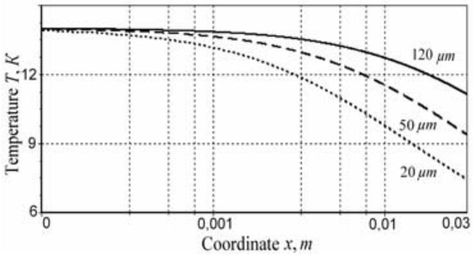

Fig. 3. Dependence of drop temperature on coordinate in first chamber

With the initial temperature of $T_н = 14$ K and chamber pressure of $P \approx 70\ldots100$ µbar the drop temperature decreases in case of movement a little, and drop radius practically doesn't change, the drop remains liquid. Dependence of temperature on longitudinal coordinate has been plotted in Fig. 3. Cooling of drops is carried out on very small section.

2.2. VACUUM SLUICE

From results of calculations follows that gas pressure in the sluice falls approximately twice, temperature decreases slightly (*ΔT~2 K*), and the Reynolds number increases from Re=3521 to Re=16970. Therefore, the mode of a current can be turbulent.

The estimates show that such gas flow can't destroy a hydrogen drop with diameter to smaller $D \approx 120$ µm, the capillary pressure exceeds pressure connected to external forces approximately on the order much. However such flow strongly accelerates a drop.

Results of calculation of change of drops speed on longitudinal coordinate in the sluice are shown in Fig. 4.

For drops with a diameter of 50 µm the final drop speed after passing of the sluice can be from 30 m/s (for sluices length of 5 cm) to 60 m/s (for sluices length of 20 cm). And only for drops with a diameter of 20 µm the final speed can reach 120 m/s with a length of the sluice of 20 cm. With a length of the sluice 10 cm the drops will have the speed of 90 m/s on an output from the sluice.

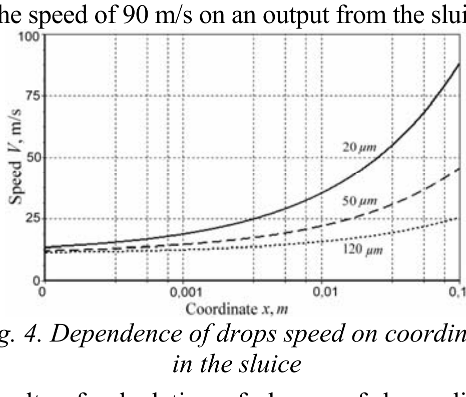

Fig. 4. Dependence of drops speed on coordinate in the sluice

Results of calculation of change of drops diameter and temperature on longitudinal coordinate in the sluice are shown in Fig. 5 and 6. In calculations the length of the sluice was of 10 cm. Such length provides input speed of microtargets in the accelerator necessary for the detector PANDA.

It will be noted that the freezing of drops take place with the motion in the sluice. The drops with the diameter of 120 µm freeze on a section from 1.3 cm to 2.6 cm from the sluice beginning. Drops of the smaller size freeze even quicker. Drops temperature is reduced to T ≈ 10 K, and the drops radius decreases by 5%.

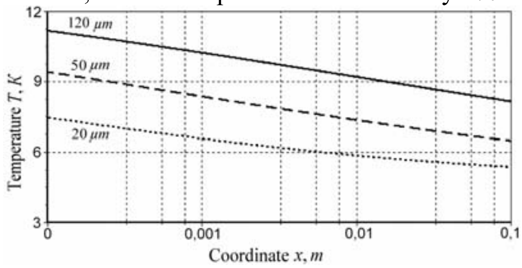

Fig. 5. Dependence of drops temperature on coordinate in the sluice

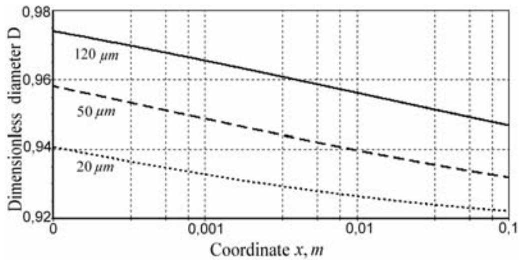

Fig. 6. Dependence of drops diameter on coordinate in the sluice

2.3. SECOND AND THIRD CHAMBERS

In the second and third chambers the drops which became solid granules, move in the vacuum conditions. There is some distinction between chambers. In the second chamber the walls cool, and in the third chamber the walls are hot. Last it is caused by features of spectrometer construction PANDA.

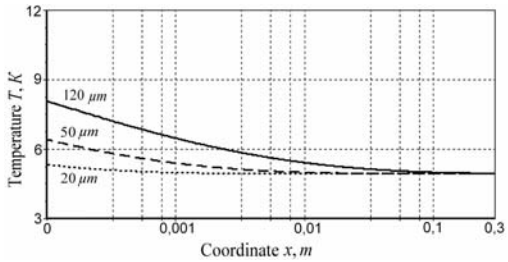

Fig. 7. Dependence of drops temperature on coordinate in the second chamber

Results of calculation of change of granules temperature on longitudinal coordinate in the second chamber are shown in Fig. 7. Input parameters are the parameters calculated for the previous chamber. From the given results it is visible that there is a sharp reduction of granules temperature due by evaporation in the second chamber on an initial section, however only small part of granules (~0.5% from radius) have time to evaporate. The change of radius and temperature of granules terminates at distance about 20 cm from an input in the chamber. The outlet temperature of the chamber is T ≈ 4.85 K.

Results of calculation of change of granules temperature on longitudinal coordinate for the third chamber are shown in Fig. 8. There is radiation heating of drops from warm walls in the third chamber.

Granules temperature quickly increases and reaches a stationary value already at distance of 10 cm from an input in the chamber. Under the influence of radiation the granule begins to evaporate. The granule with the diameter of 50 μm decreases by only 0.5% at distance of 50 cm from an input in the chamber. Granule speed in the chamber is 44 m/s.

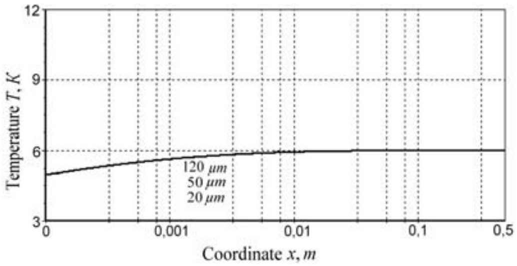

Fig. 8. Dependence of drops temperature onl coordinate in the third chamber

CONCLUSIONS

The analysis of the received results allows to draw the conclusion on existence of the problems requiring additional researches.

It is the problem of determination of drops parameters during the passing of the vacuum sluice and extracting drops into vacuum. The calculations indicates that the Reynolds number can significantly exceed critical Re =2300 value for some sluices, and, therefore, the gas flow can be highly turbulent. It may happen that a path of drops deviate from an installation axis.

Besides, according to results of calculations,it is possible situation in case of supercritical differential pressures near the output section of a nozzle when the drop passes a compression discontinuty. By our estimates, the strength of solid hydrogen and nitrogen sufficient to avoid adiabatic explosion when the drop passes a compression discontinuty. However the liquid or not completely frozen granule can desintegrates in these conditions.

In calculations in determining the freezing moment of drops the possible overcooling of drops isn't considered. Thus, it is possible that the drop overcools in the vacuum sluice and doesn`t freeze, and the probability of adiabatic explosion increases.

Results of calculations on offered mathematical model were used at creation of a prototype of a cryogenic corpuscular target for spectrometer PANDA.

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REFERENCES

1. W. Erni, I. Keshelashvili, A. Aab, et al. Technical design report for the PANDA (Anti Proton Annihilations at Darmstadt) Straw Tube Tracker Strong interaction studies with antiprotons // *Germany, The European physical journal.* 2013, A 49(2), p. 25.
2. J.M. Dawson. Plasma Particle Accelerators // *Scientific American.* 1989, v. 260, № 3, p. 54-61.
3. A. Bukharov, M. Buscher, A. Gerasimov, et al. Using of cryogenic corpuscular targets in the experiments for particle acceleration and in the experiments for study of the interaction of laser radiation with matter // *The 11th Cryogenics 2010 - IIR International Conference PUBLISHED BY ICARIS Ltd.* Praha Czech Republic ISBN 978-2-913149-77-9 ISSN 0151-1637 IIR Code: 2010-3, p. 51-56; *Method of receiving a cryogenic corpuscular target and the device for its implementation*. Russian Federation Patent № 2298890 RU.
4. Lord Rayleigh. On the instability of a cylinder of viscous liquid under capillary force // *Phil. Mag.* 1892, v. 34, p. 145-154.
5. A.V. Bukharov, W. Borgs, V.N. Afanasyev, et al. *Cryogenic corpuscular targets. Generation of hydrogen granules: calculation of the basic constructional elements, the experimental bench, tests:* Preprint of ITEP № 9-05.2005.
6. A. Bukharov, M. Buscher, A. Gerasimov, et al. Dynamics of Cryogenic Jets: Non Rayleigh Breakup and Onset of Non Axisymmetric Motions // *Phys. Rev. Lett.* 100:174505, 2008.

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ТЕПЛОФИЗИЧЕСКИЕ ПРОБЛЕМЫ КРИОГЕННЫХ КОРПУСКУЛЯРНЫХ МИШЕНЕЙ

А.В. Бухаров, Е.В. Аметистов, А.Ф. Гиневский, М.А. Бухарова

Для решения теплофизических проблем получения криогенных корпускулярных мишеней разработана специальная математическая модель, в которой были учтены: капиллярный распад струй жидкого криоагента, конвективный теплообмен с окружающей средой, ускорение капель в газовом потоке, радиационный теплообмен, охлаждение и замерзание капель. Модель позволяет определять основные параметры мишени (температуру, скорость, отклонение от вертикали) начиная с момента получения монодисперсных капель жидкого криоагента до момента получения твёрдых гранул. Результаты расчётов по предлагаемой математической модели были использованы при создании прототипа криогенной корпускулярной мишени для спектрометра PANDA. Работа была поддержана грантом РФФИ 12-08-01170-а и грантом МЭИ.

ТЕПЛОФІЗИЧНІ ПРОБЛЕМИ КРІОГЕННИХ КОРПУСКУЛЯРНИХ МІШЕНЕЙ

А.В. Бухаров, Є.В. Аметістов, А.Ф. Гіневський, М.А. Бухарова

Для вирішення теплофізичних проблем отримання кріогенних корпускулярних мішеней розроблена спеціальна математична модель, у якій були враховані: капілярний розпад струменів рідкого кріоагента, конвективний теплообмін з довкіллям, прискорення крапель у газовому потоці, радіаційний теплообмін, охолодження і замерзання крапель. Модель дозволяє визначати основні параметри мішені (температуру, швидкість, відхилення від вертикалі) починаючи з моменту отримання монодисперсних крапель рідкого кріоагента до моменту отримання твердих гранул. Результати розрахунків з запропонованої математичної моделі були використані при створенні прототипу кріогенної корпускулярної мішені для спектрометра PANDA. Робота була підтримана грантом РФФД 12-08-01170-а і грантом МЕІ.