EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 325

COMBINED THERMO-HYDRAULIC ANALYSIS OF A CRYOGENIC JET

M. Chorowski

Abstract

A cryogenic jet is a phenomenon encountered in different fields like some technological processes and cryosurgery. It may also be a result of cryogenic equipment rupture or a cryogen discharge from the cryostats following resistive transition in superconducting magnets. Heat exchange between a cold jet and a warm steel element (e.g. a buffer tank wall or a transfer line vacuum vessel wall) may result in an excessive localisation of thermal strains and stresses. The objective of the analysis is to get a combined (analytical and experimental) one-dimensional model of a cryogenic jet that will enable estimation of heat transfer intensity between the jet and steel plate with a suitable accuracy for engineering applications. The jet diameter can only be determined experimentally. The mean velocity profile can be calculated from the fact that the total flux of momentum along the jet axis is conserved. The proposed model allows deriving the jet crown area with respect to the distance from the vent and the mean velocity profile along the jet axis. A simple formula to assess convective heat exchange between the jet and a solid obstacle has been proposed and experimentally verified.

Wroclaw University of Technology, Institute of Power Engineering and Fluid Mechanics,
50-370 Wroclaw, Poland

Presented at the 1999 Cryogenic Engineering and International Cryogenic Materials Conference
(CEC-ICMC'99), 12-16 July 1999, Montreal, Canada

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 1 December 1999

COMBINED THERMO-HYDRAULIC ANALYSIS OF A CRYOGENIC JET

M. Chorowski

Wroclaw University of Technology
Institute of Power Engineering and Fluid Mechanics
50-370 Wroclaw, Poland

ABSTRACT

A cryogenic jet is a phenomenon encountered in different fields like some technological processes and cryosurgery. It may also be a result of cryogenic equipment rupture or a cryogen discharge from the cryostats following resistive transition in superconducting magnets. Heat exchange between a cold jet and a warm steel element (e.g. a buffer tank wall or a transfer line vacuum vessel wall) may result in an excessive localisation of thermal strains and stresses. The objective of the analysis is to get a combined (analytical and experimental) one-dimensional model of a cryogenic jet that will enable estimation of heat transfer intensity between the jet and steel plate with a suitable accuracy for engineering applications. The jet diameter can only be determined experimentally. The mean velocity profile can be calculated from the fact that the total flux of momentum along the jet axis is conserved. The proposed model allows deriving the jet crown area with respect to the distance from the vent and the mean velocity profile along the jet axis. A simple formula to assess convective heat exchange between the jet and a solid obstacle has been proposed and experimentally verified.

INTRODUCTION

The paper describes a turbulent jet of a cryogenic fluid issuing from a nozzle into a space filled with the same or different fluid. The phenomenon may be encountered in some technological processes like grinding, where cryogenic cooling seems to have the edge on other coolants.[1] It is used in cryosurgery. The jet may be also a result of cryogenic equipment break or malfunctioning and create danger to people or equipment in its neighbourhood. It may also be observed inside buffer tanks as a result of a rapid cryostat discharge following resistive transitions in superconducting magnets.[2, 3] In all cases it is important to assess the jet basic hydrodynamic features as well as a convective heat exchange intensity between the jet and a solid object.

The form of the turbulent region in the jet results from similarity considerations and is conical. The diameter of the jet at a given distance from the nozzle cannot be defined theoretically but must be determined from experiments.[4] The velocity in the jet results from the fact that the total steady state flux of momentum through a spherical surface centred at the nozzle must be independent of the sphere radius.

Test Facilities

Figure 1 shows the conceptual scheme of the test rig used during the experiment. The vent was designed to allow changes of the orifice diameter (1, 3 and 5 mm). Gaseous nitrogen was supplied from a 0.15 m^3 dewar vessel of maximum pressure 2 MPa, while helium was vented from a 4.2 m^3 container of 0.33 MPa . The initial temperature of the gases was 115 K for nitrogen and 35 K for helium. The velocity at the outlet was equal to the speed of sound for both nitrogen and helium. Both fluids were vented to air at a temperature of 290 K and 275 K for nitrogen and helium respectively.

The jet temperature was measured by type T thermocouples (Cu-CuNi) placed on a thin wire along the jet axis, the velocity was measured by means of a vane anemometer of a 30 mm diameter, both at different distances from the vent. To measure the jet diameter, a simple device was used in form of a rod with light flaps located every 0.025 m. A flowing jet caused the flaps to move enabling an estimation of the jet diameter.

RESULTS

Diameter of the jet

The summary of the jet diameter measurements is shown in Figure 2. The cone angle does not depend on the orifice diameter or the gas vented but is constant and of about 13 degrees.

Temperature profile along the jet axis

During venting of nitrogen and helium, the temperature along the jet axis was measured. The results are shown in Figure 3. The orifice diameter was 3 mm and 5 mm for nitrogen, and 3 mm for helium. The results show that the biggest intake of air occurs in the first region of the jet. During the first 0.2 m the jet temperature rises approximately by 160 K for nitrogen and 180 K for helium.

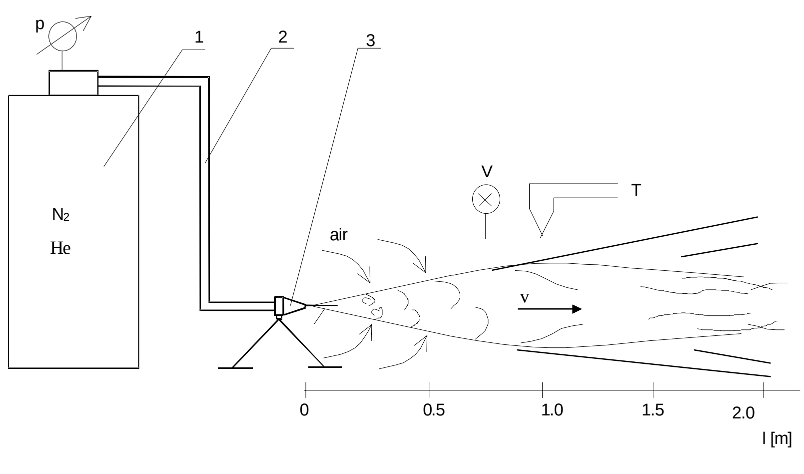

Figure 1. Test rig, 1 – LN2 / LHe vessel, 2 – transfer line, 3 – orifice, p – pressure gauge, v – velocity meter (vane anemometer), T – temperature sensor (thermocouple).

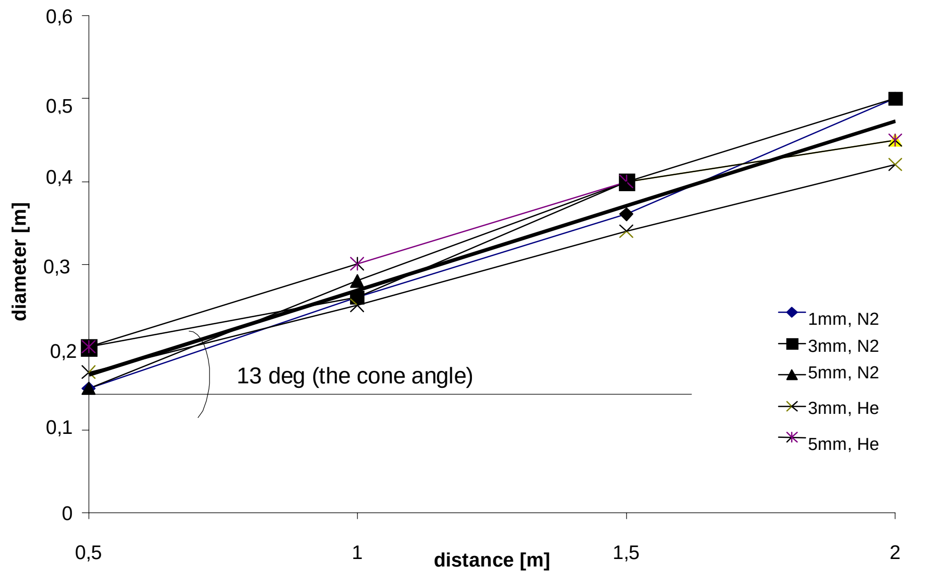

Figure 2. Jet diameter measured along the axis.

In the following 1.5 m the temperature rises only by about 15 K and 40 K, respectively. The jet temperature increase results from the mixing process and it approaches the temperature of the environment.

Velocity profile along the jet axis

The jet mean velocity decreases along the jet axis what directly results from the conservation of momentum principle, with the basic assumption that the momentum of the air entrained in the jet is negligible and the control surface can be defined as the actual cross section of the jet:

$$\frac{d(\rho \cdot v^2 \cdot A)}{dx} = 0 \tag{1}$$

where: ρ - cryogen density; v - cryogen mean velocity, A- jet cross section area, x – distance from the vent,

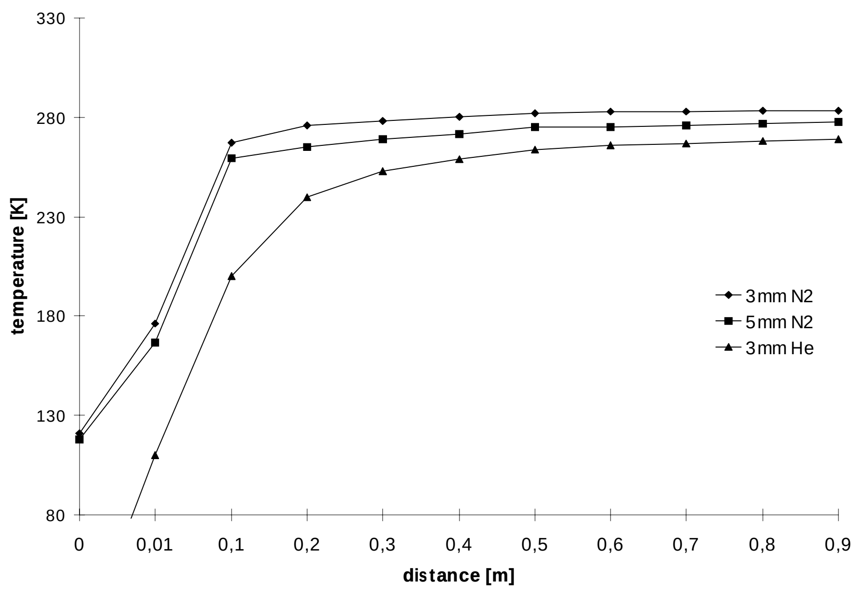

Figure 3. Temperature profile measured along the jet axis.

The relation defining velocity *v(x)* variation along the jet axis is as follows:

$$v(x) = \sqrt{\frac{\rho_1 \cdot v_1^2 \cdot A_1}{\rho(x) \cdot A(x)}} \tag{2}$$

where subscript 1 denotes the jet outlet cross section.

A(x) is a jet cross section area dependent on the distance from the orifice outlet and:

$$A(x) = \frac{\pi \cdot (D(x))^2}{4} \quad , \qquad D(x) = 0.23 \cdot x \tag{3}$$

where: *D(x)* is the jet diameter and the number 0.23 results from the fact that a jet cone equals 13 degrees- compare Figure 2.

In the zone close to the orifice the cryogen undergoes a non-equilibrium free expansion until its pressure is equalised with the environment. The zone ends at *x'* and the distance depends on the pressure ratio. For the purpose of this analysis we assume that for *x* less than *x'* the jet mass flux is constant and no air is entrained – see Figure 4. The assumption enables to calculate the distance *x'* and then at larger distances the jet mean velocity from the gas conditions at the nozzle and the entrained gas parameters. The distance *x'* is of about 10 times the orifice diameter.

The jet density at the distance from the vent $x > x'$ is given by

$$\tilde{n}(x) = g_{air}(x) \cdot \tilde{n}_{air}(x) + g_{cr}(x) \cdot \tilde{n}(x)_{cr} \tag{4}$$

where: ρ_{cr} , ρ_{air} are the densities of the cryogen and air for $T = T(x)$ and g_{air} , g_{cr} are mass concentrations of air and cryogen in the jet, *x* denotes the distance from the vent.

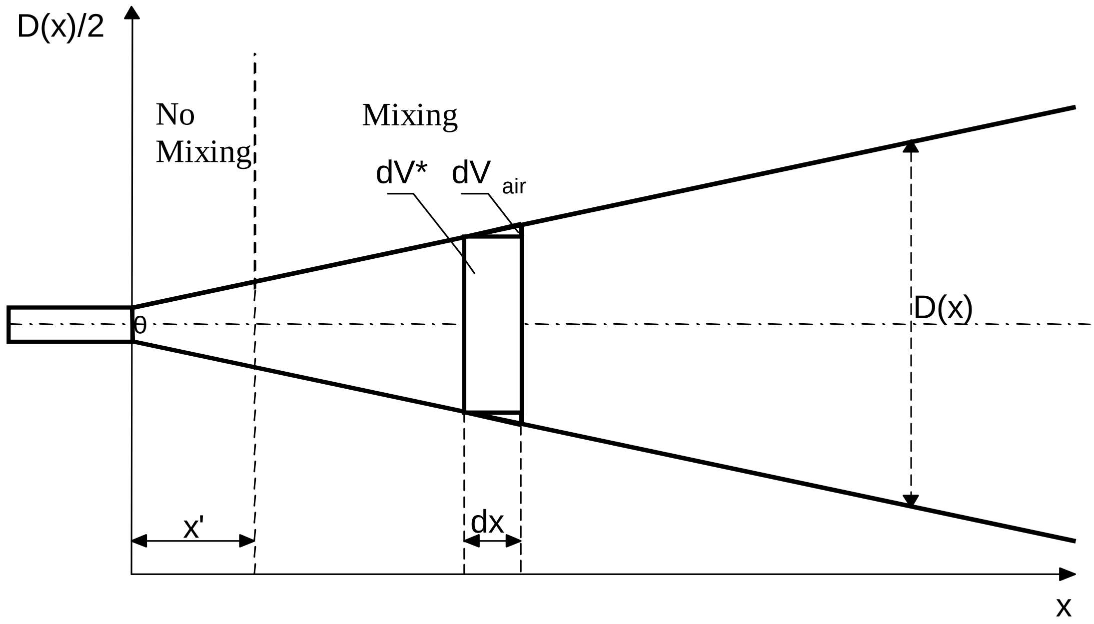

Figure 4. Schematic representation of a turbulent cryogenic jet development.

The average mass concentration of air in the jet at the distance $x > x'$ is given by Eq. (5, 6) resulting from the conical geometry of the jet.

$$g_{air}(x+dx) = \frac{dM_{air} + M(x)\cdot g_{air}(x)}{M(x+dx)} \tag{5}$$

where: dM_{air} is the mass of the air taken in the distance interval dx, $M(x)$ is the total mass of the jet at the distance x, and:

$$dM_{air} = \frac{dV_{air}}{dx}dx\cdot\rho_{air} \quad , \quad M(x+dx) = \frac{dM_{air}}{dx}dx + M(x) \quad , \quad \frac{dV_{air}(x)}{dx} = \frac{dV(x)}{dx} - \frac{dV^*(x)}{dx} \tag{6}$$

and $dV = dV_{air} + dV^*$ (compare Figure 4).

The calculated and measured nitrogen and helium velocity distribution along the jet axis is presented in Figure 5 and 6.

Heat transfer

The objective of this experiment was the estimation of the heat flux between the cryogenic jet and a solid obstacle represented here by a carbon steel plate, simulating a wall of a quench buffer vessel.[2] The conceptual scheme of the test rig is shown in Fig. 7. The diameter of the plate was 0.116 m and its thickness 0.02 m. The mass of the plate was 1.5 kg. The sides and back part of the plate were insulated. The temperature of the plate was

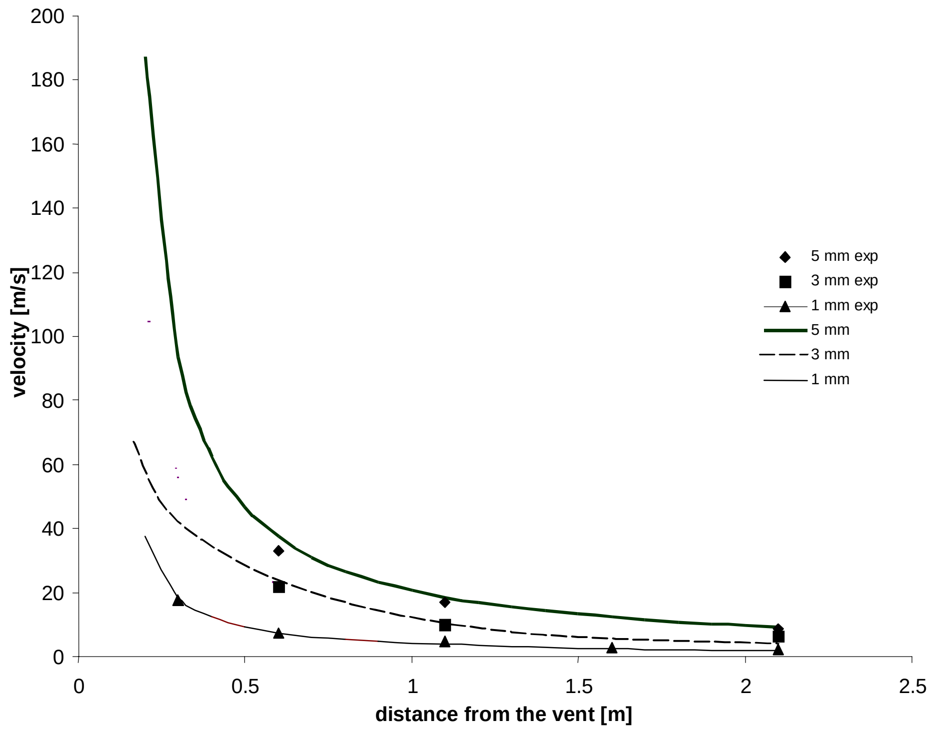

Figure 5. Nitrogen velocity along the jet axis (measured - dots and calculated - lines).

measured in three points. Due to the good thermal diffusivity of carbon steel, temperature differences across the plate cross-section were small and the average value was taken for further considerations.

The heat flux between the steel plate and the jet was calculated according to the formula:

$$\dot{Q} = M \cdot c_p \cdot \frac{\Delta T}{\Delta t} \tag{7}$$

where M – denotes mass of the plate, ΔT is an average temperature drop during the time interval Δt, c_p stands for heat capacity of the steel plate.

A heat transfer coefficient h results from Eq. (7) and is equal to:

$$h = \frac{\dot{Q}}{A_p \cdot (T_p - T_J) \cdot \Delta t} \tag{8}$$

where: T_p is the average steel plate temperature and T_J is the jet temperature close to the plate, A_p stands for the front area of the plate.

To describe the process of convective heat transfer between steel plate and jet the following formula has been proposed:

$$Nu = c \cdot Re^n \tag{9}$$

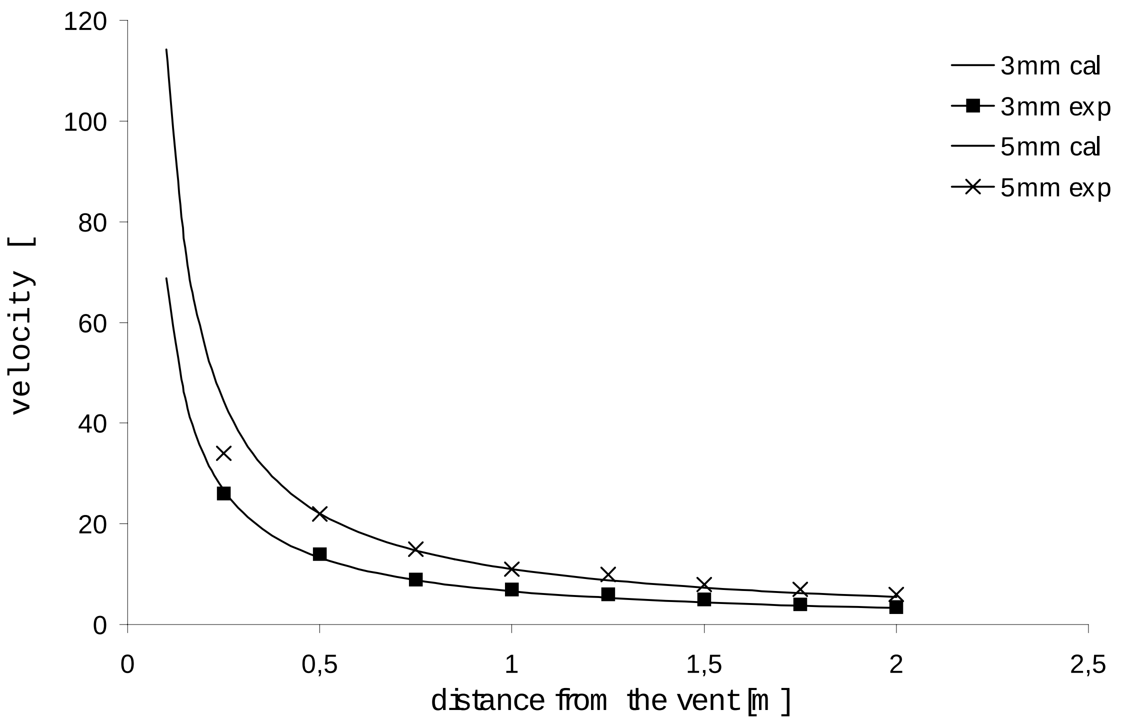

Figure 6. Helium velocity along the jet axis (measured - dots, calculated - lines).

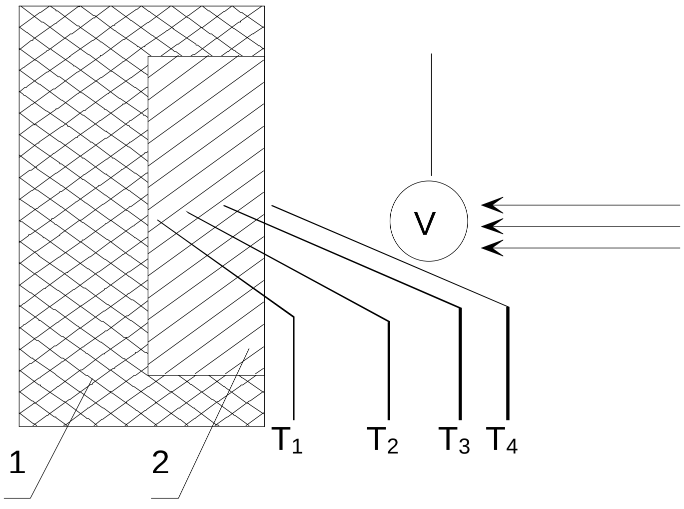

Figure 7. Conceptual scheme for heat transfer measurements between the jet and steel plate, 1 – insulation, 2 – steel plate, T – thermocouples (T_1-T_3 – steel plate, T_4 – boundary layer), V – vane anemometer.

The experimentally determined coefficients *c* and *n* are 0.107 and 0.77, respectively.

$$Re = \frac{v \cdot \rho \cdot \sqrt{A}}{\eta} \quad , \quad Nu = \frac{h \cdot \sqrt{A}}{\lambda} \tag{10}$$

where: ρ- jet density, *A*- jet cross section area, η- jet viscosity, λ- jet conductivity, *Nu*- Nusselt number, *Re*- Reynolds number, *h*- heat transfer coefficient.

Figure 8 shows the calculated heat transfer coefficient for nitrogen and helium jets as a function of the distance from the vent.

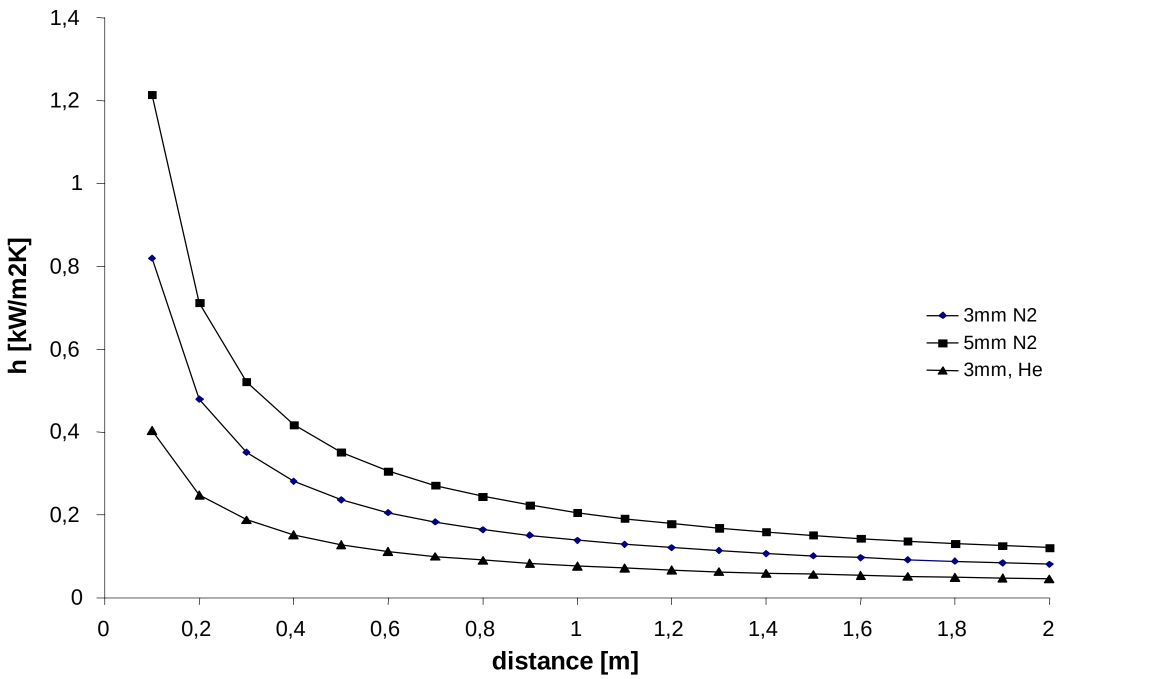

Figure 8. Calculated (Eq. 9) convective heat transfer coefficient versus distance from the vent (venting to air at the temperature of 290 K), initial conditions were: for nitrogen – pressure 1 MPa, saturated temperature, for helium – pressure 0.2 MPa, temperature 60 K.

CONCLUSIONS

It follows from literature data and the performed experiments that the cone angle of a cryogenic jet can be considered as constant and of about 13 degrees. It does not depend either on the orifice diameter or on the gas vented.

At distances large compared with the nozzle diameter (about 0.2 m in the studied case) the mean velocity can be calculated from the model based on the fact that the total flux of momentum along the jet axis is conserved.

At distances large compared with the nozzle diameter heat transfer between jet and any solid object can be calculated using a dimensionless Eq. (9).

A turbulent cryogenic jet is an efficient mixing mechanism ensuring fast equalising of the jet temperature and the environment.

ACKNOWLEDGEMENTS

The work reported here was conducted under contract with CERN. The author would like to thank W. Erdt, Ph. Lebrun and L. Tavian for fruitful discussions and support of the study.

REFERENCES

1. S. Paul and A.B. Chattopadhyay, Effects of cryogenic cooling by liquid nitrogen jet on forces, temperature and residual stresses in grinding steels, *Cryogenics*, 35,8 (1995).
2. M. Chorowski and B. Skoczen, Thermo-mechanical analysis of cold helium injection into gas storage tanks made of carbon steel following resistive transitions of LHC magnets, Proc. Of the XVII ICEC, Inst. of Phys., Bristol and Philadelphia (1998), p. 755.
3. M. Chorowski, P. Grzegory, G. Konopka, Thermo-hydraulic analysis of a cryogenic jet: application to helium recovery following resistive transitions in the LHC, LHC Project Note 177, CERN, Geneva, 1999.
4. L.D. Landau and E.M. Lifshitz, “Fluid Mechanics,” Pergamon Press, Oxford (1966).