

Study of Cavitation Characteristics of a Cryogenic Pump by Computational Fluid Dynamic Methods

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Abstract. This article is devoted to the study of cavitation characteristics of a centrifugal cryogenic pump. Hydrodynamic simulation of the fluid flow in the wet part of the pump was carried out in order to determine the output parameters of the pump. A critical increase in the temperature of liquid helium, corresponding to the beginning of cavitation in the pump, was determined. A cavitation performance of the pump was built under given operating conditions and a critical NPSH was determined.

Introduction

In the modern world, cryogenic products are an integral part of many technological processes in the energy sector, oil and gas industry, metallurgy, astronautics, chemical industry, medicine and many other areas of human life [1–4]. Cryogenic products include substances or mixtures of substances at cryogenic temperatures (below 120K). One of the most important cryogenic products is liquid helium. It is used as a refrigerant to obtain and maintain ultra-low temperatures [5–8]. For example, helium is used to cool superconducting magnets in various scientific and technical installations. The low boiling point of helium (4.23K at normal atmospheric pressure) imposes certain restrictions on the design and operation of technical devices used in units with this cryoproduct [9–12]. So, often to maintain the required temperature of helium, additional cooling of the equipment with liquid nitrogen is used. Fig. 1 shows a cryostat for liquid helium, which is a Dewar vessel, the inner vessel of which is filled with liquid helium, and the outer one is cooled with liquid nitrogen.

A pump is located in the inner vessel of the cryostat; it supplies helium directly to the cooling system of superconducting magnets. The pump can be centrifugal or displacement, depending on the required flow and pressure values in the system.

An important problem in the operation of such a pump is the possibility of cavitation in it. Even with the smallest change (increase) in the temperature of liquid helium in a vessel, the pump can switch to super-cavitation mode, which will negatively affect the operation of the entire system. Therefore, it is very important to calculate the operation of the pump on liquid helium in the permissible temperature range, and accurately determine the moment of the beginning of cavitation.

In this work, we studied the cavitation characteristics of a BNHEP-35-000 centrifugal pump manufactured by Barber-Nichols Inc., USA. This is a 240 W submersible pump with overhung impeller. Fig. 2 shows the general view of the pump and its schematic drawing.



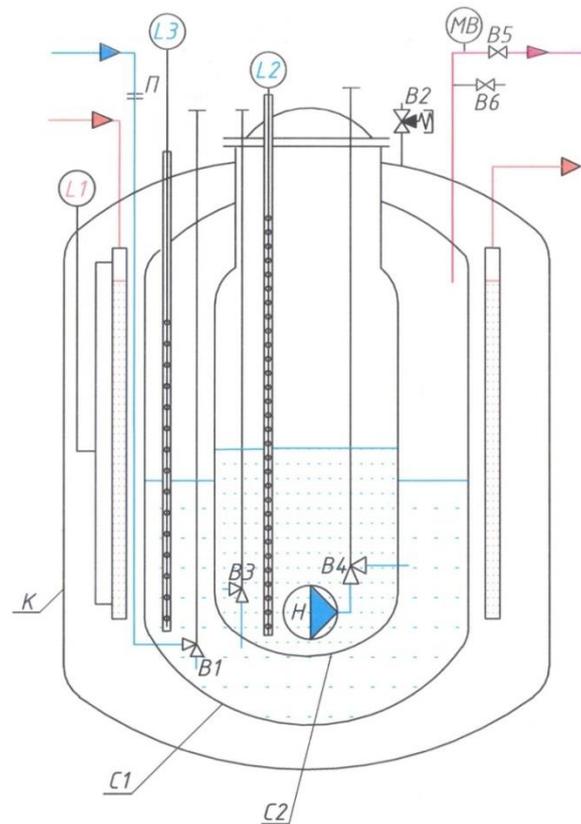


Figure 1. Cryostat for liquid helium. (K — cryostat, C1 — external vessel of the cryostat, C2 — internal vessel of the cryostat, L1 — differential pressure gauge, L2 — level sensor in the internal vessel, L3 — level sensor in the external vessel, B1 — valve for filling the external vessel, B2 — valve for evacuation and protection of the insulating chamber from pressure rise, B3 — valve for filling the internal vessel, B4 — valve for regulating the supply of the pump, B5 — valve for the return flow, B6 — valve for evacuating the helium chamber of the cryostat, MB — vacuum pressure gauge, P — plug of the liquid helium filling line)

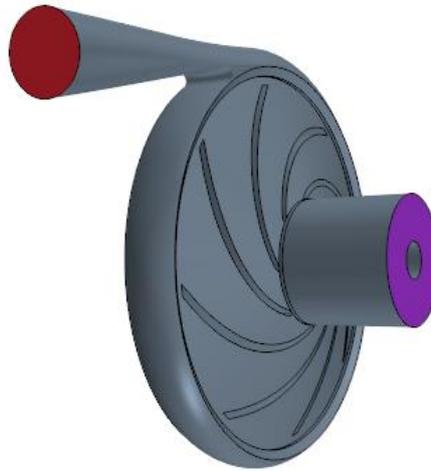


Figure 3. Wet part of the BNHEP-35-000 pump (pockets are not shown).

For this problem, it was decided to simulate a single-phase turbulent flow. To verify the flow regime, the Reynolds number for the flow at the pump inlet was calculated.

$$Re = \frac{\rho v D}{\eta} = \frac{125.4 \cdot 1.12 \cdot 0.03}{2.94 \cdot 10^{-6}} = 1.4 \cdot 10^6, \text{ which corresponds to turbulent mode. In the simulation, we}$$

used the equations of hydrodynamics for an incompressible fluid ($\rho = const$).

The mass conservation equation (continuity equation):

$$\left(\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} \right) = -\frac{1}{\tilde{p}} \frac{\partial \tilde{p}}{\partial x_j} + \mathfrak{g} \frac{\partial^2 \tilde{u}_i}{\partial x_j^2},$$

where $\tilde{u}_i = U_i + u_i$ — instantaneous value of velocity (U_i is the average component, u_i is the fluctuation component);

$\tilde{p} = P + p$ — instantaneous value of pressure (P is the average component, p is the fluctuation component);

The Reynolds-averaged Navier–Stokes equations:

$$\rho \left(\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left(T_{ij}^{(v)} - \rho u_i u_j \right),$$

where U, P — averaged values of velocity and pressure, respectively;

$T_{ij}^{(v)} = 2\mu \tilde{s}_{ij}$ — viscous stress tensor for incompressible fluid;

$\tilde{s}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right)$ — instant strain velocity tensor;

$\rho u_i u_j$ — Reynolds stresses.

In addition, a semi-empirical $k-\omega SST$ turbulence model was chosen to close the system of equations. It includes:

kinetic energy of turbulence transfer equation

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta k \omega + \frac{\partial}{\partial x_j} \left[(v + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right];$$

equation for the relative dissipation rate of the kinetic energy of turbulence

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(v + \sigma_\omega v_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}.$$

To study the cavitation characteristics of the pump, the task was to determine the critical increase in the temperature of helium at which developed cavitation would be observed in the pump, with the existing overpressure in the inner vessel of the cryostat equal to 0.05 MPa. Several calculations were carried out in a CFD package to simulate different temperatures of the liquid in a cryostat. For each of the points, the pressure of saturated helium vapor and the density of liquid helium were determined from the tables of characteristics of liquefied helium and set in accordance with the temperature.

To visualize cavitation phenomena, the field function “VaporPressure = (\$ {AbsolutePressure} <<151025 Pa>)? 1 : 0”. In the syntax of the program used, this means that the absolute pressure at each point is compared with the pressure of saturated helium vapor (in the recorded example, the pressure of saturated vapor is 151025 Pa for helium at a temperature of 4.668K). If the absolute pressure at a point is lower than the saturated vapor pressure, then the function takes the value 1 (cavitation is possible), otherwise 0.

Results

In this study, a number of pump operation modes with a temperature of liquid helium from 4.23 to 4.668 K were simulated. The pump head obtained during hydrodynamic simulation, as well as the calculated NPSH (Δh) for each of the points are presented in Table 2.

Table 2.Simulation results.

№	T, K	H, m	Δh , m
1	4,23	10,41	39,220
2	4,3	10,40	33,881
3	4,5	10,39	16,902
4	4,6	10,25	7,315
5	4,65	10,15	2,178
6	4,66	10,13	1,119
7	4,665	10,11	0,586
8	4,668	10,02	0,264

According to the values presented in Table 2, the cavitation performance of the pump was plotted (Fig. 4). The solid line in the graph shows the cavitation performance itself, and the dashed line represents a 3% drop in head relative to the first point. For ease of graph perception, points 1-3 are outside the plot area.

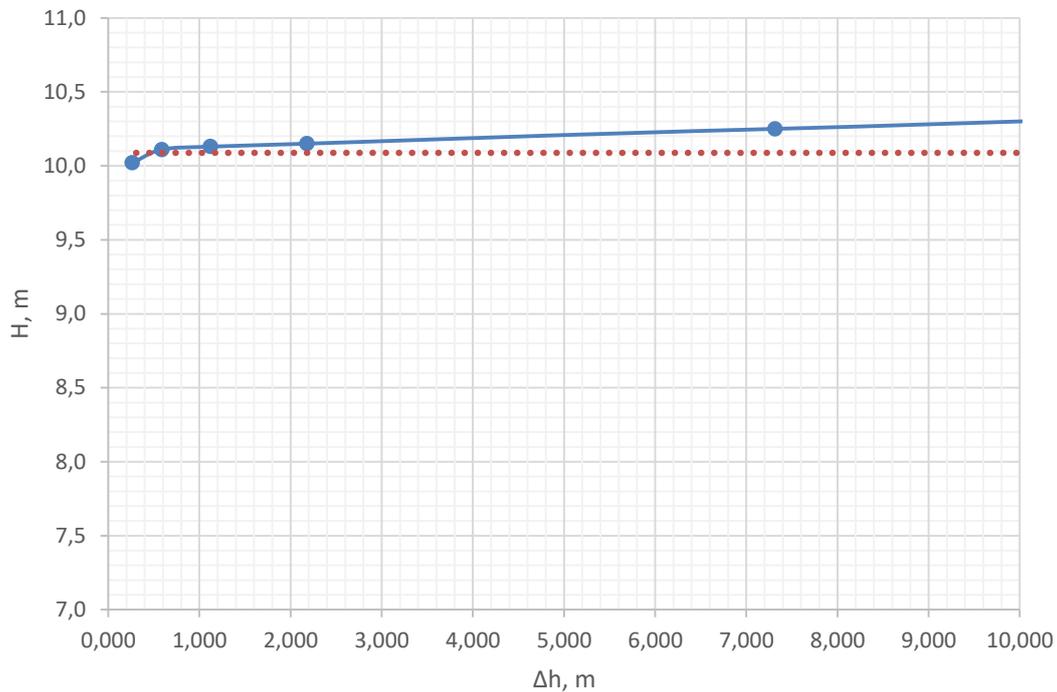


Figure 4. Cavitation performance of the pump.

Using the graph obtained, we determined the critical NPSH of the pump is 0.4 m. Thus, with an increase in the temperature of helium in the cryostat to about 4.667K, cavitation can begin in the pump. Fig. 5 shows the distribution of the created field function in the pump section, in which the zones in which cavitation is possible are red. This scene was obtained at a temperature of 4.668K.

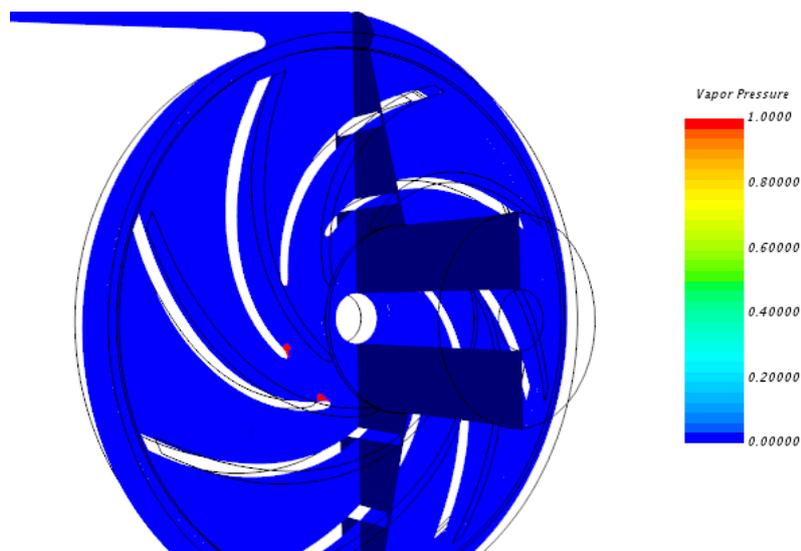


Figure 5. Distribution of the field function in the cross section of the pump.

It can be seen that cavitation in the pump is possible only at the inlet tip of the blade. It was not possible to achieve the super-cavitation mode for this pump, since at a temperature greater than 4.668K, the absolute pressure in the inner vessel of the cryostat is less than the pressure of saturated helium vapor, i.e., helium in the cryostat will begin to evaporate. Such pump operating conditions are not permitted.

Conclusion

As a result of hydrodynamic simulation, it was revealed that the BNHEP-35-000 pump does not enter the super-cavitation mode when pumping liquid helium from a cryostat with an overpressure of 0.05 MPa. The beginning of cavitation at the inlet tips of the pump blades can be observed at a temperature of 4.668K. This may be due to the fact that liquid helium has a low density (6–8 times less than the water density), and, accordingly, the pressure drop at the inlet tip of the blade at the pump running on liquid helium is also less significant. Using the plotted cavitation performance of the pump, the critical NPSH for these operating conditions was determined, it amounted to 0.4 m.

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