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Experimental study on the cavitation characteristics of a centrifugal pump in liquid helium

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Abstract In the past, a compact centrifugal pump for liquid helium was designed and successfully tested at TU Dresden University. The pump is an integral part of a dual-flow transfer system which reduces the decanting losses of liquid helium from 30% down to 4%. Since the pump transfers the liquid close to saturated conditions, the cavitation characteristics of the pump need to be further investigated. This article presents the latest experimental data on the cavitation performance of the pump.

1. Introduction

Liquefying helium requires up to 4 kWh/l of specific energy, given the existing liquefier stock. Previous optimization initiatives primarily addressed losses within the liquefaction process itself, such as the efficiency of expansion turbines and heat exchangers. However, the evaporation losses that occur during transfer operations, particularly during the decanting of mobile dewars, were usually ignored. Depending on the transfer line, up to 30% of the initial helium volume can evaporate during decanting. This is followed by energy-intensive recovery, purification, and re-liquefaction processes. Thus, operational costs scale significantly with transfer losses.

TUD developed and operates a dual flow transfer system with a cold pump to overcome the high transfer losses [1]. In this system, liquid is transferred by a cold, single-stage centrifugal pump from the main reservoir to a mobile dewar. During filling, the displaced cold gas is simultaneously guided back into the reservoir, recovering a large portion of the displaced cold gas enthalpy. In operation, evaporation losses were lowered to 4%, and the transfer rate increased by a factor of five depending on the applied pump speed.

Since the centrifugal pump is located inside the sump of the main reservoir dewar under nearly saturated conditions, cavitation performance plays a crucial role in dimensioning the transfer line, particularly the riser line length. If the pump's pressure head decreases at medium liquid levels, a large portion of the dewar's volume remains unused and cannot be transferred.

Over the past few decades, other research groups have investigated cavitation in liquid helium:

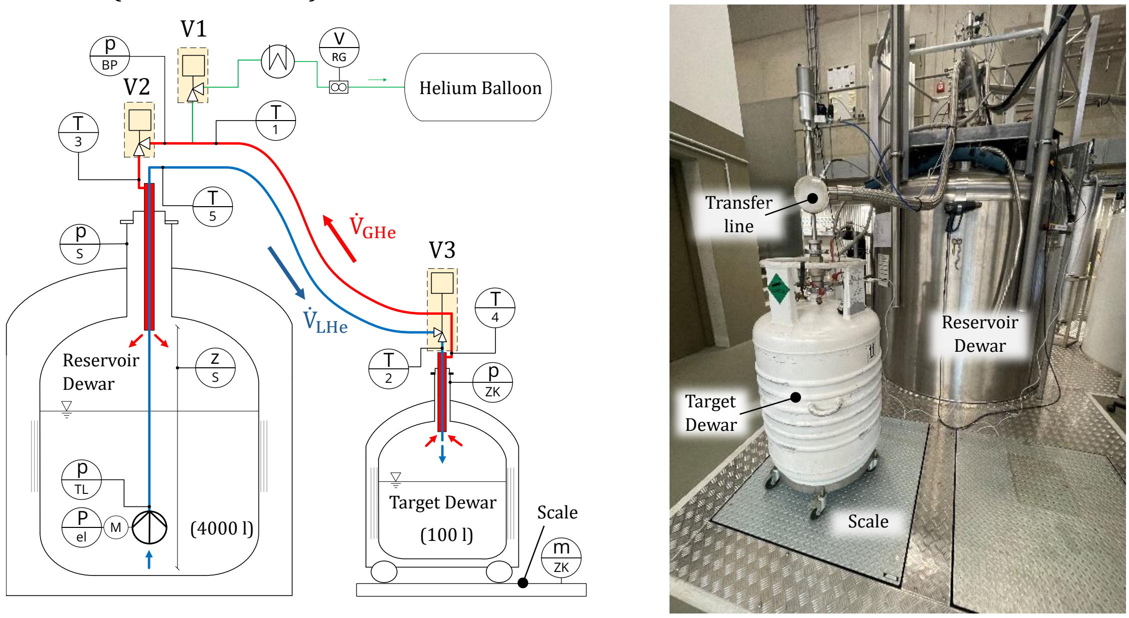
- Ludtke and Daney found no significant cavitation inception in normal fluid He I, even at negative NPSH values [2]. However, measurements in superfluid He II showed a significant reduction in the pump's pressure head at low liquid levels due to the fluid's properties.
- Baudouy et al. investigated the cavitation performance of a centrifugal pump with straight blades in He-I [3]. In this study, the pressure head degraded only at negative NPSH values.
- Haruyama et al., however, measured the pressure rise of the pump at variable NPSH in He-I and found a decrease in pump head even at low positive NPSH values of 72 mm [4].

For sufficient dimensioning, the centrifugal pump of the transfer system must be investigated concerning its cavitation performance ($NPSH_R$).

2. Dual flow transfer system with cold pump

2.1. Overview

Figure 1 (a) shows the P&ID of the transfer system. The cold single-stage centrifugal pump is located inside the reservoir dewar (Wessington CH4000) and transfers the liquid helium through the liquid line (blue) into the target dewar (100 l). Simultaneously, the rejected cold gas flows in counter flow back through the gas line (red) into the reservoir dewar. During cool-down, the gas is bypassed to the helium recovery system (green), where it warms up and is stored at ambient temperatures (helium balloon).



(a) Transfer system (P&ID)
(b) Filling of a mobile dewar

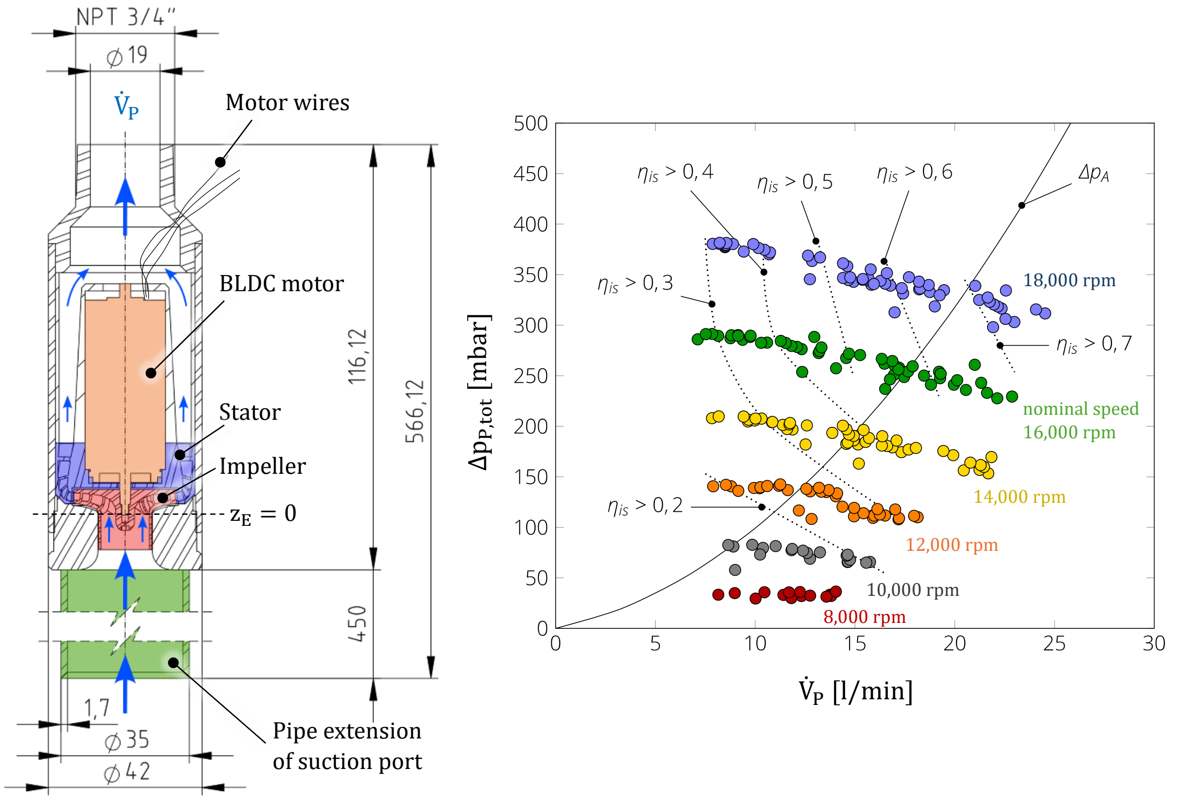
Figure 1. Overview dual flow transfer system

Figure 1(b) shows the transfer system during the filling process. The target dewar is placed on a stationary scale to measure mass changes. The rigid, vertical section of the transfer line is inserted into the dewar. The horizontal part is made of flexible corrugated tubes for easy coupling. The liquid and gas lines run parallel inside the outer corrugated tube, which has a common vacuum, allowing maximum flexibility. Only the lower tip of the transfer line is cold, reducing the additional effort required for the time-consuming warm-up procedure of the bottleneck fittings, as is the case with single-flow transfer lines. The current transfer system is equipped with various sensors that allow for an in-depth analysis of all transfer parameters.

2.2. Liquid Helium Pump

Figure 2 (a) displays the cross-section of the single-stage pump. Liquid helium is sucked from the sump of the reservoir dewar by impeller rotation, driven by a brushless DC motor with dry-running hybrid ball bearings, enabling operation under cryogenic conditions. The impeller has an outer diameter of 28 mm with 18 blades (including 9 splitter blades) in a shrouded design. The leading edge of the impeller main blades serves as the reference level for the cavitation tests ($z_E = 0$ cm).

After passing the stator with 22 blades, liquid flows toward the connection fitting and cools the motor. For the cavitation tests, the motor cables are routed through the pump housing into the environment. After testing the pump with the standard suction port for the transfer system, we installed an extension in the form of a pipe welded to the original suction port.



(a) Cross-section of pump (dimensions in milli-meter)

(b) Pump and Plant Characteristics

Figure 2. Centrifugal pump for liquid helium transfer

Figure 2 (b) shows the pump's characteristic lines at different rotational speeds. At a nominal speed of 16,000 rpm, the pump delivers a total pressure difference of 255 mbar and a flow rate of 17.4 l/min during steady-state operation of the transfer system. Therefore, compared to a common single flow decanting system with flow rates of up to 5 l/min, the filling speed increases drastically by a factor of 3.5.

Varying the speed adjusts the decanting flow rate by moving the operating point along the system characteristic line Δp_A. During steady-state operation, the pump's isentropic efficiency is approximately 55%. Higher efficiencies can be achieved at higher flow rates and increased rotational speeds.

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3. Experimental investigation

3.1. Cavitation Test Stand

To measure the cavitation characteristics in respect to the fluid level, we used a circulation test stand, as shown in figure 3. This cavitation test stand consists of a bath cryostat, containing an internal liquid helium tank, which is thermally isolated by a high vacuum and a liquid nitrogen shield against the outer cryostat wall at ambient temperatures. The pump is immersed in the liquid and circulates helium through a measurement loop containing a cryogenic turbine flowmeter and a cryogenic valve for flow restriction.

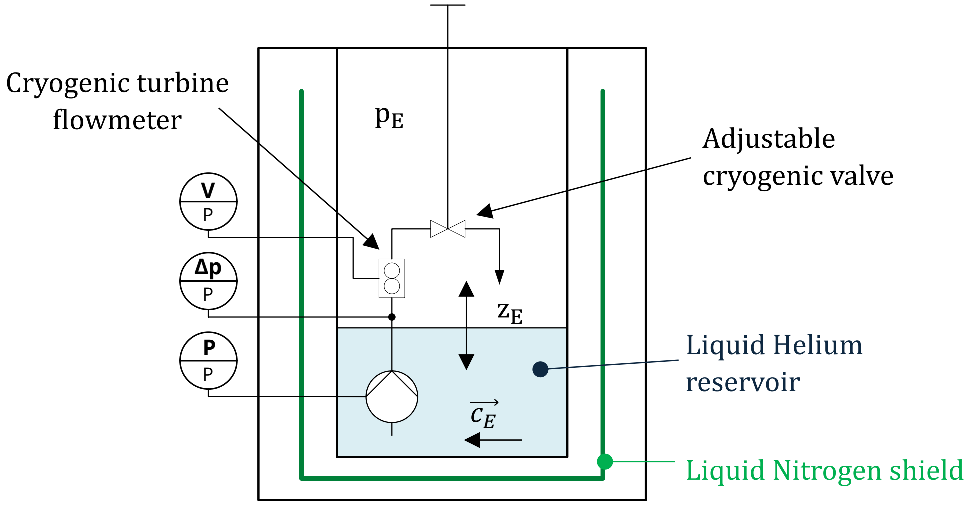

Figure 3. Cavitation Test Stand (P&ID)

The pump's delivered pressure difference is measured by a differential pressure transmitter at ambient pressure, which is connected by capillaries to the cold pressure port and inner volume. The authors used a dip stick, using Taconis oscillations, to determine the height of the liquid-gas boundary. Table 1 provides an overview of the used sensors and their accuracy.

Table 1. Sensors and Accuracies

Variable	Sensor [Range]	Accuracy
Liquid level	Dip stick (Taconis oscillation)	±0.5 cm (estimate)
Volume flow	Turbine flow meter, Hoffer Flow Controls HO3/4x5/8 [3.4… 76 l/min]	0.6% of reading
Differential pressure	KELLER Pressure PD-33X [0 … 1 bar]	(max.) ±0.05% FS (± 0.5 mbar)
Cryostat pressure	KELLER Pressure PD-33X [0 … 40 bar]	(max.) ±0.05% FS (± 20 mbar)

3.2. Calculus and measurement procedure

The parameter NPSH (net positive suction head) was introduced to describe the difference between the total pressure and the vapor pressure at the suction port of a pump. The available NPSH, which is provided by the pump system, is defined as:

$$NPSH_A = \frac{p_{E,tot} - p_v(T)}{\rho \cdot g} = \frac{p_{E,stat} - p_V(T)}{\rho \cdot g} + z_e + \frac{c_E^2}{2\,g} - \frac{\Delta p_{Ext}}{\rho \cdot g} \qquad \text{Eq. 1}$$

In the given system, the pump test cryostat operates close to ambient pressure. After filling, the liquid inside nearly reaches saturated conditions. Thus, the first term of equation 1 can be neglected. Second, the fluid velocity in the liquid bath is very low and can also be neglected. Therefore, only the liquid height above the leading edge of the impeller z_E, must be considered, as well as the additional pressure loss due to the pipe extension at the suction port Δp_{Ext}. This pressure loss depends on the fluid velocity. Subsequently, equation 1 is simplified to:

$$NPSH_A \approx z_e - \frac{\Delta p_{Ext}}{\rho \cdot g} \qquad \text{Eq. 2}$$

To ensure cavitation-free operation, the available suction head $NPSH_A$ must exceed the required suction head of the respective pump ($NPSH_R$). To determine the $NPSH_R$, one can lower the $NPSH_A$ by changing the liquid level until a specific cavitation criterion is reached. In this case, the authors use a reduction of 3% of the pump pressure head to determine the cavitation inception.

3.3. Cavitation characteristics

Since the cavitation test was originally developed for different test setup, the maximum possible flow rate of the pump is restricted to the part-load operating area of the pump below the operating point of 17.4 l/min. Therefore, the maximum valve opening was applied consistently throughout the tests. The flow rate varies with the rotational speed.
Figure 4 displays the change in pressure head as a function of the liquid height above the leading edge of the impeller. The vertical axis is normalized with respect to the non-cavitating pressure head at nominal speed (16,000 rpm) to visualize the inception of cavitation.
Basically, the liquid is pumped without any sign of decrease in pressure head until the liquid level reaches the bottom edge of the suction port which is located 1.5 cm below the impeller's leading edge. At this level, the pump starts to suck cold gas near the liquid surface, resulting in a reduced pressure head. Hence, the centrifugal pump can operate without performance degradation until the lowest geometrically useful liquid level. In this case, the $NPSH_R$ value cannot be determined. The results are comparable to the findings of Ludtke [2].
Additionally, the rotational speed was varied to some extent to determine its influence on the cavitation inception. The pump did not react differently at higher or lower speeds.
In parallel, we observed the cavitation performance of the transfer system during operation at higher flow rates close to the operating point (see Figure 1(a)). Although the cavitation performance tends to decrease at higher flow rates due to higher dynamic pressure loss at the inlet, no substantial degradation in pressure head was observed.
To extend the measurements to negative $NPSH_A$ values, an additional pipe with a length of 450 mm was installed at the suction port of the pump. In this scenario, the pressure loss resulting from the pipe inlet and the wall friction must be taken into account, as outlined in equation 2. The corresponding loss height in the NPSH calculation is approximately 2 cm at the given flow rates. This loss can be determined by subtracting the pump head of the simple inlet setup from that of the setup with the pipe extension, at the same flow rate.

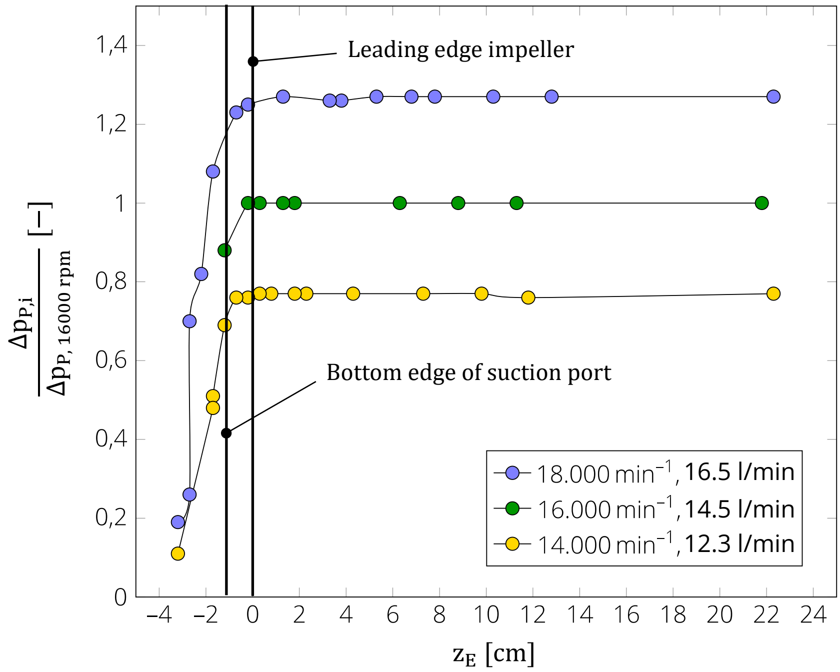

Figure 4. Cavitation characteristics without pipe extension at suction port

Figure 5 presents the results of the specific pressure head over the $NPSH_A$. At nominal or higher speed, the pump showed self-priming capability due to the high gas density. The density ratio of

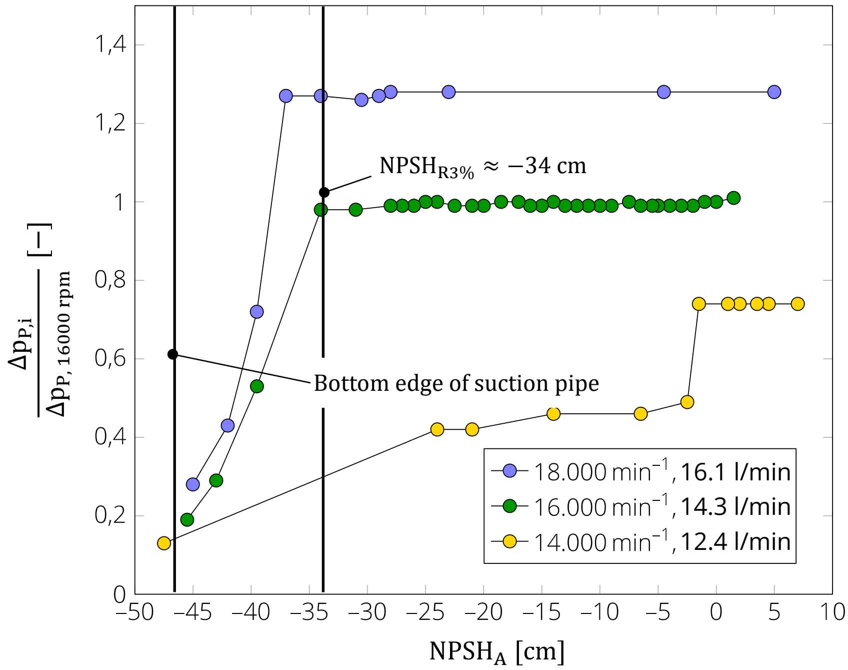

Figure 5. Cavitation characteristics with pipe extension at suction port

saturated liquid to saturated gas is about 7.5 for helium, which is remarkably low compared to water with a ratio of about 1700. Consequently, the suction pressure generated by the gas-filled impeller is sufficient to overcome the geodetic pressure difference from the liquid level to the leading edge. At the nominal speed, the pressure head showed a significant decrease of 3% at

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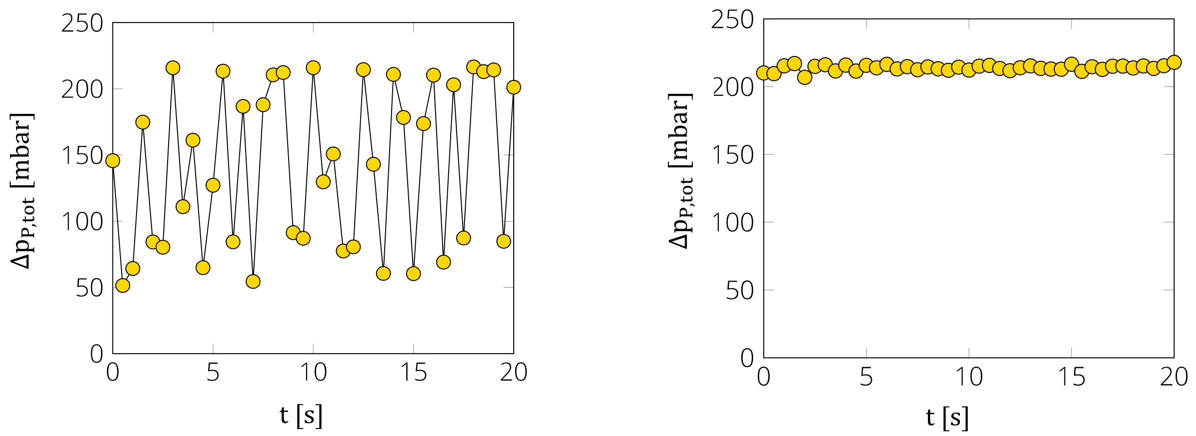
$NPSH_A$ lower than -34 cm. Therefore, the required NPSH of the pump was determined as $NPSH_R \approx -34$ cm (interpolated). Since calibrated pressure transducers were used, the overall uncertainty is mainly influenced by the dip stick measurement and can be specified as ± 0.5 cm. Empirical correlations that predict the $NPSH_R$ frequently depend on cavitation data from water pumps and yield high positive values of several meters for the investigated pump. For this reason, correlations generated with other fluids are certainly not applicable for He I.

Typically, the $NPSH_R$ exhibits an upward trend in response to an increase in flow rate or pump speed, due to elevated pressure losses that occur at the impeller's leading edge. However, in this particular instance, the opposite has been observed: At higher pump speeds and larger flow rates, the pump was able to operate at lower liquid levels. The observed behavior can be attributed to elevated flow losses, particularly shock losses at the pump's inlet, which are more pronounced at lower speeds when considering the specified flow rates. At 14,000 rpm, the pump cannot deliver enough suction performance to counteract the geodetic pressure loss in combination with the losses at the impeller entry. Therefore, the mean pressure head of the pump exhibits a sudden decline when the liquid level falls below the leading edge of the impeller (taking into account the pipe loss at $NPSH_A = -2$ cm).

Figure 6 shows the pressure difference of the pump during operation at a specific liquid level. At negative levels of z_E, the pump may experience a brief period of priming before the collapse of the liquid stream in the impeller vanes. In this scenario, the pump exhibits a fluctuating pressure difference in contrast to a steady trend at positive levels.



a) $z_E = -1$ cm b) $z_E = 9$ cm

Figure 6. Pressure head of pump at 14.000 rpm during pumping in respect to liquid level

Negative NPSH values for liquid helium pumps, however, had already been observed by other authors. One reason is that nearly no dissolved gases exist in the cryogenic liquid, which can cause weak spots that exceed the liquid's tensile strengths. Depending on the liquefier arrangement, there is a chance that hydrogen and neon are dissolved in very small quantities (<100 parts per billion(v)) [5]. In the setup for this work, the authors used liquid helium from a Linde L140 liquefier, which has a low temperature adsorber that removes these contaminants. Therefore, the presence of soluted hydrogen can be excluded for this study. Furthermore, thermodynamic suppression of the liquid phase may contribute to the observed low NPSH values. During the formation of a cavitation bubble, a temperature difference between the core of the cavitation bubble and the surrounding liquid must be established to deliver the heat of vaporization [6]. This results in the formation of a subcooled bubble boundary layer, which prevents further propagation and expansion of the bubbles. Due to the low liquid-gas-density ratio of helium, a higher magnitude of heat and mass transfer is necessary to form the same vapour cavity as in water [7]. Consequently, a higher cavitation suppression effect due to the subcooling can be achieved. The thermodynamic suppression also plays a role in other cryogenic fluids close to the critical pressure such as hydrogen [6], [8] and has been described many times.

4. Conclusion and Outlook

The tested centrifugal pump demonstrated remarkable self-priming capability, even at negative NPSH values. This is due to the special fluid properties of He I, which differ from those of conventional fluids commonly referenced in pump literature, such as water. For low flow rates, no significant decrease in pressure head was detected for the simple suction port until the liquid level falls below the suction port edge. In future, the valve of the stand needs to be adapted to allow the investigation of the cavitation characteristics at higher flow rates.
Considering the experimental findings and the literature, cavitation does not need to be considered when operating the dual flow transfer system. The usable liquid volume in the reservoir dewar corresponds to the selected length of the riser line, which is designed according to the local premises. For this particular pump, the use of an inducer is not necessary, as it would only reduce the overall hydraulic performance.

Nomenclature

c	Fluid velocity (m/s)	ρ	Density (kg m^{-3})
g	Gravitational acceleration (kg/s)	η_{is}	Isentropic efficiency (-)
m	Mass (kg)		
$NPSH_A$	Net positive suction head available (cm)		
$NPSH_R$	Net positive suction head required (cm)		
P	Power (W)	A	Plant
p	Pressure (mbar)	Ext	Extension
Δp	Pressure lift (mbar)	GHe	Gasous helium (saturated)
T	Temperature	LHe	Liquid helium (saturated)
t	Time (s)	E	Entry
$\dot{V}$	Flow rate (l/min, l/h)	P	Pump
z	Liquid level (cm)	tot	Total (pressure)

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