Overview of the experimental setup for the visualization of a cryogenic pump

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Abstract. An experimental setup for the visualization of a cryogenic pump, which is to investigate the relationship between the flowfield in a pump and the thermodynamic effect of a cavitation, was constructed. The experimental setup with the cryogenic pump is a closed loop and is consisted of a tank, a suction pipe, a visualization section, a test pump and a flow meter. There are two visualization sections in this system. One is the visualization section for the pump impeller cavitation using liquid nitrogen and this section is established on the pump casing. Another is the visualization section for the blade cavitation using liquid nitrogen and this section is inserted in the pump suction side. These sections are set up individually for the object of the visualization. From pilot study using this visualization system with the cryogenic pump, it was shown that the subcooled liquid nitrogen could be generated by this system and this liquid nitrogen could be circulated in this pump system with the visualization section. And it was indicated that various visualization experiments of the cavitating pump and blade using the subcooled liquid nitrogen can be conducted by using the developed setup.

1. Introduction

Research into cavitating pumps is becoming increasingly important because of the request for advanced pump specifications and the spread of application fields such as hydrogen energy systems. It is known that the cavitation performance of a turbopump using cryogenic fluids, such as liquid hydrogen/oxygen/nitrogen, is improved when compared with that using cold water due to the so-called thermodynamic effect of the cavitation[1, 2]. This can be explained as follows: The vaporization requires latent heat to be supplied from the liquid to the interface. The vapor pressure decreases with the depression of the liquid temperature due to this latent heat caused by the appearance of the cavitation. Therefore, the appearance region of the cavitation decreases with this decrease in vapor pressure. This thermodynamic effect occurs remarkably with a large vapor-liquid density ratio($\rho_v/\rho_l$) and a large gradient of the vapor pressure to temperature change($dp_v/dT$). A rocket engine turbopump can be operated even at very low suction pressure and high rotational speed due to this thermodynamic effect[3].

The turbopump in cryogenic fluids was basically designed using the results of the examination with cold water. However, for the design of the cavitation characteristics, the results from the cold water cannot be used for the design of the turbopump due to the thermodynamic effect of the cavitation. Therefore, research into both the improvement of cavitation performance due to the thermodynamic effect[4-6] and the unsteady cavitation phenomena which are affected by the thermodynamic effect[7-9] were conducted.
In our previous research[10], the thermodynamic effect which affects the cavitation performance of a cavitating centrifugal pump has been investigated experimentally using liquid nitrogen (hereinafter called LN2). From experimental results, it was indicated that the cavitation performance using liquid nitrogen is better than that using cold water due to the thermodynamic effect of the cavitation. And the estimated temperature depression due to the thermodynamic effect decreases with decreasing flow coefficient. Moreover, it was shown that the estimated temperature depression due to the thermodynamic effect on high cavitation performance impeller is smaller than that on low cavitation performance impeller at same flow coefficient. However, the relationship between the flowfield in the pump and the thermodynamic effect of the cavitation, which is important to understand the mechanism of the cavitation performance using cryogenic fluids, have not been made clear.

In the present study, therefore, an experimental setup for the visualization of a cryogenic pump, which is to investigate the relationship between the flowfield in pump and the thermodynamic effect of the cavitation, was constructed. And it was shown that the subcooled LN2 can be generated using this experimental system and LN2 can be circulated in this pump system with the visualization section. Moreover it was indicated that various experiments of the cavitating pump and blade using subcooled LN2 can be conducted by using the developed setup.

2. Thermodynamic effect of cavitation

2.1. Test equipment in previous research

The arrangement of the test setup and instrumentation system in our previous work is schematically illustrated in Figure 1. The test setup is a closed-loop and consists of a suction tank, a test pump, a mass flow meter, a ball valve and pipes. Vacuum insulated pipes are used in the test setup and a polyurethane form is used as thermal insulation for other piping elements. The vacuum pump is connected to the suction tank in order to achieve the cavitation test using cold water and a helium gas cylinder is also connected to the suction tank to control the occurrence of heat from condensation of nitrogen gas. A centrifugal type magnetic pump is used for the experiments with principal specifications as summarized in Table 1. Two impellers, which differ in cavitation performance, are used for the experiments. Impeller A is a standard impeller; Impeller B differs from Impeller A in the impeller inlet diameter and blade angle. Both impellers are semi-open impellers, to conduct the visualization of cavitation. The main shroud thickness and the blade height of both impellers are the same, so that the clearance between the impeller and the wall surface of the casing is equal in both impellers. And the clearance between the

![Figure 1. Schematic view of previous test setup and instrumentation system](image)

| Table 1. Specifications of test pump |
|-------------------------------------|
| Impeller A | Impeller B |
| Suction pipe diameter | 22 mm | 22 mm |
| Discharge pipe diameter | 22 mm | 22 mm |

| Impeller | Inner diameter | Outer diameter | Outer passage width | Number of blade | Inlet blade angle | Outlet blade angle | Rating (BEF in cold water case) |
|----------|----------------|---------------|-------------------|----------------|-----------------|-------------------|-------------------------------|
| Impeller A | 42 mm | 82 mm | 6.3 mm | 5 | 20° | 35° | 3450 rpm | 0.011 m³/min | 7 m | 84.1 Hg(H₂O) | 96.8Hg(H₂O) |
| Impeller B | 39 mm | 82 mm | 6.3 mm | 5 | 20° | 32° | 3520 rpm | 0.014 m³/min | 7 m | 84.1 Hg(H₂O) | 96.8Hg(H₂O) |

Return speed | Specific speed | NPSHg (3% head drop) |
|----------------|----------------|----------------------|
| 7 m | 84.1 Hg(H₂O) | 2.0 m |
| 7 m | 96.8Hg(H₂O) | 7.5 m |
impeller and the casing in LN2 is similar to that in cold water, because the thermal contraction of the impeller and the casing is denied by those movements caused by the thermal contraction on the structure of the test magnetic pump. The best efficiency of the test pump is below 25% in both impellers because of the low specific speed. And the flow rate at the best efficiency point, which is also defined as the rating flow rate, is a partial flow rate and the half of the flow rate at zero incidence angles to the blade inlet of the impeller. This is thought to be due to the fact that the friction loss near the tongue is larger with a high flow rate, because the cross-sectional area of the tongue throat is small enough due to the manufacturing restriction of the pump casing[11].

2.2. Test method
Experiments in LN2 can be conducted after sufficient pre-cooling of the setup and filling up LN2 in the pump system. Cavitation performance can be obtained from the measurement of the pump suction pressure $p_s\,[kPa]$, and delivery pressure $p_d\,[kPa]$, the pump suction temperature $T_s\,[K]$, and delivery temperature $T_d\,[K]$, and the discharge flow rate $Q_d\,[m^3/min]$ and rotational speed $N\,[rpm]$ under a adjusted the cavitation number $\sigma$ at a constant rotational speed and flow rate. The pump suction and delivery pressures are measured by strain-gage type pressure transducers which can be used in LN2 temperatures(below 77K). The pump suction and delivery temperatures are detected by resistance type thermometers whose tip diameters are 0.8[mm] and these have enough responsiveness for the changing temperature. The flow rate is measured using a Coriolis type mass flow meter, which generates a pulse signal relative to the mass flow rate. And this mass flow rate is translated to the flow rate using the density, which is estimated from the measured delivery pressure and temperature. Pump rotational speed is detected by the pulse signals(5 pulses per revolution), which are fed to a frequency-analog converter. The adjustment of the cavitation number is conducted as follows: (1) In the case of cold water, the pump suction pressure is adjusted by using a vacuum pump connected to a suction tank. (2) In the case of LN2, the pump suction pressure is compressed by using a helium gas line which is also connected to a suction tank. The vapor pressure and density of LN2 vary with the changes in its pressure and temperature. In this study, these material properties are estimated in the sphere of experiments using thermodynamic tables[12].

2.3. Cavitation performance and thermodynamic effect
Figure 2 shows a comparison of the cavitation performance between that in cold water and that in LN2 on Impellers A and B. Figures 2(a) and (b) correspond to Impellers A and B, respectively. The horizontal axis is the cavitation number $\sigma$, and the vertical axis is the head coefficient $\psi$ in both figures. The

![Figure 2. Comparison of cavitation performance between using liquid nitrogen and cold water](image-url)
cavitation performance of Impeller A in LN2 is illustrated for four different flow rates, namely, ○: $\phi/\phi_0=0.5$, △: $\phi/\phi_0=0.8$, ▲: $\phi/\phi_0=1.0$, and ▼: $\phi/\phi_0=1.1$. The cavitation performance of Impeller A in cold water is illustrated for four different flow rates, namely, ●: $\phi/\phi_0=0.5$, ▲: $\phi/\phi_0=0.8$, ■: $\phi/\phi_0=1.0$, and ▼: $\phi/\phi_0=1.1$. As well, the cavitation performance of Impeller B in LN2 is shown for three different flow rates, namely, ○: $\phi/\phi_0=0.30$, △: $\phi/\phi_0=0.30$, and ▲: $\phi/\phi_0=0.43$. The total head of Impeller A at $\phi/\phi_0=1.0$ in LN2(□) drops near $\sigma=0.1$ due to the effect of the cavitation, though Impeller B at $\phi/\phi_0=0.18$ in LN2(○) drops near $\sigma=0.7$, as shown in Figure 2. Therefore, the cavitation performance of Impeller A in LN2, as well as in cold water, is better than that of Impeller B. In both impellers, the cavitation number at total head drop in LN2 is smaller than that in cold water on same $\phi/\phi_0$. Cavitation performance is greatly improved due to the thermodynamic effect in LN2.

2.4. Cavitation performance and thermodynamic effect

Let us find the temperature depression $\Delta T = (T_s - T_c)$ between the liquid temperature at the critical point and the cavity region to know the degree of the thermodynamic effect. In this study, $\Delta T$ is estimated from Figure 2 using the same method employed by Yoshida et al.[2] and Franc et al.[8].

Vapor pressure decreases with decreasing cavitation temperature caused by the latent heat in the actual cavitation phenomena which occur remarkably in cryogenic fluids such as LN2. In the case of the remarkable occurrence of the thermodynamic effect, the cavitation number $\sigma_{c, LN2}$ is calculated from the actual cavitation pressure $p_c$ equal to the vapor pressure at the actual cavitation temperature $T_c$. ($T_c$ cannot be measured directly in this study):

$$
\sigma_{c, LN2} = \frac{P_i - p_c}{\frac{1}{2} \rho \mu_i^2} = \frac{P_i - p_c}{\frac{1}{2} \rho \mu_i^2} (T_c)
$$

(1)

where $P_i$ is the suction total pressure, $p_c$ is the vapor pressure to the temperature in cavitation, $p_c$ is the vapor pressure and $\rho$ is the fluid density.

On the other hand, the cavitation temperature $T_c$ is thought to be equal to the liquid temperature $T_s$ which is measured at the pump suction port if the thermodynamic effect can be neglected. Therefore, the cavitation number $\sigma_{c, LN2}$ is calculated from the vapor pressure with no thermodynamic effect:

$$
\sigma_{c, LN2} = \frac{P_i - p_c}{\frac{1}{2} \rho \mu_i^2} = \frac{P_i - p_c}{\frac{1}{2} \rho \mu_i^2} (T_s)
$$

(2)

In this study, it is assumed that the aspect of the cavitation flow is the same between in LN2 and in cold water at 3% total head drop point due to cavitation[1,2], and it is also assumed that the thermodynamic effect is very small in cold water. Under these assumptions, the temperature depression $\Delta T$ is obtained by Eq.(1) and (2), as follows

$$
\frac{dp}{dT} \Delta T = \frac{1}{2} \rho \mu_i^2 (\sigma_{c, LN2} - \sigma_{c, LN2})
$$

(3)

From Eq. (3), the temperature depression $\Delta T$ can be calculated from the difference of the cavitation number, $(\sigma_{c, LN2} - \sigma_{c, LN2})$ of two corresponding conditions. The value $\sigma_{c, LN2}$ is used the cavitation number at 3% total head drop in the experimental results in which the thermodynamic effect occurs remarkably, as in LN2, while the value $\sigma_{c, LN2}$ is used at the cavitation number at 3% total head drop in experimental results in which the thermodynamic effect can be neglected, as in cold water.

To calculate the temperature depression $\Delta T$, it is assumed that the aspect of the cavitating flow in the pump impeller is the same between in LN2 and in cold water when 3% total head drop occurs due to cavitation.
The temperature depression $\Delta T$ is calculated using the cavitation performance at $\phi/\phi_0 = 1.0$ (■) in LN2 and at $\phi/\phi_0 = 1.0$ in cold water, as shown in Figure 2(a). The difference between $\sigma_{r,\text{LN2}}$ and $\sigma_{r,\text{H2O}}$ is $(\sigma_{r,\text{H2O}} - \sigma_{r,\text{LN2}}) = 0.61$ at $\phi/\phi_0 = 1.0$ in Fig. 2(a), because the cavitation number $\sigma_{r,\text{LN2}}$ is 0.08 in LN2 and $\sigma_{r,\text{H2O}}$ is 0.69 in cold water at 3% head drop. Therefore, $\Delta T$ is calculated as $\Delta T = 0.81K$ in Impeller A, also using $dp/dT$ and $\rho$ calculated using thermodynamic tables and rotational speed $u_1 = 7.58$m/s. In a similar manner, $\Delta T$ is calculated as $\Delta T = 1.76K$ at $\phi/\phi_0 = 0.43$ of Impeller B using the cavitation performance at $\phi/\phi_0 = 0.43$ (■) in LN2 and at $\phi/\phi_0 = 0.43$ in cold water, as shown in Figure 2(b).

As mentioned above, the cavitation performance is improved about $\sigma = 0.61$ (NPSH=1.8m) due to the temperature depression $\Delta T = 0.81K$ of the thermodynamic effect at $\phi/\phi_0 = 1.0$ on Impeller A and about $\sigma = 2.4$ (NPSH=3.7m) due to the temperature depression $\Delta T = 1.76K$ of the thermodynamic effect at $\phi/\phi_0 = 0.43$ on Impeller B.

The changing values of $\sigma_{r,\text{LN2}}$ and $\sigma_{r,\text{H2O}}$ to decreasing $\phi/\phi_0$ for Impellers A and B are shown in Figure 3, based on the cavitation performance in Figure 2. $\sigma_{r,\text{LN2}}$ and $\sigma_{r,\text{H2O}}$ are cavitation numbers at 3% total head drop due to the cavitation in the cases of liquid nitrogen and cold water, respectively. In Figure 3, the horizontal axis is $\phi/\phi_0$, and the vertical axis is $\sigma_{r,\text{LN2}}$ (for LN2) and $\sigma_{r,\text{H2O}}$ (for cold water).

From Figure 3, $\sigma_{r,\text{LN2}}$ in LN2 decreases with decreasing $\phi/\phi_0$ for both Impeller A and Impeller B. And the gradients, which are $d(\sigma_{r,\text{LN2}})/d(\phi/\phi_0)$ and $d(\sigma_{r,\text{H2O}})/d(\phi/\phi_0)$, indicate $d(\sigma_{r,\text{LN2}})/d(\phi/\phi_0) < d(\sigma_{r,\text{H2O}})/d(\phi/\phi_0)$. More concretely, the value of $d(\sigma_{r,\text{LN2}})/d(\phi/\phi_0)$ is about half of $d(\sigma_{r,\text{H2O}})/d(\phi/\phi_0)$ for both Impeller A and Impeller B. This result means that the total head drop due to the cavitation in LN2 occurs with a small decrease in $\phi/\phi_0$ compared with that in cold water. And the total head of the cavitating test pump in LN2 is easily affected by cavitation with a decreasing $\phi/\phi_0$ compared with that in cold water. Moreover, the difference between $\sigma_{r,\text{LN2}}$ and $\sigma_{r,\text{H2O}}$ at same $\phi/\phi_0$, $(\sigma_{r,\text{H2O}} - \sigma_{r,\text{LN2}})$, decreases with a decreasing $\phi/\phi_0$ in both impellers. This is thought to be due to the fact that there is a difference between the change in $\sigma_{r,\text{LN2}}$ and $\sigma_{r,\text{H2O}}$ with a decreasing flow rate $\phi/\phi_0$, as mentioned above.

Figure 4 presents the temperature depression $\Delta T$ to the flow rate $\phi/\phi_0$ on Impellers A and B. The temperature depression $\Delta T$ is calculated using $(\sigma_{r,\text{H2O}} - \sigma_{r,\text{LN2}})$ and Eq. (3). The horizontal axis represents the flow rate $\phi/\phi_0$, the vertical axis represents $\Delta T$. 

![Figure 3](image3.png)

**Figure 3.** Cavitation number at 3% head drop due to the cavitation using liquid nitrogen and cold water on Impeller A and Impeller B

![Figure 4](image4.png)

**Figure 4.** Estimated temperature depression $\Delta T$ as a function of flow coefficient $\phi/\phi_0$ on Impeller A and Impeller B
As can be seen in Figure 4, \( \Delta T \) caused by the thermodynamic effect decreases with a decreasing \( \phi/\phi_r \) in both test impellers. This result indicates that the thermodynamic effect is affected by \( \phi/\phi_r \). The effect of \( \phi/\phi_r \) on the thermodynamic effect is thought to be due to the change in cavitation volume in the pump with a decreasing \( \phi/\phi_r \), as follows: As mentioned above, the rating flow rate \( \phi \) of both impellers is a partial flow rate and it is half of the flow rate at zero incidence angle to the blade inlet of the impeller. Therefore, the cavitation volume in the pump decreases with a decreasing \( \phi/\phi_r \), because of the effect of a reverse flow near the leading edge of the impeller blade due to the pre-whirl flow in the suction pipe[13]. Then the thermodynamic effect in LN2 decreases due to a decrease in the temperature depression around the cavitation with a decrease in the cavitation volume caused by the decreasing flow rate \( \phi/\phi_r \). And this decrease in the temperature depression leads to an increase in vapor pressure. Therefore, the reason for \( d(\sigma_{\infty, LN2})/d(\phi/\phi_r) < d(\sigma_{\infty, H2O})/d(\phi/\phi_r) \) in Figure 3 maybe due to the fact that decreasing the cavitation volume with the decreasing flow rate \( \phi/\phi_r \) in LN2 leads to a decrease in the temperature depression and an increase in vapor pressure, though the vapor pressure does not change with the decreasing the cavitation volume at decreasing flow rate \( \phi/\phi_r \) in cold water.

3. Experimental setup and test method for visualization in cryogenic pump

As mentioned above, it was indicated that the estimated temperature depression \( \Delta T \) due to the thermodynamic effect decreases with decreasing flow rate \( \phi/\phi_r \), and the estimated temperature depression \( \Delta T \) on high cavitation performance impeller is smaller than that on low cavitation performance impeller at same flow rate \( \phi/\phi_r \). These results indicate that the thermodynamic effect of the cavitation is affected by the flowfield in the cavitating pump. However the relationship between the flowfield in the pump and the thermodynamic effect of the cavitation, which is important to understand the mechanism of the cavitation performance using cryogenic fluids, have not been made clear. Therefore an experimental setup for the visualization of the cryogenic pump, which is to investigate the relationship between the flowfield in the pump and the thermodynamic effect of the cavitation, was constructed.

The arrangement of the experimental setup for the visualization in the cryogenic pump is schematically illustrated in Figure 5 and the photograph of the setup is showed in Figure 6. The test setup is a closed-loop and consists of a suction tank, a visualization section, a test pump, a flow meter, a valve and pipes. There are two visualization sections in this system. One is the visualization section for the pump impeller cavitation using LN2 and this section is established on the pump casing. The inner pipe and pump shroud casing of this visualization section are made by transparent polycarbonate and the outer pipe of this section is made by a stainless steel. And the pressure of the space between the outer and inner pipe is reduced to below 0.1Pa by a vacuum pump. The cavitation in the impeller is visualized using a reflecting mirror which is set up on the suction inner pipe. Another is the visualization section for the blade cavitation using LN2 and this section is inserted in the pump suction side. This visualization section is also made by transparent polycarbonate for the inner pipe and this inner pipe is square section(30mm x 30mm). The outer pipe is made by an acrylic pipe and square section. The pressure of the space between

![Figure 5. Schematic view of experimental setup for visualization in cryogenic pump](image)

![Figure 6. Photograph of setup for visualization](image)
the outer and the inner pipe is also reduced to below 0.1Pa by vacuum pump. These visualization sections are set up individually in the experimental setup for the object of the visualization, namely the impeller cavitation or the blade cavitation.

The suction tank, the valve, the mass flow meter and pipes are made by vacuum insulation. AEROFLEX® is used as thermal insulation for other piping elements. The vacuum pump is connected to the suction tank in order to achieve the cavitation test using cold water and helium gas cylinder is also connected to the suction tank to achieve the test under the subcooling condition of LN2. A centrifugal type magnetic pump, which is the same as previous research, is used for the visualization experiments with principal specifications as summarized in above Table 1.

Before visualization tests, it needs a pre-cooling for the experimental setup. The pre-cooling is very important especially for the polycarbonate pipe, which contacts with LN2, in the visualization section. Therefore a low temperature nitrogen gas(hereinafter called GN2) is passed through in the setup from the upstream of the visualization section to the pump delivery side for the pre-cooling. The filling up of LN2 is carried out, when the temperature at the visualization section is below 130K.

Visualization tests for the blade cavitation using a high speed video camera is carried out under the adjusted the velocity and cavitation number $\sigma$. And visualization tests for the pump impeller cavitation is carried out under the adjusted the cavitation number $\sigma$ at a constant rotational speed and a flow rate. The pressures at the suction tank, the visualization section, the pump suction and delivery port and the flow meter are measured by strain-gage type pressure transducers which can be used in LN2 temperatures(below 77K). The temperatures at the suction tank, the visualization section, the pump suction and delivery port and the flow meter are detected by resistance type thermometers or thermocouples and these have enough responsiveness for the changing temperature. The flow rate is measured using a Coriolis type mass flow meter, which generates a pulse signal relative to the mass flow rate. And this mass flow rate is translated to the(volume) flow rate using the density, which is estimated from the measured delivery pressure and temperature. The pump rotational speed is detected by the pulse signals(5 pulses per revolution), which are fed to a frequency-analog converter.

4. Experimental setup and test method for visualization in cryogenic pump

4.1. Test for pre-cooling

Figure 7 shows an example of results for the pre-cooling, filling up of LN2, and the depression and compression of the suction tank to get subcooled LN2 in the case of using the visualization section for the blade cavitation. (However, the blade was not established in the present study because the test this time is to be pilot study.) The horizontal axis is time(hour) and the vertical axis is temperatures at the suction tank, the upstream of the visualization section, the visualization section, the pump suction port and the flow meter. As mentioned above, GN2 is passed through between the visualization section and the pump delivery side for the pre-cooling, so the pre-cooling using GN2 isn’t carried out for the suction tank and the flow mater.

As can be seen in Figure 7, the inside temperature of the pipe at the upstream of the visualization section(●) is cooled to about 120K during a half hour from the start of the pre-cooling. However, temperatures at the outside of the polycarbonate pipe in the visualization section(▲ and ■) don’t respond to the inside temperature of the pipe at the upstream of the visualization section(●). This means that there is a large temperature difference between the pipe inside and outside, and this large temperature difference leads to a damage to the polycarbonate pipe of the visualization section. Therefore the pre-cooling is carried out slowly by controlling GN2 flow rate to avoid this large temperature difference. In the case of Figure 7, the pre-cooling was finished and the filling up of LN2 started, when temperatures at the outside of the polycarbonate pipe(▲ and ■) reached to below 130K at elapse of 5.5 hours from the start of the pre-cooling. Filling LN2 into the test setup was completed about 20 minute. Figure 8 shows photographs of the visualization section at the halfway of the filling (Fig.8(a)) and at the finishing of the filling (Figure 8(b)) LN2.

4.2. Pressure control for subcooling
The time histories of the temperature at the bottom of suction tank (○), the upstream of the visualization section (△) and the downstream of the flow meter (□) due to the depression and compression of the suction tank to get the subcooled LN2 is shown in Figure 9. The horizontal axis is time (hour) and the vertical axis is temperature in Figure 9.

The temperature of LN2 at the bottom of the suction tank (○) decreases with decreasing the pressure (0kPa to -60kPa) and the temperature reaches to 70K at elapse of 0.4 hours from the start of the depression. On the other hand, the temperature of LN2 at the bottom of the suction tank increases with increasing the pressure (-60kPa to 10kPa) and the temperature reaches to 72K at elapse of 0.15 hours from the start of the compression. The temperatures of LN2 at the upstream of the visualization section (△) and the downstream of the flow meter (□) also indicate similar change to that of the bottom of the suction tank (○).

From the results of Figure 9, it is found that the subcooled LN2 can be generated by this experimental setup.
4.3. Test of pump operation

Figure 10 indicates the time histories of the pressures and temperatures at the bottom of the suction tank (○), the upstream of the visualization section (△) and the downstream of the flow meter (□) during a period from pump startup to stopping. Time histories of the pressures and temperatures are shown in Fig.10(a) and in Fig.10(b), respectively. The both horizontal axes are time(second) and the vertical axes are pressure in Figure10(a) and temperature in Figure 10(b).

As can be seen Figure 10, the pressures at the bottom of the suction tank (○) and the upstream of the visualization section (△) gradually increase from pump startup. On the other hand, the temperature at the upstream of the visualization section (△) gradually decrease from pump startup. And the temperature at the bottom of the suction tank (○) is an almost constant during a period from pump startup to stopping. The pressure at the downstream of the flow meter (□) greatly increases from pump startup due to the increase in pump head. On the other hand, the temperature at the downstream of the flow meter (□) decreases from pump startup. These results indicate that various visualization experiments of the cavitating pump and blade using subcooled LN2 can be conducted by using this developed setup.

5. Conclusions

An experimental setup for the visualization of a cryogenic pump, which is to investigate the relationship between the flowfield in the pump and the thermodynamic effect of the cavitation, was constructed.
Pilot study using this visualization system with the cryogenic pump was carried out, leading to the following conclusions:

1. The subcooled liquid nitrogen could be generated by this system and the liquid nitrogen could be circulated in the developed pump system with the visualization section.

2. Various visualization experiments of the cavitating pump and blade using subcooled liquid nitrogen can be conducted by using this developed setup.

The visualization of the cavitating pump and blade under LN2 condition will be carried out to understand the relationship between the flowfield in the pump and the thermodynamic effect of the cavitation in the future researches.

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