A new capacitance type void fraction sensor was designed, produced, and tested. This sensor applies the difference between the relative permittivity \( \epsilon \) of gaseous hydrogen (\( \epsilon = 1.0 \)) and that of liquid hydrogen (\( \epsilon = 1.2 \)). Following the sensor verification test using light diesel oil and air, a cryogenic experiment using liquid nitrogen was conducted. As a result, the void fraction measured by the sensor showed good agreement with the result obtained by an optical analysis using a high speed camera. One of the key problems on the sensor is an existence of the temperature drift caused by the change of the relative permittivity of the glass tube. In order to reduce the temperature drift, the length of electrodes and material of tubes were changed. Combination of short arc length electrodes and iupilon tube is ideal for reducing the unwanted temperature drift. The sensor which has shorter electrodes reduces the quantity of the temperature drift by 63% compared to the original sensor.

**Key Words:** Two Phase Flow, Void Fraction, Capacitance Sensor

### Nomenclature

\[
\begin{align*}
 a &: \text{ external radius} \\
 b &: \text{ internal radius} \\
 C &: \text{ electrostatic capacitance} \\
 T &: \text{ temperature} \\
 \alpha &: \text{ void fraction} \\
 \varepsilon &: \text{ relative permittivity} \\
 \mu &: \text{ viscosity} \\
 \rho &: \text{ density} \\
 L &: \text{ stream-wise length of the electrodes} \\
 \theta &: \text{ angle of external radius} \\
 \delta &: \text{ angle of the tube uncovered by the electrodes}
\end{align*}
\]

### Subscripts

\[
\begin{align*}
 0 &: \text{ internal bottom surface of the tube} \\
 a &: \text{ border surface between the liquid and gas} \\
 G, g &: \text{ gas phase} \\
 L, l &: \text{ liquid phase} \\
 TP &: \text{ two-phase}
\end{align*}
\]

### 1. Introduction

The hypersonic Pre-cooled Turbojet Engine (PCTJ) is currently being developed by Japan Aerospace Exploration Agency (JAXA).\(^1\)\(^-\)\(^3\) This engine uses liquid hydrogen as both its fuel and coolant to counteract the aerodynamic heating. Controlling the mass flow of the hydrogen fuel is a challenging task on this engine system since fuel liquid hydrogen easily evaporates and turns into two phase or gaseous phase flows due to the heat capacity of tubes and valves.

The engine simulator that constructs an engine start-up sequence is now under development. It is still imprecise due to the deficiency of the characteristics of the flowing cryogenic hydrogen: heat transfer and pressure drop. Therefore, acquisition of thermo-fluid data of the hydrogen two phase flow is essential.

The void fraction is one of the key parameters used to determine the state of the two phase flow along with the density, viscosity, velocity and quality. In this field, many researches have been performed focusing on methods for measuring the void fraction.\(^4\)\(^-\)\(^10\). These methods are commonly used in chemical or atomic power plants; however, there is little application on the cryogenic two phase flow. For example, the optical fiber sensor which hinata et al\(^4\) developed based on Snell’s low and the wire-mesh method which Pietruske et al\(^5\) employed are a contact type. This type affects a flow. The gamma-ray attenuation method which Hori et al\(^6\) employed and the Laser Doppler Velocity meter which Ohba et al\(^7\) used. This type is difficult to be downsized.

As for the sensor for the cryogenic flow, Ohira et al\(^10\) applied the capacitance-type sensor for slush hydrogen. The sensor uses the principle that the void fraction of the flow depends on its relative permittivity. However, the temperature drift problem must be solved if the sensor is applied for the cryogenic engine which is used under the wide operation range from room temperature to cryogenic. So, we newly developed the compact void fraction sensor for PTCJ which reduces the temperature drift by changing the electrodes’ shape and reduced the electrical noise by additional shields.

This paper describes the development study of the capacitance type void fraction sensor. The experiments using gas oil and air and cryogenic nitrogen flow were conducted to check the sensors by comparing them with the image analysis using a high speed camera. An analytical study of the...
temperature drift was performed and the results were demonstrated by the low-temperature test.

2. Development of the Capacitance Type Void Fraction Sensor

In this section, the basic idea of the capacitance type void fraction sensor is introduced and the accuracy of the sensor is checked through comparison with the image analysis.

2.1. Basic idea

The basic idea of the void fraction sensor comes from a capacitance sensor created by Shu. This sensor measured the void fraction of the vertical annular flow or stratified flow.

Fig. 1. Void fraction sensor for cryogenic two phase flow.

The cross-section view of the void fraction sensor for the two-phase flow is shown in Fig. 1. The tube is made of iupilon: a dielectric material used for the bulletproof glass. A pair of electrodes is placed on both sides of the tube and is covered with metallic shields that act as the casing. The electrodes are connected to the capacitance sensor (C hitester hioki : 3515) by coaxial cables. Both the shields and coaxial cables help preventing unwanted noise. Specification of the capacitance measurement is shown in Table 1. Accuracy of the capacitance measurement depends not only on the capacitance sensor but also on the environment condition such as the length of cables. Therefore, the value of the accuracy for gas oil and air test is different from that of nitrogen two phase flow test.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Hioki C hitester, Model 3505</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Gas oil and air, Nitrogen</td>
</tr>
<tr>
<td>Variation of capacitance against void fraction</td>
<td>0.24 pF – 0.40 pF (0.16 pF)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 3.25 ~ 3.04 %</td>
</tr>
</tbody>
</table>

The application of the capacitance type sensor on the hydrogen flow yields number of problems. Firstly, very high accurate measurement is required to discriminate the minute difference between the relative permittivity of its gaseous phase and liquid phase. The relative permittivity of various fluids is shown in Table 2. For example, the relative permittivity of water and air is 80 and 1.0 respectively, making them quite easy to be measured the void fraction. However, the relative permittivity of liquid and gaseous phases of hydrogen is approximately 1.2 and 1.0; thus, the sensor must be very precise and sensitive in order to detect the difference. Secondly, it is difficult to keep the relative permittivity of the tube constant during the test due to the change in the tube’s temperature from room temperature to cryogenic. The capacitance measured by the sensor is affected by the change of the relative permittivity of the tubes. This phenomenon is called temperature drift.

2.2. Gas oil and air flow test

Prior to the cryogenic flow test, the preliminary validation test of the void fraction sensor using gas oil and air was conducted. The relative permittivity of the gas oil is approximately \( \varepsilon = 1.8 \), which is closer to that of liquid hydrogen than that of water. The variation of capacitance for the gas oil and air is about twice as that for the nitrogen shown in Table 1. In this test, mixture of gas oil and air does not undergo any phase-change so that each mass flow rate is known.

2.2.1. Test apparatus

The void fraction was measured by two methods. One is using the capacitance sensor and another is using the optical method of detecting the bubbles with a high speed camera. Figure 2 shows the general view of the test apparatus. The vertically standing acrylic tube with internal diameter of 10.2 mm was filled with gas oil. Air is supplied intermittently into the tube by a pump. The stream-wise length of the electrodes is 30 mm and the measurement data of the capacitance indicate the averaged value in this region.
2.2.2. Methods and results

During the experiment, slug-like air bubbles were generated and flowed through the sensors as shown in Fig. 3. Figure 4 shows the void fraction data by the capacitance sensor and optical method\textsuperscript{11}). As can be seen in the graph, the value measured by the capacitance sensor agrees well with that measured by the optical method in the difference within 5%.

\[ \alpha = \frac{C_L - C_{TP}}{C_L - C_G} \]  

where \( C_L \), \( C_G \), and \( C_{TP} \) are the capacitance of the liquid phase, gaseous phase and two phase respectively. This equation is based on the presumption that the void fraction is linearly proportional to the capacitance of the two phase flow.

3. Cryogenic Experiment using Liquid Nitrogen

With the gas oil and air flow test being successful, the void fraction sensor was tested using the cryogenic flow. First, the sensor was validated through comparison with the results of the image analysis. In addition, the effect of temperature drift was investigated.

3.1. Test apparatus and methodology

The experiment was conducted to measure the thermal-fluid properties of nitrogen two phase flow using the testing facilities in Chofu Aerospace Center of JAXA. Figure 5 shows the schematic of the test apparatus. The liquid nitrogen is supplied from the run tank, which has the volume capacity of 20 liters and is pressurized by gaseous nitrogen.

The test section consists of three sections: the heater section, visualization section and pressure drop measurement section. The test section is installed in the vacuum chamber located downstream of the run tank to cut off any heat influx from the exterior. Within the test section, a turbine mass flow meter is installed upstream of the heater section.

The heater section made of a copper tube wrapped with a coil of manganin heat wire that heats the flow to change its phase. The maximum voltage and power of the heater are 150 VDC and 1.6 kW respectively.

The visualization section shown in Fig. 6 is made of an iupilon tube with internal diameter of 10.2 mm and external diameter of 25.4 mm. Two void fraction sensors are installed at both ends of the section. One located at the upstream side is used for measuring the void fraction. The flow velocity is supposed to be measured using both sensors by the correlation method. Pictures of the flow inside of the iupilon tube are recorded by a high speed camera through the window of the vacuum chamber.

The temperature is measured by silicon diode thermometers (Lake shore : 218S) located in six points: one point upstream of the heater section, two points on the wall surface at the end of the heater section, one point at the exit of the visualization section and two points at the both ends of the pressure drop measurement section.
3.2. Results

Figure 7 shows the time variation of the void fraction measured by the sensor. The vertical lines (a), (b), (c), (d), and (e) correspond to the timings to record the photographs by the high-speed camera shown in Fig. 8. In this experiment, the pressure and the thermal dose within the test section were kept constant at 0.4 MPa and 160 W respectively. The mass flow rate of the flow was controlled to create various flow patterns.

As can be seen in Fig. 7 and Fig. 8, in the beginning, the flow was in a gaseous phase due to the common temperature of the supply tube ((a) : before 100 s). Several dots shown in the tube is not bubbles but the frost attached on the tube surface. Then, small liquid droplets were observed at the center of the tube while the tube wall remained dry (100-180 s). The droplets gradually disappeared and then flow pattern shifted from annular flow to liquid phase ((b): 180-500 s). It is impossible to distinguish between gaseous phase and liquid phase by the photographs. So, the void fraction sensor must be used together. After the formation of the liquid phase, the electric heater began to heat up the tube and the flow pattern changed from bubbly flow ((c): 500-650 s) to slug flow ((d): 650-950 s). In the end ((e): after 950 s), the supply of nitrogen was stopped and the flow became totally gaseous.

3.3. Temperature drift analysis

3.3.1. Shu’s theory

This chapter focuses on the temperature drift that occurred during the experiment. The temperature drift is the alteration in the capacitance caused by the change in the relative permittivity of the tube. In order to examine this phenomenon, an analytical study was performed by the method based on Shu’s theory as follows. Figure 9 shows the differential capacitances corresponding to horizontal slices for stratified flow. In this way, the parallel plate capacitor is simplified into equivalent circuit model shown in the right part of Fig.9. The capacitance between the sensor electrodes is expressed by $C_T$. In this simulation, only the section between $\theta_0$ and $\pi - \theta_0$ is taken into consideration. The total differential capacitance, $dC_T$, consists of that of the tube, $dC_t$, and that of the fluid $dC_p$, by

$$\frac{1}{dC_T} = \frac{2}{dC_t} + \frac{1}{dC_p}$$  \hspace{1cm} (2)

Integrating over $\theta$ from $\theta_0$ to $\pi - \theta_0$, we have

$$C_T = \frac{\varepsilon_r \varepsilon_0 a L}{2(a-b) \varepsilon_L + \left( \frac{b}{a-b} \right) \varepsilon_T} \ln \left( \frac{\tan \left( \frac{\theta_0}{2} \right)}{\tan \left( \frac{\pi - \theta_0}{2} \right)} \right)$$  \hspace{1cm} (3)

where $\theta_0$ is related to $\left( \frac{b}{a} \right)$ by

$$\theta_0 = \cos^{-1} \left( \frac{b}{a} \right)$$  \hspace{1cm} (4)

and $\theta_\alpha$ is a function of the void fraction, $\alpha$, expressed by

$$\alpha = 1 - \frac{\theta_\alpha - \cos \theta_\alpha \sin \theta_\alpha}{\pi}$$  \hspace{1cm} (5)

It was observed that the actual void fraction reached 1.0 at around 950 s; however, the indicated void fraction in Fig. 7 is around 1.1. This error cannot be explained by the measurement error. Therefore, the error may be due to the change of the relative permittivity of the iupilon tube, which is called temperature drift. The temperature drift must be taken into account on the measurement of the cryogenic fluid. Two methods against the temperature drift are considered: one is to correct the value by measuring the temperature of the tube and the other is to reduce the temperature drift by modifying the sensor as shown in the next section.
3.3.2. Evolving Shu’s theory

As the theory described above, neither top nor bottom areas, which are added the two differential capacitances corresponding to horizontal slices in the Fig. 9 are taken into consideration. Therefore, we modified so as to consider the capacitance of the top and bottom areas, $dC_{T}^{ex}$, expressed by Eq. (6).

![Fig. 10. Geometric rearrangement for Shu’s model.](image)

$$dC_{T}^{ex} = \varepsilon_{T} \frac{d\theta}{2 \sin \theta} : \frac{\delta}{2} \leq \theta \leq \theta_{0}, \pi - \theta_{0} \leq \theta \leq \pi - \frac{\delta}{2}$$  \hspace{1cm} (6)

Rearranging Eq. (2), we have

$$\frac{1}{dC_{t}} = \frac{2}{dC_{t}} + \frac{1}{dC_{p}} ; \theta_{0} \leq \theta \leq \pi - \theta_{0}$$  \hspace{1cm} (7)

$$\frac{1}{dC_{t}} = \frac{1}{dC_{T}^{ex}} : \frac{\delta}{2} \leq \theta < \theta_{0}, \pi - \theta_{0} < \theta \leq \pi - \frac{\delta}{2}$$  \hspace{1cm} (8)

As a result of integrating over $\theta$ from $\frac{\delta}{2}$ to $\pi - \frac{\delta}{2}$, we obtain

$$C_{t} = \frac{\varepsilon_{T} \varepsilon_{1} aL}{2(a-b)} \left[ \varepsilon_{L} + \left( \frac{b}{a-b} \right) \varepsilon_{T} \right] \ln \left( \frac{\tan \left( \frac{\theta_{0}}{2} \right)}{\tan \left( \frac{\theta_{0}}{2} \right)} \right)$$

$$+ \frac{\varepsilon_{T} \varepsilon_{1} aL}{2(a-b)} \left[ \varepsilon_{L} + \left( \frac{b}{a-b} \right) \varepsilon_{T} \right] \ln \left( \frac{\tan \left( \frac{\pi - \theta_{0}}{2} \right)}{\tan \left( \frac{\theta_{0}}{2} \right)} \right)$$

$$+ \varepsilon_{T} L \ln \left( \frac{\tan \left( \frac{\theta_{1}}{2} \right)}{\tan \left( \frac{\delta/2}{2} \right)} \right)$$  \hspace{1cm} (9)

Since $\theta_{a} = \theta_{0}$ when void fractions, $a = 1$ and $\theta_{a} = \pi - \theta_{0}$ when $a = 0$, the total capacitance are as follows:

$$C_{T}(a = 1) = \frac{\varepsilon_{T} \varepsilon_{1} aL}{(a-b)} \left[ \varepsilon_{L} + \left( \frac{b}{a-b} \right) \varepsilon_{T} \right] \ln \left( \frac{\tan \left( \frac{\theta_{0}}{2} \right)}{\tan \left( \frac{\theta_{0}}{2} \right)} \right)$$

$$+ \varepsilon_{T} L \ln \left( \frac{\tan \left( \frac{\theta_{0}}{2} \right)}{\tan \left( \frac{\delta/2}{2} \right)} \right)$$  \hspace{1cm} (10)

$$C_{T}(a = 0) = \frac{\varepsilon_{T} \varepsilon_{1} aL}{(a-b)} \left[ \varepsilon_{L} + \left( \frac{b}{a-b} \right) \varepsilon_{T} \right] \ln \left( \frac{\tan \left( \frac{\theta_{0}}{2} \right)}{\tan \left( \frac{\theta_{0}}{2} \right)} \right)$$

$$+ \varepsilon_{T} L \ln \left( \frac{\tan \left( \frac{\theta_{0}}{2} \right)}{\tan \left( \frac{\delta/2}{2} \right)} \right)$$  \hspace{1cm} (11)

Figure 11 shows the relationship between the capacitance and the relative permittivity of the tube obtained by using the above equations. The parameters used in the experiment are substituted in Eq. (10) and Eq. (11): $a = 25.4 \text{mm}, b = 15.0 \text{mm}, L = 30.0 \text{mm}, \varepsilon_{B} = 1.0, \varepsilon_{T} = 1.4$ and $\delta = 49.0\text{deg}$. 

![Fig. 11. Predictive result of relation between capacitance and relative permittivity with Eq. (10) and (11): $a = 25.4 \text{mm}, b = 15.0 \text{mm}, L = 30.0 \text{mm}, \varepsilon_{B} = 1.0, \varepsilon_{T} = 1.4$ and $\delta = 49.0\text{deg}$.](image)
in Fig. 11. That is to say, the capacitance is less affected by the change in the relative permittivity of tubes when the arc length of the electrodes is equal.

Additionally, as revealed by Fig. 12, the capacitance is less sensitive to the relative permittivity of the tube ($\varepsilon_f$) when the relative permittivity is larger. This is understandable by the Eq. (7). The capacitances $dC_t$ and $dC_p$ are proportional to the relative permittivity of the tube and fluid respectively. If $dC_t$ is much larger than $dC_p$, $dC_t$ is negligible in the Eq. (7). Therefore, if the chord length of the electrodes is equal to the internal diameter of the tube and the relative permittivity of the tube is much larger, the temperature drift may be reduced.

In order to validate the above hypothesis, an experiment was performed using four different void fraction sensors: the sensor No. 1, the original sensor used in the past experiments; the sensor No. 2 whose chord length of electrodes is smaller than sensor No.1; the sensor No. 3, whose chord length of electrodes is the same as sensor No. 2 and internal diameter of the tube is almost the same as that of chord length of electrodes. The sensor No. 4, which is identical to sensor No. 3 except for the material of the tube, which is made from zirconia whose relative permittivity is over ten times as large as Iupilon has. The details of the sensors are shown in Table 3. In the table, the slope of temperature drift means the variation of the normalized capacitance against 1 K of the change of the wall temperature in Fig.13.

The result of the experiment is shown in Fig.13. The normalized capacitance, $C_N$, is given by

$$C_N = \frac{C - C_G}{C_{G0} - C_G}$$  \hspace{1cm} (12)

where $C_{G0}$, $C_{G0}$ are the capacitance of the liquid and gaseous nitrogen when the tube is cooled down extracted from the previous vertical test. $C_G$ is the capacitance of gaseous phase when the tube temperature is room temperature extracted at the beginning in this test. $C$ is the capacitance of gaseous phase measured in real time in this test.

Comparing the slope between the sensors, No. 2 reduces 63% of the temperature drift in comparison with No.1. Also, the sensor No. 3 reduces 66 % in comparison with No.2. Those results means the first hypothesis is validated, that the same arc length of the electrodes is effective. The temperature drift of the shield or coaxial cables had a dominant influence when the cord length is shorter than the diameter of the pipe. Hence, No.3 has the contrast trend to the No.1, the No.2.

The temperature drift by using the sensor No.4 shows the worst result on the temperature drift, that is against the second hypothesis on the relative permittivity of the tube. The cause of this increase in the temperature drift on the sensor No.4 can be explained by the end effect of the electrodes. The lines of electric force of the sensor are shown in Fig. 14. In our analysis, all of the lines of electric force are supposed to be parallel straight lines; however, in actuality, the lines from the edges of the electrodes are curved as can be seen in Fig. 14. Thus, the measured capacitance includes the extra capacitance, that is measured in the outside of the region sandwiched by the electrodes. If the sensor measures the extra capacitance, using the material with high relative permittivity causes the large temperature drift as guessed by Eq. (9).

![Fig. 14. Edge effect of the lines of electric force.](image)
To avoid this phenomenon, the size of the electrodes must be further decreased so that the chord length of them should be shorter than the internal diameter. On the other hand, if the size of electrodes is too short, working fluid in the tube is not completely covered with the lines of electric force between the electrodes. Therefore, it is thought that the size of the electrodes has its optimal chord length.

4. Conclusion

A capacitance type void fraction sensor was developed and tested on the cryogenic fluid. This study provides the following knowledge and achievements.
1. The function of the capacitance type void fraction sensor was validated by the gas-oil and air flow. The void fraction measured by the sensor was compared to the result of the optical method. The difference between the values using the two methods is about 5%.
2. The sensor was able to function on the cryogenic nitrogen flow; however the temperature drift due to the change of the temperature of the tube caused the errors of 10%.
3. Two methods for reducing the temperature drift were devised. The method to reduce the size of the electrodes is effective; the short electrodes reduce the quantity of the temperature drift by 63% compared to the original sensor.
4. The method to use the tube material which has large relative permittivity cannot show the good results due to the edge effect of the lines of electric force.

References