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Experimental study of liquid level gauge for liquid hydrogen using Helmholtz resonance technique

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ABSTRACT

The Helmholtz resonance technique was applied to a liquid level gauge for liquid hydrogen to confirm the applicability of the technique in the cryogenic industrial field. A specially designed liquid level gauge that has a Helmholtz resonator with a small loudspeaker was installed in a glass cryostat. A swept frequency signal was supplied to the loudspeaker, and the acoustic response was detected by measuring the electrical impedance of the loudspeaker's voice coil. The penetration depth obtained from the Helmholtz resonance frequency was compared with the true value, which was read from a scale. In principle, the Helmholtz resonance technique is available for use with liquid hydrogen, however there are certain problems as regards practical applications. The applicability of the Helmholtz resonance technique to liquid hydrogen is discussed in this study.

1. Introduction

There are several methods for measuring the liquid level in a tank, but there are few realistic options as regards liquid hydrogen. In the industrial field, it is common for resistance temperature detectors to be arranged linearly in a tank to detect the position of a liquid/vapor interface but this is a non-continuous measurement method. In terms of a continuous measurement method, an electric capacitance type level gauge is commercially available. However, calibration operations are required for each measurement because of the small difference between the electric permittivities of vapors and liquids. As an alternative method, a superconducting level sensor using MgB_2 has been developed, but heating is needed to adjust the superconducting transition temperature of MgB_2 under the atmospheric pressure condition [1,2]. In the field of space development, Radio Frequency Mass Gauging (RFMG) has been developed and has successfully measured the masses of liquid hydrogen and liquid oxygen under terrestrial conditions [3]; it has also measured the mass of liquid oxygen under micro-gravity conditions [4]. RFMG is a novel technology for gauging propellant quantity that is being developed at NASA. It is a powerful method but it requires a database of simulated eigen-mode frequencies at various tank fill levels prior to the measurement.

The Helmholtz resonance technique is a volume measurement technique that uses acoustic waves, and many studies have employed this technique to measure the volumes of gases, liquids, and solids [5–9]. We have also attempted to employ this technique to measure the volumes of liquids under micro-gravity conditions [10]. In that study, we prepared a semi-open-type Helmholtz resonance cell and successfully measured the volume of water using this technique. However, with liquid nitrogen, the volume could not be measured accurately due to the existence of a large temperature gradient in the vapor phase. After that experimental study, an equation for a closed Helmholtz resonator was proposed, and liquid volume measurements were carried out using liquid nitrogen with a closed Helmholtz resonator, which was designed to maintain a homogeneous spatial temperature distribution in the vapor phase [11]. It was ascertained that the equation for a closed Helmholtz resonator was both correct and useful. It was also confirmed that the Helmholtz resonance technique was applicable to cryogens under micro-gravity conditions [12]. In this study, the Helmholtz resonance technique was applied to a liquid level gauge for liquid hydrogen to adapt this technique for industrial applications in the cryogenic engineering and hydrogen energy technology fields.

It is known that the Helmholtz resonance frequency of a large volume resonator is lower than that of a small volume resonator.

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If the Helmholtz resonance technique is applied to large-scale tanks, the resonance frequencies become very low and in some cases they are lower than the audible frequencies. It is difficult to measure the volume of liquid in a large-scale tank directly with this technique. The best approach with a large-scale tank is to install a small Helmholtz resonator in the tank, and use it as a liquid level gauge. However, a large temperature gradient is formed in the vapor phase in almost all industrial cryogenic tanks due to heat leaks. The temperature gradient strongly affects the velocity of sound thus preventing precise measurement. Therefore, an equation that included sound velocity correction was proposed and liquid volume measurements were carried out using liquid hydrogen to confirm the validity of the equation. The applicability of this measurement technique to liquid hydrogen and related problems are discussed in this paper.

2. Experimental set-up

Fig. 1 shows a photograph of the experimental set-up. The liquid hydrogen was prepared using the hydrogen liquefier seen in the center of the photograph. The hydrogen liquefier has a two-stage Gifford-MacMahon refrigerator that cools and liquefies the gaseous hydrogen obtained from the hydrogen cylinder. The liquid hydrogen is stored in a tank with a capacity of 30 L in the liquefier [13]. A liquid level gauge employing the Helmholtz resonance technique was installed in the glass cryostat shown on the right in the photograph. Liquid hydrogen was transferred from the hydrogen liquefier to the cryostat through a transfer tube.

Fig. 2 shows schematic views of the cryostat and the liquid level gauge. The cryostat consists of two glass Dewars, which are silvered to minimize the radiation heat input except for 10 mm wide observation slits. The outer Dewar holds liquid nitrogen for pre-cooling, and the liquid hydrogen was transferred to the inner Dewar with an inner diameter of 6 cm. The liquid level gauge was installed in the inner Dewar. A photograph and a schematic of the liquid level gauge are also shown in Fig. 2. The liquid level gauge consists of a resonance body, a neck tube, and a main body, which is a Helmholtz resonator. The inner diameter of the resonance body is 18 mm. A 20 mm diameter loudspeaker (Foster 334495) is installed in the resonance body. The 30 mm long neck tube, which is made of 3/8″ stainless steel tube, is welded under the center of the resonance body. The 600 mm long main body is made of 1/2″ stainless steel tube. The scale was marked on the outer surface of the main body. The main body and the neck tube are connected with a straight bore-through SWAGELOK reducing union. The bottom part of the main body was submerged in liquid hydrogen, and so a closed Helmholtz resonator was realized as shown in Fig. 2. There is a small (0.5 mm diameter) hole at the top of the main body to maintain the pressure balance between the inside and outside of the main body, but this does not influence the Helmholtz resonance frequency from an acoustic point of view. The pressure in the experimental space was monitored with the pressure transducer shown in Fig. 2.

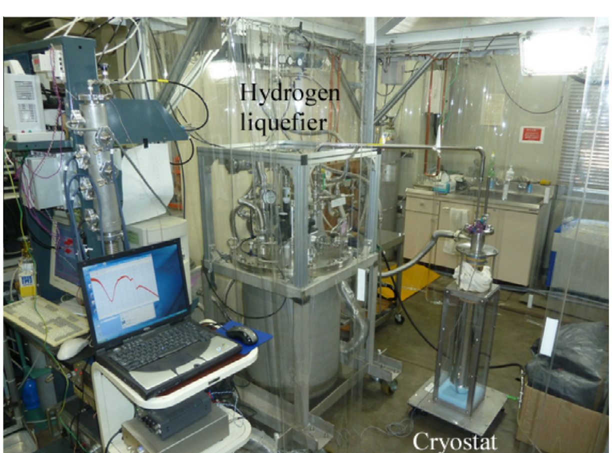

Fig. 1. Photograph of experimental set-up.

A swept frequency signal was supplied to the loudspeaker, and the acoustic response was detected by measuring the electrical impedance of the loudspeaker's voice coil. We processed the swept frequency signal and the electrical impedance signal, which were the output and input signals, using a personal computer with a sound function and our own software. The output signal was amplified with an ONKYO A-905TX amplifier, through a loudspeaker characteristic arithmetic unit EKUREA KU-1AEH, which is the special order product. The input signal was recorded at a sampling rate of 44.1 kHz and with 16 bit resolution. It is noted from the schematic of the liquid level gauge in Fig. 2 that there is a space behind the loudspeaker. It is important to keep an appropriate space behind the loudspeaker to detect the Helmholtz resonance signal by measuring the electrical impedance of the loudspeaker's voice coil in a closed Helmholtz resonator. In this experiment, the volume adjustment was also made by using clay to obtain a strong Helmholtz resonance signal.

Fig. 3 shows a schematic in the cryostat, a photo of the liquid/vapor interface of liquid hydrogen and the outer surface of the main body observed though the observation slit. The geometrical configuration of the liquid level gauge is also shown in the figure. V_1 is the volume of the resonance body, which is the spatial volume in front of the loudspeaker. V_2 is the volume of the main body, which is the inner volume of the 1/2″ stainless steel tube with the length of 600 mm. A, and L are the cross-sectional area and the length of the neck tube. B is the cross-sectional area of the main body. V_L represents the volume of liquid hydrogen in the main body where the part illustrated by the shaded area in Fig. 3. L_P shows the penetration depth, which can be easily obtained from V_L and B. The V_L was obtained from the Helmholtz resonance frequency and the L_P was calculated. At the same time, the penetration depth, L_P, was read using the scale from the outside through the observation slit. The liquid/vapor interface of the liquid hydrogen and the scale are seen in the photo in Fig. 3. In this case, the interface is located at 416 mm from the bottom of the liquid level gauge. The penetration depth read by the scale indicates the true value of L_P (or V_L). The L_P calculated from V_L which is obtained from the Helmholtz resonance frequency, is compared with the true value.

3. Experimental results and discussion

Fig. 4 shows an example of the experimental results we obtained when the liquid surface was located 20.0 cm from the bottom of the main body. The frequency of the sound was swept from 200 to 3000 Hz for 5 s. The data were collected under atmospheric pressure. Fig. 4a shows the recorded sound signal, which was obtained by using a loudspeaker impedance measurement. The loudspeaker was operated with a constant voltage, and so the voice coil impedance was obtained from the electric current measurement. In this case, the input signal was proportional to the inverse of the voice coil impedance [12]. The maximum voice coil impedance is represented by the minimum. The depressions seen in the sound signal are induced by the Helmholtz resonance phenomenon. Fig. 4b shows the power spectrum obtained from a Fast Fourier Transformation (FFT) analysis. Here, the power spectrum suppressed at the frequencies those are related to the