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Development of a system for measuring head differential pressure and density of working fluid at high pressures

Tokihiko Kobata *, Hiroaki Kajikawa

National Metrology Institute of Japan (NMIJ), AIST, AIST Tsukuba Central 3, 1-1-1Umezono, Tsukuba, Ibaraki 305-8563, Japan

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ABSTRACT

A system for accurately measuring the head differential pressure between a reference level and a measurement level at high line pressures has been developed. The system mainly consists of a pressure transducer, a motorized slider, a high-pressure flexible metal tube, and pressure generation apparatuses, including a pressure balance. The head differential pressure is obtained from the pressures measured by the transducer at two levels whose vertical distance was varied from 0 mm to 1000 mm. The line pressure was varied from 20 MPa to 200 MPa. The results of our experiments showed that the head differential pressure for a vertical height difference of 1000 mm could be measured accurately as a function of line pressure. From the measured head differential pressure, the density of the working fluid used could be evaluated as a function of pressure up to 200 MPa with a relative expanded uncertainty of 1.3×10^{-2}.

1. Introduction

Recently, there has been growing demand for precise pressure measurement in scientific research and in industry. In cases where there is a height difference between a reference level and a measurement level in a pressure circuit, the head differential pressure needs to be measured with the necessary measurement uncertainty and then compensated. In the case of a pressure measurement using a liquid medium, the head differential pressure should be evaluated more accurately since liquid density is generally much higher than gas density in smaller pressure range.

Usually, the head differential pressure can be obtained by evaluating a formula that includes the densities of the working fluid and surrounding atmosphere, the gravitational acceleration at the measurement site, and the vertical height difference between the reference and measurement levels. However, if the density of the working fluid is unknown, the head differential pressure cannot be obtained by this method.

In this study, a system for accurately measuring the head differential pressure between reference and measurement levels in a hydraulic pressure circuit at high pressures was developed. The system can measure the head differential pressure even when the density of the working fluid is unknown. The system mainly consists of a pressure transducer, a motorized slider, a high-pressure flexible metal tube, and pressure generation apparatuses, including a pressure balance. Using the developed system, the head differential pressure between reference and measurement levels, whose vertical height difference was varied form 0 mm to 1000 mm, was accurately measured for line pressures up to 200 MPa. From the measured head differential pressure, the density of the working fluid could be evaluated as a function of pressure.

We first describe the principles of measuring the head differential pressure using the system developed, explaining its components and the proposed measurement method. We then present results for the head differential pressure measured using the system and the method. From the measured head differential pressures, we obtain the density of the working fluid as a function of pressure and evaluate its uncertainty. We also compare the results with values obtained from the equation that has been previously reported. Finally, we summarize our conclusions and the features of the developed system.

2. Measurement principles

Fig. 1 shows the concept for measuring head differential pressure by changing the vertical position of a pressure measuring device. The pressure measuring device and a pressure controller are connected using a deformable pressure tube. The pressure controller is used to generate accurate and stable pressures. If stable pressure, p_s, is generated by the pressure controller, then the pressure measured at an arbitrary measurement level $z = a$ mm, $P_{z=a}$, is given by

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* Corresponding author.
E-mail address: tokihiko.kobata@aist.go.jp (T. Kobata).

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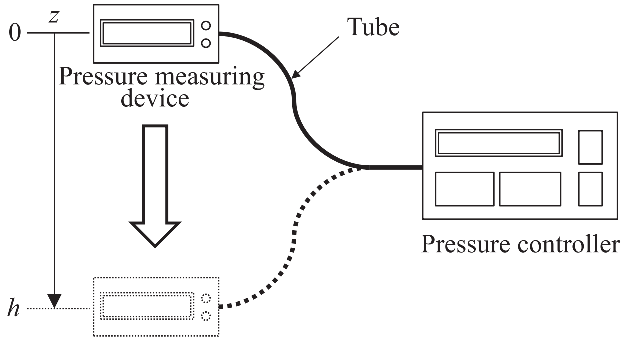

Fig. 1. Concept for measuring head differential pressure by changing the vertical position of a pressure measuring device.

$$P_{z=a} = p_s + dp_{z=a}, \tag{1}$$

where $dp_{z=a}$ is the pressure head difference between the reference level of the pressure controller and measurement level, $z = a$ mm.

As shown in Fig. 1, by using a deformable tube, the vertical position of the pressure measuring device can be moved while continuously applying stable high pressures. On the other hand, the pressure controller is firmly mounted at a fixed vertical level during all the measurements. By changing the vertical position of the pressure measuring device from its reference level to the measurement level, the pressures at the two levels are measured and the head differential pressure between the two levels can be obtained. First the pressure measuring device is set at its reference level, $z = 0$ mm, and p_s is generated by the pressure controller. Thus, the pressure measured by the measuring device at $z = 0$ mm, $P_{z=0}$, is obtained. After that the vertical position of the pressure measuring device is changed to $z = h$ mm, while maintaining constant line pressure and the pressure measured at $z = h$ mm, $P_{z=h}$, is obtained. When the measurement position is lower than the reference level, h is positive. From the pressures measured at the different levels, the head differential pressure, DP_h, is obtained from

$$DP_h = P_{z=h} - P_{z=0}. \tag{2}$$

It is well known that the head differential pressure, DP_h, can also be obtained from

$$DP_h = \left(\rho_f - \rho_a\right) \cdot g \cdot h \tag{3}$$

where ρ_f is the density of the working fluid as a function of temperature and pressure, ρ_a is the density of the surrounding atmosphere, and g is the acceleration due to gravity at the location where the measurement is made. In case of an absolute pressure measurement in a vacuum, Eq. (3) can be simplified to Eq. (4) since $\rho_a = 0$:

$$DP_h = \rho_f \cdot g \cdot h \tag{4}$$

The density of working fluid can then be obtained from

$$\rho_f = \frac{DP_h}{g \cdot h}, \tag{5}$$

where DP_h is obtained from Eq. (2).

3. Measuring system

Fig. 2 shows a schematic drawing of the measuring system developed in this study. The system mainly consists of two sections: a pressure generation section and a pressure measurement section, which are drawn on right and left sides in the figure, respectively. In this study, dioctyl sebacate was used as the working fluid.

In the pressure generation section, there is a hydraulic pressure balance with an automatic weight handler, a pressure controller, and an environmental measuring device. The pressure balance, which is used as an accurate pressure generator, is mainly composed of a piston–cylinder assembly, weights, and a base. It can generate stable hydraulic pressures by loading the known mass of its piston and weights on the known effective area of its piston–cylinder assembly [1–3]. The maximum generating pressure can be changed by replacing the piston-cylinder assembly. In this study, a piston-cylinder assembly with a nominal effective area of about 4.9 mm^2 was used for generating stable pressures up to 200 MPa. The total mass, including the piston and bell, is around 100 kg. The characteristics of the pressure balance used, such as the effective area of the piston–cylinder as a function of pressure, were evaluated through comparison with NMIJ pressure standards beforehand. When the piston is floated in the appropriate position and is rotated in the cylinder with appropriate rotational speed, accurate and stable pressure is generated. An automatic weight handler is used to load and unload pressure balance weights. The pressure controller can automatically generate an accurate pressure and control the piston floating position through fine pressure adjustments via feedback control by a computer. The environmental measuring device measures the environmental temperature, humidity, and atmospheric pressure for mass buoyancy correction and to calculate the pressure generated. The pressure balance and the pressure controller are connected using a rigid metal tube in a hydraulic circuit. The pressure generation section can automatically generate hydraulic pressures from 10% to 100% of the full scale in steps of 10%.

In the pressure measurement section, there is a precise pressure transducer attached to an electric motorized slider. The height of the transducer can be changed by moving it vertically with the motorized slider. The motorized slider can be controlled by using a controller and an interactive terminal. It can also be controlled from a personal computer through a serial interface. Using the motorized slider, the vertical distance between the reference level and the measurement level can be changed from 0 to 1000 mm with respect to the reference level. The velocity of the movement was set to 50 mm/s in this study so the time needed for moving 1000 mm was about 20 s. A quartz Bourdon-type absolute pressure transducer [4] of maximum pressure 200 MPa was used. Commands and data requests to the transducer were sent via a bidirectional RS-232 serial interface. It has been reported that the resolution of a pressure transducer under a specific setting condition corresponds to less than about 5×10^{-8} of the full scale of the transducer [5]. The pressure transducer was connected to the pressure generation section through a flexible metal tube made of stainless steel with an outer diameter of 1.6 mm (1/16 in.) and a length of 1500 mm. By using the flexible metal tube and the motorized slider, the vertical position of the pressure transducer can be moved while continuously applying stable high pressures up to 200 MPa.

All the equipment in the system can be operated from a computer and fully automatic measurement can be performed using software developed for the system.

4. Measurement method

The measurement and the calculation can be performed as a series of operations by executing the program. At each target pressure, the weights are loaded or unloaded on the pressure balance by the automatic weight handler and the system is pressurized by the pressure controller. After pressurizing the system and waiting more than 10 min following establishment of a steady pressure, the piston position of the pressure balance is finely adjusted by the pressure controller, to the target floating range. Then the data collection process is started.