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A comparative study of flow rate characteristics of an averaging Pitot tube type flow meter according to H parameters based on two kinds of differential pressure measured at the flow meter with varying air temperature †

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Abstract

A new averaging Pitot tube flow meter that has a shape similar to an Annubar® type flow meter was designed and its flow rate characteristic was evaluated. The air temperature supplied to the developed flow meter was maintained at a constant by controlling electric power supply to an electric heater during the calibration. Two kinds of differential pressure measured at the flow meter were used in calculating the H parameters, which represent characteristics of the developed flow meter. One H parameter ($H_{\Delta P1}$) which was newly proposed in this research was calculated based on the difference between upstream pressure (stagnation pressure) at the flow meter and static pressure of the measured flow. The differential pressure is equivalent to the dynamic pressure of the flow. The other H parameter ($H_{\Delta P2}$) which is used in a typical Annubar® type flow meter was calculated based on the difference between upstream and downstream pressure at the developed flow meters. Relationship curves between the two H parameters and the mass flow rate at the developed flow meter were obtained. The curves based on the $H_{\Delta P2}$ parameter, which uses the difference between up and down stream pressure, show different gradients for varying the controlled air temperature. However, the other curve, based on the other $H_{\Delta P1}$ parameter, which uses the dynamic pressure, can be represented by one linear curve even with varying air temperature.

Keywords: Annubar® type flow meter; Gas temperature; Differential flow meter; Hydraulic parameter; Flow rate

1. Introduction

Several flow meters such as differential pressure, positive displacement, turbine, Karman vortex, Corioli and thermal type etc. are used to measure the flow rate of gas [1]. The differential pressure type flow meter which is based on the Bernoulli's equation is more widely used than other types due to its simple structure and standardized method of the flow rate calculation [2]. Flow rate of some fluids can be obtained by measuring a differential pressure across a flow meter that is mounted in a pipe. The flow rate is calculated from the measured differential pressure and the empirical correlation coefficient. The differential pressure at the flow meters can be caused by either an obstruction of the fluid meter or the dynamic flow velocity around the fluid meter [3, 4]. The obstruction flow meters such as orifice plates, Venturi tubes and flow nozzles are most commonly used in industry. The averaging Pitot tube is a representative flow meter that obtains a flow rate by measuring the pressure difference caused by the dynamic flow velocity.

The obstruction flow meters causes a pressure difference between the upstream and the downstream at the flow meter due to the reduction of the flow area, and thus the pressure difference through the obstruction is higher than that of an averaging Pitot tube, which occupies a small area in the flow. Also, an averaging Pitot tube type flow meter, such as an Annubar® flow meter, has advantages of accuracy, simplicity, and reliability compared to the orifice plate, Venturi tube and flow nozzle which are expensive to install and limited in application [5, 6].

Britton and Mesnard [7] studied the outer shape of the Annubar® type flow meter. Cutler [8] and Lee [9] investigated the effect of a pressure tap on the flow rate characteristics of an Annubar® type flow meter. However, there has been little research into flow rate characteristics with gas temperature controlled conditions. In previous research [10, 11, 12] Annubar® type flow meters have shown that mass flow rate has a linear relationship with H, which is a parameter based on the root of differential pressure. The differential pressure found in the previous research [10, 11, 12] was obtained by measuring pressures at both upstream and downstream pressure taps of the flow meters.

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In this study, a new flow meter similar to the Annubar® type flow meter was developed and its flow rate characteristics were evaluated. In addition to the H parameter proposed in the previous research [10], a new H parameter was proposed in this research. The new H parameter proposed in this research is based on the dynamic pressure in the flow, that is, differential pressure between the upstream pressure (stagnation pressure) of the flow meter and the static pressure of the flow, that is, the dynamic pressure of the flow in the developed flow meter. A comparative study of flow rate characteristics according to the two H parameters was undertaken. Also, the effect of air temperature on the flow rate characteristics of the flow meter was investigated by controlling the supplied air low temperature.

2. Experiments

The developed new flow meter has a shape similar to that of an Annubar® type flow meter as shown in Fig. 1 [5]. The outer appearance of the cross section in the developed flow meter has a diamond shape as shown in Fig. 2. The inner structure of the developed flow meter is composed of two pressure detecting chambers that are separated from each other. The pressure detecting chambers in the developed flow meter are machined by a drill. The stagnation pressure of the flow is sensed at the upstream chamber of the developed flow meter. The pressure sensed at the downstream chamber of the flow meter is not stagnation pressure but lower than the static pressure at the pipe wall due to incomplete pressure recovery by flow separation at the flow meter. The pressure taps for sensing both the upstream and downstream pressure of the developed flow meter are drilled at either 1 mm, 2 mm, or 3 mm in diameter with 6 mm intervals between consecutive taps. The stagnation number of pressure taps is seven, allowing the sensing of each average pressure of upstream and downstream at the developed flow meters.

In order to calibrate the flow rate of the developed flow meters, a flow measurement system was constructed as shown in Fig. 3. The flow calibration system consists of a laminar flow meter, the developed flow meter, a blower, a temperature measurement system, four U-tube manometers, an inclined manometer, and electric heater with temperature controller. The inlet pressure of the laminar flow meter, by discharge of the blower, was measured to compensate for the air density using the U1 manometer. The inclined manometer is used for measuring the differential pressure at the laminar flow meter. The U2 manometer measures the static pressure in the pipe wall to compensate for the air flow density. The differential pressure at the developed flow meter is measured with the U3 manometer. The pressure at the downstream tap is measured with the U4 manometer. The stagnation pressure of the flow can be measured by adding the differential pressure $\Delta P2$ to the pressure measured by the U4 manometer, that is, $\Delta P2+P_{U4}$. The dynamic pressure of the flow can be calculated by subtracting the static pressure from the stagnation pressure of the flow, that is, $(\Delta P2+P_{U4})-P_{U2}$.

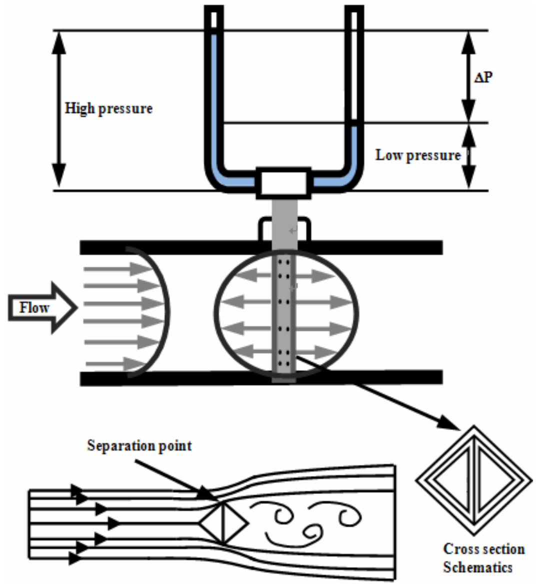

Fig. 1. Schematic diagram of an Annubar® type flow meter.

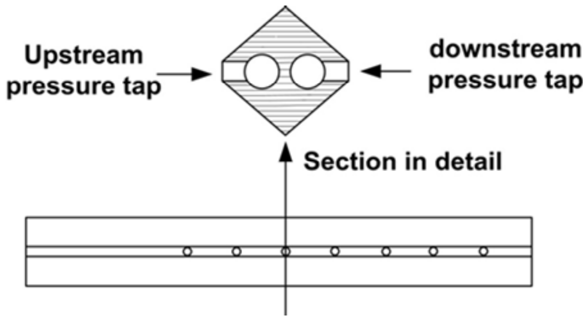

Fig. 2. Cross section of the developed flow meter.

The temperature to compensate for the air density is measured using a J-type thermocouple at the inlet of the laminar flow meter. The temperature to compensate for the air density for the developed flow meter is measured at two locations of the upstream and downstream of the developed flow meter. The laminar flow meter is used as a reference flow meter for calibrating the flow meter. The blower motor can rotate its blade at 3480 rev./min at rated power conditions. Electric power of 220V/3 phase was supplied to the blower. Target temperatures of the intake air were constantly controlled using the electric heating controller, which gated electric power supply from the feedback temperature in the entrance of the developed flow meter. The electric heater has a capacity of 10kW at maximum. The electric power source supplied to the heater was also 220V/3 phase.

For the calibration of the flow rate, the air is drawn in by the blower through the air cleaner and laminar flow meter and past the developed flow meter, following the arrows shown in Fig. 3. With the air flow rate maintained constantly by positioning the inverter knob to set the rotating speed of the blower, the differential hydraulic head in the inclined ma-

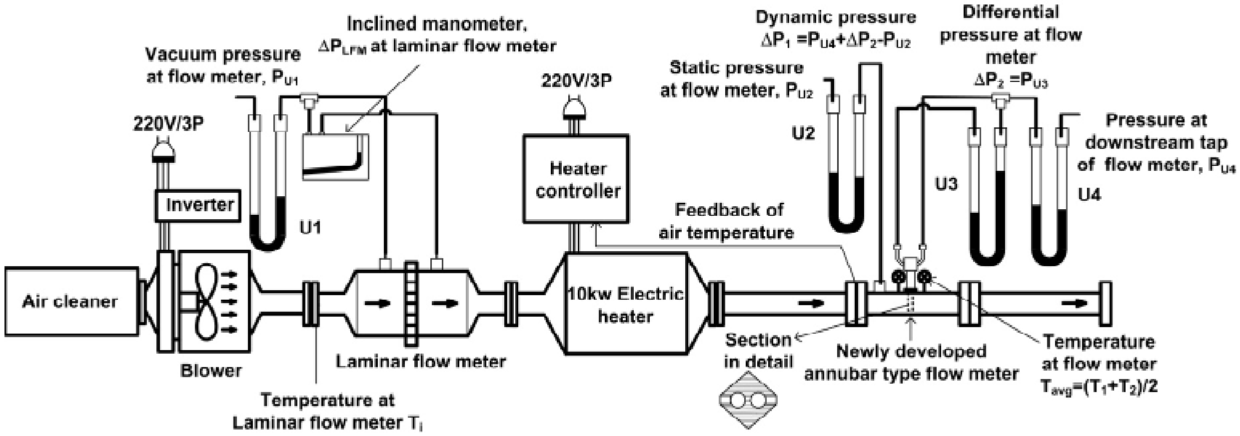

Fig. 3. Experimental setup for calibrating the developed flow meter.

nometer, the hydraulic head in 4 U-tube manometers, the intake air temperature, and the temperature in the developed flow meter were recorded. Because both the laminar and developed flow meters are connected in a straight line, the flow rate at the developed flow meter is the same as that of the laminar flow meter, which has an accuracy of 0.5%. After adjusting the inverter knob again for the next target flow rate of the calibration, the process of the experiments is repeated as explained previously. The measurements were repeated nine times with variations of flow rate.

3. Results and discussions

3.1 H parameters

The flow rate of the Annubar® [5] flow meter was calculated from the differential pressure (ΔP_2) between the upstream and downstream pressure tap. A parameter $H_{\Delta}P2$ based on the ΔP_2 is introduced to evaluate the flow rate characteristics [10]. This value, $H_{\Delta P2}$, can be calculated from Eq. (1) using the differential pressure ΔP_2. ΔP_2 is measured using the U3 manometer, as shown in Fig. 2.

$$H_{\Delta P_2} = \frac{P_{U2}}{101.3(kPa)} \times \frac{293.15(K)}{T_{avg}} \sqrt{\frac{\Delta P_2}{\rho_{std}}} \quad (1)$$

P_{U2} : Static pressure at the developed flow meter (kPa)
T_{avg} : Average temperature at the developed flow meter $(T_1+T_2)/2$ (K)
ρ_{std} : Density of the air at standard conditions of 101.3 kPa and 293.15 K (kg/m^3)
ΔP_2 : Differential pressure between upstream and downstream of the developed flow meter

Another new H parameter $H_{\Delta P1}$, which is newly introduced in this research for comparison with the $H_{\Delta P2}$, can be calculated from Eq. (2) by substituting both ΔP_2 with ΔP_1, for including the dynamic pressure at the developed flow meter, and ρ_{std} with ρ_{FL}, for including the effect of temperature on the air density, respectively. ΔP_1 is the difference between the upstream pressure of the developed flow meter and the static pressure at the pipe wall (P_{U2}).

$$H_{\Delta P_1} = \frac{P_{U2}}{101.3(kPa)} \times \frac{298.15(K)}{T_{avg}} \sqrt{\frac{\Delta P_1}{\rho_{FL}}} \quad (2)$$

3.2 Results of flow rate characteristics at the developed flow meter

In order to investigate the effect of air temperature on the flow rate characteristics of the developed flow meter, the air drawn in by the blower was heated by the electric power heater to achieve the target air temperature T_{avg} at the developed flow meter under four temperature conditions: 25, 50, 75, and 100℃. The target temperatures of 25 and 100℃ of the supplied air at the flow meter were controlled within approximately ±5℃. The target temperatures of 50 and 75℃ of the supplied air were controlled more exactly within approximately ±3℃.

The several hydraulic heads using the U-tubes and the inclined manometer were measured at the pressure taps of the calibration system for the developed flow meter. Fig. 4 shows both $H_{\Delta P1}$ and $H_{\Delta P2}$ parameters versus Reynolds number at the flow meter. The values of $H_{\Delta P1}$ and $H_{\Delta P2}$ increase as the Reynolds number increase. Reynolds number at the developed flow meter ranges from 40000 to 200000. The value of $H_{\Delta P2}$ is nearly two times of that of $H_{\Delta P1}$. This means the hydraulic height of the U-tube correspondent to the $H_{\Delta P2}$ is two times higher than that of $H_{\Delta P1}$, in case the differential pressures correspondent to each H are measured. The measurement results are shown in Fig. 5(a)-(c), which corresponds to the pressure taps' diameters of 1 mm, 2 mm, and 3 mm in the developed flow meters, respectively. The notation of the flow meter 1-1, 2-2, 3-3 displayed in Fig. 5(a)-(c) means the pressure taps' diameter of the upstream and downstream respectively. The hydraulic head at both the upstream and static pressure taps increased as the parameter $H_{\Delta}P1$ increased, due to the increasing flow rate in the pipe. The hydraulic heads at both the upstream and static pressure taps showed a steeper increasing

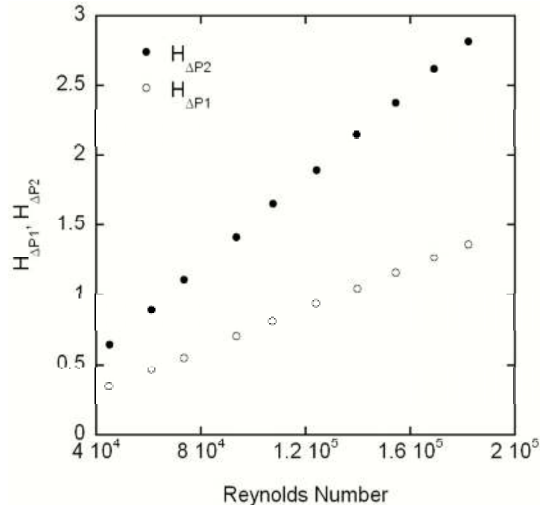

Fig. 4. $H_{\Delta P1}$ and $H_{\Delta P2}$ parameters versus reynolds number at the flow meter.

trend as the supplied air temperature increased, due to expansion of the heated air. Similarly, the differential hydraulic head between the upstream and the downstream pressure taps increased as the heated air temperature increased. However, the hydraulic head at the downstream pressure tap of the flow meter decreased as the $H_{\Delta P1}$ increased. The negative values at the downstream pressure are due to the incomplete pressure recovery at the downstream pressure tap with the separation of the flow. Also, the hydraulic head at the downstream pressure tap decreased more steeply as the air temperature increased due to the expansion of the heated air.

Fig. 6(a)-(c) ,which correspond to the pressure taps' diameters of 1 mm, 2 mm, and 3 mm in the developed flow meters, respectively, show the experimental results, which indicate the mass flow rate at the flow meter while constantly controlling the air temperature at 25, 50, 75, and 100℃. The mass flow rates at the developed flow meter, according to the parameter $H_{\Delta}P2$, are displayed. The mass flow rates show higher values for the same $H_{\Delta}P2$ with increase of the air temperature from 25 to 100℃. The gradients of the mass flow rate curves for each constantly controlled air temperature show different values from one another. On the contrary, the curves plotted according to $H_{\Delta}P1$ merged into one curve, as shown in Figs. 7(a)-(c), which correspond to the pressure taps' diameters of 1 mm, 2 mm, and 3 mm in the developed flow meters, respectively. The mass flow rate increased linearly with the parameter $H_{\Delta P1}$. Also, the merged linear curve shows a correlation coefficient of R = 0.999. These results mean that the calibration curve of the developed flow meters can be merged into a curve independent of the air temperature, which is a very good characteristic for the flow meter.

Fig. 8(a)-(c) shows the pressure heads, which are used in calculating the parameters $H_{\Delta P1}$ and $H_{\Delta P2}$, according to the $H_{\Delta P1}$. The differences of hydraulic head at the flow meter, which are measured by the U3 manometer, diverge as the constantly controlled air temperature increases from 25 to 100℃. On the contrary, the dynamic head at the flow meter is

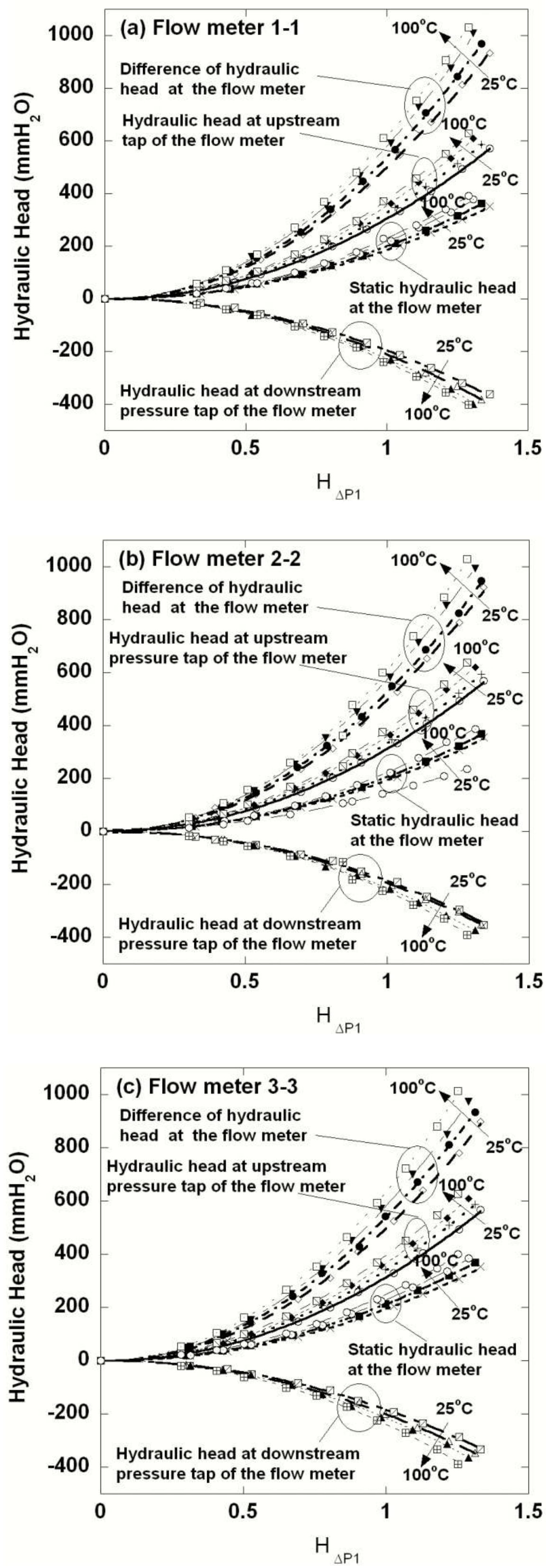

Fig. 5. Hydraulic heads according to $H_{\Delta P1}$ parameter while controlling air temperature for the diameter of the pressure taps' size: (a) 1 mm; (b) 2 mm; (c) 3 mm.

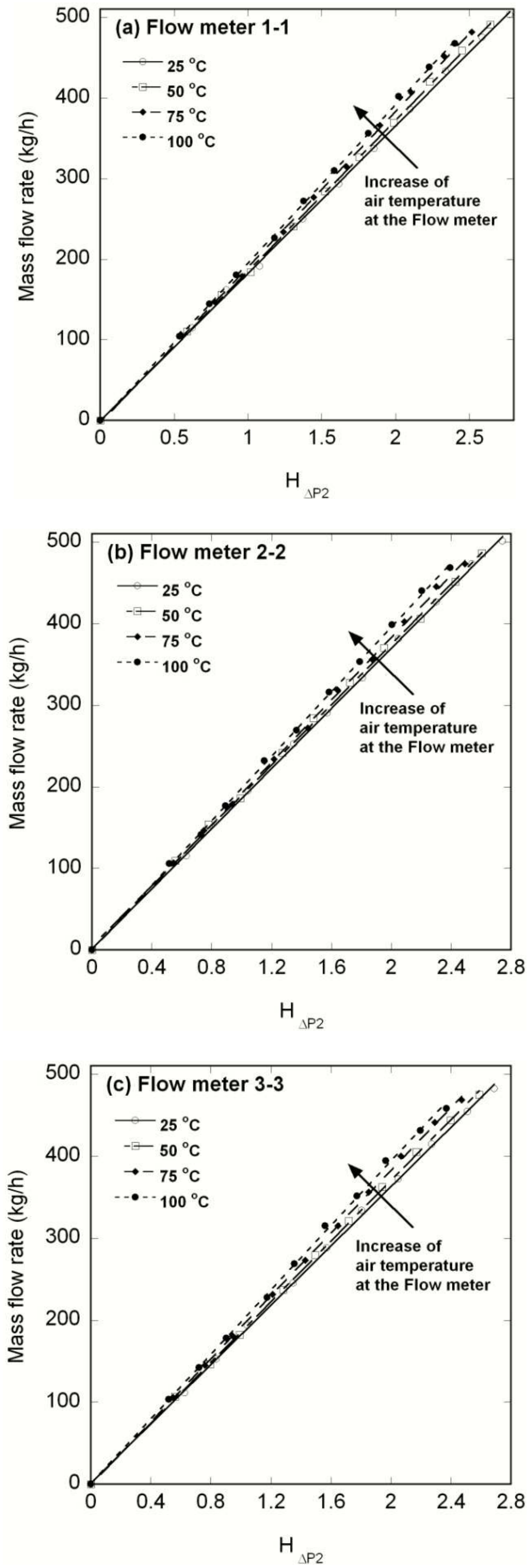

Fig. 6. Characteristics of the mass flow rate according to $H_{\Delta P2}$ parameter while controlling air temperature for the diameter of the pressure taps' size: (a) 1 mm; (b) 2 mm; (c) 3 mm.

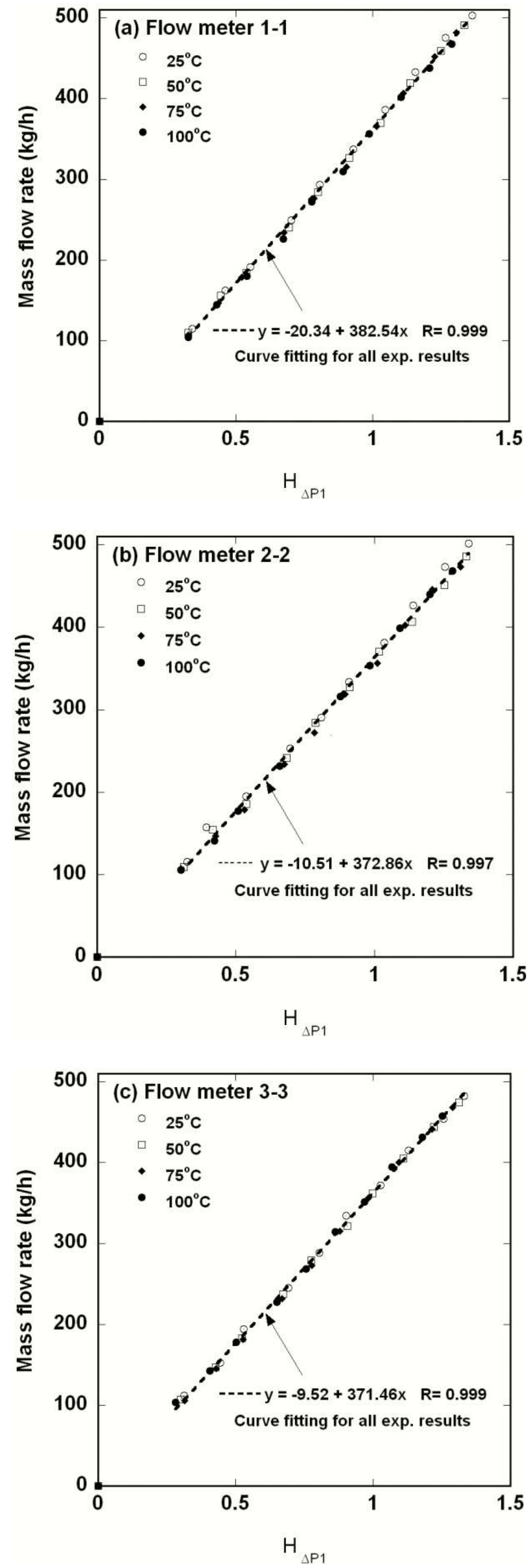

Fig. 7. Characteristics of the mass flow rate according to $H_{\Delta P1}$ parameter while controlling air temperature for the diameter of the pressure taps' size: (a) 1 mm; (b) 2 mm; (c) 3 mm.

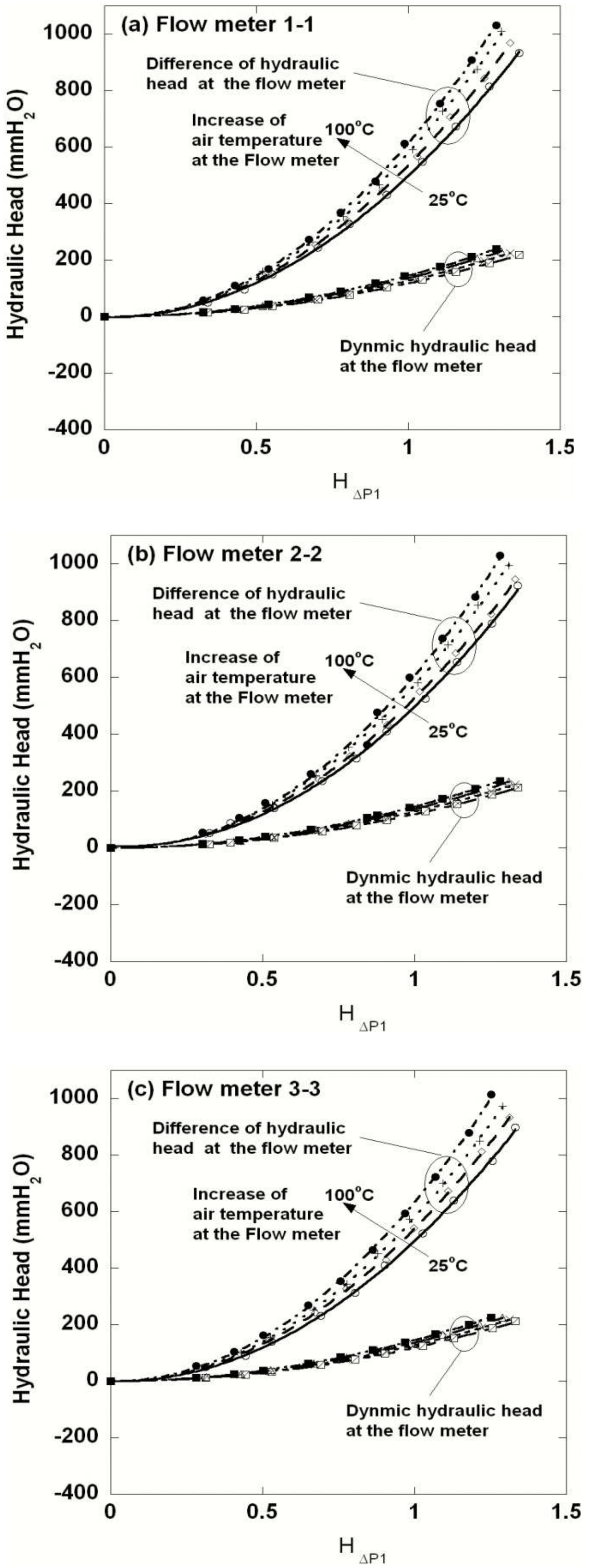

Fig. 8. Difference of hydraulic head between upstream and downstream pressure tap versus dynamic hydraulic head at the flow meter while controlling air temperature for the diameter of the pressure taps' size: (a) 1 mm; (b) 2 mm; (c) 3 mm.

nearly merged into one curve, even if the air temperature is varied from 20 to 100℃.

Regarding the effects of pressure taps' diameters of 1 mm, 2 mm and 3 mm, there is no big difference in the mass flow rate characteristics of the developed flow meter. Considering the mass flow rate characteristics with varying of the pressure taps' sizes, the 3 mm case is preferable to avoid blocking the tapping hole.

4. Conclusion

Mass flow rate curves based on the $H_{\Delta P2}$ parameter, which uses the difference between upstream and downstream pressure of the developed flow meters, showed different gradients according to the controlled air temperature. The mass flow rate curves based on the new $H_{\Delta P1}$ parameter proposed in this research, which uses dynamic pressure, merge into a curve independent of the supplied air temperature. The effects of pressure taps' diameters of 1 mm, 2 mm, and 3 mm shows no big difference in the mass flow rate characteristics of the developed flow meter.

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