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A comparative study of the flow rate characteristics of flange-embedded averaging Pitot tube (APT) flow meters for various cross-section shapes

Choong Hoon Lee

Department of Mechanical and Automotive Engineering, Seoul National University of Science and Technology, Seoul-01811, Korea.

ORCID ID: 0000-0002-2930-5786

Abstract

In order to enhance the productivity and maintenance of the APT flow meter, a flange-embedded averaging Pitot tube (FEAPT) flow meter was newly designed. Generally, the APT flow meter is detached from the pipe for maintenance and repair, after which it is reassembled into the pipe. The maintenance processes cause a problem of misalignment of the APT flow meter to the axial axis of the pipe when attaching it to the pipe. Moreover, the flow fluids can leak due to sealing problems between the APT flow meter and the pipe. The FEAPT flow meter can prevent the aforementioned problem during maintenance because the probe element is embedded into a standard flange as one body. In this study, the FEAPT flow meters with several shapes were designed and the flow rate characteristics of the FEAPT flow meters were investigated. The dynamic pressure of the flow across the APT flow meter is obtained for various shapes of the FEAPT flow meter. The dynamic pressure correlation curve with the H-parameter for the various shapes was represented by a parabola equation. The coefficient of the correlation curve was 0.99996. Also, a comparative study of the flow rate characteristics according to the shapes of the newly developed FEAPT flow meter was undertaken.

Key words: flange-embedded, averaging pitot tube flow meter, differential pressure flow meter, hydraulic height, alignment of APT flow meter element

INTRODUCTION

Flow rates of fluids which flow in a pipe generally can be measured with an averaging Pitot tube (APT) flow meter [1-3]. The flow rate is calculated from a differential pressure across the APT flow meter, which is mounted in the pipe. The differential pressure is caused by the dynamic flow velocity around the APT flow meters. The APT flow meter has the advantages of simplicity in its shape, occupying a small area portion in the pipe, and applicability to a wide range of pipe sizes from 10 to 5000 mm.

Britton and Mesnard [4] investigated the flow rate characteristics as influenced by the probe element's cross-sectional shapes. There were circle, diamond, and hexagon shapes. Britton and Mesnard [4] mainly studied the variation of the flow coefficient according to several shapes and obtained results showing that the variation with the diamond and hexagonal shapes is smaller than that with the circle shape. Kabacinski and Pospolita [5,6] proposed a two-profile probe that could magnify small differential pressure signals by two to four times, overcoming a weakness associated with small differential pressure signals at APT meters; they carried out CFD simulations of different cross-sections of APT meters as part of their study. Cutler [7] investigated the effect of the number of pressure taps on the pressure difference between the upstream and downstream areas of an APT flow meter probe element, finding that even one tap showed only a slight difference. Oh and Lee [8] investigated the effects of the air temperature on the flow characteristics of APT flow meters and found a linear relationship between the flow rate and the H-parameter independent of the gas temperature.

These previous studies related to APT flow meters concentrated on the effects of the both the shape of the APT probe element and the fluid properties on the flow characteristics. Studies on enhancing the productivity and maintenance of APT flow meters are rare. In this study, a flange-embedded Pitot averaging tube (FEAPT) flow meter was developed and its flow characteristics were evaluated. A typical APT flow meter is assembled into a pipe body with bolts. Generally, the APT flow meter is detached from the pipe for maintenance, after which it is reassembled into the pipe. The maintenance process may cause the problem of the misalignment of the probe element assembly angle to the axial axis of the pipe. Also, the flow fluids can leak through the gasket between the probe element and the pipe. The FEAPT flow meter can avoid such maintenance problems because the probe element is embedded into a standard flange as one body.

In this study, FEAPT flow meters with several shapes were designed and their flow characteristics were investigated. The upstream and downstream pressure at the FEAPT flow meter was also measured, and the dynamic pressure of the flow across the APT flow meter was obtained. A comparative study of the flow rate characteristics with the different shapes of the newly developed FEAPT flow meters was undertaken.

FEAPT FLOW METER

A typical APT flow meter is shown in Fig. 1 [3]. The probe element is assembled into the pipe and the outer appearance of the cross-section has a diamond shape. The inner shape of the APT flow meter cross-section is composed of two pressure-detecting chambers that are separate from each other. The stagnation pressure of the flow is sensed at the upstream chamber of the flow meter. The pressure sensed at the downstream chamber of the flow meter is not the stagnation pressure but is lower than the static pressure at the pipe wall due to the incomplete pressure recovery caused by flow separation in the flow meter.

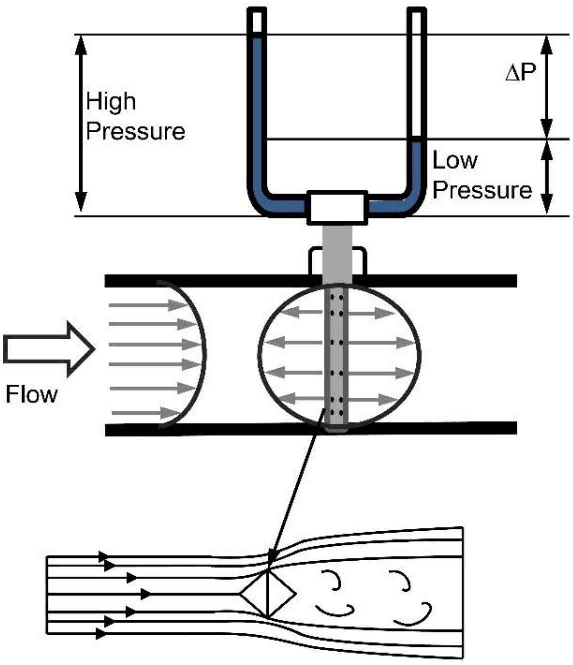
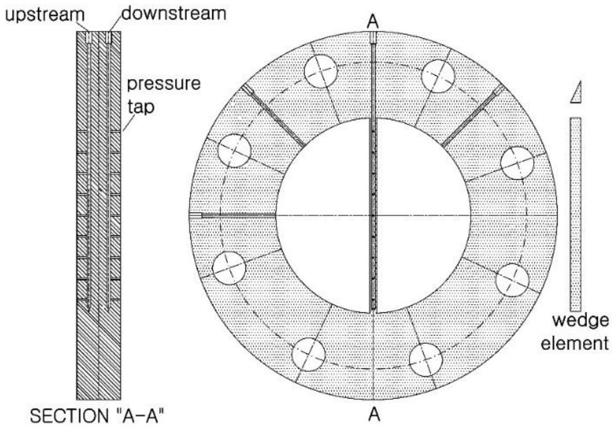


Figure 1: Schematic diagram of a typical averaging Pitot flow meter [3]

Figure 2 shows the newly developed FEAPT flow meter. The several upstream and downstream pressure taps which are separate each other and which are used to detect the upstream and downstream pressure at the FEAPT flow meter are machined in the horizontal direction as shown in the A-A cross-section of the FEAPT flow meter in Fig. 2(a). Wedge elements attached to the base FEAPT flow meter were used for generating various shapes of the FEAPT flow meter. The base FEAPT flow meter was made by machining a 30mm thickness aluminum plate using a water jet cutting machine. Fig. 2(b) shows the photograph of the base FEAPT flow meter. Four wedge pieces were created to generate the six shapes of the FEAPT flow meter, as shown in Fig. 3. The six shapes are a base, a diamond, a T, a wing, a wide T and a wide wing.



(a)

(b)

Figure 2: Base FEAPT flow meter: (a) Schematic of the FEAPT flow meter, cross-section A-A showing both the upstream and downstream pressure taps, and wedge element (b) Photograph of the base FEAPT flow meter

EXPERIMENTS

To evaluate the flow rate characteristics of the developed FEAPT flow meters, an experimental setup was constructed, as shown in Fig. 4. Figure 4 also shows a

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photograph of the FEAPT flow meter which is assembled between two standard flanges.

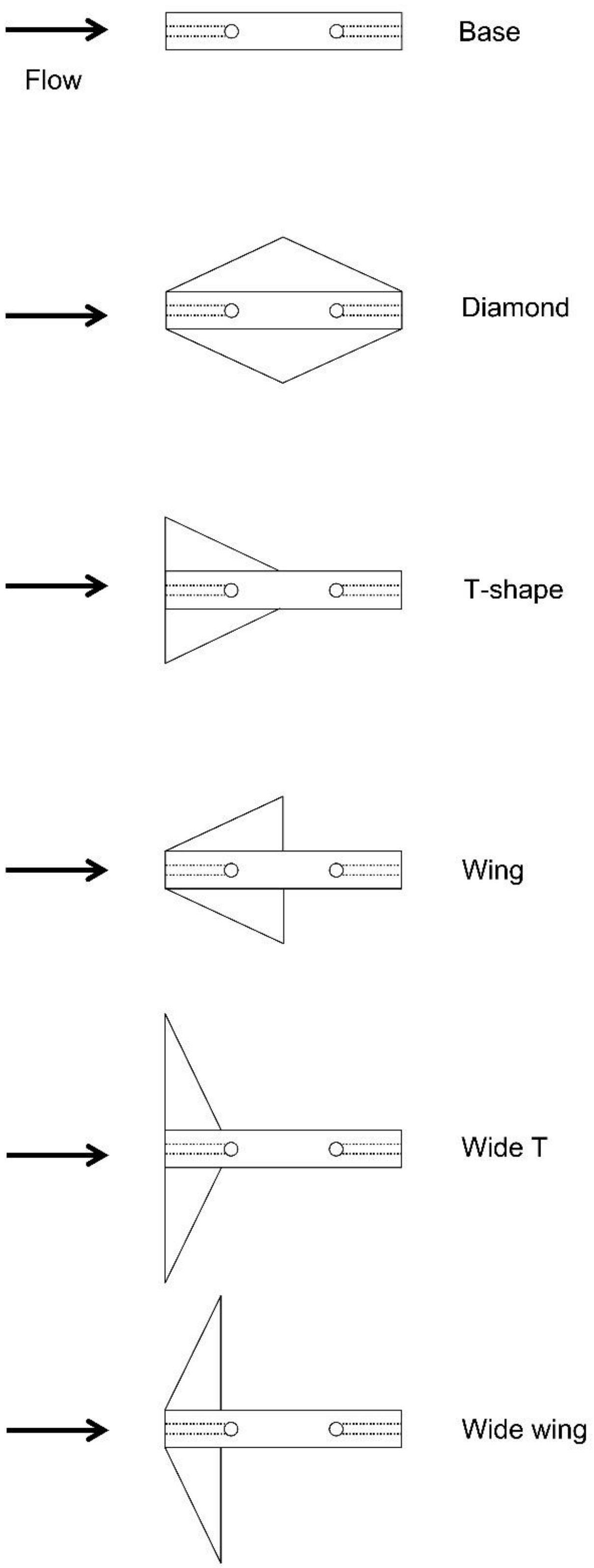


Figure 3: Various shapes of the FEAPT flow meter by combining the 4 wedge elements

The flow measurement system consists of a laminar flow meter, the developed FEAPT flow meter, a blower, a temperature measurement system, four U-tube manometers, and an inclined manometer. The inlet pressure of the laminar flow meter, with the discharge of the blower, was measured to compensate for the air density using a 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 across the FEAPT flow meter is measured with a U3 manometer. The pressure at the downstream tap is measured with a U4 manometer.

The temperature to compensate for the air density is measured using a J-type thermocouple at the inlet of the laminar flow meter. Also, the temperature to compensate for the air density for the FEAPT flow meter is measured at two locations: upstream and downstream. A 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 under its rated power condition.

For the calibration of the flow rate, air is drawn in by the blower through an air cleaner and a laminar flow meter and past the FEAPT flow meter, following the arrows shown in Fig. 4. With the air flow rate constantly maintained by positioning the inverter knob to set the rotating speed of the blower, the differential hydraulic head in the inclined manometer, the hydraulic head in the four 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 identical to that of the laminar flow meter to an accuracy level of 0.5%. After adjusting the inverter knob again for the next target flow rate for calibration, the experimental process is repeated, as explained previously. The measurements were repeated several times with variations of the flow rate.

RESULTS AND DISCUSSIONS

The H-parameter, which is the hydraulic height as represented by Eq. (1), was introduced to evaluate the flow characteristics of the FEAPT flow meter [8]. In Eq. (1), the H-parameter is calculated from the measured differential pressure ($\Delta P_{\text{up-down}}$) between the upstream and downstream pressure, the intake average air temperature (T_{avg}) and density (ρ_{real}), and static pressure (P_{static}) at the FEAPT flow meter. Generally, differential pressure flow meters such as the orifice, flow nozzle, and Venturi tube types are proportional to $\sqrt{\Delta P_{up-dwon}}$ [10]. Both APT and FEAPT flow meter show similar characteristics. Thus, the flow rate of the FEAPT flow meter is linearly related to the H-parameter.

$$H_{\Delta P_{up-down},\, \rho_{real}} = \frac{P_{static}}{101.3(kPa)} \times \frac{293.15(K)}{T_{avg}} \sqrt{\frac{\Delta P_{up-down}}{\rho_{real}}} \quad (1)$$

Here,

P_{static}: static pressure at the APT flow meter (kPa)

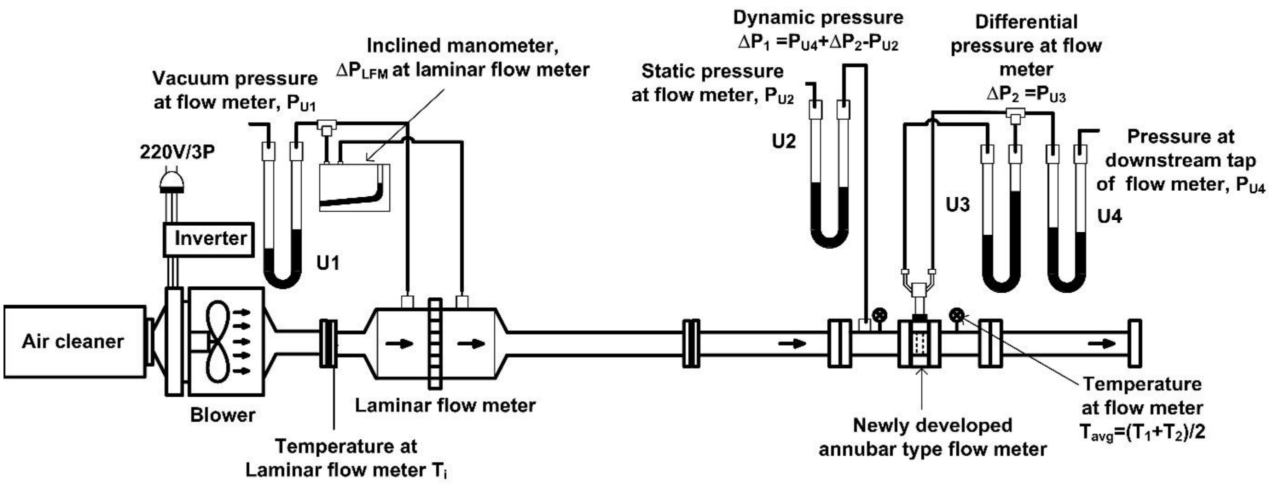
T_{avg}: average temperature at the APT flow meter (K)

ρ_{real}: density of the intake air flow

$\Delta P_{up-down}$: differential pressure between the upstream and downstream areas of the FEAPT flow meter probe

Figure 5 shows the intake air temperature curve at the inlet of the FEAPT flow meter as the H-parameter for the six shapes of the FEAPT flow meter increases. A high value of the H-parameter indicates a higher flow velocity. The intake air temperature is increased from 20 to 40 ℃ as the H-parameter increases from 0.2 to 0.7, as the blower blades heats the intake air via the rotation of the blower. The blower heating effect on the intake air is increased with the rotation speed of the blower. The intake air temperature curves differ according to the FEAPT flow meter shape. The different gradients of the intake air temperature curves are caused by both the environment condition at the start of the calibration experiment and the different flow restrictions according to the shape of the FEAPT flow meter. Even if the intake air temperature is varied, the variation effect on the H-parameter is included in Eq. (1).

Figure 6 shows the mass flow rate at the FEAPT flow meter as the H-parameter increases for the six shapes of the FEAPT flow meter. The mass flow rates for all six shapes increased linearly as the H-parameter increases. The gradient of the linear curves is greatest with the base shape and subsequently decreases in the order of the diamond and the wing, the T, the wide wing, and the wide T. The different gradients according to the shapes of the FEAPT flow meter are related to the differences in the flow



restriction with the shapes. The gradient of the mass flow rate curve is increased as the flow restriction is decreased. The flow restriction is decreased as the cross-section area of the probe element of the FEAPT flow meter is decreased.

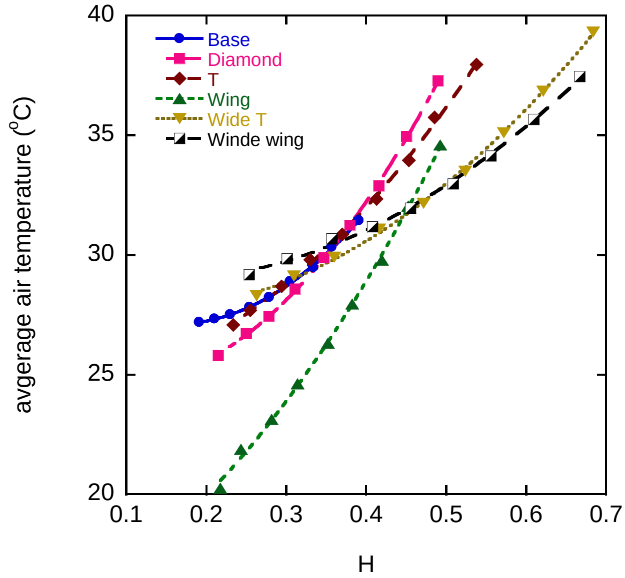


Figure 5: Intake air temperature variation at the FEAPT flow meter as the H-parameter increases for six shapes of the FEAPT flow meter

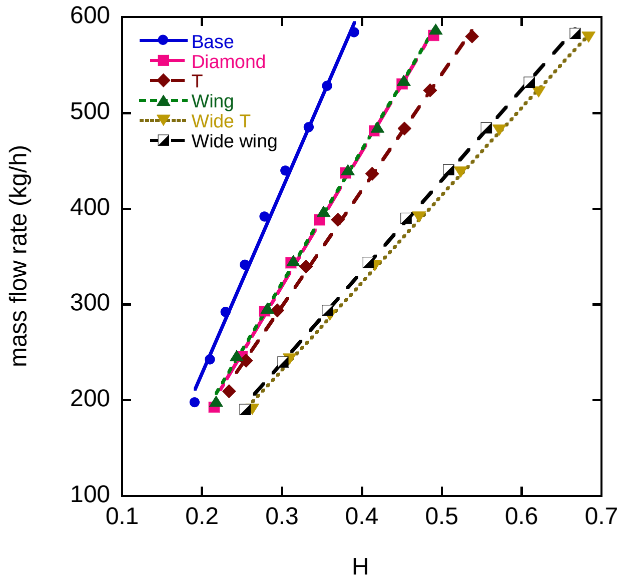


Figure 6: Mass flow rate variation at the FEAPT flow meter as the H-parameter increases for six shapes of the FEAPT flow meter

Also, the flow restriction is lower with an aerodynamic shape of the cross-section. The cross-section area of the probe element is smallest in case of the base shape, resulting in the largest gradient of the curve. The diamond and the wing shape, which have the same cross-section area and aerodynamic shape, show the nearly same gradient of the mass flow rate curve. The gradient of the mass flow rate curve with the T shape, which has the same cross-section area as the wing and the diamond shape, is lower than that of the diamond or the wing shape due to the non-aerodynamic shapes of the former. The gradient of the mass flow rate curve with both the wide T and the wide wing shapes shows the lowest value due to the largest cross-section area of the probe element. The difference in the gradient of the mass flow rate curve between the wide wing and wide T shapes is related to the aerodynamic shape effect. The gradient with the wide wing shape, which has an aerodynamic shape, is larger than that with the wide T shape.

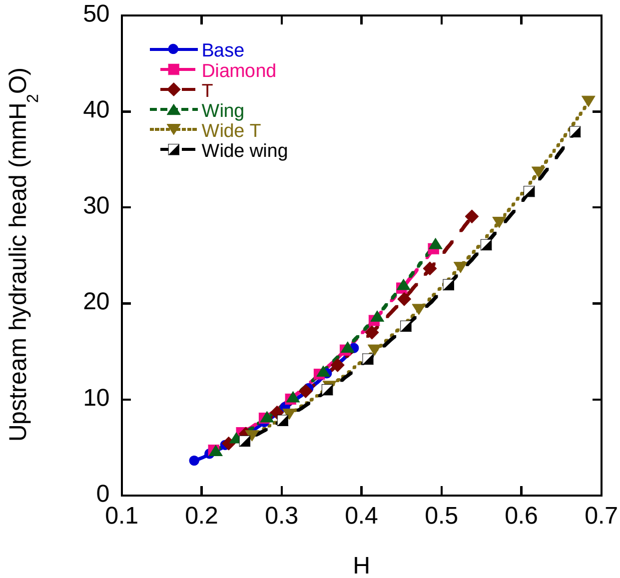


Figure 7: Upstream hydraulic pressure head distribution measured at the FEAPT flow meter relative to atmospheric pressure as the H-parameter increases for six shapes of the FEAPT flow meter

Figure 7 shows the upstream hydraulic pressure head measured at the FEAPT flow meter relative to the atmospheric pressure using a U-tube. The total pressure of the flow, which includes both the static and dynamic pressure, is transferred to the upstream pressure tap of the FEAPT flow meter. The total pressure is increased as the H-parameter increases for all the six shapes. The gradients of the upstream hydraulic head curves can be categorized into two groups according to the cross-section area of the FEAPT flow meters. The upstream hydraulic head curves with the base, diamond, T, and wing shapes demonstrate a higher gradient than those with the wide T and wide wing shapes due to the low flow restriction.

Figure 8 shows the downstream hydraulic pressure head measured at the FEAPT flow meter relative to atmospheric pressure using a U-tube. The downstream hydraulic head of the FEAPT flow meter decreased as the H-parameter increased. Also, the values of the downstream hydraulic head are negative. The negative values of the downstream pressure hydraulic head are due to the incomplete pressure recovery at the downstream pressure tap with the separation of the flow. Also, the downstream hydraulic head at the FEAPT flow meter decreased with the different gradients caused by the shapes of the FEAPT flow meter.

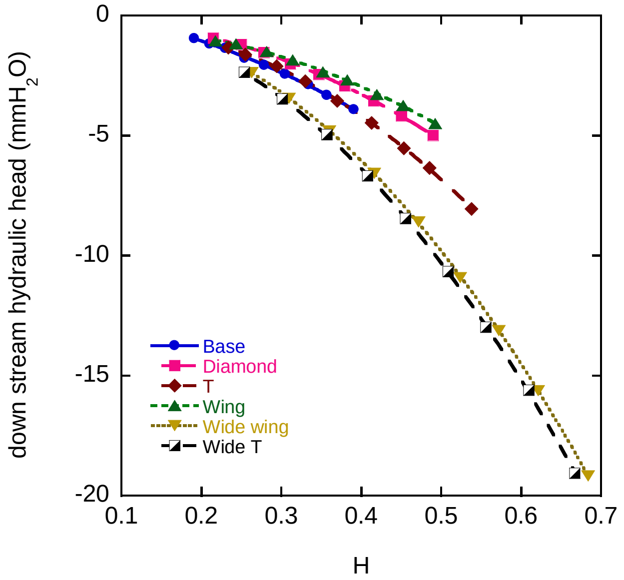


Figure 8: Downstream hydraulic pressure head distribution measured at the FEAPT flow meter relative to atmospheric pressure as the H-parameter increases for six shapes of the FEAPT flow meter

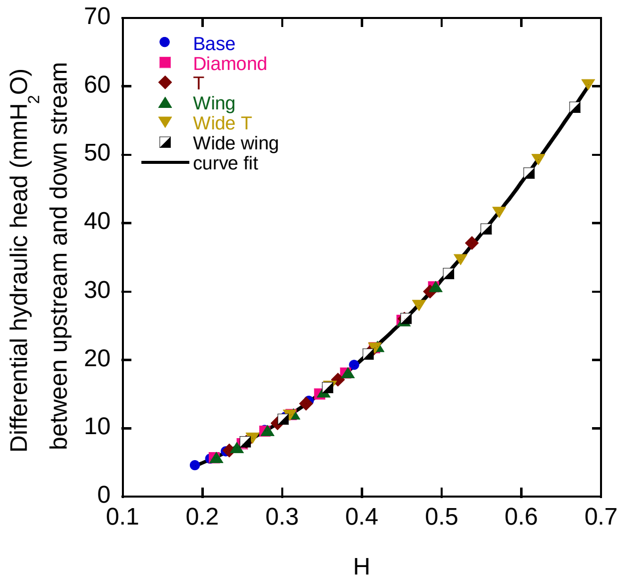


Figure 9: Distribution of the differential hydraulic heads between the upstream and downstream areas at the pressure taps of FEAPT flow meters as the H-parameter increases for six shapes of the FEAPT flow meter

Figure 9 shows the differential hydraulic heads between the upstream and downstream areas at the pressure taps of the FEAPT flow meters for the six shapes. The differential hydraulic head increases as the H-parameter increases. The differential hydraulic head curves merged into a curve independent of the shapes for the six shapes of the FEAPT flow meters. The one merged curve can be represented as a parabola equation, as expressed by Eq. (2). The coefficient of the correlation for Eq. (2) is 0.99996.

$$\mathrm{DHH} = 134.22x^2 - 4.9198x + 0.56305 \quad (2)$$

Although the differential hydraulic head curve can be represented as a curve independent of the shapes, the flow measurement range differs according to the shape of the FEAPT flow meter. As shown in Fig. 8, for all six shapes the mass flow rate with the same range of 200-600 kg/h, the base shape has an H-parameter range of 0.2-0.4; the diamond wing and T shape have a range of 0.2-0.5, and the wide T and the wide wing shapes have a range of 0.25-0.68. For the same mass flow rate range, a FEAPT flow meter with a wider H-parameter range means a wider measurement range of the flow.

CONCLUSION

Various shapes of FEAPT meters which were newly designed to enhance the productivity of this tool and simplify its maintenance processes were created. The flow rate characteristics of the FEAPT flow meters were evaluated and the following conclusions were obtained.

1) The differential hydraulic head curves merged into a curve independent of the shapes for the six shapes of the FEAPT flow meters. The one merged curve can be represented as a parabola equation. The coefficient of correlation equation is 0.99996.
2) The smaller cross-section area of the FEAPT flow meter reduces its flow range.
3) Both the smaller cross-section area and the aerodynamic shape of the probe element in the FEAPT flow meter reduce flow restrictions; thus, the gradient of the linear mass flow rate curve with the H-parameter is increased.

Acknowledgement

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