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Application of averaging bidirectional flow tube for measurement of single-phase flow rate in a piping system †

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Abstract

A new instrument, an averaging bidirectional flow tube (BDFT), is proposed to measure single-phase flow rates. This averaging BDFT has unique measuring characteristics foremost among which is the capability to measure bi-directional flow and insensitivity of the fluid attack angle. Single phase calibration tests were conducted to demonstrate the performance of the averaging BDFT. Likewise, to enhance the applicability of the averaging BDFT on various flow conditions, flow analyses using CFD code were performed focusing on design optimization of the BDFT. The calibration test results indicated that this averaging BDFT has a linearity within 0.5 % in the Reynolds (Re) number range of above 10,000 where it is meaningful in terms of application. The flow analyses results demonstrate a good linearity of the averaging BDFT with various design features. Therefore, averaging BDFT can be applied for measurement of flow rates within a wide range of flow conditions.

Keywords: Averaging bidirectional flow tube (BDFT); Calibration test; Flow analysis

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1. Introduction

Single- and two-phase flow rates are two of the most important parameters for analyzing flow systems in the chemical, oil, and nuclear industries. Recently, measurement techniques of two-phase flow rate have been developed by many researchers. Examples of these are the single or combination of pressure drop devices, turbine meter, drag body, and Pitot tube together with gamma densitometer. Among the various commercial flow meters, the local bidirectional flow tube (BDFT) is one of the most useful devices that measures flow rates as it was developed especially for low velocity and large variation flow conditions. The relative insensitivity to flow direction of the local BDFT makes it useful for measuring reliable flow velocity compared with the Pitot tube.

The local BDFT was first suggested for the measurement of flame velocity in the fire system by Heskestad [1]. It has unique measuring characteristics; primarily the capability to measure bi-directional flow and insensitivity of fluid attack angle on flow tube. Mccaffery and Heskestad [2] applied it to an air flowing system. They found that the calibrations of the local BDFT ranging from 12.7mm to 25.4mm in diameter were independent of the size of the flow tube and has unique characteristics such as the capability for bi-directional flow measurement and angular insensitivity to about 50° in the normal plane to the axes of the flow tube. Liu et al. [3] tried to develop a miniature local BDFT of 4.7mm to 8.8mm diameter which could be applied to the measurement of low velocity air flow. They also found that the calibration factor of the flow tube is almost independent of the Reynolds (Re) number.

Based on the concept of previously available local BDFT, an averaging BDFT [4] was suggested for application in the measurement of single-phase flow

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rates in the primary pipes of the integral effect test facility, the Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) which is now operated at the KAERI [5]. The averaging BDFT was installed in the primary pipes of the ATLAS, as shown in Fig. 1. The major expected flow in the ATLAS is a single- or two-phase natural and convective water and steam flow. Of course, other flow meters available for measuring flow rates have also been used. Table 1 summarizes the comparison of the measuring characteristics between the various flow meters and the averaging BDFT. Compared with the various flow meters, the averaging BDFT is more promising in its applicability to various flow conditions in terms of accuracy, applicability, and price as shown in Table 1.

The working principle of the averaging BDFT is similar to that of the Pitot tube. However, it creates the possibility of the elimination of the cooling system, which is normally needed to prevent flashing in the pressure impulse line of the Pitot tube when it is used in the depressurization condition. Fig. 2 shows the schematic diagram of the averaging BDFT. In this study, the proposed averaging BDFT was calibrated in air/water vertical and horizontal test sections, the inner diameter of which was 0.08 m. A test was performed primarily in the single-phase water and air flow condition to demonstrate the performance of the averaging BDFT and to obtain the amplification factor *K* of the averaging BDFT in the vertical and horizontal pipes. After demonstrating the applicability of the averaging BDFT to the ATLAS facility, we tried to extend its use to the large diameter piping system. First, we designed and manufactured the averaging BDFT applicable to a piping system with diameters of 200 mm and 500 mm. Single-phase calibration tests were carried out to demonstrate the performance of these large-sized averaging BDFT.

Table. 1. Comparison of the measuring characteristics between the various flow meters.

Flow meter	Temp.	Press.	Precision	ΔP	Price
Orifice	N. R*.	N. R.	Med.	Large	Low
Venturi	N. R.	N. R.	High	Small	Med
Pitot	N. R.	N. R.	Med.	Small	Med
Turbine	N. R.	N. R.	High	Med.	High
Vortex	N. R.	under 50 bar	Medium	Small	Med.
Coriolis	under 420 °C	under 100 bar	Very High	Large	Very High
BDFT	N. R.	N. R.	High	Small	Med.

N. R.: Not restricted

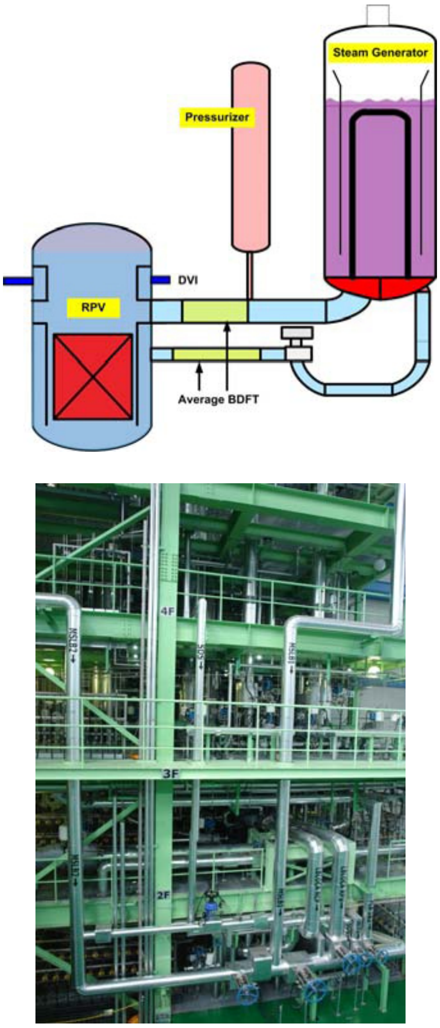


Fig. 1. Schematic diagram of the average BDFT installation in the primary pipes of the ATLAS.

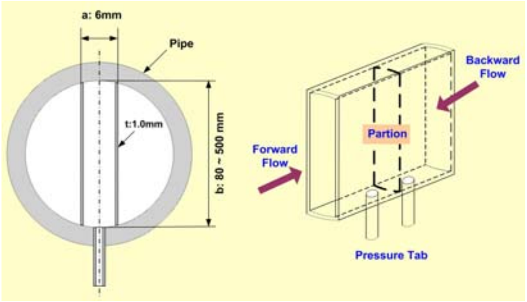


Fig. 2. Schematic diagram of the average BDFT.

To enhance the applicability of the local and averaging BDFT, the measuring performance of the BDFT should be validated under various flow conditions. For this reason, the calibration tests for the local and averaging BDFT were conducted under atmospheric pressure condition. Additionally, the validation tests for the local BDFT were limited to an air flow. For an extended application of the local and averaging BDFT to the experimental and industrial areas, the inherent measuring characteristics of the BDFT should be proven under a wide range of flow types, pressures, and temperatures. Another important point in terms of application is the flexibility of the BDFT design for installation in typical test facilities and pipe arrangements. In this study, flow analyses using computational fluid dynamics (CFD) code were performed to validate the application of the averaging BDFT for various flow conditions. Sensitivity studies were likewise conducted to optimize the design features of the averaging BDFT so that they can be applied to various experimental facilities and pipe arrangements.

2. Measuring principles of local and averaging BDFT

The measuring principles of local and averaging BDFT are similar to those of the Pitot tube. In Fig. 2, the pressure measured at the front of the averaging BDFT is equal to the total pressure while the one measured at the rear tube, called the base pressure, is less than the static pressure of the flow field. The lower base pressure is caused by the suction effect induced by the flow velocity at the downstream [3]. Thus, the differential pressure measured by the flow tube is larger than the dynamic pressure in the flow stream and its magnitude is changed to a flow velocity. The square root of the ratio of the differential pressure to the dynamic pressure is defined as the amplification factor *K*. If the amplification factor *K* has linearity and is known, the flow velocity can be obtained by measuring the differential pressure across the flow tube as shown in Eq. (1). The value of *K* can then be measured through the calibration tests with an air or water flow.

$$K \equiv \frac{\sqrt{2\Delta p/\rho}}{V} \tag{1}$$

The local and averaging BDFT have unique measuring characteristics, i.e. the capability to measure bi-directional flow and insensitivity of fluid attack angle on flow tube. Contrary to the conventional Pitot tube, this makes them very useful in the flow path where the flow direction changes periodically or abruptly. In addition, due to the suction effect, pressure is slightly lower than the static pressure at the rear pressure hole of the BDFT, which improves the measuring performance at a low velocity range. The main objective of this study is to validate the applicability of the local and averaging BDFT within a wide range of flow and system conditions. The design optimization of the BDFT towards its application to various test facilities and pipe arrangements is another concern of this paper. For the attainment of these objectives, flow analyses using the FLUENT 5.4 and CFX 5.7.1 codes, as well as single-phase flow tests for the averaging BDFT were performed.

3. The development of the averaging BDFT

The averaging BDFT was designed and manufactured for the measurement of the flow rates in the primary pipes of the integral effect test facility ATLAS. This averaging BDFT was installed and tested in the piping system with an 80 mm inner diameter. After demonstrating the applicability of the averaging BDFT to the ATLAS facility, we tried to extend the use of the averaging BDFT to a large diameter piping system. As a first step towards commercialization, we designed and manufactured flow meters applicable to piping systems with diameters of 200 mm and 500 mm, as shown in Figs. 3 and 4, respectively. The averaging BDFT with a diameter of 200 mm is an integral type and the averaging BDFT whose diameter is 500 mm is an insertion type that allows for the convenience of installation and handling.

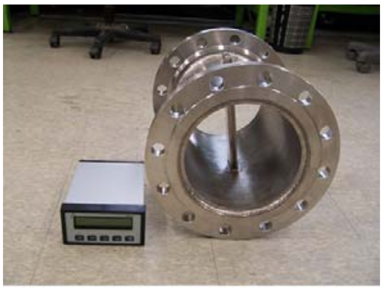


Fig. 3. Photograph of the averaging BDFT: Integral type with an inner diameter of 200 mm.

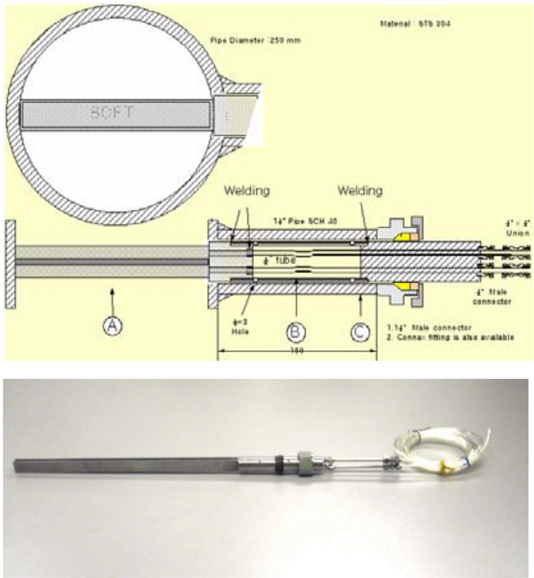


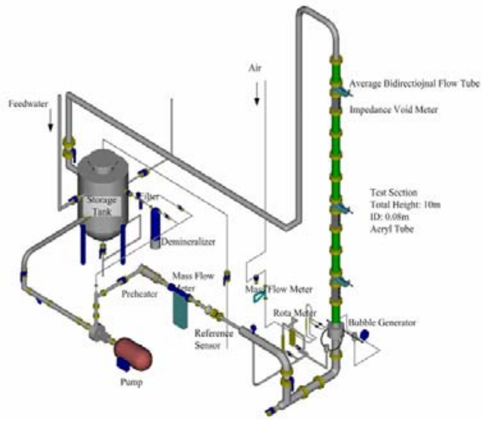
Fig. 4. Photograph of the averaging BDFT: Insertion type with an inner diameter of 500 mm.

4. Calibration tests for the averaging BDFT

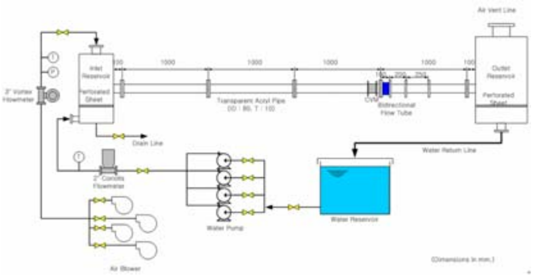
The averaging BDFT with an inner diameter of 80 mm was tested in an air/water vertical calibration test loop at the KAERI. The calibration test was performed primarily in a single-phase water and air flow condition to obtain the amplification factor *K* of the flow tube in vertical and horizontal pipes. After the completion of the calibration tests for the averaging BDFT with an inner diameter of 80 mm, the calibration tests were conducted for the averaging BDFT with the large diameters of 200 mm and 500 mm at the Korea Research Institute of Standards and Science (KRISS) and Oval Korea, Ltd.

4.1 Experimental facility for the calibration tests

The single-phase calibration tests were performed in the air/water test loop, which consisted of a test section, a bubble generator, a water supply system, an air supply system, a pre-heater, instrumentations, and a data acquisition system. Fig. 5 shows a bird's eye view of the air/water vertical and horizontal test loop. The test section was composed of a transparent acryl pipe whose diameter was 0.08 m and height was 10 m. The averaging BDFT was installed at 120 L/D from the entrance. The pressure drop across the averaging BDFT was measured by a Rosemount SMART type 3051CD differential pressure transmitter. A static



(a) Vertical test loop



(b) Horizontal test loop

Fig. 5. Bird’s eye view of air/water vertical and horizontal test loops.

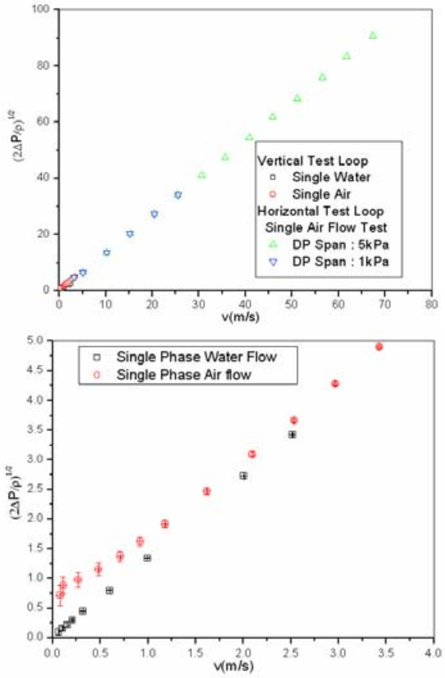


Fig. 6. Trends of the *K* values in the calibration tests for the averaging BDFT with an inner diameter of 80 mm.

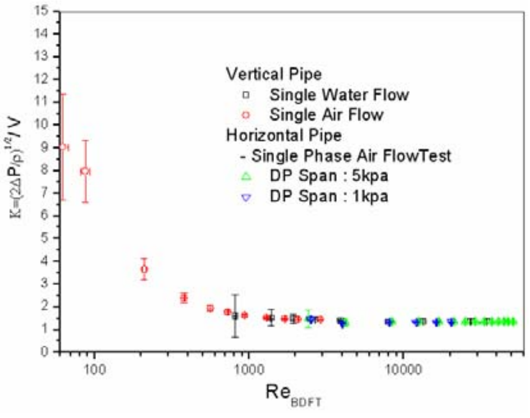


Fig. 7. Dependencies of the *K* values on the Re number in the calibration tests.

pressure transmitter (Rosemount SMART type 3051C) was also installed between them. The uncertainty of the measured pressure and differential pressure was 0.11% of the span. In the test, the span of the differential pressure transmitter was changed according to the measurement range to minimize measurement error. Two Rosemount Coriolis mass flow meters were installed at the inlet of the test section to measure the water and air injection flow rates. The measurement errors of the water and air flow rate in this test were 0.6% and 0.4% of the reading, respectively. An RTD with a PT-100 was installed at the inlet of the test section to measure the fluid temperature. The estimated uncertainty of the temperature measurement was 0.5 K.

4.2 Single-phase calibration test results

To obtain the amplification factor *K* for the averaging BDFT with an inner diameter of 80 mm, single-phase calibration tests were performed in air and water flow conditions, respectively. In the vertical test loop, the velocity ranges were 0.06 m/s - 2.5 m/s and 0.07 m/s - 3.4 m/s for the water and air flows, respectively. A convective air flow higher than 3 m/s was tested in the horizontal test loop. Fig. 6 shows the trends of the *K* values in the calibration tests. It illustrates the linear relationship between the two parameters in the whole range of the velocity. The plots show that the constant *K* value can be assumed to be in a high flow condition. However, in a low flow condition such as that of less than 3.5 m/s, the *K* values of air and water flows are different from each other for a given velocity. In addition, the inclinations of each fluid are slightly different. This is natural because the Re number of the BDFT is small in this flow condition. For a general and extensive applicability, the *K* factor should be expressed by a single function reflecting a flow velocity and the properties of the fluids regardless of the fluid types. Fig. 7 shows the plot of the *K* value against the Re number of an averaging BDFT. Here, the Re number is defined for the BDFT as follows,

$$\mathrm{Re}_{BDFT} = \frac{\rho D_h V}{\mu} \tag{2}$$

where D_h is the hydraulic diameter of the averaging BDFT which is defined as $2ab/(a + b)$.

The *K* value is fitted by the Re of the BDFT in Fig. 7. According to this figure, the *K* value in the viscous regime increases drastically as the flow velocity decreases and it could be fitted by a single function of the Re number regardless of the fluid types. However, it can also be assumed to be constant in a turbulent region larger than 2,000 of the Re number of the averaging BDFT. In the present study, the *K* value was obtained by a piecewise least square fitting method using a polynomial equation for its application to the single-phase flow conditions [6].

Single-phase calibration tests were carried out to demonstrate the performance of the averaging BDFT which will be installed into a piping system with diameters of 200 mm and 500 mm. A calibration test was performed primarily in the single-phase water and air flow condition to obtain the amplification factor *K* of the BDFT in horizontal pipes. In the test, the velocity ranges were 0.1 m/s - 5.0 m/s and 0.1 m/s - 50.0 m/s for the water and air flows, respectively. The averaging BDFT was calibrated against a certified flow meter according to national measurement standards. Based on the measured differential pressure and flow velocity, the amplification factor *K* was determined under various flow conditions. Figs. 8-9 show the plot of the *K* value against the Re number of an averaging BDFT in the calibration tests of 200 mm and 500 mm, respectively. The calibration test results indicate that this flow meter has a linearity within 0.5% in the Re number range of above 10,000 where it is meaningful in terms of application.

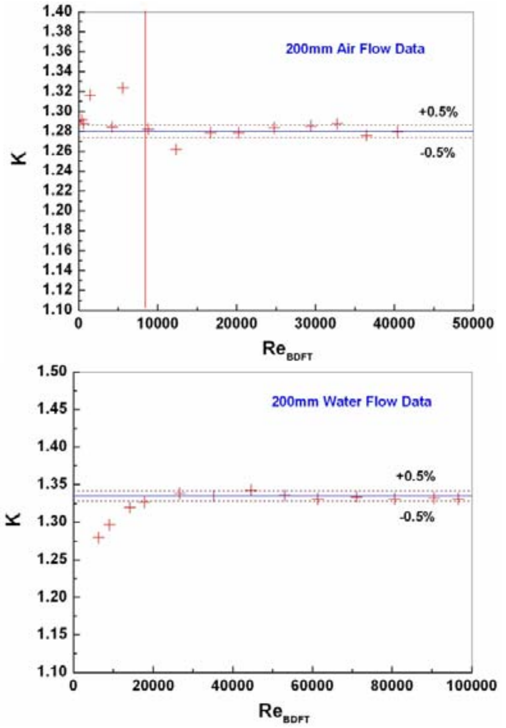


Fig. 8. Calibration test results for the averaging BDFT with an inner diameter of 200 mm.

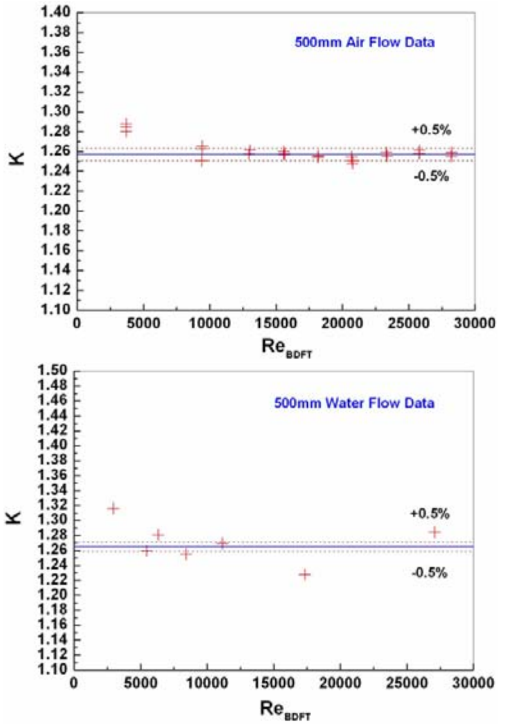


Fig. 9. Calibration test results for the averaging BDFT with an inner diameter of 500 mm.

5. Flow analyses for the averaging BDFT

Three-dimensional steady state flow analyses using FLUENT 5.4 code and CFX5.7.1 code were performed to simulate the calibration tests of the averaging BDFT. By calculating the differential pressure at both the front and the rear hole, the amplification factor *K* values were evaluated. In this study, the second order upwind scheme was used in the momentum calculations and the SIMPLE algorithm was used in pressure-velocity coupling. Laminar and turbulent flows were simulated according to the range of Re number and the turbulent flow was calculated using the standard k-e model.

In this study, the single-phase calibration test results for the averaging BDFT with an inner diameter of 80 mm were compared with the flow analyses results of FLUENT 5.4 code calculation. Sensitivity studies were conducted to optimize the design features of the averaging BDFT, which could be applied to various experimental facilities and pipe arrangements. The volume of the flow path, pipe, and averaging BDFT were meshed with a hexahedron cell with a cell number of about 0.35 million. The inlet velocity ranged from 0.02 m/s to 3.0 m/s and from 0.07 m/s to 3.5 m/s for the water and air flows, respectively.

As a first step, calculations were performed to validate the application of the averaging BDFT for a single-phase flow of water or air by comparing the calculation results with the calibration test results. Fig. 10 shows the dependencies of *K* values on the Re number in both the air and water flows. In the region of the Re numbers above 1000, the *K* values are nearly constant and the FLUENT calculation simulates the flow tests quite well, regardless of the Re numbers and the flow types. For a velocity region below 1.0 m/s, however, the discrepancy in the *K* values between calculations and experiments are very large, especially in the case of a single-phase air flow. This is a highly viscous region of the Re number less than 1000. The discrepancy might be attributed to the inherent limitation in the performance of the commercial CFD code at the region of very low Re number. However, the reasons should be further investigated. Fig. 11 shows the pressure and velocity contours inside the averaging BDFT under the inlet water velocity of 3.0 m/s. The pressure values are relative values against the initial pressure of 0.1 MPa. The back pressure due to the suction effect is clearly shown at the rear of the BDFT in Fig. 11.

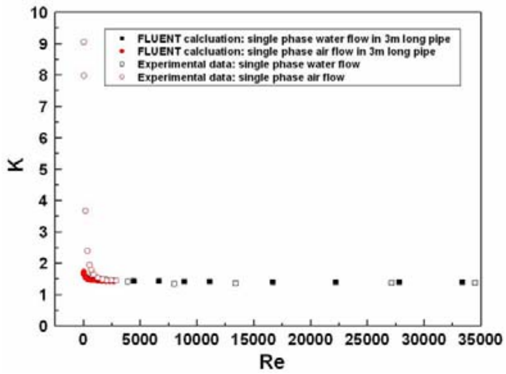
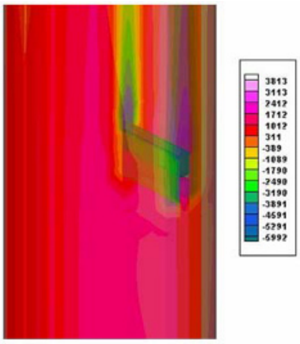
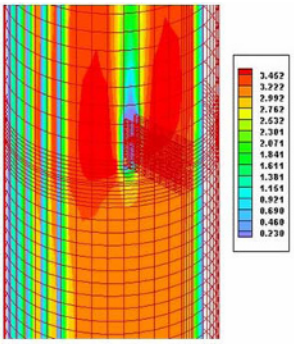


Fig. 10. Dependencies of the *K* values on the Re number in both the air and water flow.



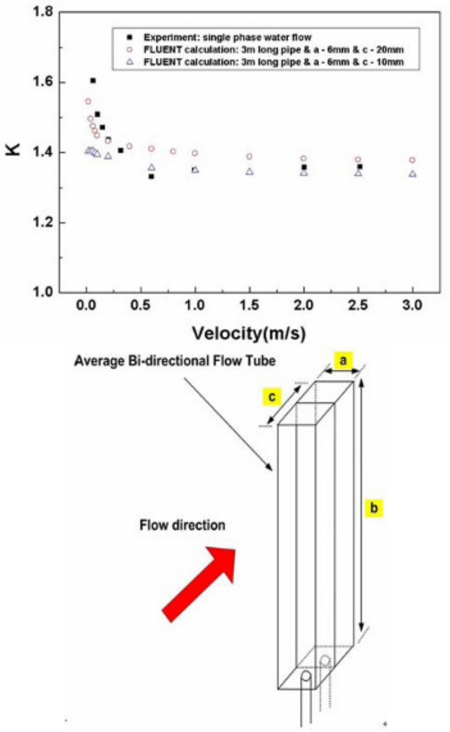
(a) Pressure contour (Pa)



(b) Velocity contour (m/s)

Fig. 11. Pressure and velocity contours under the inlet water velocity of 3.0 m/s.

Sensitivity studies were conducted to optimize the design features of the averaging BDFT which could be applied to various experimental conditions. Compared with the base design used in the calibration tests, the length (c) and width (a) of the averaging BDFT were changed. Fig. 12 shows the variations of the *K* values according to the inlet water velocity. In the case of a short length of the averaging BDFT, the *K*



(a) Effect of BDFT length

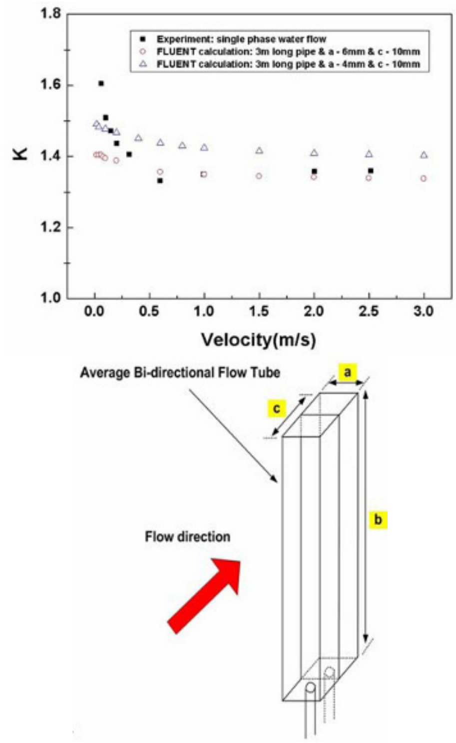


Fig. 12. Dependencies of the *K* values according to the inlet water velocity: effect of tube width.

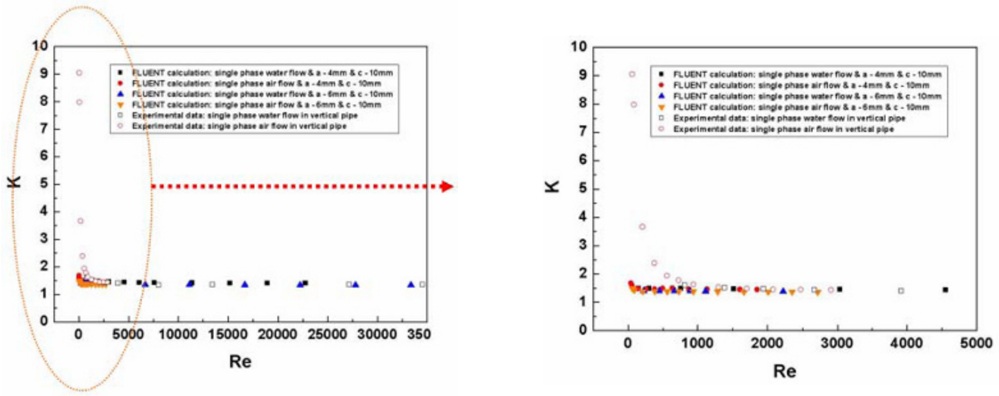


Fig. 13. Dependencies of the *K* values on the Re numbers for all the cases.

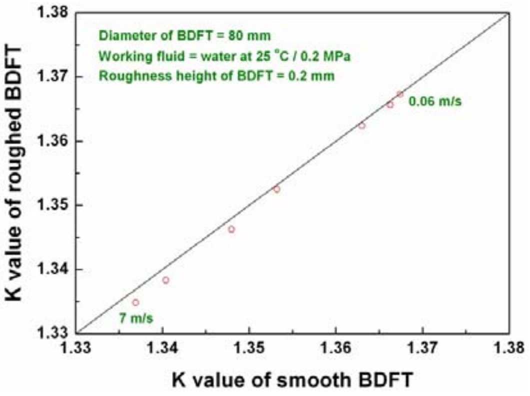


Fig. 14. Comparison of the *K* values between the two cases of smooth tube and roughed tube.

values have shown little dependence on the inlet velocity of water flow. In the case of a narrow horizontal width of the averaging BDFT, the *K* values are larger than those of the broad horizontal width of the flow tube. In terms of the averaging BDFT performance according to the geometric design, the case of the short length (c = 10 mm) with the broad horizontal width (a = 6 mm) is the best candidate for simulating the current experimental data. Fig. 13 shows the dependencies of the *K* values on the Re number for all the cases. In the region of the Re number above 1000 as shown in Fig. 13, the *K* values are nearly constant regardless of the Re numbers, the flow type, and the BDFT design. Therefore, it is quite reasonable to select the typical design of the averaging BDFT for the convenience it can provide to the experimental conditions and piping system arrangement.

In terms of application in the piping system, the performance of the averaging BDFT under the corrosion environment is another important concern. Flow analysis was carried out to examine the performance of the averaging BDFT under the corrosion environment. The height of the surface roughness of the averaging BDFT was assumed to be 0.2 mm. Fig. 14 shows the comparison of the *K* values between the two cases of smooth tube and roughed tube. According to Fig. 14, the averaging BDFT does not lose the

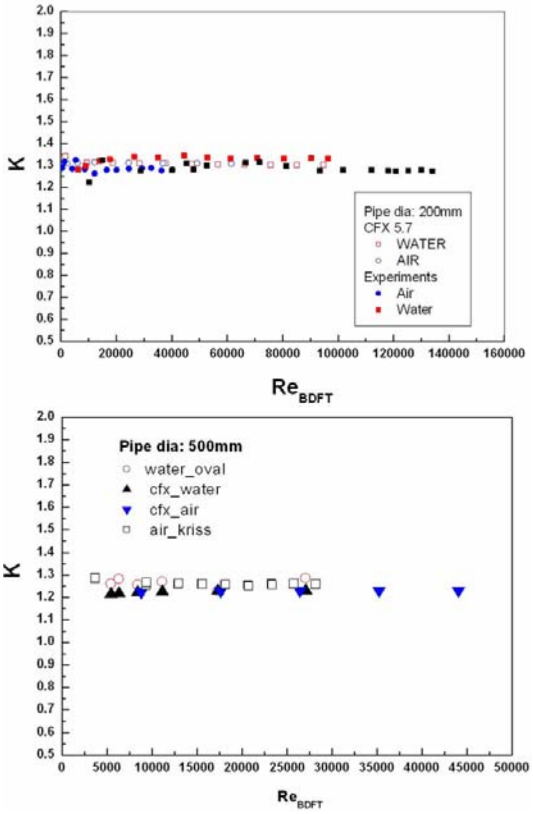


Fig. 15. Dependencies of the *K* values on the Re number for the averaging BDFT with a large diameter.

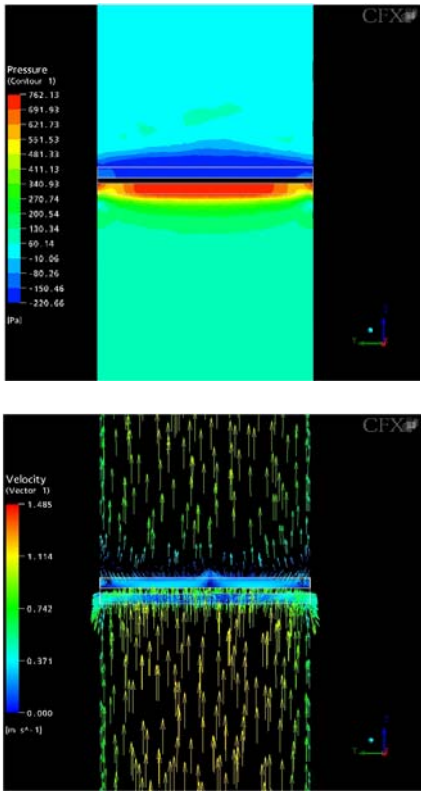


Fig. 16. Pressure contour and velocity vector for the averaging BDFT with a diameter of 200 mm.

measuring performance even under the corrosion environment.

Fig. 15 shows the dependencies of *K* values on the Re number in both the air and water flows for the averaging BDFT having a large diameter of 200 mm and 500 mm. According to Fig. 15, the *K* values are nearly constant and the CFX calculation simulates the flow tests quite well regardless of the Re numbers and the flow types. Fig. 16 shows the pressure and velocity contours inside the averaging BDFT under the inlet water velocity of 1.0 m/s. The pressure values are relative values against the initial pressure of 0.1 MPa. The back pressure due to the suction effect is clearly shown at the rear of the BDFT in Fig. 16.

6. Conclusion

A new instrumentation, an averaging BDFT, was proposed to measure the single-phase flow rate. This averaging BDFT has been shown to be applicable to the low or bidirectional flow condition. In this study, an advanced flow meter applicable to a large diameter piping system was developed using the averaging BDFT. This flow meter can be used to measure the flow rate of discharged gas with fine floating particles in the stack of the chemical reactor and the large-sized boiler. Likewise, it can be applied to the large-sized industrial piping system for the flow of oil without the possibility of structural instability. Among the various flow meters, the averaging BDFT can be one of the most promising flow meter applicable to the various flow conditions in terms of accuracy, applicability, and price.

In this study, single-phase calibration tests were conducted to demonstrate the performance of the averaging BDFT. To enhance the applicability of the local and averaging BDFT on the various flow conditions, flow analyses using the CFD code were performed focusing on the design optimization and the validation of the applicability of the BDFT. The calibration test results indicated that this averaging BDFT has a linearity within 0.5% in the Re number range of above 10,000 where it is meaningful in terms of its application. The flow analyses results using the CFD code demonstrate that the averaging BDFT has a good linearity with various design features. Therefore, it is quite reasonable to consider the typical design of the averaging BDFT for the convenience it provides to the experimental conditions and pipe arrangements.

For the design of commercially available flow meters, the prototype flow meters consisting of the integral type with a diameter of 200 mm and the insertion type with a diameter of 500 mm are designed and manufactured. The calibration tests showed that the linearity of the proposed flow meter is ± 0.5 % of full scale and flow turn down ratio is 1:20 where the Reynolds (Re) number is larger than 10,000. The structural analyses results imply that the yield stress of SUS316 is considerably larger than the maximum bending stress imposed on the averaging BDFT. This indicates the structural integrity of the averaging BDFT.

Acknowledgment

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Nomenclature

a : Width of averaging BDFT (m)
b : Height of averaging BDFT (m)
ΔP : Differential pressure (Pa)
V : Velocity (m/s)

Greek Symbols

ρ : Density of fluid (kg/m^3)
μ : Viscosity of fluid (N · s/m^2)

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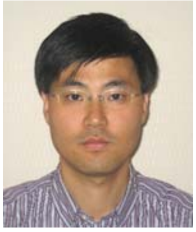

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