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A Novel Technique to Reduce Measurement Errors due to Flow–Sensor Interactions in Multi-Sensor Conductivity Probes

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ABSTRACT

Multi-sensor conductivity probes rely on multiple sensors intruding into the flow field for the measurement of conductivity variations. This may cause sensors to deflect due to flow-sensor and flow-body interactions. Since this deflection relocates the sensor tips causing inaccuracy in the flow property measurements, many techniques have been used to overcome this issue [1-6]; such as increasing the sensors diameter and reducing the sensors length. However, most of these methods increase the bubble-sensor interactions. In the present work, a novel technique has been developed with the aid of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) based solvers to reduce the errors that may arise because of the sensor's and probes body's deflections. The developed technique compensates for the errors within the signal processing stage. The CFD model has been validated against experimental data obtained from the literature. Different variables have been investigated to quantify the sensor tip relocation process as a function of pipe diameter, flow velocity and radial probe locations. The results have been presented in the form of mathematical equations using multiple variable regression analyses, and thereafter embedded into the signal processing code.

Keywords: CFD; FEA; Two-phase flow measurement; Four-sensor probe

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1. INTRODUCTION

Multiphase flows are integral to many engineering applications; such as boiling, condensing, cavitation, chemical reactions, heat exchanger, oil and gas industries, nuclear plants, etc. Therefore, a wide spectrum of literature is available in which various aspects of multiphase flows have been investigated experimentally and numerically. The dispersed phase flow parameters have been investigated experimentally primarily by using two types of methods; intrusive methods and non-intrusive methods. Among the intrusive methods, various multi-sensor probes have been used successfully for measuring flow properties by various researchers [1-7]. Kataoka et al. [1] have numerically simulated bubbly multiphase flows across two-sensor and four-sensor probes. The authors have investigated the effect of sensor spacing, bubble diameter and bubble-probe contact angle on the accuracy of measurements. In a further development, Kim et al. [2] have developed a four-sensor conductive probe to investigate various flow parameters in a multiphase flow. The studies have also been carried out to quantify the local time average shapes of the bubbles. These results have been benchmarked by processing the images captured using a video camera. Herring and Davies [3] have used a dual-sensor probe to study the dispersed phase local properties in air-water two-phase vertical flow. The authors have reported that the local void fraction profile has remained unaffected by the inlet conditions. Many researchers have been conducted about the effect of probe dimension on the measurement accuracy of the bubble properties. Wu et al. [4] who have concluded that if the axial sensor separation distance (s) to the bubbles diameter (D) ratio is smaller than the maximum relative fluctuation of the bubble velocity the measured bubble velocity may approach infinity value. Therefore, the authors have reported that the accurate results could be achieved only if the range of the axial sensor separation distance locates within 0.5 to 2 of the bubble diameter. Corre and Ishii [5] have numerically simulated the effect of probe geometry on the dispersed phase velocity and interfacial concentration measurements. The authors have suggested a non-dimensional sensor separation parameter (axial separation divided by bubble diameter) (S/X) in the range of 0.6–1 to achieve accurate velocity measurements in cases where the bubble velocity fluctuations have been relatively low. Shen et al.[6] have experimentally investigated the error sources for optical four-sensor probes in two-phase flow. The authors have attributed the measurement discrepancies to two main sources, namely signal processing and hydrodynamic effect sources. The signal processing source has been related to the threshold value selection, whilst, the hydrodynamic errors have been associated to various phenomena associated with oncoming bubble errors. The probe stiffness has been examined against pressurised air flow; it has been concluded that the optical sensors should be of short length to overcome any deflection.

Based on the literature, it can be concluded that are several factors that affect the accuracy of multi-sensor probes such as the effect of probe location in a pipe and the flow field which causes probe and sensor deflections. Previously, the sensor deflection issue has been dealt with by strengthening the sensors using high strength materials for the sensor body, or by adding sensor support materials around the sensor body or by shortening the sensors length. However, these methods increase the bubble-sensor interactions. Further, none of the researchers tried to overcome this issue by using an embedded code at the signal processing stage instead of the physical treatment. The aim of this research is to estimate and reduce the errors that may occur due to the relocations of the sensors tip because of the deflections of the sensors and the probe body in multi-sensor conductivity probe, using an embedded code at the signal processing stage. The relevant information for the code development is proposed to be obtained from CFD simulations.

1.1. CFD Model and Simulation

Three-dimension computational domains of a vertical straight pipe of 80, 100 and 200mm internal diameter and 2000mm length have been created for simulations. Upward bubbly gas-liquid flows have been modelled using the Eulerian framework of multiphase flow modelling. The continuity and momentum equations for each phase have been solved separately for low volume fractions of approximately 3.8% at three water superficial velocities of 0.76, 3 and 6m/s. The radial velocity and volume fraction distributions of the air have been employed as a criterion for comparing the CFD calculations with the experiments. For the geometry validation, inlet conditions have been assumed to be homogeneous in terms of superficial liquid and gas velocities and volume fractions for both phases in accordance with the experimental setup conditions[8].

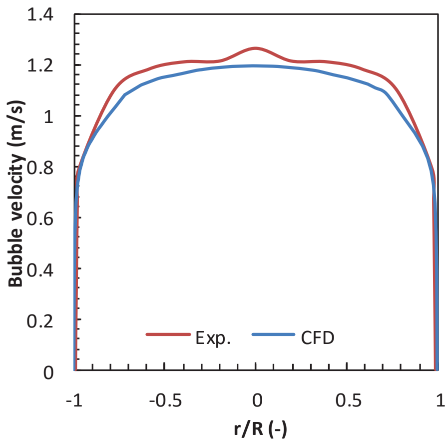

Figure 1. Bubble velocity distribution across the test pipe

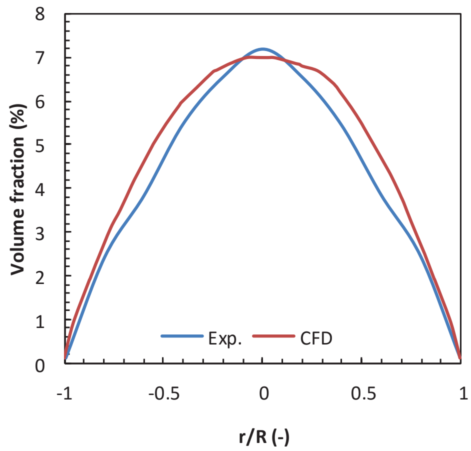

Figure 2. Volume fraction distribution across the test pipe

Figures 1 and 2 depict the ability of the numerical simulation to reproduce the radial volume fraction and the bubble velocity profile and show a good agreement with the experimental measurements. This distribution is mainly influenced by the non-drag forces, which act perpendicular to the flow direction. A lift-force, a wall-force, and a turbulent dispersion-force have been considered in the simulations. For the lift force, the formulation of Tomiyama model has been used since it can predict the lift force on larger-scale deformable bubbles in the ellipsoidal and spherical cap regimes. As with the Tomiyama drag and wall lubrication models, this model depends on the Eötvös number (Eo).

$$Eo = \frac{g(\rho_L - \rho_G)d_p^2}{\sigma}$$

Where, g is gravity, ρ_L and ρ_G are liquid and gas density respectively and d_p is bubble diameter.
Its main feature is the prediction of the crossover point in bubble size in which particle distortion causes a reversal in the sign of the lift force. The void fraction profile in gas-liquid two-phase flows depends on the drag force to be formed as well as on the non-drag forces [9].

The Shear-Stress Transport (SST) $k - \omega$ model has been selected as a turbulent model. This model has been used to capture the turbulence phenomenon and the flow separation that occurs due to the intrusion of the four-sensor probe. The k-omega SST model is a combination of the k-omega and k-epsilon model, in addition to a shear stress transport model [10]. The typical schematic of the four-sensor probe that had been used by [8] is shown in figure 3.

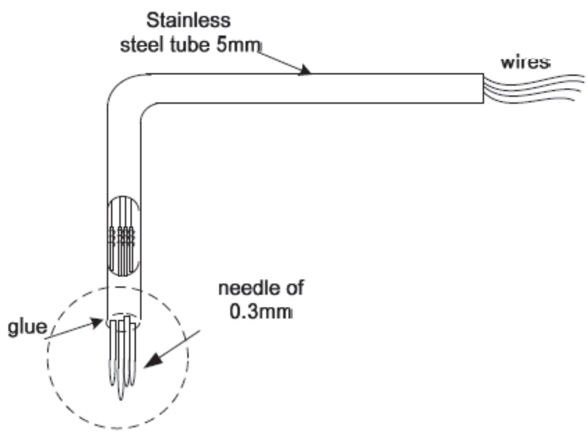

Figure 3. Schematic of four-sensor probe [8].

1.2. FEA simulation

Numerical evaluations have been performed using a commercial finite element code for depicting sensors and probe body displacement effectively. Three-dimensional finite element models have been developed to quantify the maximum displacement that each sensor could have. The static pressure has been transformed from the CFD simulations prediction that have been calculated for two perpendicular planes at each sensor and the probe body dividing each surface into four surfaces, as shown in figure 4.

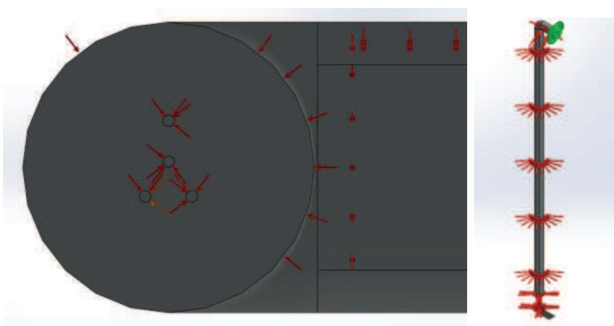

Figure 4. Static pressure distribution around both the four sensors and the probe body

The probe dimension that has been exposed to the fluid flow was 6mm outer diameter and 4.2mm inner diameter. The probe has been assumed to be immersed in the flow domain by 10, 50 and 90mm with 25 and 50mm downstream axial distance.

Chrome stainless steel material has been selected to be the material assigned for both the probe and the four sensors with the specifications, as shown in table 1.

Table 1. The probe and the four-sensor material specification

Property	Value	Units
Elastic Modulus	2.00E+11	N/m^2
Poisson's Ratio	0.28	
Shear Modulus	7.70E+10	N/m^2
Density	7.85	Mg/m^3
Tensile Strength	413613000	N/m^2
Yield Strength	172339000	N/m^2
Thermal Expansion Coefficient	1.10E-05	/K
Thermal Conductivity	18	W/(m•K)
Specific Heat	460	J/(kg•K)

2. RESULTS AND DISCUSSION

In this paper, three parameters have been taken into consideration for investigations namely, the effect of the pipe diameter, the effect of the probe radial distance and the effect of the mixed velocity on the sensor deflection. Whilst the effect of materials that have been used in sensor and probe fabrication, the sensors' length and diameter, and the probe's body diameter have not been taken into consideration and left over for future work.

2.1. The effect of pipe diameter on sensor deflection

One of the important parameter that affects sensor deflection is the use of conductivity probe in different pipe diameters. By using conductivity, probe in larger pipe diameters, with keeping the mixture velocity constant, the sensor deflection decreases, as shown in figure 5. As the pipe diameter increases the pressure drop decreases, which is the reason behind sensor deflection decrease.

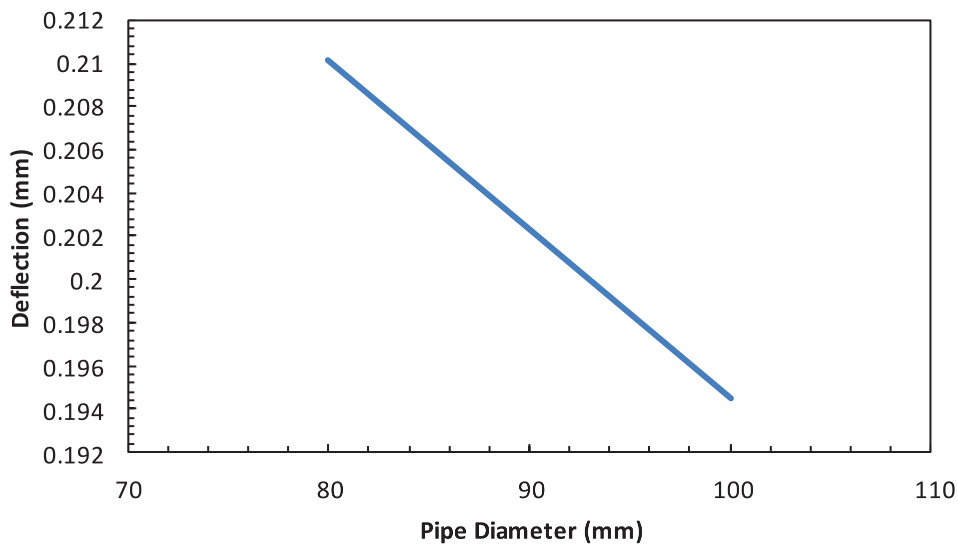

Figure 5. The effect of the change in pipe diameter on the sensor deflection.

2.2. The effect of probe's radial location on the sensor deflection

The effect of the probe location within the pipe on the sensor and the probe body has been considered in this paper at three pipe locations of 10, 50 and 90% of each pipe diameter.

From figure 6, it can be clearly observed that location of probe with respect to pipe walls have a significant effect on the sensor deflection in cases where the flow velocity is relatively low. Maximum deflection can be found when the probe is close to the pipe wall, whilst almost no deflection can be found at the pipe centreline .

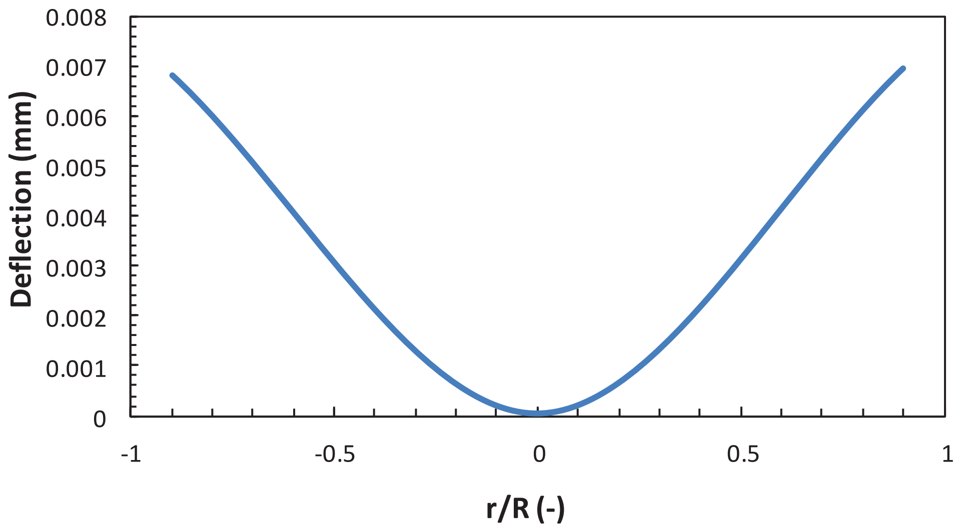

Figure 6. The effect of the change in radial location on the sensor deflection for low flow velocity

Figure 7 depicts the amount of the deflection that is affected by the change in probe's radial location at high velocity of 6m/s. It can be seen that the amount of deflection increases as the probe's stem is exposed to the high flow velocity because maximum probe deflection depends on the perpendicular distance between the applied force and the probe support.

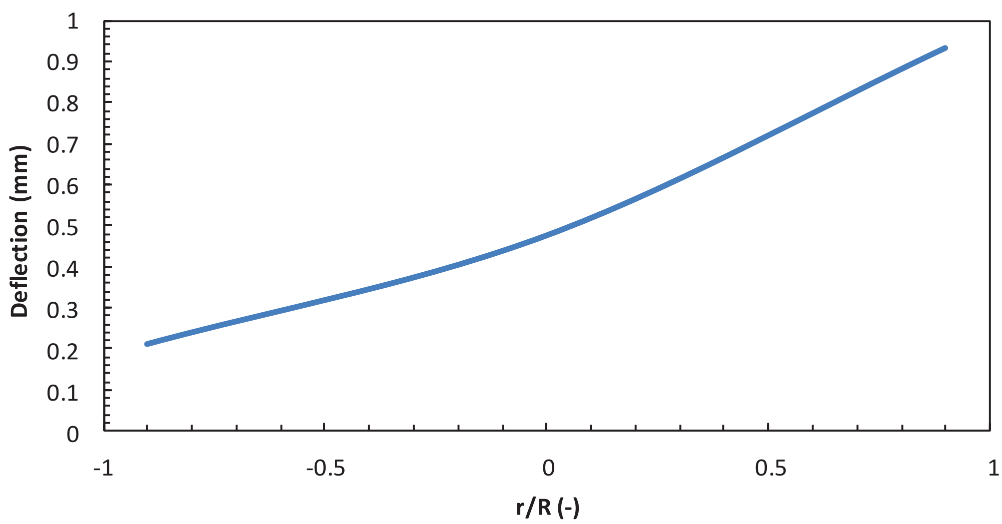

Figure 7. The effect of the change of probes radial location on the sensor deflection

2.3. The effect of the mixed velocity variation on the sensor deflection

Three mixture velocity values of 0.76, 1 and 6m/s have been considered in this study to quantify the effect of the mixed velocity variation on the sensor and probe deflections.

Figure 8, depicts sensor deflection due to the increase in mixture velocity. It can be clearly observed that the increase in flow velocity increases the sensor deflection. This process occurs because of the increase in static pressure that is induced from the frictional shear force at the sensor surfaces due to the high velocity.

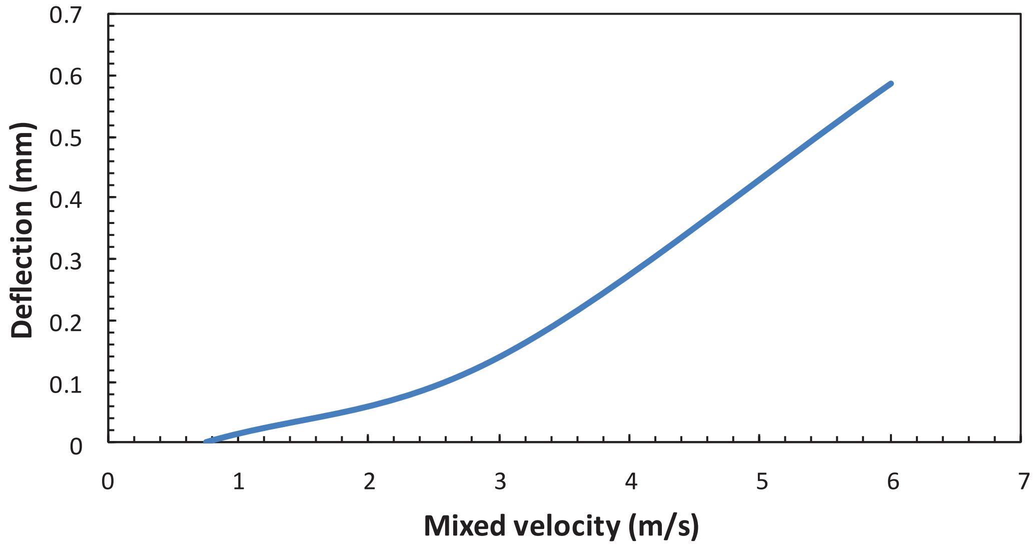

Figure 8. The effect of the change in the mixed velocity on the sensor deflection

2.4. Three-dimensional self-compensation equations

After the investigation of all parameters, the data have been arranged through a regression analysis, which has been used to develop equations represent the sensor deflection in the three directions. For each sensor, three sets of independent deflection equations have been developed.

Sensor 1

$$S1\_x = -0.3612 + (1E-9)Re + (0.0053)r$$

$$S1\_Y = -3E-06 - (8E-14)Re + (2.42E-07)r$$

$$S1\_Z = 0.0026222 - (4.4457E-11)Re + (1.1257E-05)r$$

Sensor 2

$$S2\_X = -0.17866225 + (6.64975E-10)Re + (0.0017776)r$$

$$S2\_Y = -0.000411 - (1.5E-12)Re - (6E-06)r$$

$$S2\_Z = -0.00364 + (4.17E-11)Re + (1.86E-05)r$$

Sensor 3

$$S3\_X = -0.34975 + (9.96E-10)Re + (0.0059336)r$$

$$S3\_Y = -0.0004 - (1.57E-12)Re - (5.53E-06)r$$

$$S2\_Z = -0.00375 + (4.09E-11)Re + (2.2E-05)r$$

The above equations have been embedded into the signal processing to compensate the experimental data that had been introduced by Pradhan [8]. Figure 10 depicts the effect of the new technique on the bubble velocity distributions. This being the predominant component of flow velocity; the effect of the sensors' deflection on the probe measurement is quite trivial. The maximum discrepancy can be found in the regions where the sensors are close to the pipe wall, whereas almost no compensation can be found at the pipe centreline.

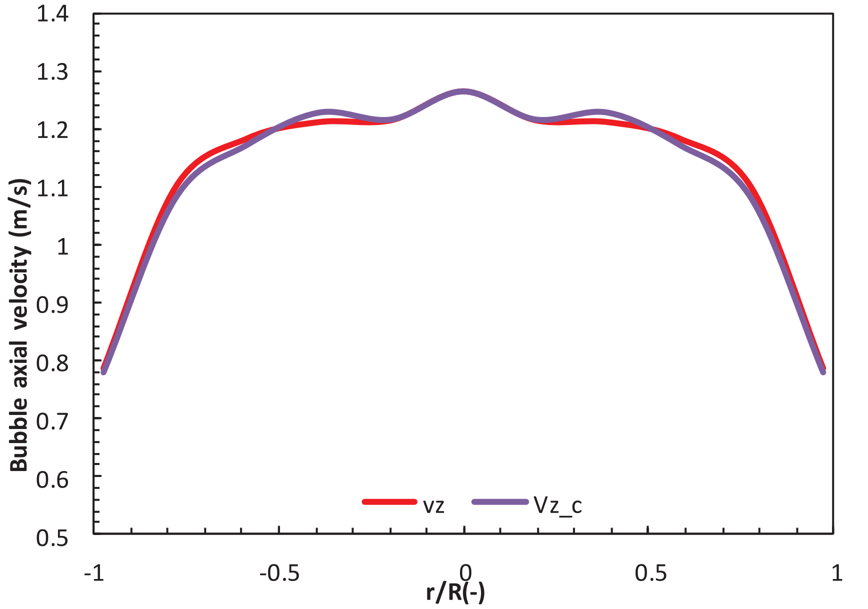

Figure 10. The air axial velocity without correction (vz) and with correction (vz_c)

Figure 11 depicts the effect of the self-compensation technique on the radial velocity. Since the radial velocity is low, the small sensor deflection has high influence on the radial velocity measurement especially in the wall region. However, no effect is found at the pipe centreline.

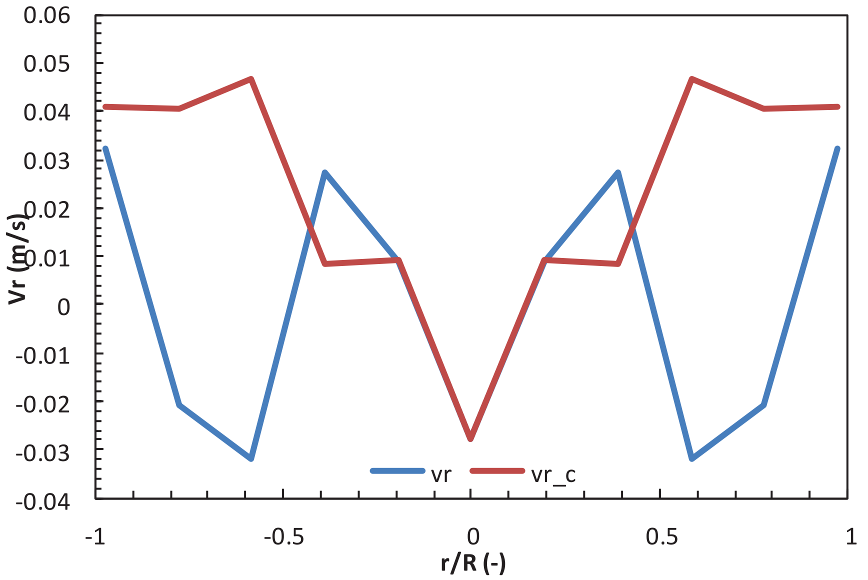

Figure 11. The air radial velocity without correction (vr) and with correction (vr_c).

Figure 12 depicts the effect of the self-compensation method on the azimuthal air velocity. The effect of the investigated variables on the azimuthal air velocity is trivial in the cases where the mixed velocity is relatively low.

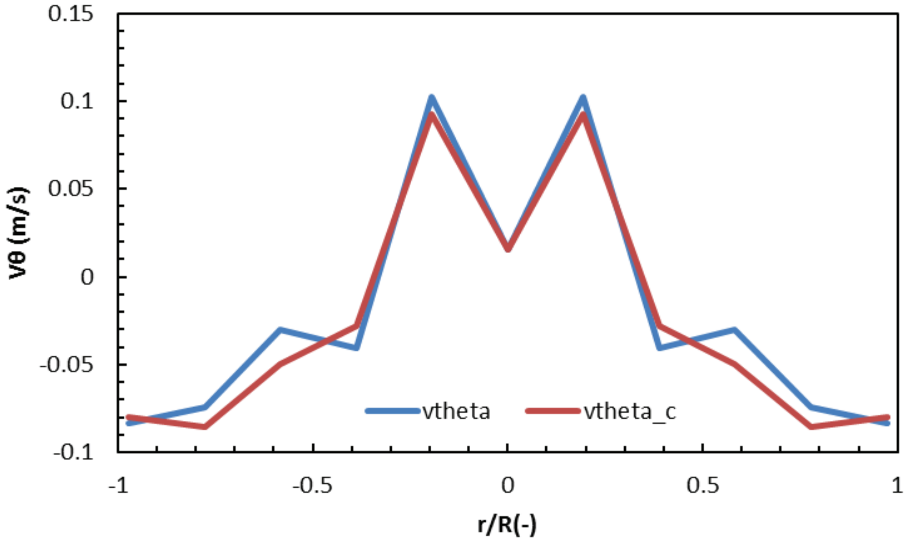

Figure 12. The air azimuthal velocity without correction (vθ) and with correction (vθ_c).

3. CONCLUSION

Measurement accuracy using multi-sensor conductivity probe depends on a number of factors such as uncertainty in measurement due to sensor and probe deflection, which have been taken into consideration in this paper. The following are the main conclusions:

1. Pipe diameter has a direct effect on the sensor deflection.
2. The position of probe radially affects the sensor deflection rate. At low flow velocity, maximum deflection occurs when the probe gets close to the pipe's wall, whereas at high velocity, the deflection rate increases with the increase of the probe radial intrusiveness.
3. The increase of the mixed flow velocity increases the sensor deflection rate.
4. Using self-compensation technique can effectively reduce errors generated due to sensor and probe body deflections.
5. Combining fluid and structure interaction codes can predict reasonable estimation for the sensor deflection rate.

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