

ULTRASONIC FLOWMETER FOR COAL SEAM GAS APPLICATION

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ABSTRACT

The use of ultrasound to measure flow is now well established with many installations worldwide in chemical and petrochemical plants, and refineries. In general, it is more challenging to apply ultrasonic techniques to gas flow measurement than liquid due to a variety of reasons, including the much lower acoustic impedance, higher Mach numbers, higher turn-down ratios, and larger pressure variations, associated with gas flow measurement. In this paper, ultrasonic flowmetering of Coal Seam Gas (CSG) or Coal Bed Methane Gas (CBMG) is investigated and reported. A theoretical model has been developed to understand how the received ultrasound signal strength changes with temperature, pressure and gas contents. Ultrasonic flowmeter dynamic range and the build-up on transducer faces for this application have also been explored and tested. CFD models have been set up to investigate the effects of transducer location and nozzle opening on flow profiles, meter repeatability and overall system accuracy. Finally, external flow calibration results have been presented.

INTRODUCTION

Using ultrasound to measure flow has been a well-known technique for decades [1]. Over the years, many different versions of ultrasonic flowmeters have been developed—the operating principle varies from transit time to Doppler and to Transflexion; the arrangement of transducers from wetted to clamped-on (non-wetted); the installation from portable to dedicated (permanently installed); applications from water or wasted water, to process in chemical and petrochemical plants, to custody transfer and topside or upstream multiphase; and the number of channels from single to multiple [1-3]. In recent years, the transit-time based ultrasonic flowmeter (to which the scope of this paper is limited), built as a one-piece “drop-in” flowcell with wetted transducers, has been gaining steam, due to its superior accuracy, low maintenance (and thus low cost of ownership), high reliability associated with no moving parts, no or minimal pressure drop, and high turn down ratio. This opens up the window of applying ultrasonic flowmeters to new applications, among which is Coal Seam Gas (CSG).

Coal Seam Gas (CSG) is a form of natural gas—which is a low emission alternative to coal for electricity generation—trapped in underground coal seams by water

and underground pressure. The most common gas found in CSG is methane which was formed millions of years ago as part of the burial of peat to form coal. Unlike natural gas from conventional reservoirs, CSG contains very little heavy hydrocarbons, such as propane or butane, and it often contains up to a few percent of carbon dioxide. In recent decades, CSG has become an important source of energy worldwide, especially, in Australia, U.S., Canada, China and other countries. CSG gathering has never been on this scale before and the well operators are still defining and refining extraction processes. As a result, flowmetering of CSG is imperative from both process control and monitoring, and volume measurement perspectives. The fact that many of the abundant CGS wellheads are located in remote and environmentally sensitive areas demands a highly reliable and cost-effective measurement technology, and this makes ultrasonic flowmetering well suitable, thanks to its aforementioned advantages. In this paper, ultrasonic flowmetering of CSG has been investigated and reported, including Model development, Lab Testing, CFD simulation and Flow calibration.

MODEL

Transit-time ultrasonic flowmeters take advantage of a simple principle, called “time of flight” [2][3]. Specifically, the time it takes for an ultrasonic signal to travel against the flow (i.e., upstream), t_{up} , is longer than that it takes following the flow (i.e., downstream), t_{dn} . The difference between upstream and downstream traveling times, Δt , is directly proportional to the flow velocity. The operation of an ultrasonic flowmeter strongly depends on the timing of t_{up} , t_{dn} , and Δt . The measurements of t_{up} , t_{dn} , and Δt conversely rely on the quality of the received ultrasonic signal, i.e., signal-to-noise ratio (SNR). Therefore, it is important to understand how the ultrasonic signal generated by an ultrasonic transducer is received by the other one after propagating through a gas medium.

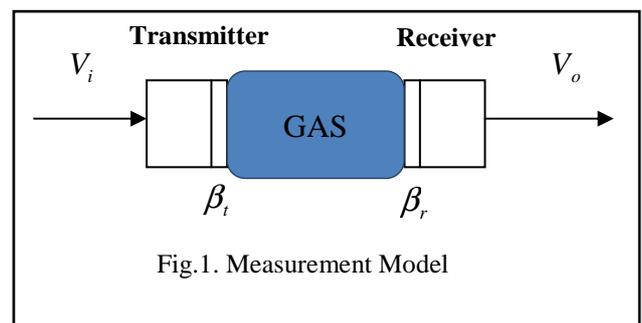


Figure 1 shows a typical ultrasonic measurement configuration, where one transmitting transducer (Transmitter) transmits ultrasonic waves into the gas medium and one receiving transducer (Receiver) receives these waves.

The receiving voltage from the measurement model can be written as [4][5]:

$$V_o = V_i \beta_t C A \beta_r \quad (1)$$

where

V_o is the output voltage,

V_i is the input voltage,

β_t is the transmission efficiency factor

C is the diffraction coefficient

A is the attenuation of the medium

and β_r is the receiving efficiency factor.

The above model can be further simplified for a given pair of transducers with a fixed separation distance. Normally, the separation distance between the transducers is larger than the near field distance of the transducers and the gas acoustic impedance is much smaller compared to transducer acoustic impedance. With that, β_t , C , A , and β_r can be further simplified as:

$$\beta_t \propto \rho c, \quad (2)$$

$$C \propto \frac{ka^2}{D} \propto \frac{1}{cD}, \quad (3)$$

$$A \propto e^{-\alpha D}, \quad (4)$$

and $\beta_r \cong \text{constant}, \quad (5)$

where

c is the sound speed in the gas medium,

D is the transducer separation distance,

and α is the attenuation coefficient.

Combining the above four terms, Eq. (2)-(5), yields:

$$V_o / V_i \propto \rho e^{-\alpha D} \quad (6)$$

In an ideal gas, we have

$$\rho = \frac{P}{RT} \quad (7)$$

where P is the absolute pressure, R is the specific gas constant and T is temperature.

Combining Eq. 6 and Eq. 7, we finally have

$$V_o / V_i \propto \frac{P}{RT} e^{-\alpha D} \quad (8)$$

Or we can rewrite Eq. (8) as:

$$V_o \propto V_i \frac{P}{RT} e^{-\alpha D} \quad (9)$$

Equation 9 clearly shows that the received ultrasound signal strength is proportional to the transmitting signal strength, and pressure: the higher the operating pressure, the higher the received ultrasound signal strength. On the other hand, the received signal strength is inversely

proportional to Temperature and specific gas constant. If everything else is equal, then the higher the process temperature, the lower the received signal strength; and the higher the specific gas constant, the lower the received ultrasound signal strength.

LAB TESTING

A series of tests have been designed to verify that ultrasonic flowmetering is suitable for CSG flow measurement. Figure 2 below shows our test setup, where a pair of gas transducers has been installed into a 3" flowcell. One transducer will be used as the transmitter and the other as receiver.



Fig. 2. Test Setup: a 3" flowcell with a pair of gas transducers installed into .

Figure 3 shows a typical received ultrasound waveform from the above setup at ambient temperature and pressure. Normally, for gas flow measurement, a portion of ultrasound propagates inside the metal pipe wall, and it does not carry any useful flow information and thus acts as noise, called Short-circuit (SC) Noise. On the other hand, another portion of ultrasound traverses through the gas medium, and it does carry flow related information and thus acts as Signal. Since ultrasound travels much faster in solids, such as pipe wall, than in gases, SC Noise arrives ahead of Signal. In addition, the large acoustic impedance difference between transducer, which is normally made of metal and ceramic materials, and gas media, makes it much harder for ultrasound to propagate in gases, compared to in liquids or solids. The ratio between the amplitude of Signal and that of SC Noise is defined as SNR. A high SNR is required to make accurate and reliable flow measurements.

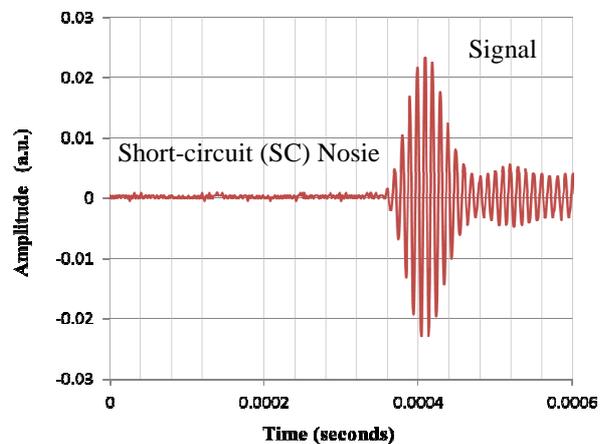


Fig. 3. A typical received ultrasound waveform

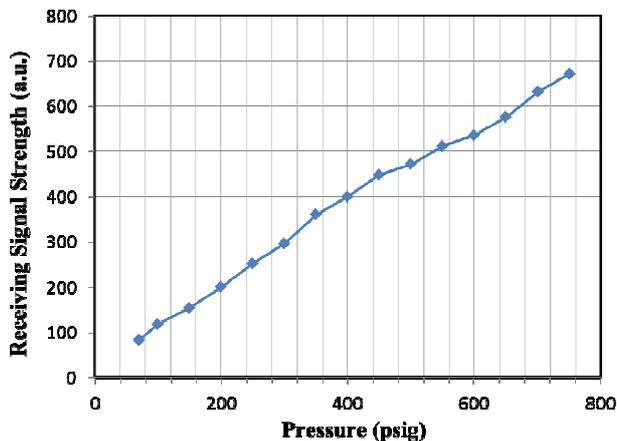


Fig. 4. Received Signal Strength vs Pressure.

In CSG application, an important factor that needs to be taken into account is pressure variation. Normally, CSG pressure varies from 0 to hundreds of psig, and thus a large dynamic range is required for metering electronics. Figure 4 shows the testing data about how the received ultrasound signal strength varies with pressure, with the aforementioned testing setup pressurized. As predicted in our Model, the testing results show that the received signal strength increases with pressure, to a large extent, following a linear trend.

Another critical consideration in ultrasonic flowmetering of CSG is the build-up on transducer faces due to the fact that CSG is not perfectly clean and thus the build-up on transducer faces could accumulate over time. If it did occur, ultrasonic flowmeters need to be robust enough to tolerate certain level of build-ups; otherwise, service to the flowmeters and transducers would be required with increased cost of ownership. In our lab testing, clay is used to form layers of different thicknesses and then glued to the faces of both transmitting and receiving transducers. Signal-to-Noise Ratio (SNR) is then monitored for different clay thicknesses. Figure 5 shows how SNR changes with the build-up thickness, at ambient pressure. As expected, SNR decreases with build-up thickness and signal is reaching the noise level at the thickness of 0.08" (2mm). Depending on the build-up rate, ultrasonic flowmetering could tolerate a certain level of build-up, especially under pressure, beyond which service to flowmeters and transducers might be needed.

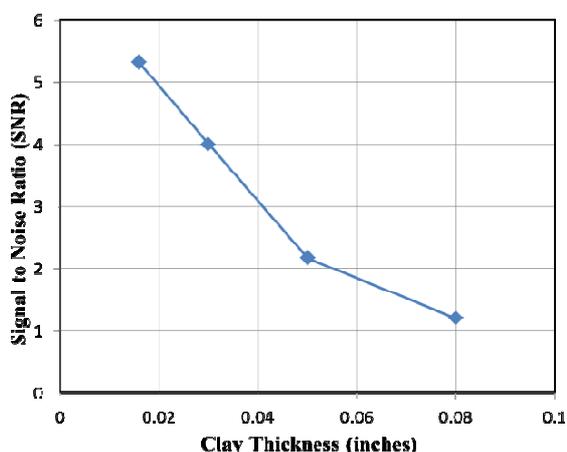


Fig. 5. SNR changes with clay thickness.

CFD SIMULATION

A Computational Fluid Dynamic model has been set up to analyse the flow around the transducer and nozzle geometry. The goal is to first understand the effects of both transducer positioning and nozzle opening on flow measurement, in terms of accuracy and repeatability, and then to optimize the transducer location and nozzle opening to minimize the adverse effects. The flow domain is modelled with 14 pipe diameters upstream and downstream of the transducer pair. The transducers are placed diametrically opposite at 45 degree angle with the flow direction (X direction). Fully developed flow was assumed at the inlet of the 3" flowcell. Air is assumed to be flowing at 3.28 ft/s bulk velocity. For this purpose we used ANSYS/CFX finite element CFD computer program to analyse the steady state turbulent flow conditions. A finite element grid (mesh) is designed, consisting of approximately 3 million elements with proper turbulent shear boundary layer inflation regions near all walls (flowcell and transducers).

We present here results for three cases, consisting of the "nominal" CSG transducer geometry, the "protruding" transducer geometry and "small port" geometry. The nominal geometry places the transducers recessed into the cavities of the nozzles so that the transducer itself is minimally exposed to the flow. The protruding case places the transducers approximately half an inch protruding into the flow. Finally, the small port case attempts to minimize the size of the ports where the recessed transducers are placed. We aim to ascertain the different effects of these cases onto the flow as well as the ability of the transducers to produce accurate and repeatable readings. To this effect we show two types of results. First, Velocity Magnitude contour plots, to show the effect of the transducers and ports onto the incoming flow. Secondly, we show, Turbulence Kinetic Energy (TKE) plots, which measure the levels of turbulence intensity within the flow domain. We expect that the TKE intensity can be associated with flow measurement repeatability. In other words, highly turbulent flows, in the near vicinity of the transducers, will produce less reliable measurements than quiescent flows. In the same light, a less "perturbed" flow will show more accurate flow measurements than those of highly disturbed flows.

Figure 6 shows the velocity (magnitude) contour plot on the pipe's mid-plane, for both the nominal (top) and the protruding (bottom) cases (flow is in the positive X direction). This shows that the protruding transducers have a major impact on flow uniformity. In particular, the protruding transducers "constrict" the flow substantially shortly after the transducer's location. They present an important flow blockage condition which is felt many tens of diameters downstream of their location.

Figure 7 shows a close-up view for the velocity profiles in the vicinity of the transducers. In this Figure, the top portion shows the nominal transducers, the middle one shows the protruding case, whereas the bottom part shows the case with transducers in small ports. Of importance is the velocity distribution in the line between

the faces of the transducers, as this is the ultrasonic path where the velocity is “line” averaged by the ultrasonic flow meter. In particular, the middle protruding transducer shows highly irregular velocity profile above its face, which will impact the accuracy of the “protruding” measurement.

In general, the path between protruding transducers shows more irregular behaviour than the path between the nominal transducers. This is shown in Fig. 8 as a line plot for the axial Velocity component (X direction) along the path line between the mid-points top to bottom transducers (dashed black lines in Fig.7). The protruding transducer velocity profile shows larger negative values near the left side (top transducer). On the other hand, the case with small ports shows only minimal improvement in the velocity profile vis-à-vis the nominal case. In the context of ultrasonic flowmetering, the port size plays a much smaller effect compared to the protrusion of transducer when it comes to absolute accuracy, however, port size plays a larger role in measurement repeatability, which is to be shown in the below TKE investigation.

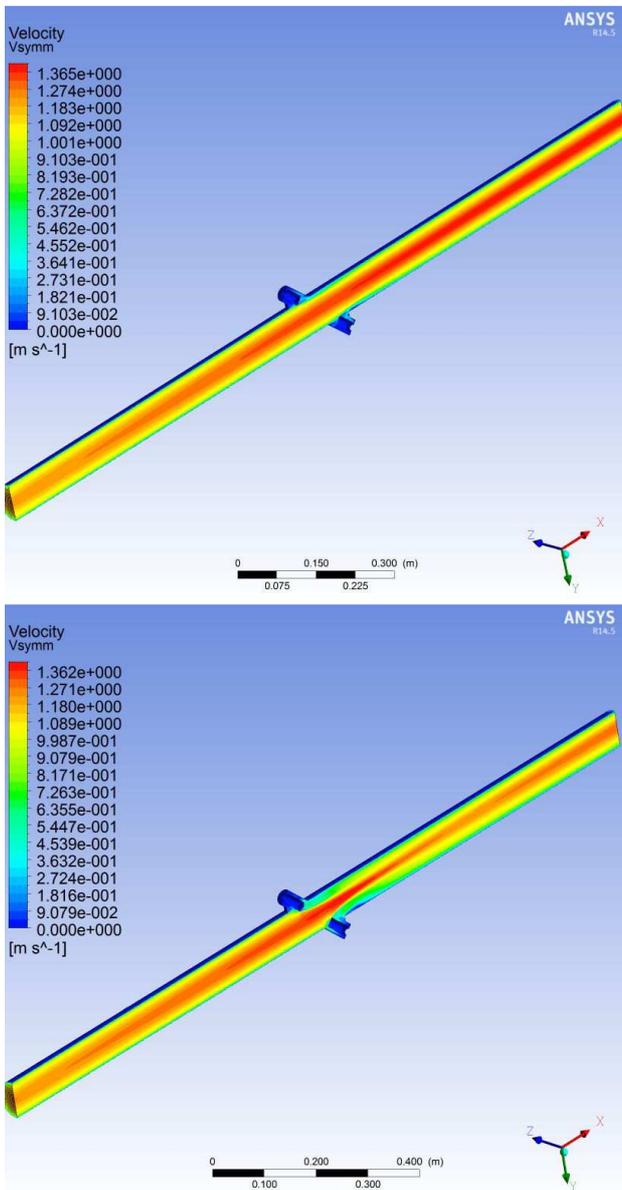


Fig. 6. Velocity Contour Plots for Nominal and Protruding Transducer cases

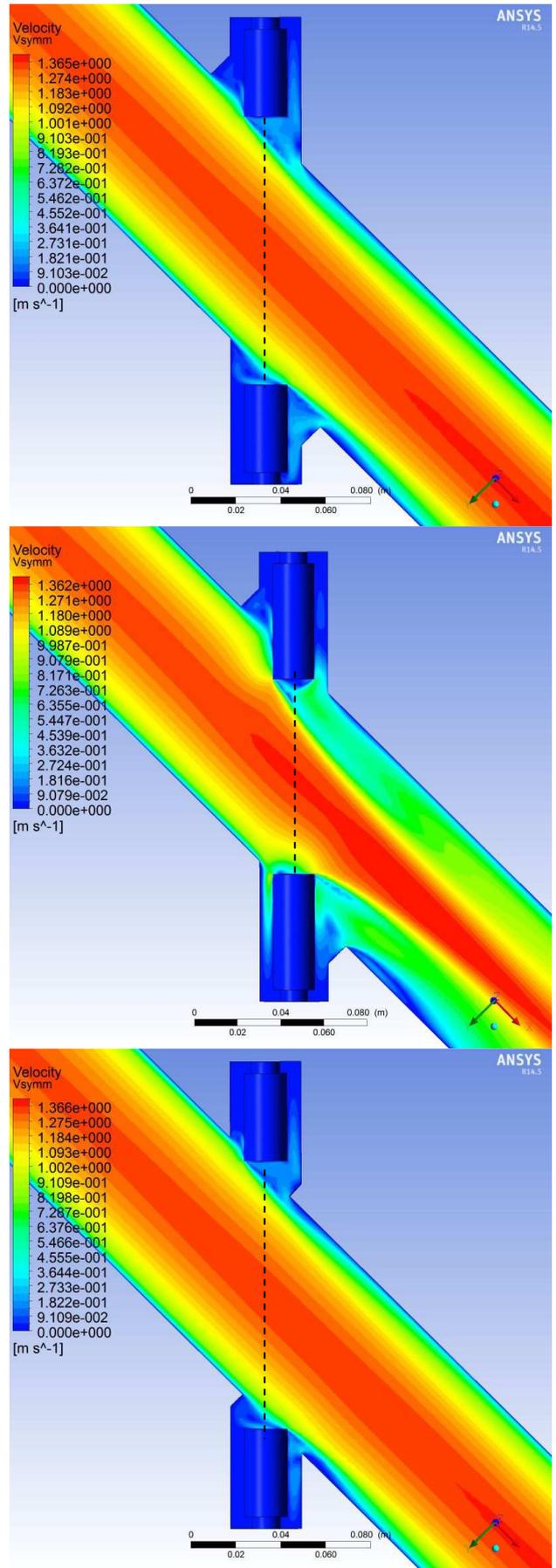


Fig. 7. Velocity Contour Plots – Close-up, for Nominal, Protruding and Small Port Transducer cases

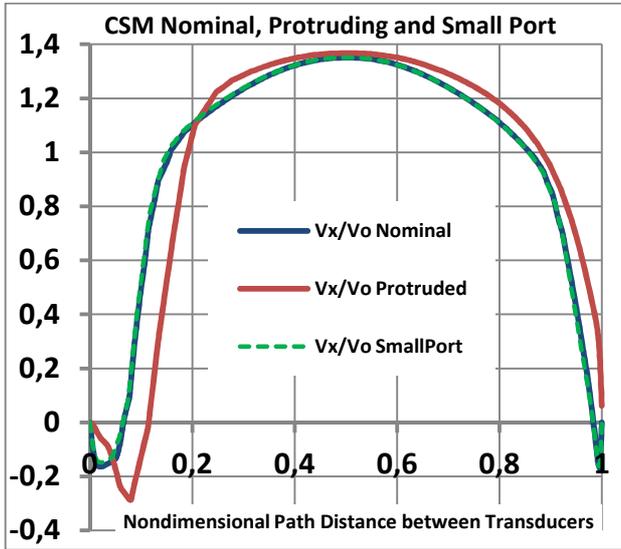


Fig. 8. Velocity Profile along mid transducer paths

Contour plots for the TKE are shown in Fig. 9, nominal case on the top portion, protruded case in the middle and small port case on the bottom. All TKE plots have been made in the same range, so that the redder contour colouring for the protruding case indicates a much larger level of Turbulence as opposed to the nominal case. In addition, we see a marked decrease in TKE for the small port geometry. This is seen more explicitly by plotting the square root of the TKE divided by the bulk velocity—which represents the turbulence fluctuating velocity expressed as a percentage of the bulk velocity—on the path line between transducers. This is shown in Fig. 10 where it is obvious that the protruding transducers develop a larger fluctuating velocity component than the nominal ones, along its measuring path line. By the same token, small port geometry contributes to a further reduction in turbulence intensity and fluctuating velocities. The line average fluctuating velocity for the protruding transducers is 9% whereas the nominal non-protruding one is 7.7%. Additionally, small port geometry decreases this to 7.4%. These numbers are related to ultrasonic meter repeatability and the lower number will lead to more repeatable and accurate measurements.

It should be noted that the above simulations have been conducted with a 3” flowcell (which is a relatively small one in ultrasonic flowmetering), and the effects of transducer protrusion and port size on flow measurements should be less prominent for larger flowcells where the same protrusion or port size is relatively smaller. Nevertheless, from the above CFD analysis, minimized transducer protrusion and port size are clearly desirable in order to make accurate and repeatable ultrasonic flow measurements.

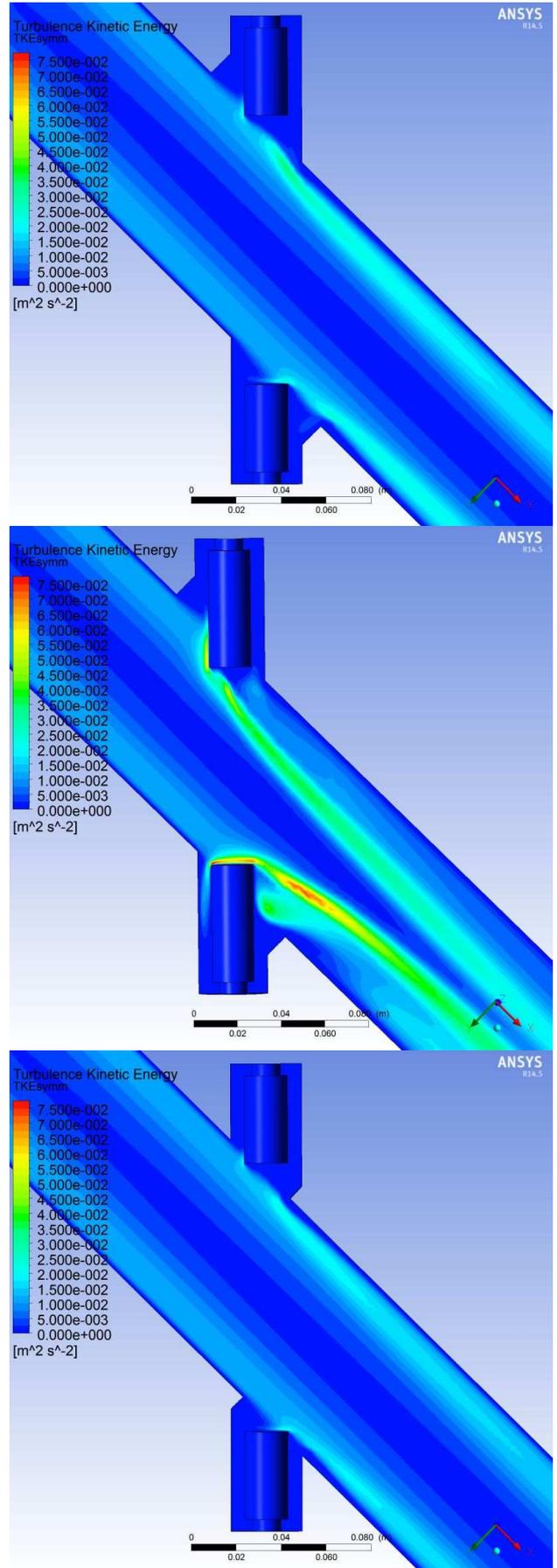


Fig. 9. Turbulence Kinetic Energy Contour Plots

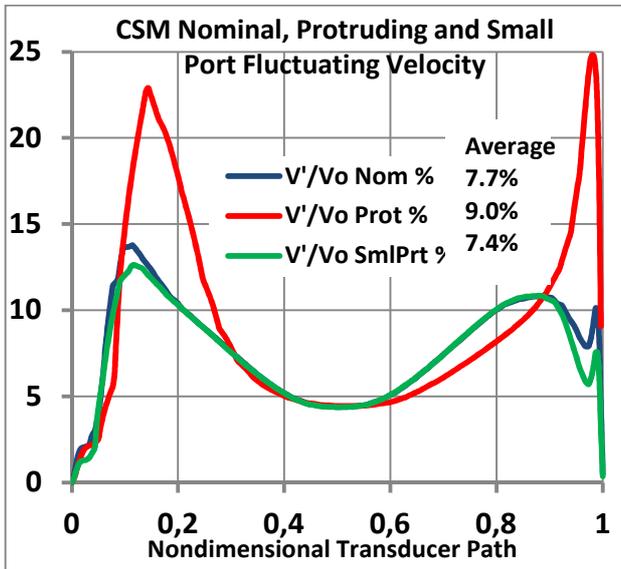


Fig. 10. Fluctuating Velocity Profile along mid transducer paths

FLOW CALIBRATION

With the above design and optimization being implemented, we have built many 3" ultrasonic flowmeters and sent them to a gas calibration facility for testing. The testing is conducted in air at ambient temperature and pressure. Figure 11 shows a calibration report of 20 such meters. It can be seen that the ultrasonic flowmeters consistently meet 1.5% accuracy across the flow velocity range, from 1.7 ft/s up to 60 ft/s. In general, as expected, the meters show better accuracy at higher flows; for example, all the meters meet 0.5% accuracy at 60 ft/s. Some of these meters have been sent to CSG customers for trial and the meters have been installed and running at customer's sites for about half a year. While the details of the results from customers' sites are not immediately available, the feedbacks from the customers have been positive: the meters have been functioning well with satisfying accuracy.

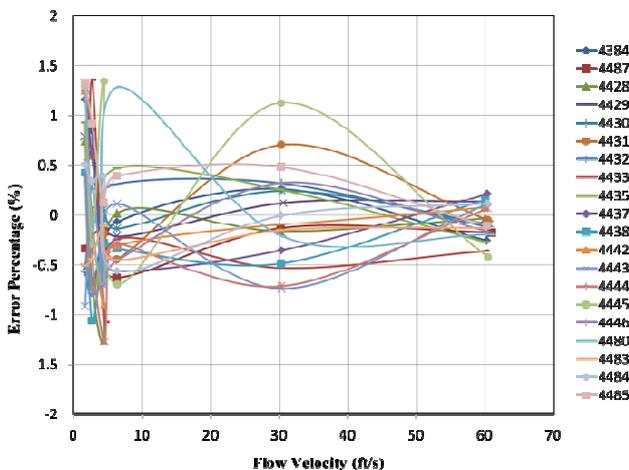


Fig. 11. Calibration reports of 20 CSG ultrasonic flowmeters

CONCLUSION

The use of ultrasound to measure CSG flow is investigated and reported. A theoretical model has been developed to understand the ultrasound propagation in gas media and to understand how ultrasound signal strength changes with process pressure, temperature and gas contents. CFD models have also been set up to analyse the effects of both transducer positioning and nozzle opening on flow measurement, in terms of both accuracy and repeatability. The implication of simulation results has been incorporated into the design to optimize the transducer location and nozzle opening to minimize the adverse effects. External flow calibration results have been presented to prove that ultrasonic flowmetring is a promising technique for CSG applications .

References

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