VELOCITY MEASUREMENT IN BOILER TUBES USING A NOVEL ULTRASONIC FLOW MEASUREMENT TECHNIQUE.

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Abstract

A method is reported here for the ultrasonic measurement of flow in boiler super-heater tubes. The tubes are in a tube bank formation running at high temperature (typically 300°C) and pressure (typically 100bar). To enhance heat transfer, the tubes in this application are ribbed internally with thick helical ribs. Further, all measurements have to be made on one side of the tube bank to avoid direct radiation on the fire side. Conventional ultrasound methods are difficult to apply in these conditions. The combination of thick steel walls, internal ribbing and the substantial temperature and density gradients do not provide for a well defined sound beam path. Instead a new method is proposed to measure the flow rate using the properties of the frequency spectrum of the noise imposed on the sound beam by random fluctuations in the velocity and density of the fluid caused by the nature of the flow in such tubes.

The measurement system consists of an ultrasonic beam generated using a conventional piezoelectric disc transducer/buffered from the hot boiler tubes by long threaded steel stalks which are bolted to a bracket welded to the tube bank. A second similar probe is fitted to receive the reflected sound beam signal. A resonant cavity is formed composed of the tubes, the water and the buffer rods. Envelop detection and frequency analysis is then applied to the received signal and the flow rate is deduced from the frequency contents of the noise spectrum. Such noise is caused by small changes to the effective path length of the sound beam caused by the temperature and density variations accompanying the flow. The received spectrum shows random components and its frequency content correlates well with the flow velocity.

A simple theoretical model in which the sound beam is assumed to be deflected by velocity and density variations is used to model the events leading to the observed results. Both laboratory and site measurements made during commissioning of a 300MW boiler are reported showing very similar behaviour when the frequency spectrum of the demodulated signal is considered. A similar observation applies to the frequency spectrum obtained from the theoretical model. A linear relationship is observed in all these cases between the flow velocity and the frequency content of the received signal- within the range of velocities considered. Further experimental and theoretical work is needed to cover a wider range of velocity and include effects of the internal ribbing and other factors not taken into the theoretical or the experimental treatment of the present work.

Introduction

Measurement of water velocity in boiler tubes is a particularly challenging problem due to the very high temperature involved, coupled with very thick walled steel tubes that might be ribbed from inside to aid heat transfer, as in the present case. The tubes are often in the form of a tube bank and the fire side of this bank is to be avoided. This restricts the application to the measurement of reflected sound only. The presence of the internal ribs and the severe density variations and turbulence does not allow conventional ultrasonic methods to be used. The uncertainty in the sound beam path is expected to show some random fluctuations that are related to the turbulence as well as the flow velocity. Therefore, a close study of the frequency spectrum of the received sound intensity after

reflection from the internal side of the tube can reveal any correlation between the frequency content of the spectrum and the flow velocity inside the tubes.
To protect ultrasonic flowmeter transducers and their bonds from temperature extremes, Lynnworth [1],[2] used stainless steel and fused silica rods as buffers for pipe diameters from 1.25 cm to 75 cm in steel and copper tubes in temperatures ranging from those of cryogenic liquids to 260°C degrees. Earlier applications used carbon rod. The attenuation of the sound beam is considerable for non-metalic buffer rods, but the thermal insulation is excellent. Metal buffers are less fragile when industrial application is at hand. Lynnworth used welded yokes to hold the probes in position and end pieces made to match the curvature of the probes to that of the outside pipe surface. The transit time method employing cross correlation methods were used to determine the arrival times.
The effect of random flows and density changed on the propagation of 1D sound waves in media has been studied among others by Medrek et al [3]. Space dependent random flows were found to effect both the beam amplitude and frequency of the acoustic waves dependent on the wave and the random field characteristics. The effect on transit time by temperature and density fluctuations were also studied by Ioos [4] using the geometric ray theory. A marching technique is used to approximate the behaviour of sound beams by Jensen [5] in inhomogeneous media. Zemp [6] used operator splitting method to investigate ultrasound propagation in tissue from array transducers. The effects of attenuation, diffraction and non-linearity were treated separately over incremental distances to produce a solution of the wave equation along the path of the sound beam. The present paper uses some of these approaches to model the behaviour of the novel flowmeter.

Mechanical Design

The flow meter as shown in figure 1 consists of a number of identical transducers used in pairs for transmitting and receiving ultrasound signals through thick steel tubes with significant internal ribbing. The transducers are clamped onto a bracket welded to the body of a section of a tube bank similar to an arrangement that was incorporated in a working 300MW. Altogether, four measuring stations were used to compare the flow at different parts of the boiler. All transducers are to be placed on one side of the tube bank to avoid high intensity thermal radiation on the fire side of the tube bank. 0.1mm silver shims were used to facilitate good coupling between the transducers and the steel pipes and 16mm, 2MHz ceramic piezoelectric crystals were used to produce and receive the ultrasound. The crystals were bonded to the buffer rods using high temperature titanium filled epoxy and the signal was carried by high temperature coaxial cables. Further protection was given to the crystal by a metal cap and the whole crystal was cast in a high temperature silicone potting compound. Two nuts were used to hold the threaded 15mm steel rods and a third welded nut was used to correctly position the probes on the surface with respect to the pipe axis. The overall length of the steel rods is 240mm and the end part was tapered and bent by 45° over the last 20mm of its length and then shaped to match the pipe surface. To limit the temperature of the crystal, the length of the rods need to be increased. Excessively long buffer rods are not practical in an industrial environment and the present choice was a trade off that proved effective in this instance. The large difference between the speed of sound in steel and water requires a large incident angle of the sound beam in order to direct the reflected sound to the receiving probe. The probes are nearly touching at their ends on the pipe surface. The best position was found by moving the probes relative to each other and observing the received signal.

Measurements and Results

The steel pipe, the liquid and steel rods act in combination as a resonant cavity. An ultrasound beam is generated by simple square wave generator and transmitted through the first of the pair of stalks. The high Q factor of the resonant circuits filters all components except the resonance frequency and a fairly clean sinusoidal signal is observed at the receiving end. The stalks are wave guides for the ultrasound beam. The bent end of the stalks gives an initial large incidence angle to the sound beam. This ensures that the reflected beam is displaced well away from the transmitting point and onto the receiving point. The relative position of the receiver needs to be adjusted first to maximise the received signal. The time signal at no flow conditions at any receiver was as a result observed to pass through a series of maxima and minima. These correspond to the compound resonance and anti-resonance of the pipe work/liquid cavity. Once a resonance has been found then any small variation in the effective path length of one of the components of the system will give rise to a modulation of the received signal. Within the boiler these are caused by small temperature changes across the liquid path of the sound beam.

A simple dedicated transmitter/receiver circuit was built composed of three parts in one common weatherproof box. The first stage generates an adjustable 0-1 MHz square wave that is fed directly to the transmitters. The received signal is fed to the second part to be amplified and then passed to the third part to be diode detected to find the envelope and filtered to remove the high frequency components. The demodulated signal out of the box was collected by data acquisition equipment in the case of site measurements or fed to measuring equipment, data acquisition and a frequency analyser for the case of laboratory measurements. The site data were sent by email and processed in Cranfield and then fed back to the site.

Sample frequency spectra obtained in the laboratory experiments are shown in figure 2 for two flow rates. A shift in the frequency content can be observed in these figures. Figure 3 shows a calibration curve for the frequency content and flow velocity at 62°C and 3 bar pressure. The frequency content is estimated in this case by the intersection of the spectrum curve with a horizontal axis corresponding to a vertical value of one in this case. Alternatively the break frequency of the log-log plot can be taken.

Most of the tests were conducted around 100kHz excitation. The data from site were varying in clarity and at high power production a loss of low frequency components was observed in the spectrum. Figure 4 shows a typical spectrum from processed boiler data for two flow rates. Again a shift in the frequency content of the data is visible. The interpretation of the site data using the laboratory findings are compared in Figure 5 with expected results using a software package to predict the flow in the boiler tubes in various parts of the boiler.

Theoretical considerations

In the present application, special consideration should be given to the very thick walls, spirally ribbed internal pipe walls and the high heat flux from the outside causing severe hydraulic and density fluctuations. The beam of sound crossing the walls reflecting back and crossing the walls again to be picked up by the receiving transducer will not be able to keep a definite direction or time of flight.

The fluctuations in the beam are expected to be random and will manifest itself in the form of changes in the phase and the amplitude of the received signal. The need to work at a resonance frequency to obtain a signal of reasonable amplitude will further accentuate the effects of any changes in the beam character.

In this section a simplified treatment is considered in an attempt to explain the frequency fluctuations. Neglecting for the moment the internal ribs, we shall consider effects on the cavity resonance brought about by random fluctuations in the velocity and density. The beam width is assumed to be of the same size as the buffer rods themselves. A volume of the liquid having a certain velocity and different temperature/density to the neighbouring stream will cause the beam to change direction. As a result it will not always be received on the same location on the other side of the wall. Such variations cause interference and phase changes and a corresponding change in the amplitude of the received signal. If we assume Snell's law then as shown in figure 6 we have: -

$$\frac{c_1}{c_2} = \frac{\sin(\theta_1)}{\sin(\theta_2)} \qquad (1)$$

Where c_1 and c_2 are the speeds of sound at two neighbouring regions 1 and 2, and q_1 and θ_2 are the incident and refraction angles across the surface separating the two regions. The distance between the upper and lower sides of the pipe assumed to be flat can be divided into smaller equal regions separated by equal spacing dy and the deflection of the sound beam dx is related for any two adjacent regions by the approximate formula;

$$\frac{c_1}{c_2} = \frac{dx_1}{dx_2} \qquad (2)$$

If the beam starts at position X1 then it will arrive at X2 where;

$$X2 = X1 + \sum_{i=1}^{n} dx_i \qquad (3)$$

where dx_i is the beam deflection in each section i along the path L, and n is the number of divisions.

The total distance travelled by the beam is given by: -

$$L = \sum_{i=1}^{n} dx_i^2 + dy^2 \qquad (4)$$

And the total time of flight of the beam is given by: -

$$T = \sum_{i=1}^{n} \frac{\sqrt{dx_i^2 + dy^2}}{c_i} \qquad (5)$$

The interference of this beam with another from a different route gives rise to both an amplitude and phase variation due to spatial and temporal differences. A Monte Carlo calculation is undertaken to model the effects over the expected beam width, changing the value of X1 in (3) above. The absolute FFT of the amplitude variation is then calculated and used to determine the relation between the fluid velocity and the frequency components of the received signal, with an assumed velocity profile. A random augmentation to the velocity, temperature and beam direction of the order of 1% was introduced in order to simulate random velocity and temperature changes.

The path of a single beam is shown in figure 7 as it is affected by random velocity and temperature variations. Figure 8 shows projected frequency spectra of the noise. Figure 9 gives the relation between the frequency content of the predicted spectrum and the flow velocity employing the same methods as in the experiments. It can be seen that the slope of graph is similar to the slope obtained in the laboratory tests.

Conclusions

A method has been described to measure the flow velocity in thick internally ribbed steel tubes of the type used in boilers and super heaters. The difficulties posed by the high temperature and pressure and thick steel walls in addition to the unpredictable position and effects of the internal ribbing precludes the conventional ways of ultrasonic flow measuring methods. It has been shown in laboratory and site measurement that the frequency content of the noise signal produced by random fluctuations in the sound beam path caused by density fluctuations are well correlated to the flow inside the tube. This correlation is a result of the spectrum being related to the speed with which elements of the flow at different temperatures pass through the sensor volume. A reasonably linear relationship has been observed between the break frequency as a measure of the frequency content of the frequency spectrum and the flow rate. Also the site measurements showed reasonable agreement with figures for the velocity at different boiler tubes as predicted using software based calculations with those obtained from the spectrum studies. The method has an accuracy of ±10%, which although not high is acceptable for flow comparisons of the flow between tubes located in different parts of the boiler.

A simplified theory based on geometrical optics in which a bundle of sound rays where followed up as they bend by flow and random fluctuations in fluid properties also seem to give the result that the frequency content of the spectrum of the resulting modulation is linearly related to the flow velocity. The theory neglected the effects of the internal ribbing which is significant and the complicated temperature and velocity profiles resulting from the internal ribbing being helical. A more detail study may throw some light on the process and enable a conventional correlation method to be used for processing. Such a method will have a better time constant and can be used to determine flow direction as well as magnitude. Such a method was actually tried in our work but failed to produce consistent answers.

Reference

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[2] Lynnworth, L C ''Buffer rod design for ultrasonic flow measurement at cryogenic and high temperatures, +/ - 200 ° C ''. ISA, 1988 – Paper 88-0777.

[3] Medrek, M, Michalczyk, J, Murawski, K, and Nocera, L, ''Numerical simulations of random sound waves'', Waves Random Media,12(2002), pp 211-221.

[4] Iooss, B, Lhuillier, C, Jeanneau H, ''Numerical simulation of transit time ultrasonic flowmeters: uncertainties due to flow profile and fluid turbulence''. Ultrasonics 40 (2002) pp 1009 –1015.

[5] Jensen, F B, ''Numerical models of sound propagation in inhomogeneous media'', Ultrasonic Int.87 Conf Proc.

[6] Zemp, R J, Tavakoli, J, Cobbold R S C, ''Modelling of non-linear ultrasound propagation in tissue from array transducers'', J Acoustic Soc Am 113(1), Jan 2003.

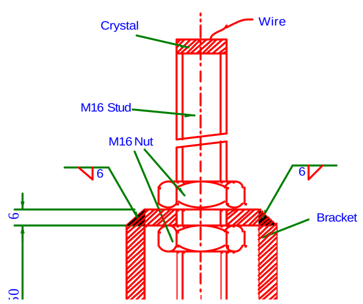
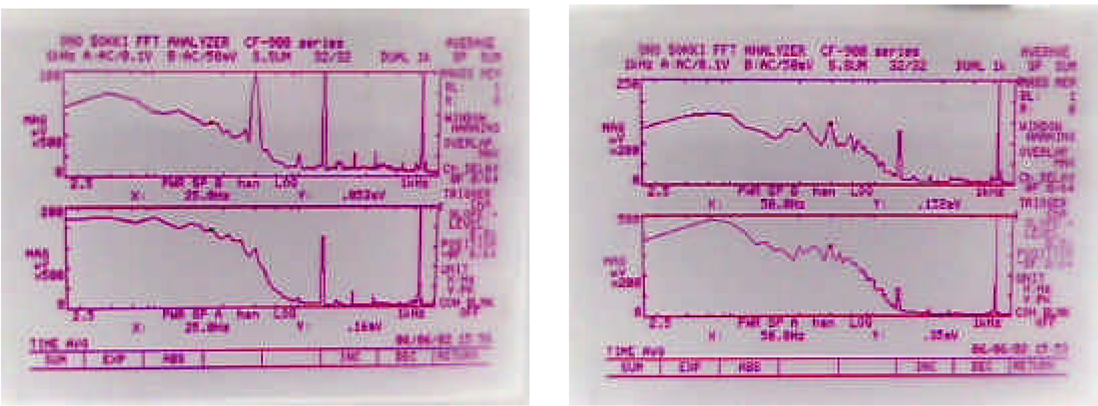


Fig 1 Drawing of transmitter/receiver clamped to bracket welded to tube bank. (Lab set up)



2a 2b

Fig 2 Frequency spectrum from two probes in laboratory test at two velocities

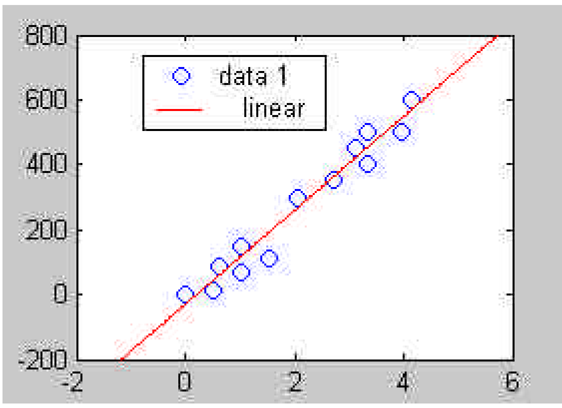


Fig 3 Frequency content figure(Hz) versus flow rate(m/s) (Lab results)

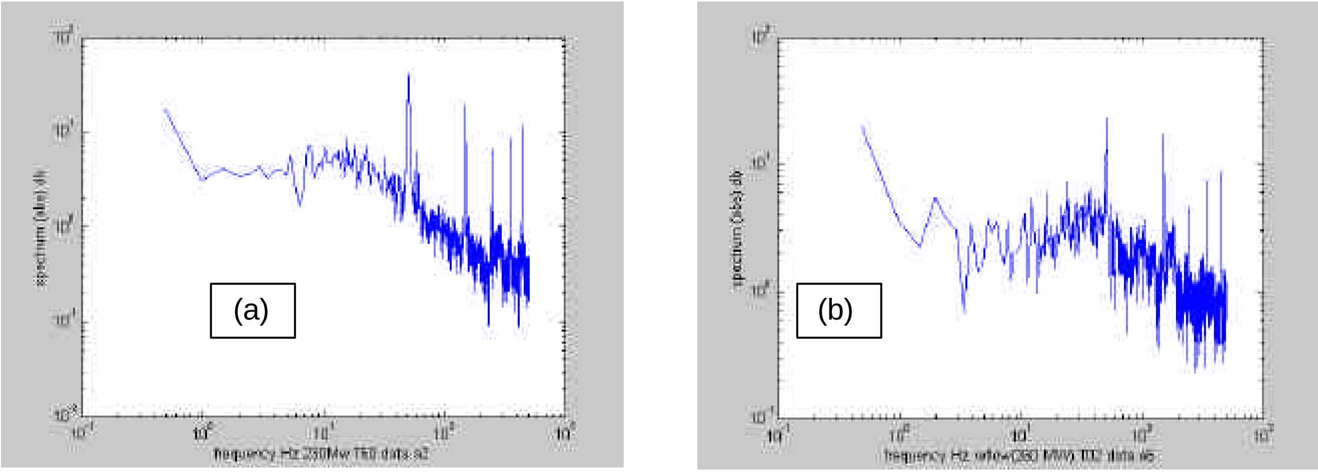


Fig 4 (a),(b) Frequency spectrum of site data. Boiler working at 230& 260 MW.

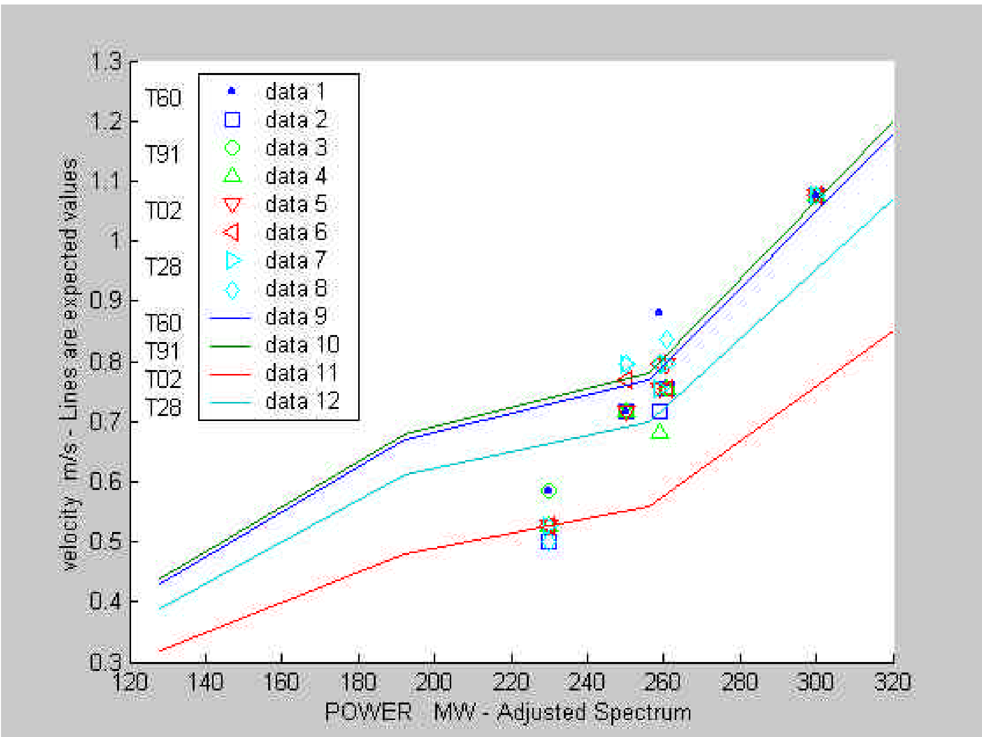


Fig 5 Predicted flow velocity using boiler software compared to velocity values deduced from frequency spectrum

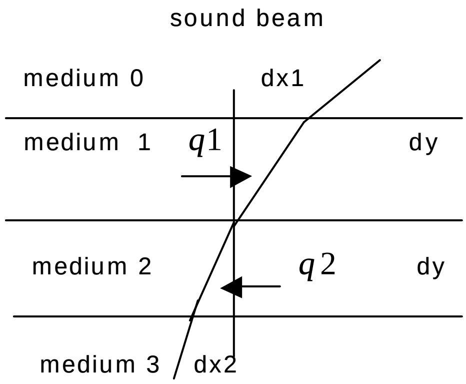
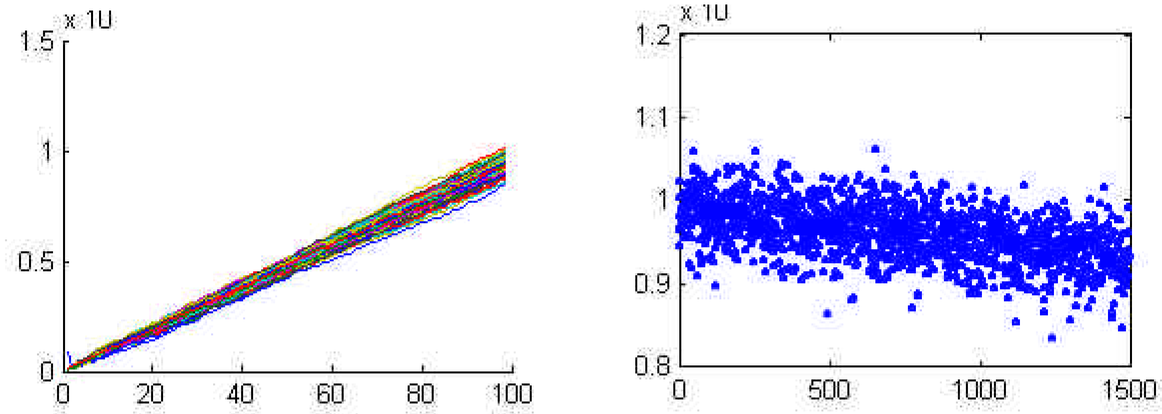


Fig 6 Ray bending by density variations.



(a) (b)

Fig 7 (a) Path of sound beam deflected by fluid velocity and density fluctuations.
(b) Corresponding beam arrival position. (arbitrary scales).

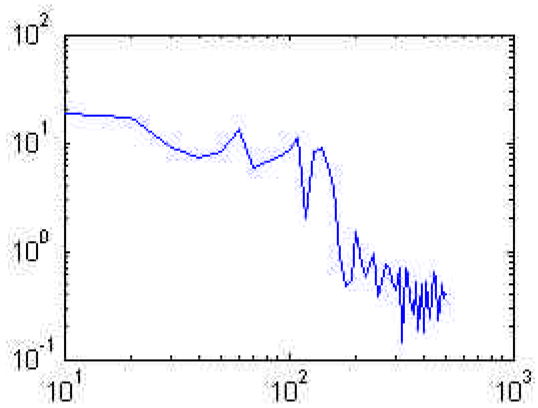


Fig 8 Frequency spectrum of received signal- a result of changes in the received beam intensity for v=1m/s. (arbitrary scales).

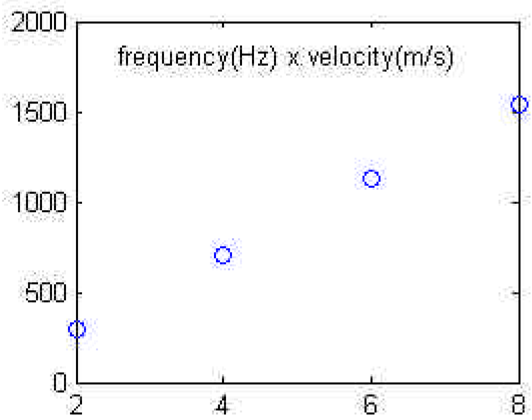


Fig 9 Variation with frequency content (Hz) with flow velocities (m/s) as calculated using the sound beam model.