Effect of second phase on single phase flow meters in steam quality measurement

Mongkol Pusayatanont[1] and Peter J. Unsworth[2]
[1]School of Engineering, Ubonratchatani University, Warinchamrap, Ubonratchatani, Thailand, 34190
[2]School of Science and Engineering, University of Sussex, Brighton, United Kingdom BN1 9QT

This paper presents results from an investigation of the two phase flow, especially liquid in gas phase, in most mainly used flow meter in steam industry namely differential pressure meter is investigated. As in general, a flowmeter is designed and employed to measure flow rate of single phase fluid. There are many types of meter available in the market characterize by their working principles, installed conditions and measured fluid. All meters represent their accuracies under the single phase flow condition. However, when they are working in unusual conditions especially under multiphase flow, most meters lose their accuracies significantly even there is small amount of second phase introduced into the system. To understand the deteriorated performance of the meter under two phase flow, additional study on the effect the second phase on the meter is required.

The laboratory experiment is set up to simulate the wet steam by flowing compressed air in the 2 inch pipe. Water droplet is generated by pressurized water flowing through a nozzle and then spayed into the system in range of 25% maximum by mass fraction. The signal from each flowmeter is collected by digital computer and analyzed using FFT and power spectrum density. The results show that the presence of the second phase in the system causes high frequency fluctuation and causes significant error on meter reading. Flow manufacturers always add low-pass filter circuit to remove this high frequency signal, however, this paper shows that the high frequency signal in specific region is useful as it can be use to estimated the percentage of the second phase in the main phase system.

1. INTRODUCTION

Steam referred to vaporized water known as working fluid is widely used in many process applications. When water is heated in a boiler, it begins to absorb energy. Depending on the pressure in the boiler, the water will evaporate at a certain temperature to form steam. The steam contains a large quantity of stored energy which can hold five or six times as much potential energy as an equivalent mass of water. Steam is one of the most widely used media to convey heat over distances. Because steam flows in response to the pressure drop along the line, then expensive circulating pumps are not needed. Due to the high heat content of steam, only relatively small bore pipework is required to distribute the steam at high pressure. The pressure is then reduced at the point of use, if necessary. This arrangement makes installation easier and less expensive than for some other heat transfer fluids. It can be generated at high pressures to give high steam temperatures. The higher the pressure, the higher the temperature. More heat energy is contained within high temperature steam so its potential to do work is greater. Steam carries energy in term of heat and may be converted to other energy forms i.e. mechanical form in power plant. Steam can be classified to 3 main groups, i.e. wet steam, dry saturated steam and super heat steam. Many applications use dry saturated steam to transfer energy from one to another location mainly by insulated pipes. However, in real condition, temperature loss due to non ideal pipe insulation as well as pressure loss due to bents, elbows and values cause steam vapor condensed back to water droplet and loss its carrying energy. Steam quality is used to indicate the quality of steam at certain point of the process where it is measured by amount of saturated steam that coexists with its condensate in a given system. Calculate it by dividing the mass of steam by the total mass of steam and condensate the mass ratio of condensate by saturates steam. If the water content in steam is 5% by mass, then the steam is said to be 95% dry and has a dryness fraction of 0.95 or 95% steam quality.

Historically, calorimeters have been used in steam quality measurement but their slow response and range ability limit their in many applications. Optical technique [1,2] is an alternative technology available in steam quality measurement. Its principle of operation is to compare the intensity of light passed though a flow of wet steam containing water droplets in suspension to the intensity of light passed through a flow of dry steam. Offline technique [3] is also available by sampling steam sampled from live line process and separated water content from steam then calculated its quality. However, those methods are complicated, time consuming and expensive. In contrast, this work presents the straightforward technique to measure quality of steam by using the signal available from a conventional flowmeter installed in the process then applying signal analysis technique to discover the relation between high frequency fluctuation and percentage of water droplet in the pipe [4].

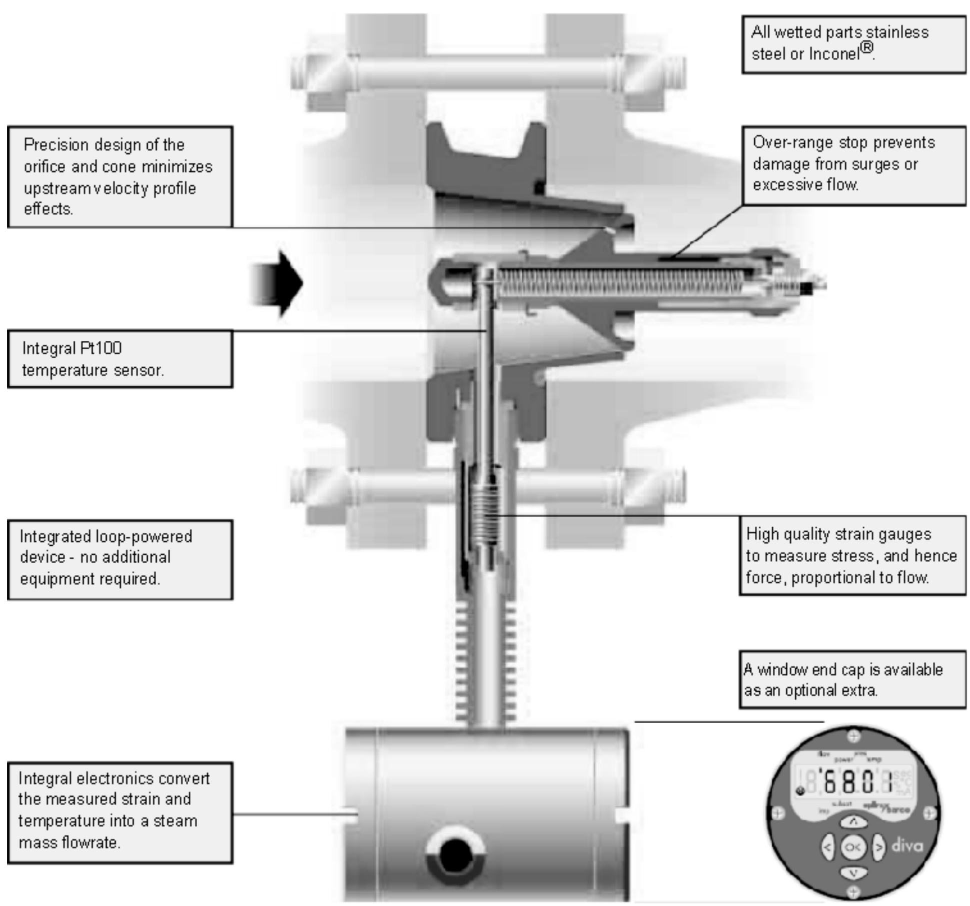


Figure 1 Variable area meter.

2. SPRING LOAD VARIABLE AREA FLOW METER

There are many types of flow meters available in market to measure volume or mass flow rate of steam. They are different in their operating principles and designs. Orifice meter is dominant in most applications because it exhibits good accuracy over wide range of operation, easy to use, no moving part but it has square law relation which limits its turn down ratio. In order to overcome this restriction, spring load plug is added into the orifice bore that it can move forward when fluid flows through the meter as shown in Figure 1. Historically, differential pressure sensor is placed across inlet and outlet of the meter to measure pressure difference and used to calculate volumetric flow rate by Bernoulli's equation. Meter manufacturers claim that their meters have 1:100 turn down ratio comparing with 1:10 from orifice or other differential pressure meter types. The new design is also available by adding strain gauge on meter (see Figure 1). The displacement of spring besides output of strain gauge has linear relation with steam volume flow rate. In order to measure steam mass flow rate, line pressure in pipe is also measured then use microprocessor in the meter to calculate steam mass flow rate.

3. SPECTRUM ESTIMATION AND SIGNAL AMPLITUDE

The plots in frequency domain of amplitude versus frequency are commonly known as amplitude spectrum. If the signal is a voltage waveform plotted against time, the amplitudes of its Fourier transform will have the dimension V/Hz, while the square of the Fourier transform amplitude gives the energy spectral density of the voltage waveform in V^2/Hz. The term "spectrum" is often referred to the plot of the energy spectral density versus frequency. The calculated signal energy is an estimated value because of the finite duration of data sequence of signal whist the true signal energy is calculated over infinite time period ($-\infty$ to $+\infty$). The total signal energy of a signal $x(t)$ can be expressed as

$$S_{xx}(t) = \int_{-\infty}^{\infty} \left| x(t) \right|^2 dt < \infty \tag{1}$$

Parseval's theorem states that

$$S_{xx}(t) = \int_{-\infty}^{\infty} \left| x(t) \right|^2 dt = \int_{-\infty}^{\infty} \left| X(f) \right|^2 dF \tag{2}$$

and the estimation of energy spectral density of discrete signal $x(n)$ is

$$E[S_{xx}(n)] = \sum_{-\infty}^{\infty} x(n)^2 \tag{3}$$

when $S_{xx}(t)$ = Energy spectral density of $x(t)$, $E[S_{xx}(n)]$ = Energy spectral density estimated of $x(n)$, $x(t)$ = Continuous time signal, $x(n)$ = Discrete signal of $x(t)$, $X(f)$ = Fourier transform of $x(t)$.

The quantity $|X(f)|^2$ represents the distribution of signal energy as a function of frequency and is therefore called the *energy density spectrum* of the signal. Hence integration of $|X(f)|^2$ over all frequencies up to f gives total signal energy or total area under $|X(f)|^2$. Power spectrum energy (signal power) in a specific frequency range is calculated by

$$E\left|S'_{xx}\right| = \frac{\sum_{i=n_1}^{n_2}\left(X_i(f)\right)^2}{N_x} \tag{4}$$

where $E\left|S'_{xx}\right|$ = Energy spectral density estimated of $x(n)$ at specific frequency range, n_1 = number of first bin of the beginning frequency, n_2 = number of last bin of the ending frequency, $N_x = n_2 - n_1$. n_1 and n_2 are the beginning and ending frequency in specific range divides by frequency resolution, respectively where frequency resolution is sampling frequency divides by number of FFT, for example the selected frequency range is 60–250 Hz sampled at 10 kHz with 65536 data points then frequency resolution is 0.1526 Hz/bin and $n_1 = 393^{th}$, $n_2 = 1638^{th}$. Equation 3 clearly shows that signal amplitude in specific range can be calculated directly by taking square root of power spectrum energy estimation in that specific range.

4. EXPERIMENTAL SETUP AND RESULTS

The experiment was carried in laboratory at University of Sussex, UK. A spring load variable area meter was tested under simulated steam flow condition in 2-inch pipeline. Steam flow was simulated by flowing compress air at high velocity in main pipe then water at room temperature was injected into simulated steam flow at 100D upstream of the test meter. Air mass flow rate is calculated by measuring volume flow rate by vortex flowmeter, line pressure and temperature simultaneously while water mass flow rate was measured by a coriolis meter with accuracy better than ±0.1% FSD therefore simulated steam quality can be calculated by equation (1).

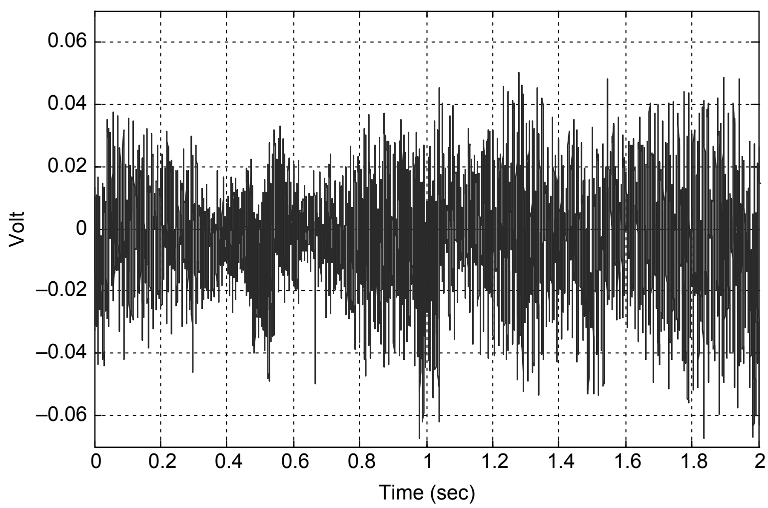
$$\text{Steam Quality} = \frac{S}{S+W} \cdot 100\% \tag{5}$$

where S = Steam mass flow rate, W = Injected water mass flow rate.

In the experiment, differential pressure between upstream and downstream of the meter is recorded by data acquisition system. The current signal has to be converted into a proportional voltage by 500 ohm resistor. This converts 4 to 20 mA signal into a voltage in the range 2 to 10 VDC. A second order high pass filter is used to remove low frequency components and amplify the high frequency signal with gain of 50 to ±5 V range. In order to achieve the widest frequency response from pressure transducer, a special transducer with high frequency response must be chosen.

Figure 2a shows signal of differential pressure sampled at 10 kS/sec while the signal amplitude fluctuation represents spring vibration inside the meter. Using FFT analysis, it reveals two main resonant frequencies from spring at 125 Hz and 190 Hz, respectively as shown in Figure 2b. When steam contains water droplet one can imagine that water droplet will flow along the bottom of pipe and then be mixed with saturated steam at the meter body. At this point, the momentum of fluid is suddenly change causing spring plug moves forth and back then generates high frequency fluctuation which can be detected by pressure transducer, the higher condensate fraction, the higher fluctuation occurs. The experiment were started by setting air flow at a constant rate i.e. 600 kg/hr then water was injected at different rates i.e. 150, 300, 500, 800 and 1000 g/min. Then steam flow rate was changed to the new rate i.e. 400 kg/hr and 200 kg/hr and repeated the test procedure again with the new series of injected water to cover meter operating ranges. The results from FFT shows that the amplitude of sensor signal in a specific frequency range (60–250 Hz) increases proportionally to water injected mass flow rate. The power spectrum of sensor signals in 60 to 250 Hz region are calculated in logarithmic scale using equation (4) and plotted in Figure 3 against water mass fraction.

Using linear regression method to fit all data of each water fraction at different steam flow rate and then calculate percentage of water mass fraction comparing with actual value. The results show that the calculated values are pretty well aligning on the actual line with average 1.6% rms error.



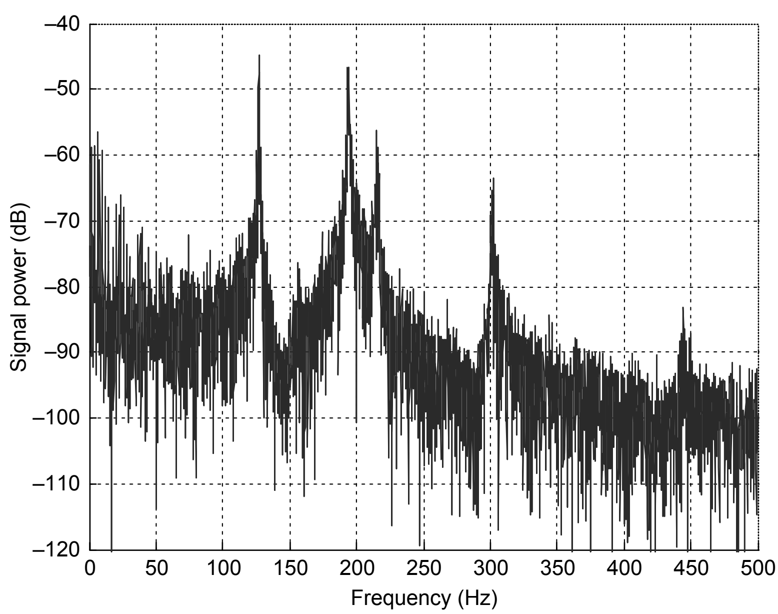


Figure 2a Signal from strain gauge. Figure 2b Power spectrum.

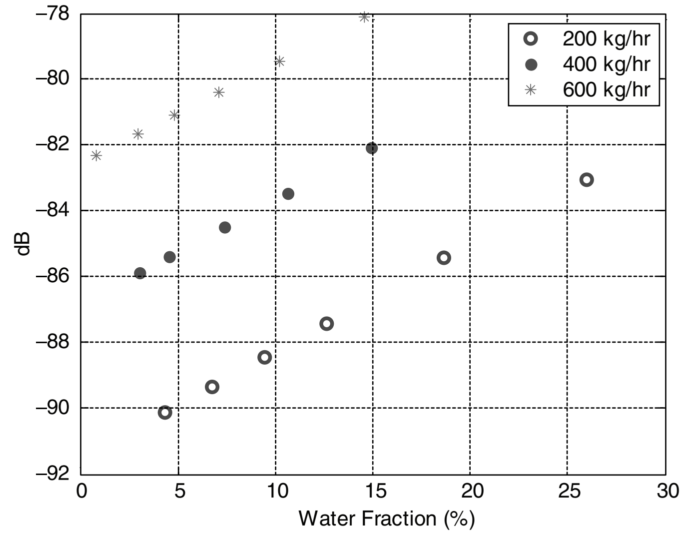


Figure 3 Power spectrum density versus water fraction at 600,400 and 200 kg/hr.

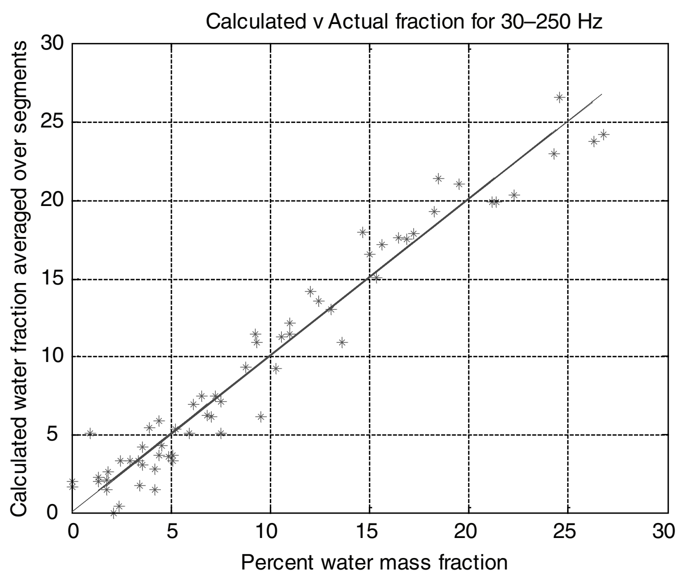


Figure 4 Fitted water fraction with actual value shown average 1.6 % rms error.

5. CONCLUSIONS

This work presents the information which is embedded in sensor signal of flowmeter to extend its typical performance to measure steam quality. A spring load variable area meter mainly used to measure steam flow rate was studied and the results shows that frequency signal in specific range has systematic relationship with water condensed fraction which can described by basic linear regression equation. In order to obtain the high frequency signal from sensor, the frequency response bandwidth of instrument must be considered as well as signal conditioning circuit may be added. The further work can will be carry on investigation of high frequency fluctuation on the signal and improve the measurement accuracy. The microcontroller can be added on top of the existing electronic circuit to provide the steam quality information.

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