THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE XIV MECHANICHAL ENGINEERING, ISSN 1224-5615
2012

OPTIMIZATION OF ULTRASONIC FLOW METERS FOR CRUDE OIL METERING AND EXPORT

Isaac Kuma YEBOAH
Engineering Department, Regent University College of Science and Technology, P.O. Box 4199, G.P. Accra, GHANA
Isaackyeboah77@yahoo.co.uk
Assistant Prof. Florin NEDELCUŢ, Ph.D.Eng,
MECMET Research Centre,
"Dunărea de Jos" University of Galaţi,
Engineering Faculty Brăila, ROMÂNIA
Florin.Nedelcut@ugal.ro

ABSTRACT

Ultrasonic flow meters, as all velocity or inference type devices, require an adequate flow stream conditioning in order to assure an accurate performance. Typical flow conditioning consists of straightening the upstream and downstream of the measuring section. The upstream section usually contains a tube bundle, which allows the upstream section to be reduced in length. This tube bundle serves to eliminate any swirl in the flow stream before reaching the meter, presenting a symmetrical velocity profile to the turbine rotor. Some ultrasonic flow meters may produce a non-uniform pulse output, which can prove a wide span of repeatability. For such cases where is a need to correct the velocity flow profiles which affect the robustness of the integration method, this research work tries to develop a mathematical modeling and simulation in MATLAB and Microsoft Excel, with the purpose to combine the individual acoustic path measurements into a full volumetric flow rate measurement procedure. The relationship between velocity and viscosity, using Reynolds Number, was calculated in Microsoft Excel. The Nusselt Number was then used to plot fluid mean temperature and wall temperature diagrams in Microsoft Excel.

Keywords: Reynolds, Nusselt, Ultrasonic meters, Velocity profile, MATLAB, Microsoft Excel, CFD

1. INTRODUCTION

Flow assurance is recognized as extremely important for the transportation of hydrocarbon fluids, since failures can be extremely costly to fix and can cause safety issues. In particular, flow assurance is vital for multiphase flows of oil, gas and water mixtures. The design, modeling and testing of subsea multiphase sampling systems has been crucial to eliminate the risk of failure to collect a sample. This failure can itself be caused by flow assurance problems such as blockages or formation of waxes and hydrates caused by temperature and pressure changes [3].

Crude oil measurement unlike refined products defines a wide range of applications from light condensates with a viscosity of less than 5.10^{-5} Pa.s to heavy crude oils over 2 Pa.s. The quality of the crude oil, that is the amount and type of containments, also varies widely [6]. Viscosity can be expressed in many different units; kinematic viscosity that is expressed in m^2/s is the most suitable for the purposes of this article.

Crude oil is normally defined by its API gravity, which is sometimes mistaken for the product's viscosity. API gravity is defined as the density of crude oil at a specific temperature compared to the density of water at a standard temperature of 15^0C. The temperature's effect for medium and heavy crude oils can significantly change a meter's performance due to the considerable change in viscosity. For this reason, it is important when evaluating any meter application that the viscosity of each product must be specified over the operating temperature range [9].

The operating principle of ultrasonic meters is the volume throughput (Q) equal to the fluid velocity measured (V_m) multiplied by the area (A). The measurement principle is simple as shown in Fig. 1 and Fig. 2 below, but there are a number of factors that must be addressed to achieve the desired custody transfer measurement accuracy [7].

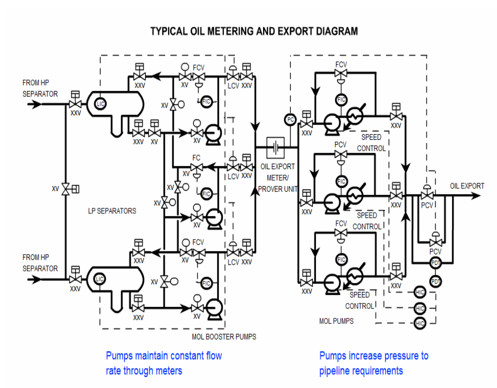

Fig. 1 Typical oil metering and export diagram

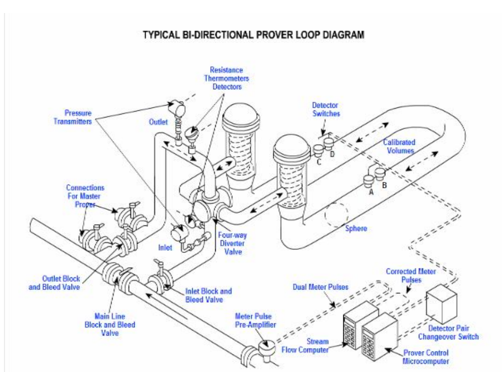

Fig. 2 Typical oil metering and export 3D diagram

2. INFLUENCE OF FLUID PROPERTIES ON PERFORMANCE

Among the four more used types of meters (positive displacement (PD), turbine, Coriolis and ultrasonic meters) some of them are more or less sensitive to fluid properties. For the ultrasonic meters, subject of this research, the influence of fluid properties on the measuring performance is one of the most reduced. In any case, to achieve the level of precision measurement available with other metering technologies, the possible effects must be addressed. This is especially important with crude oil measurement as the oil may be very viscous when it is affected by a high level of contamination. On a qualitative level, various authors have addressed the influences of fluid properties on positive displacement and turbine meters. Knowledge of the quantities effects of fluid properties on ultrasonic meter accuracy is still limited [6]. The influence of fluid properties on the ultrasonic flow meters performance may be classified in two main groups.

1. Signal quality affects the signal attenuation and signal to noise ratio (SNR) in the acoustic paths. These are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6, for wide and single beam technologies.

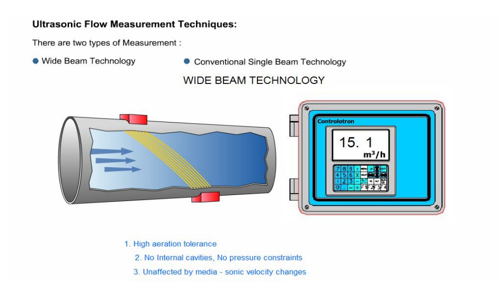

Fig. 3 Wide beam technology flow measurement

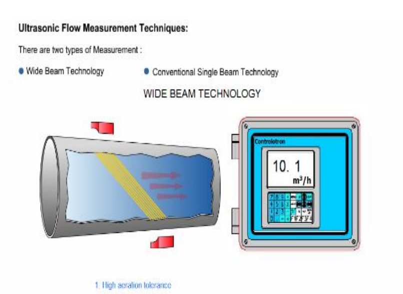

Fig. 4 Wide beam technology flow measurement

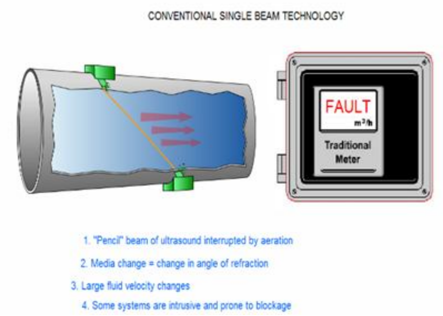

Fig. 5 Single beam technology flow measurement

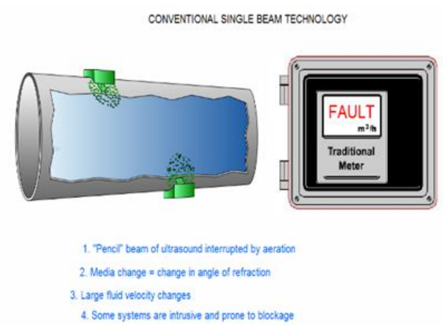

Fig. 6 Single beam technology flow measurement

The signal quality of the ultrasonic meter in crude oil application is determined by viscosity, entrained gas and wax content. The signal strength or more precisely, the signal to noise (SNR) is crucial for the accuracy of the transit time measurements made in the Liquid Ultrasonic Flow Meter (LUFM). Reduced SNR can mean higher uncertainty of the volumetric flow rate measurement. In the worst case, the signal cannot be discerned from the noise and the measured output is erroneous.

2. Flow profile affects the robustness of the integration method used to combine the individual acoustic path measurements into a full volumetric flow rate measurement. This is shown in Fig. 7 below.

Free gas in oil forms gas bubbles and causes excess sound attenuation due to the scattering of the sound waves by the bubbles and bubble resonances. The parameters that affect this coefficient are bubble size and distribution, the amount of free gas present in the oil, the pressure and temperature, the oil type and the LUFM operating frequency. Gas in oil is a highly complex condition that can have a profound effect on performance as shown above, in Fig. 5 and Fig. 6.

This paper will focus on the flow profile which affects the robustness of the integration method used to combine the individual acoustic path measurements into a full volumetric flow rate measurement in the liquid ultrasonic flow meter used in oil and gas measurement [1].

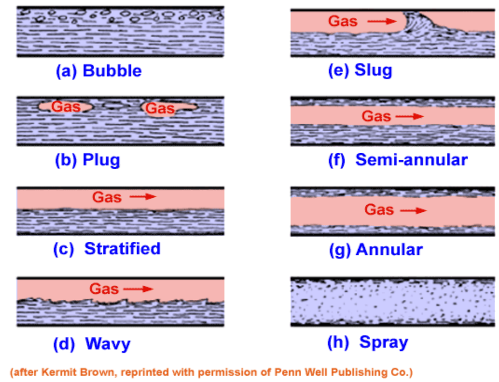

Fig. 7 Multiphase flow patterns in horizontal pipe.

To achieve the level of precision measurement available with other metering technologies, this research work will model and simulate the flow profile in MATLAB and Microsoft Excel, and then we will use these models to optimize the performance of ultrasonic flow maters.

3. MATHEMATICAL MODELLING

The principles of operation for the Liquid Ultrasonic Flow Meter (LUFM) are that a set of acoustic transducers transmit a high frequency acoustic pulse diagonally across the pipe. The transit time method measures the time intervals associated with transmission of this acoustic energy across the pipe in opposite directions. From these time measurements a flow rate can be calculated as shown in the equations below:

$$T_U = \frac{L_p}{C - V_P} \tag{1}$$

$$T_d = \frac{L_p}{C + V_p} \tag{2}$$

From these time measurements, volume can be calculated from the following equation:

$$V = \frac{L_p \times (T_u - T_d)}{2 \times T_d \times T_u \times Cos\phi} \tag{3}$$

where: T_u = Upstream transit time, T_d = Downstream transit time, L_p = Path length, C =

Speed of sound in the fluid, V_p = Flow velocity along path length, V = Flow velocity along the pipe axis and ϕ = Angle the acoustic path makes with pipe axis.

The continuity, the horizontal (x) momentum and the energy equations used to model an incompressible fluid in boundary layer form and allowing for variable transport properties are [5]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{4}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=u_e\frac{du_e}{dx}+\frac{\partial}{\partial y}\left(v+\varepsilon_m\right)\frac{\partial u}{\partial y} \tag{5}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}\left(\alpha+\varepsilon_t\right)\frac{\partial T}{\partial y} \tag{6}$$

The Bernoulli's equation was used to replace the pressure term in the horizontal (x) momentum in equation (5) which is first term on right hand side. The variable u_e represents the free stream velocity and could be a function of x, if for instance there were a free stream pressure gradient. That capability is not exercised here; for all cases $u_e = U_\infty$, the free stream velocity, and is taken as a constant. Similarly, the fluid transport properties (thermal diffusivity and kinematic viscosity) are taken as constants. The quantities ε_m and ε_t are the eddy diffusivities of momentum and heat, respectively; both are considered to be zero for laminar flows. Reynolds Number is the ratio of the flow rate to the ultrasonic flow meter size and the viscosity; it can be used to determine if flow is laminar, transient or turbulent.

For turbulent flows the dependent variable including u and v, the two velocity components and temperature (T) in Equation (6) are all understood to be time-averaged value and the eddy diffusivities will be modeled. The transformed versions of Equations (4)-(6) must be converted from PDE's into the algebraic equations that a computer can solve. There are several methods available for discretizing the transformed equivalents to the parabolic equation (5) and (6); we have chosen to implement the Crank-Nicholson scheme.

This algorithm involves solving a tridiagonal system for the horizontal velocity (u) at a particular stream wise station. Then the discretized transformed equivalent to Equation (4) is marched out from the wall to the free stream to determine the vertical velocity. The transition to turbulence is based on a model given by White based on the work of van Driest and Blumer [2]:

$$Re_{x,tr}^{1/2}=\frac{-1.0+(132500T^2)^{1/2}}{39.2T^2} \tag{7}$$

In this equation only, and consistent with above mentioned White's notation, the symbol T represents the free stream turbulence level expressed as a percentage. For 1% free stream turbulence, this expression yields $Re_{x,tr}$ = 500000, a value commonly used in heat transfer for laminar-turbulent transition according [8], [1].

4. SIMULATION RESULTS

All the simulation presented here for 5 different viscosities, were performed in MATLAB, for 5 significant values of the Prandtl number.

The graph below (Fig. 8) shows a simulation of a four path arrangement for velocity profile correction adequate for light oil, i.e. with specific gravity of 0.81, sound velocity of 1345 m/s, viscosity of 4.10-6 m^2/s and sound absorption coefficient at 1MHz of 0.043 dB/cm.

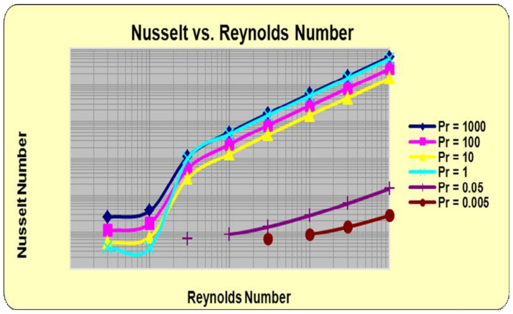

Fig. 8 Internal Flow Correlation for Light oil viscosity at 20^0C

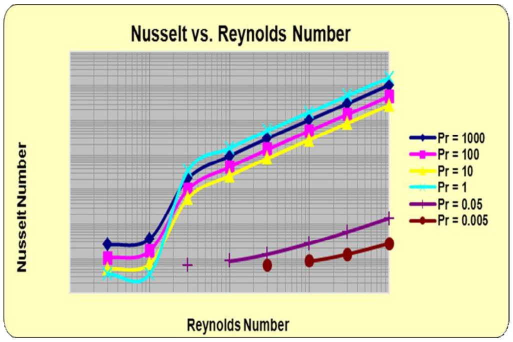

Fig. 9 Internal Flow Correlation for Medium oil viscosity at 200C

The graph in Fig. 9 above shows a simulation of a four path arrangement for velocity profile correction for Medium oil, with a specific gravity of 0.85, sound velocity of 1399 m/s, viscosity of 14.10^{-6} m^2/s and sound absorption coefficient at 1MHz of 0.18 dB/in.

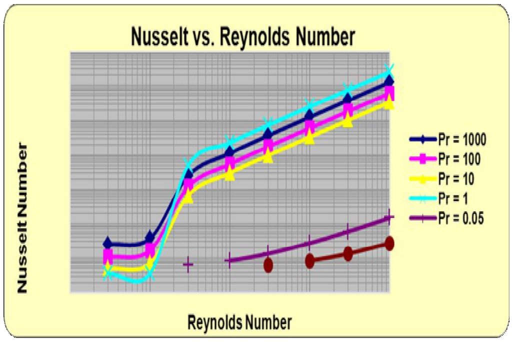

Fig. 10 Internal Flow Correlation for Brad Penn oil viscosity at 20^0C

The graph in Fig. 10 above shows a simulation of a four path arrangement for velocity profile correction for Brad Penn oil, with specific gravity of 0.86, sound velocity of 1419 m/s, viscosity of 20.10^{-6} m^2/s and sound absorption coefficient at 1MHz of 0.10 dB/in.

The graph in Fig. 11 below shows a simulation of four path arrangement for velocity profile correction for Heavy oil, with specific gravity of 0.87, sound velocity of 1439 m/s, viscosity of 55.10^{-6} m^2/s and sound absorption coefficient at 1MHz of 0.23 dB/in.

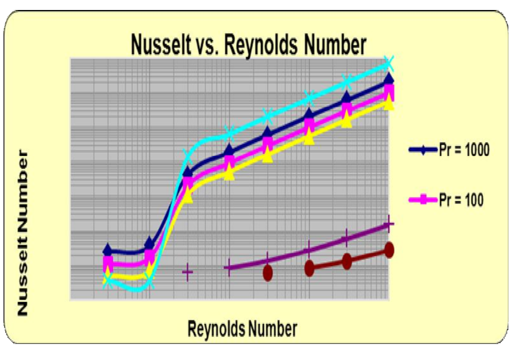

Fig. 11 Internal Flow Correlation for Heavy oil viscosity at 20^0C

The graph in Fig. 12 shows a simulation of four path arrangements for velocity profile correction of Extra heavy oil, with a specific gravity of 0.88, sound velocity of 1477 m/s, viscosity of 337.10^{-6} m^2/s and sound absorption coefficient at 1MHz of 1.14 dB/in.

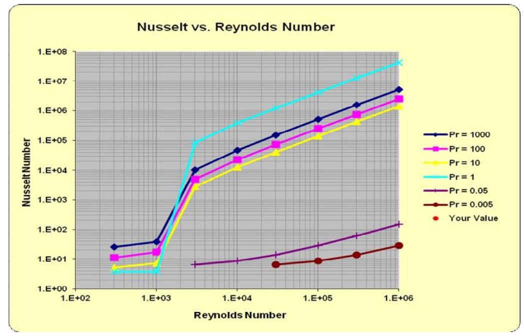

Fig. 12 Internal Flow Correlation for Extra heavy oil at 20^0C

The graph in Fig. 13 below shows an optimized performance range of a multi path ultrasonic meter, using velocity from four chordal paths, with velocity profile correction to accurately determine the average velocity over the complete flow and viscosity range.

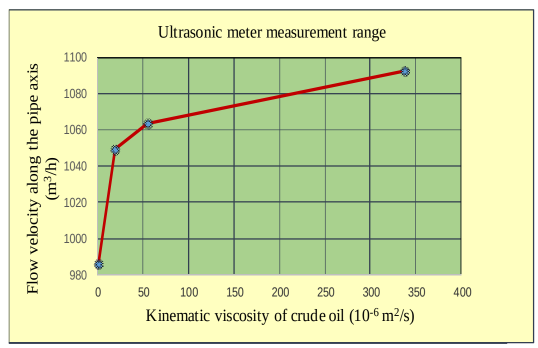

Fig. 13 Optimized Performance of Liquid Ultrasonic Meter Measurement Range

Metering systems can also have valves, strainers, elbows, tees, and header upstream of the meter. These elements can distort the flow profile and introduce swirl and cross flow upstream of the meter. Since measuring velocity, any change created by these elements will affect the measurement accuracy. Removal of cross flow and swirl is essential for accurate measurement using the technology of velocity profile correction described above.

Free gas in oil, in the form of gas bubbles, causes excess sound attenuation, due to scattering of the sound waves by the bubbles and bubble resonances. This adsorption is presented (for oil and water samples) in Table 1. Flow conditions are used to minimize these effects, but a robust integration method with cross flow compensation is also important to optimize performance.

Table 1: Sound adsorption coefficient for water and oil samples (Data at 20 ^{0}C)

Sample	Specific gravity	Sound velocity (m/s)	Viscosity $.10^{-6}$ (m^2/s)	Sound absorption coefficient (dB/cm)
Water - distilled	1.00	1477	1.004	
Light oil	0.81	1345	4	0.043
Medium oil	0.85	1399	14	0.071
Brad Penn oil	0.86	1419	20	0.039
Heavy oil	0.87	1439	55	0.091
Extra heavy oil	0.88	1477	337	0.449

5. CONCLUSIONS

This research work has shown the optimization of liquid ultrasonic flow meter through modeling and simulation, using the Reynolds and Nusselt number.

The result shows that for laminar flow (Poiseuille flow) the velocity profile is parabolic and in the case of higher Reynolds numbers the profile seems to flatten out, as expected.

For low viscosity products, the velocity profile is flat and the flow velocity is nearly constant all over the flow area, except for the region near the pipe wall. Therefore the average stream velocity can be measured at any point except near the pipe wall.

After a very short thermal developed length, the wall temperature also increases linearly, indicating a fully developed and constant heat transfer coefficient.

The graphs above show simulations of the optimized performance liquid ultrasonic meter for crude oil which has the key characteristics of the following:

1. A multipath meter with an integration method of velocity profile correction, to improve performance on high viscosity low Reynolds Numbers applications.
2. Robustness in correcting asymmetric axial flow velocity profiles.
3. Compensation transverse flow components.

Techniques such as velocity profile correction and accurate measurement at the lower flow range was achieved, as shown in the simulations. The types of oil samples which were considered are Light oil, Medium oil, Brad Penn, Heavy oil and Extra heavy oil, each at temperatures of 20^{0}C. These ranges from Reynolds number less than 2000, with high viscosity and laminar flow, to Reynolds number greater than 6000, with low viscosity and turbulent flow.

Hence it can be concluded that such a meter can be used for the accurate measurement of all types of crude oil mentioned above in the petroleum industry, for a wide range of applications.

REFERENCES

[1] **Chang Wang, Blair Perot**, *Prediction of turbulent transition in boundary layers using the turbulent potential model*, Journal of Turbulence, Volume 3, Issue 1, 2002, pp. 022

[2] **Don. Augenstein**, *Proving Liquid Ultrasonic Flow Meters*, Caldon Inc, 2007.

[3] **Emmely Graham**, *Meters, Sampling Critical for Effective Multiphase Flow Management*, PennWell Offshore, February 2012, pp.76-78.

[4] **John K. Vennard, Robert L. Street**, *Elementary Fluid Mechanics Sixth Edition*, John Wiley and Sons, 1982, pp. 357-369.

[5] **Peter P. Jakubenas**, *Measuring High Viscosity Liquids with Flow Meters*, FMC Technologies Measurement Solutions, 2007.

[6] **Peter W. Kosewicz**, *Fundamentals of Liquid Measurement III - Dynamic*, The University of Texas - PETEX, 2000.

[7] **Raymond J. Kalivoda**, *Understanding the limits of ultrasonic meters*, Hydrocarbon Engineering, Vol.17, No.1, January 2012, pp. 69 - 74.

[8] **Robert J. Ribando**, *Heat Transfer Tools*, McGraw-Hill Higher Education, 2002, pp. 46-55.

[9] **T. Cousins, D. Augenstein**, *Proving of Multi-Path Liquid Ultrasonic Flowmeters*, 20th NSFMW, 2002.