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Well Output Measurement Using the Dual Differential Pressure Method

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ABSTRACT

In 2019 Landsvirkjun, in cooperation with academic and industrial partners, launched a project geared towards finding a practical method for measuring well output in real-time. A full-size production line was assembled and connected to wells that allowed the testing of several different potential measurement methods at a wide range of realistic flow conditions.

In this paper the experiment, conducted in conjunction with Tek DPro Flow Solutions, is described along with its main conclusions with regards to the orifice meter dual differential pressure (DDP) method. The DDP method is very practical as it is based on a standard setup for differential pressure measured across an orifice plate (commonly installed at geothermal wells), with an added pressure port further downstream of the orifice plate. Using the signals from these three pressure ports, our results indicate, one can determine the steam quality, steam, water, and total flow with reasonable accuracy. The observed correlation applies for a wide range of flow conditions commonly occurring in high-enthalpy geothermal fields. Once the steam quality has been determined the total flow and enthalpy can be computed based on previously known formulations.

1. INTRODUCTION

The natural gas production industry started two-phase flow metering R&D in the 1990s. Both saturated steam and wet natural gas flows are two-phase flow metering challenges. Hence, initial wet natural gas flow metering research incorporated the existing published saturated steam metering methodologies of the nuclear and geothermal industries. The subsequent hydrocarbon industry two-phase flow metering research diverged from the other industries but the resulting new metering technologies did not seem to generally permeate back to, or be adopted by, other industries. There is often a lack of communication and idea transfer between independent industries. However, the hydrocarbon production industry has developed flow metering technology which could potentially benefit other industries, including the geothermal industry, if only the knowledge transfer was there.

Fig 1. Theistareykir Test Site Location

Fig 2. Orifice Meter Saturated Steam Flow Test.

Landsvirkjun approached Tek DPro Flow Solutions (TDFS) to field test wet natural gas orifice meter technology with geothermal field saturated steam flows (see Figs 1 and 2). This paper discusses the results of this project. Trends and comparisons of wet natural gas and wet saturated steam orifice meter performances are shown. The results show that the geothermal industry could benefit from utilizing the hydrocarbon industry methods and correlation forms.

2 LANDSVIRKJUN'S THEISTAREYKIR GEOTHERMAL POWER STATION

Landsvirkjun is the National Power Company of Iceland. Landsvirkjun strives to improve the efficiency of its geothermal power stations, and as such conducted saturated wet steam flow meter R&D between 2020 and 2021.

The Theistareykir geothermal power station (Fig 3) is supplied steam from multiple geothermal wells. It's advantageous to have reliable live saturated steam flow metering on each individual well's pipeline. Most wells are open hole with two or more feed zones. The flow's enthalpy changes as the well head pressure (WHP) and well state changes. The ability to meter wet saturated steam flow in real time, and survey well output curves every few months, would optimize control and efficiency of the well. The 'well output curves' are the WHP vs. water and steam flow curves, or the WHP vs. total flow and enthalpy curves. Such control allows the choice between maximizing revenue, minimizing fluid extraction, minimizing CO_2 or Non-Condensable Gas extraction, minimizing pressure loss etc., while keeping WHP above the level required to avoid scaling, and in Iceland at least, providing the required quantity of brine for the local natural baths (see Fig 4). However, presently the saturated steam flow is not truly metered live. Water flow is read by tracer dilution spot checks 1-4 times annually. Steam flow can then be predicted by using the resultant water flow prediction with saturated steam meter correlations.

Fig 3. Theistareykir Power Station.

Fig 4. Icelandic Geothermal Natural Bath.

Landsvirkjun staff read various wet natural gas orifice meter technical papers that described metering techniques different than were typically used by the geothermal industry. Landsvirkjun then invited Tek DPro Flow Solutions to supply such wet natural gas orifice meter equipment, and take part in geothermal plant wet saturated steam flow meter tests between 2020 and 2021.

3 GEOTHERMAL POWER STATION ORIFICE METER FIELD TESTS

There were three sets of Landsvirkjun orifice meter saturated steam field tests:

Test 1: 5th thru 9th July 2021, 14" 0.7β orifice meter
Test 2: 5th thru 9th July 2021, 10" 0.7β orifice meter
Test 3: 1st thru 9th September 2021, 14" 0.48β orifice meter

TDFS supplied Autrol pressure, temperature, and DP transmitters, and a TDFS field mount flow computer capable of wet natural gas flow orifice meter algorithms (e.g. see Fig.9). With the tests being R&D, the massed logged data was also analyzed off-line.

Fig 5 shows a Theistareykir geothermal steam well supplying an orifice meter under test. Fig 6 shows inside the well head enclosure. Fig 7 shows a well plaque. Fig 9 shows the saturated steam pipe with flow from right to left, with the orifice flange union meter under test in the foreground, and the atmospheric saturated steam separator (aka the 'silencer') venting steam to atmosphere in the background. Fig 8 shows the separator steam outlet to atmosphere inclusive of an insertion vortex meter reference meter.

Fig 10 shows a detailed view of the separator. The water flow reference metering system consisted of a magnetic flowmeter and weir installed in series on the water outlet. The reference water flow uncertainty was 1%. The steam reference was more challenging. Landsvirkjun used a James Lip Pressure Device as the primary steam flow reference. The steam flow reference uncertainty is 3%. An insertion vortex meter was installed as a check meter three quarters of the way up the separator's steam stack, see Figs 8 and 10, but scale deposits on this device was an issue.

Fig 11 shows the water flow reference meter system. All test data used had good agreement between the magnetic meter and weir. Fig 12 shows a James Lip Pressure pipe after being uninstalled. Note the pressure port at the exit (i.e. 'lip'). Fig 13 shows the 14", 0.48β orifice meter under test with the TDFS supplied flow computer, Autrol inlet pressure transmitter, and three Autrol DP transmitters reading primary, recovered, and PPL DPs. Flow is from left to right. All orifice meters tested were orifice flange union designs with D and D/2 pressure taps. All orifice meters had the inlet pressure, primary, recovered, and PPL DPs, and downstream temperature read.

The flow was controlled by varying valve settings giving different steam qualities (e.g. see Fig 14). As is normal for field tests, 'steady' flow points were in practice pseudo-steady, and hence individual data points are the average of long data logging periods. There was significant scatter between second by second points, but they averaged to give good repeatable results. During Test 3 single phase steam flow data was recorded, which allowed the baseline testing of the orifice meter diagnostics system 'Prognosis'.

The Theistareykir geothermal power station is rated to 100MW. The series of geothermal wells drilled to assure 100MW at commissioning were found to produce 115 MW, meaning there was a 15 MW excess. With surplus steam supply Landsvirkjun is able to dedicate an individual Theistareykir well to equipment field testing without compromising the station's 100 MW power output. Between 2020 and 2021 summer test seasons Landvirkjun conducted three orifice meter saturated steam flow field tests using various wells at the Theistareykir power station.

Fig 5. Orifice Meter Downstream of Well Head.

Fig 6. Inside Well Head Enclosure.

Fig 7. Test 3's Well Head Plaque.

Fig 8. Separator Steam Outlet

Fig 9. Orifice Meter Under Test with Saturated Steam Separator Downstream.

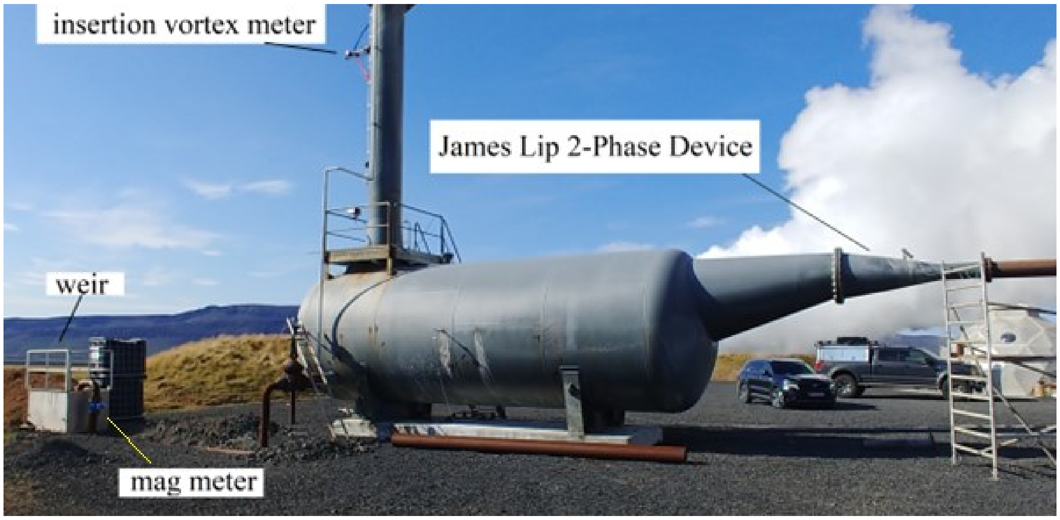

Fig 10. Atmospheric Separator (aka Silencer), with James Lip Pressure Two-Phase Device, Single Phase Steam Flow Vortex Meter, Water Magnetic Meter, and Weir.

Fig 11. Magnetic Meter and Weir Separator Discharge Reference Water Flow System.

Fig 12. James Lip Pressure Method Component Removed from System.

Fig 13. 14", 0.48β Orifice Meter with Instrumentation.

Fig 14. Flow Control Valve Upstream of Separator.

4 SATURATED STEAM AND WET GAS NATURAL GAS METERING TECHNOLOGY

Industries that utilize saturated steam flow tend to use 'quality' (aka 'dryness fraction') denoted as 'x' as a measure of water relative to steam. That is:

$$x = \frac{m_g}{m_l + m_g} \tag{1}$$

where m_g and m_l are the gas (i.e. steam) and liquid (i.e. water) mass flow rates respectively. The term 'saturated steam' represents the steam range $0 \leq x \leq 1$, ($0\% \leq x \leq 100\%$). Saturated steam is a two-phase flow, and metering two-phase flow is an order of magnitude more challenging than metering single phase flow.

A 'wet gas flow' is defined by the hydrocarbon production industry to be any two-phase (liquid and gas) flow where Lockhart-Martinelli parameter (X_{LM}) is less or equal to 0.3, i.e. $X_{LM} \leq 0.3$. The Lockhart-Martinelli parameter (equation 2) is a non-dimensional expression of the relative amount of liquid with the gas flow, where m_g and m_l are the gas and liquid mass flow rates, and ρ_g & ρ_l are the gas and liquid densities respectively. The Lockhart-Martinelli parameter, quality, and liquid to gas mass flow ratio (m_l / m_g) are related as shown in Equations 2 and 2a.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}} \tag{2}$$

$$x = \frac{1}{1+\left(\frac{m_l}{m_g}\right)} = \frac{1}{1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}} \qquad (2a)$$

For known fluid properties and set temperature, the gas to liquid density ratio (equation 3), is a non-dimensional expression of pressure. For known fluid properties and set temperature, the gas densiometric Froude numbers, Fr_g, (equation 4), is a non-dimensional expression of the gas flow rate, where g is the gravitational constant, D is the meter inlet diameter, and A is the meter inlet area.

$$DR = \frac{\rho_g}{\rho_l} \qquad (3)$$

$$Fr_g = \frac{m_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l-\rho_g)}} \qquad (4)$$

Liquid presence with the gas flow induces a positive bias on the orifice meter's gas mass flow prediction. This gas flowrate prediction is called the 'apparent' gas mass flow ($m_{g,apparent}$). The bias is called the 'over-reading', 'OR' (equation 5), sometimes described as a percentage ($OR\%$). Note that ΔP_{tp} and ΔP_g denote the read primary DP in the two-phase flow condition, and the DP that would have been read if the steam flowed alone, respectively. Correction of this over-reading is the basis for orifice meter 'wet gas corrections'.

$$OR = \frac{m_{g\,Apparent}}{m_g} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \qquad (5)$$

5 LIQUID DISPERSION: HORIZONTAL WET GAS FLOW PATTERNS

Gas flow meter reaction to the presence of liquids depends on the 'flow pattern', i.e. the liquid dispersion. The flow pattern is dictated by the balance of forces on the liquid.

For given liquid properties and liquid loading, low pressure and low gas velocity means low gas dynamic pressure, i.e. low energy gas flow, the liquid weight dominates, and the liquid flows like a river at the base of the pipe driven by the shear force of the gas flowing over it. This is called 'separated flow' or 'stratified' flow. For given liquid properties and liquid loading, high pressure and high gas velocity means high gas dynamic pressure, i.e. high energy gas flow, gas dynamic forces dominate, and the liquid tends to wet the wall but flow as entrained droplets. This is called 'annular', or 'annular mist', or 'homogenous' flow.

However, these are two ends of a spectrum. In reality flow conditions are usually such that the flow pattern is somewhere between these extremes. Fig 15 shows sketches of stratified and annular flow, and a still of a video looking upstream on air / water flow (lit by orange light) of a partially stratified / partially annular 'transitional' flow. Wet gas / saturated steam flow metering is the metering of gas and liquid flows in any such flow pattern. It is extremely challenging.

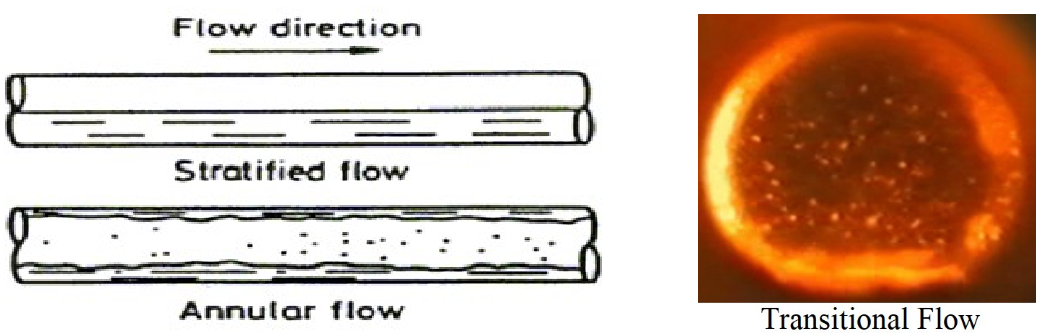

Fig 15. Horizontal Wet Gas Flow Patterns.

6 WET NATURAL GAS / SATURATED STEAM ORIFICE METER CONCEPTS

From the 1960s to early 1980's technical papers on orifice meter reaction to wet saturated steam flow were published, e.g. James [1], Chisholm [2,3] etc. By the 1990s the hydrocarbon production industry had started sporadic orifice meter wet natural gas flow metering R&D based on these steam industry publications. This hydrocarbon production industry R&D was released in the 2010s, i.e. Steven et al. [4], and ISO TR 11583 [5]. Meanwhile, sporadic geothermal industry saturated steam metering R&D continued, e.g. Zhang [6], Helbig et al [7], Campos et al [8], and Mubarok [9]. However, after the hydrocarbon industry's initial use of the steam industry's pre-1990 publications there is little evidence of any cross fertilization of ideas between the industries. The respective industry's subsequent research went down different paths.

6.1 The Geothermal Industry's Saturated Steam Orifice Meter Research

Saturated steam orifice meter correlations correct the 'over-reading', for a known quality or liquid mass flowrate. Taking Chisholm [2,3] as an example, the Chisholm saturated steam / wet gas orifice meter correlation is produced here as equation set 6 and 7.

The gas (ρ_g) and liquid (ρ_l) densities are known from the 'steam tables'. The Chisholm exponent 'C' is calculable via equation 7. The 'apparent' gas mass flowrate ($m_{g,Apparent}$), is the uncorrected gas flow reading from the meter. To find the steam mass flow rate (m_g) via equation 6 the Lockhart Martinelli parameter (X_{LM}) must be known. Substituting equation 2 into equation 6 results in the liquid mass flow (m_l), or steam quality (x), being required from an external source to predict the gas mass flowrate by iteration.

$$m_g = \frac{m_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad (6)$$

$$C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{where n = ¼} \quad (7)$$

In geothermal industry this water flowrate information tends to come from either periodic tracer dilution tests or historical separator water outlet metering data. However, under normal operation each well does not have a separator and water meter installed. Such saturated steam separators are effectively temporary tests separators that are used for short periods to test the well while it is off-line and discharging to atmosphere. That is, individual well testing is normally a temporary spot check. There is an inherent unproven assumption that the liquid flow remains constant between such spot checks. There is presently no orifice meter system based real time steam quality measurement. In present geothermal power station operation each individual well's flow quality is assumed from such historical data. The various flows from different well bores are then commingled with others, such that a communal saturated steam flow of *assumed* quality is sent to the power plant.

The geothermal industry's R&D on wet saturated steam orifice metering tends to be the incremental improvement of saturated steam correlations, i.e. the improvement of the steam flow prediction when the water flowrate is known from an external source. This external source can be periodic tracer dilution tests or historical separator data. The geothermal industry's saturated steam correlations are increasingly complex. However, biases in water flowrate entries to these correlations induce corresponding steam flow prediction biases. Hence, it would be beneficial for an orifice meter system to be able to internally and continuously meter the water flowrate or steam quality and apply live inputs into the saturated wet steam flow correlation.

6.2 Hydrocarbon Production Industry's Wet Natural Gas Orifice Meter Research

The hydrocarbon production industry has taken a different approach to Differential Pressure (DP) meter wet gas research. Comparable to the geothermal industry, they improved the orifice meter wet natural gas over-reading correction equations, although not to the same level of complexity. However, they also researched axial pressure profile analysis techniques. This allows 1) the liquid loading to be predicted internally by the meter in real time, 2) for recovered and PPL DP readings to offer some system DP reading redundancy, and 3) for a comprehensive validation system to be in place.

6.2.1 A Hydrocarbon Industry Wet Natural Gas Orifice Meter Correlation

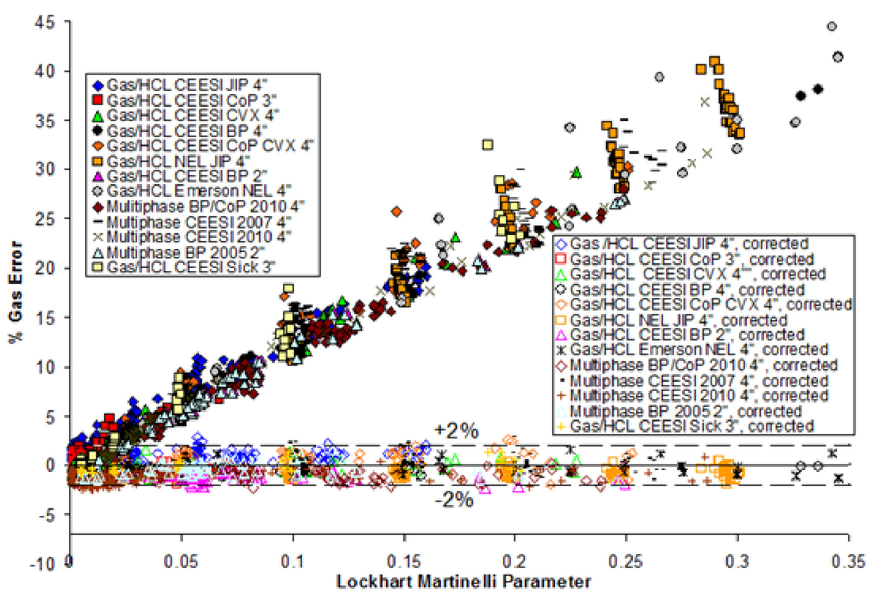

Fig 16. 2" to 4" Flange Orifice Meter Wet Gas Data With & Without ISO TR 11583 Correction for Known Liquid Flow Rate.

Chisholm derived his two-phase orifice meter correlation (equations 6 and 7) by modeling stratified flow. Indeed, as Mubarok [9] shows, saturated steam orifice meter correlations are modeled on either separated flow or homogenous flow. However, in reality, across Chisholm's saturated steam data conditions the flow pattern was certainly across the spectrum of stratified to homogenous flow. The Chisholm exponent 'n' of ¼ in Equation 7 was an average value for all the orifice meter data across the flow pattern spectrum.

$$m_g = \frac{m_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad (6)$$

$$C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad (7)$$

$$Fr_{g,tran} = 1.5 \quad (8)$$

for $Fr_g \le Fr_{g,tran}$ stratified flow: $$n_{strat} = 0.214 \quad (9)$$

for $Fr_g > Fr_{g,tran}$ transitional flow: $$n = \left(\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\#A}{\sqrt{Fr_g}}\right)\right)^2 \quad \text{where } \#A = 0.3 \quad (10)$$

In 1997 de Leeuw [10] noted Chisholm's orifice meter work, and modified and improved the Chisholm two-phase orifice meter equation for use with a wet natural gas Venturi meter. De Leeuw, considered a varying flow pattern between separated and homogenous flow, and accordingly fitted the Chisholm exponent 'n' as a function of the gas densiometric Foude number, $n = f(Fr_g)$. Subsequent orifice meter wet gas data fits followed this de Leeuw form. This led to ISO TR 11583 [5] publishing a wet natural gas orifice meter correlation, for 2" to 4" flange tap orifice meters, with natural gas and light liquid hydrocarbons, see equation set 6, thru 10.

$Fr_{g,tran}$ denotes the gas densiometric Foude number where transition from stratified to homogenous flow starts, and n_{strat} is the Chisholm exponent for stratified flow. Fig 16 shows the ISO massed wet natural gas 2" to 4" flange tap orifice meter data corrected for a known liquid loading using the ISO orifice meter wet natural gas correlation (see TR 11583 [5]). This correlation's limits are stated to be $0.24 \le \beta \le 0.73$, $X_{LM} \le 0.3$, $Fr_g > 0.2$, and meter inlet diameter ≥ 50mm, although no data was available for > 200mm.

Use of the ISO wet natural gas orifice meter correlation in geothermal saturated steam orifice meter applications includes significant extrapolations, to larger meter sizes, D and D/2 taps instead of flange taps, significantly lower gas to liquid density ratios, and significantly different liquid properties. Specifically, very hot water has a notably lower surface tension than water and light oil at ambient conditions, see Fig 17. Very low surface tension liquids facilitate annular / homogenous flow. Furthermore, unlike natural gas with hydrocarbon liquid, saturated steam is a single component some phase change. The form of the ISO correlation should work, but saturated steam flow would certainly require different parameter values.

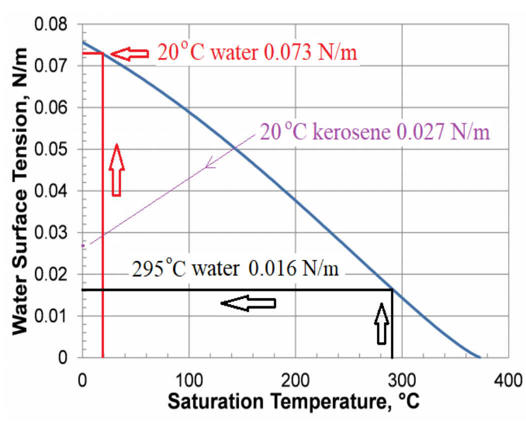

Fig 17. Liquid Surface Tensions.

6.2.2 A Wet Natural Gas Orifice Meter Liquid Loading Estimation

De Leeuw [10] showed that in wet natural gas applications, a Venturi meter's 'Pressure Loss Ratio' (PLR), i.e. the permanent pressure loss (ΔP_{PPL}) to primary DP (ΔP_t) ratio, $PLR = \Delta P_{PPL} / \Delta P_t$, is related to liquid loading. That is, for Lockhart Martinelli parameter (X_{LM}): $X_{LM} = f(PLR)$. This idea was subsequently tested on orifice meters with wet natural gas flow by a 1999-2002 Joint Industry Project (JIP).

Fig 18 shows a schematic sketch of an orifice meter with a 6D downstream tap with primary and PPL DPs read. By 2012 ISO had published ISO TR 11583 [5], showing a limited range 2" to 4" wet natural gas orifice meter $X_{LM} = f(PLR, DR, \beta)$ data fit, see equation set

11 thru 17. Fig 19 shows sample JIP 4", 0.5β flange tap orifice meter $X_{LM} = f(PLR,DR)$ data. This data fit is strictly for $\beta \geq 0.5$. The relationship between X_{LM} and *PLR* dissipates at $\beta < 0.5$.

Equations 14 and 15 show the ISO TR 11583 correlation's Lockhart Martinelli parameter (X_{LM}) and gas to liquid density ratio (*DR*) applicability range respectively. Steven [4] subsequently showed that rather than fixed by physical limitations, these limits were more due to ISO's limited data set, and the method was applicable to somewhat wider flow condition ranges. Furthermore, Steven [4] comments that the Urner PLR equation is only applicable for $\beta \leq 0.55$, and a $\beta \geq 0.55$ $PLR=f(\beta)$ fit is preferable, e.g. equation 16.

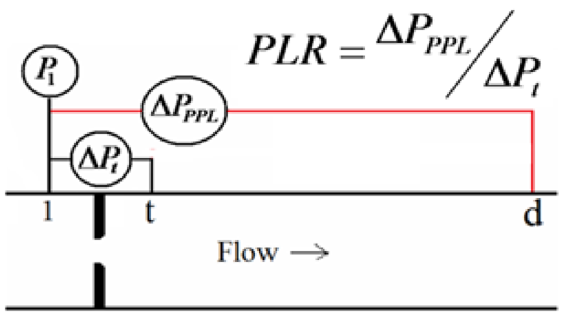

Fig 18. Orifice Meter with PLR Read.

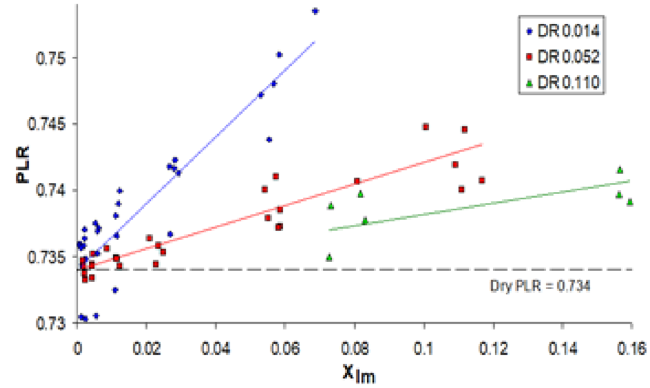

Fig 19. Sample JIP 4", 0.5β Orifice Meter PLR vs. X_{LM} Data.

$$PLR_{dry} = \frac{\sqrt{1-\{\beta^4(1-C_d^2)\}} - C_d\beta^2}{\sqrt{1-\{\beta^4(1-C_d^2)\}} + C_d\beta^2} \tag{11}$$

$$Y = (PLR_{wet}) - (PLR_{dry}) \tag{12}$$

$$X_{LM} = \frac{6.41Y}{\beta^{4.9}}(DR)^{0.92} \tag{13}$$

$$X_{LM} < 0.45(DR)^{0.46} \tag{14}$$

$$DR \leq (0.21\beta) - 0.09 \tag{15}$$

Optional for $\beta \geq 0.55$:

$$PLR_{dry} = 1.033 - (0.8552 * \beta^{1.5}) \tag{16}$$

$$m_l = m_g X_{LM}\sqrt{1/DR} \tag{17}$$

However, again use of this hydrocarbon based $X_{LM} = f(PLR, DR, \beta)$ correlation with geothermal saturated steam orifice meters represents a significant extrapolation to larger meter sizes, D and D/2 taps, inclusion of some significantly lower gas to liquid density data, and significantly different liquid properties. Again, the form of the correlation could work, but saturated steam flow would certainly require different parameter values.

6.2.3 A Hydrocarbon Industry Orifice Meter Validation System

A comprehensive orifice meter 'axial pressure profile analysis' diagnostic tool (called 'Prognosis') was developed for the hydrocarbon industry (see Appendix). This facilitates 'Condition Based Monitoring' (CBM), which can significantly reduce the amount of routine scheduled maintenance required to operate an orifice metering system. This system can warn of unexpected issues and tracks known phenomena. For example, with two-phase / wet gas flows the liquid loading (i.e. quality) is tracked. For two-phase flow *and* DP transmitter problems, the system can identify a DP transmitter issue even under two-phase flow conditions. This validation system can work with geothermal saturated steam orifice meters.

7 LANDSVIRKJUN 0.7Β ORIFICE METER SATURATED STEAM RESULTS

A 14", sch 20, 0.7β orifice meter and a 10", sch 40, 0.7β orifice meter were both field tested with saturated steam flows in July 2021. Various long pseudo-steady flow conditions were held and the data averaged. Fig 20 shows the 14" (meter 1) and 10" (meter 2) 0.7β saturated steam results. The solid points are the uncorrected steam flowrate prediction biases. The hollow points are the ISO TR 11583 equation set 6 thru 10 'corrected' steam flowrate residual errors for ***known*** steam quality / Lockhart-Martinelli parameters. The extrapolation of ISO TR 11583's $OR\% = f(X_{LM}, DR, Fr_g)$ equation to significantly larger meters, a D and D/2 pressure tap configuration, significantly lower density ratios, and lower liquid surface tension, induced a positive bias on the correlation's steam flow rate prediction. The data range was 5.9 < P (Bar a) < 12.7, 0.003 < DR < 0.0074, 0.6 < Fr_g < 3.5, 0 ≤ X_{LM} < 0.17, and 0.31 < x ≤ 1.

Fig 21 shows the two 0.7β orifice meter X_{LM} and '*x*' prediction results when using the ISO TR 11583's $X_{LM} = f(PLR, DR, \beta)$ prediction, i.e. equation set 12, 13, and 16, and converting X_{LM} to quality (*x*) via equation 2a. Extrapolation of ISO TR11583 leads to the Lockhart Martinelli parameter and quality predictions having significant negative and positive bias respectively.

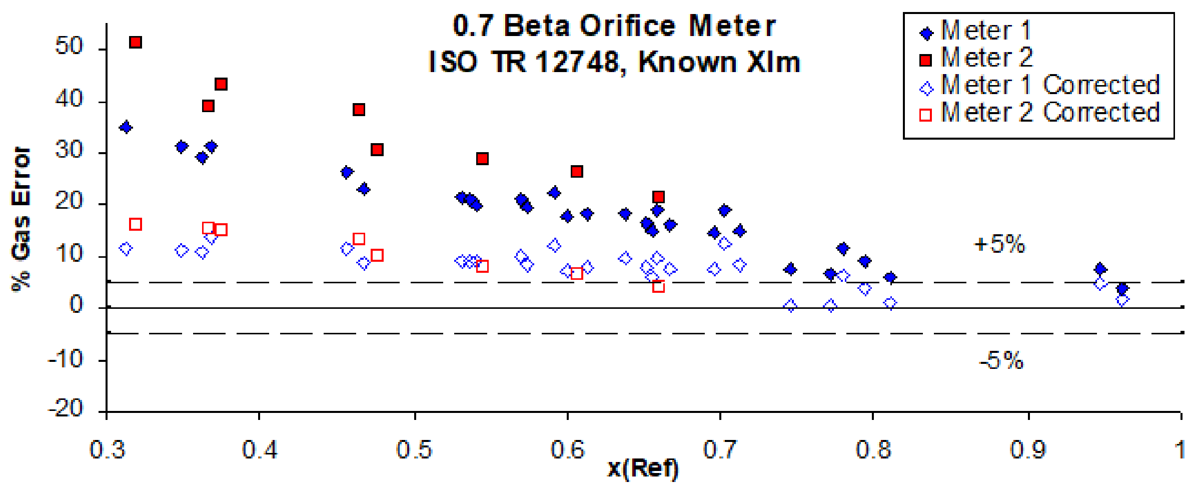

Fig 20. 14" (Meter 1) and 10" (Meter2) 0.7β Steam OR% and ISO Correction (Known 'x').

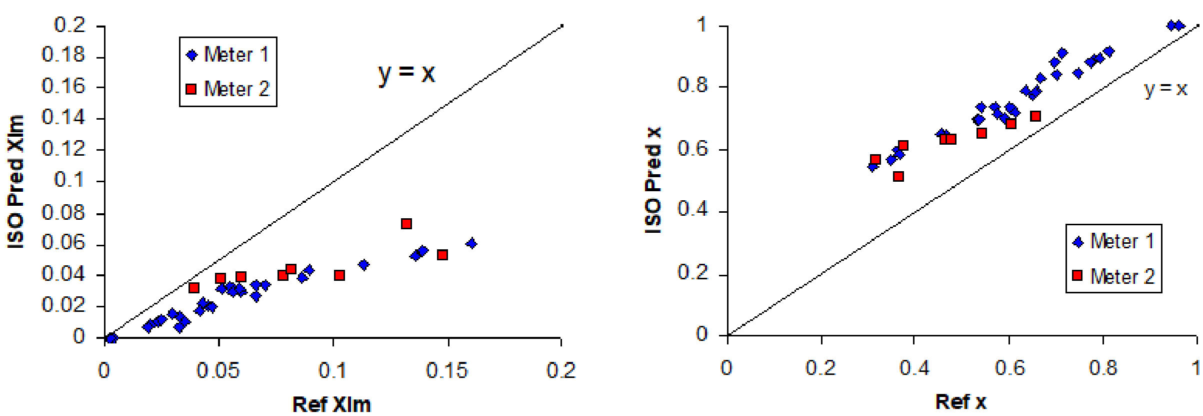

Fig 21. 14" (Meter 1) and 10" (Meter 2) 0.7β ISO X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

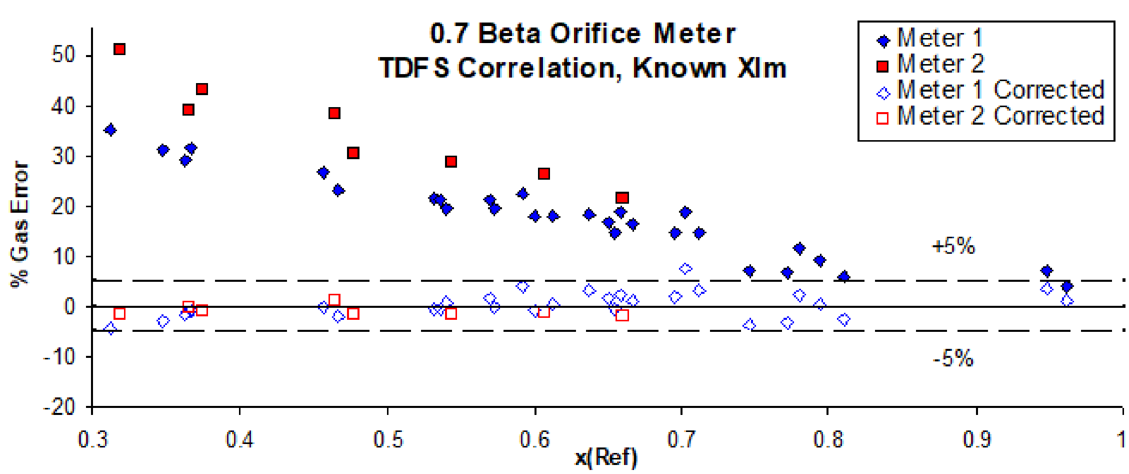

Fig 22. 14" (Meter 1) and 10" (Meter 2) 0.7β Steam OR% & TDFS Correction (Known 'x').

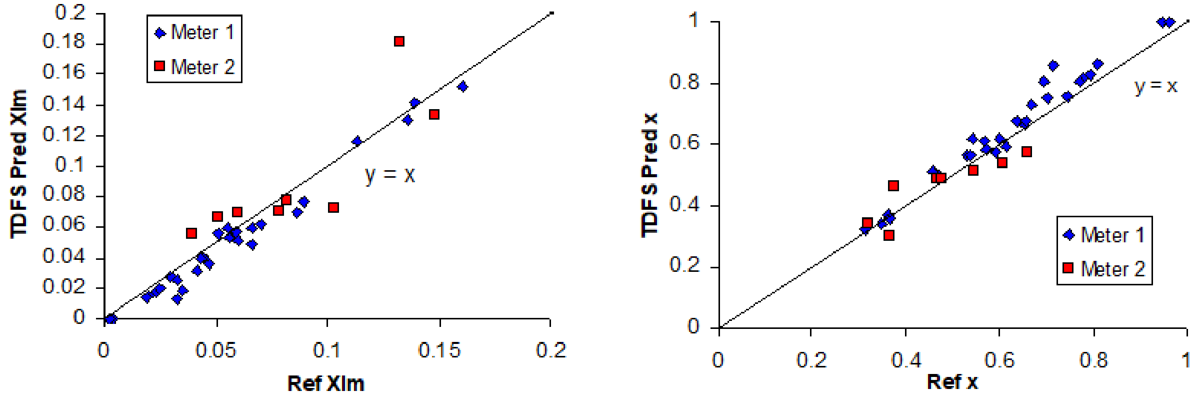

Fig 23. 14" (Meter 1) and 10" (Meter 2) 0.7β TDFS X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

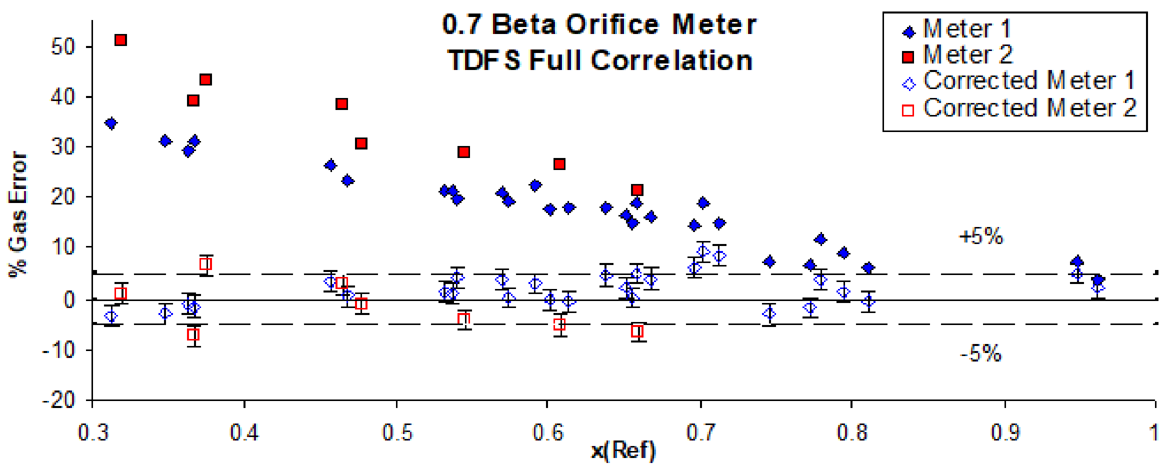

Fig 24. Gas Mass Flow % Error vs 'x' for 0.7β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits

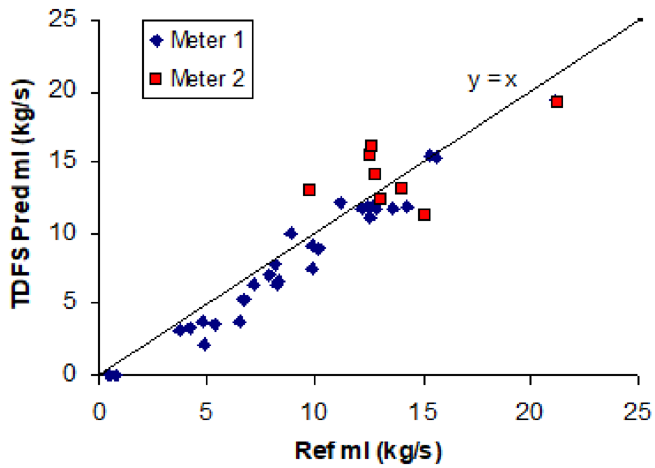

Fig 25. 14" (Meter 1) and 10" (Meter2) 0.7β Orifice Meter TDFS Data Fit Predicted to Reference Water Mass Flowrate Results.

It is clear from Fig 20 that although there is an ISO TR 11583 correlation bias, there is a clear relationship between these meter's saturated steam over-reading and steam quality / Lockhart Martinelli parameter. Hence, it was possible for TDFS and Landsvirkjun to fit their own respective saturated steam $OR\% = f(X_{LM}, DR, Fr_g)$ correlations. TDFS modified equations 8, 9, and 10, specifically altering the 'transition' gas / steam densiometric Froude number ($Fr_{g,tran}$), stratified Chisholm exponent (n_{strat}), and Chisholm exponent variable *#A*.

Fig 22 shows the results of applying such a TDFS $OR=f(X_{LM},DR,Fr_g)$ data fit on the two 0.7β orifice meters for a known quality / Lockhart Martinelli parameter. As expected with a data fit there is no significant bias, but scatter is evident. It is clear from Fig 21 that although there is an ISO TR 11583 correlation bias, there is a clear relationship between these meter's PLR and steam quality / Lockhart Martinelli parameter. Hence, it was possible for TDFS to fit their own $X_{LM} = f(PLR, DR, \beta)$ equation. This consisted of modifying equation 13 and careful choice of the PLR single phase baseline. Fig 23 shows the results of such a TDFS $X_{LM} = f(PLR, DR, \beta)$ and $x= f(PLR, DR, \beta)$ prediction.

Fig 24 shows the uncorrected 0.7β steam flow predictions with the full TDFS correlation results, i.e. using the TDFS $OR\% = f(X_{LM}, DR, Fr_g)$ and $X_{LM} = f(PLR, DR, \beta)$ predictions. The steam flowrate is predicted to 5% uncertainty.

Fig 25 shows that the TDFS data fit give approximate predictions of the water flow (via Equation 17). This performance matches the hydrocarbon industry's rule of thumb for acceptable wet gas meter performance.

8. LANDSVIRKJUN 14", 0.48B ORIFICE METER SATURATED STEAM RESULTS

A 14", sch 20, 0.48β, D and D/2 tap orifice flange union meter was tested in 2021 (see Figs 2, 5, 9, and 13). Various pseudo-steady flow conditions were held for long periods, and then the data was averaged.

Fig 26 shows the 14" 0.48β saturated steam results. The solid points are uncorrected steam flowrate biases. The hollow points are ISO TR 11583 equation set 6 thru 10 corrected steam flowrate residual errors for *known* steam quality. Extrapolation of ISO TR 11583's $OR\% = f(X_{LM}, DR, Fr_g)$ equation induced a positive bias on the correlation's steam flowrate prediction. The data range was $7.4 < P \text{ (Bar a)} < 12.4$, $0.0045 < DR < 0.0065$, $0.27 < Fr_g < 1.1$, $0 \le X_{LM} < 0.55$, and $0.13 < x \le 1$.

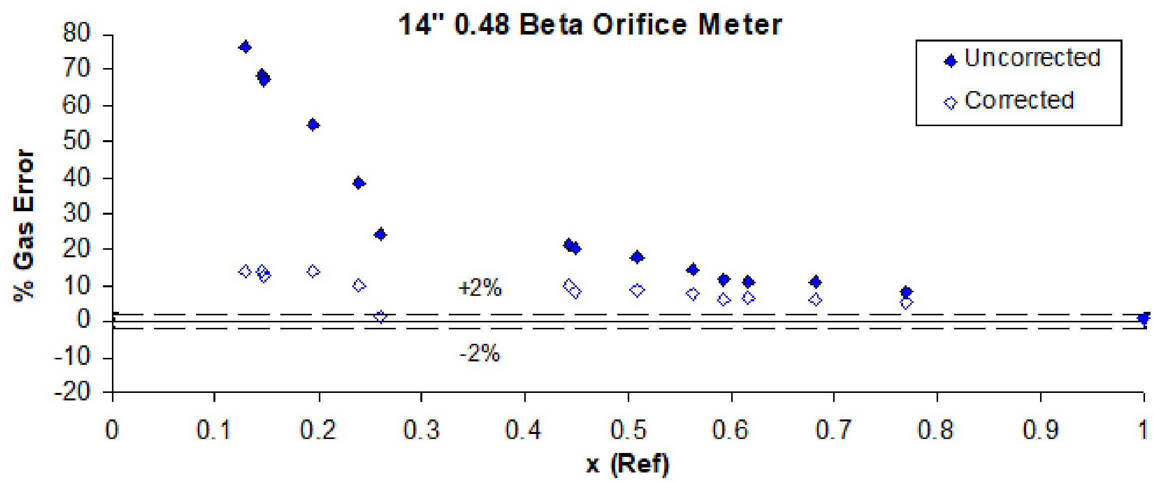

Fig 26. 14" 0.48β Steam OR% and ISO TR 11583 Correction for Known 'x'.

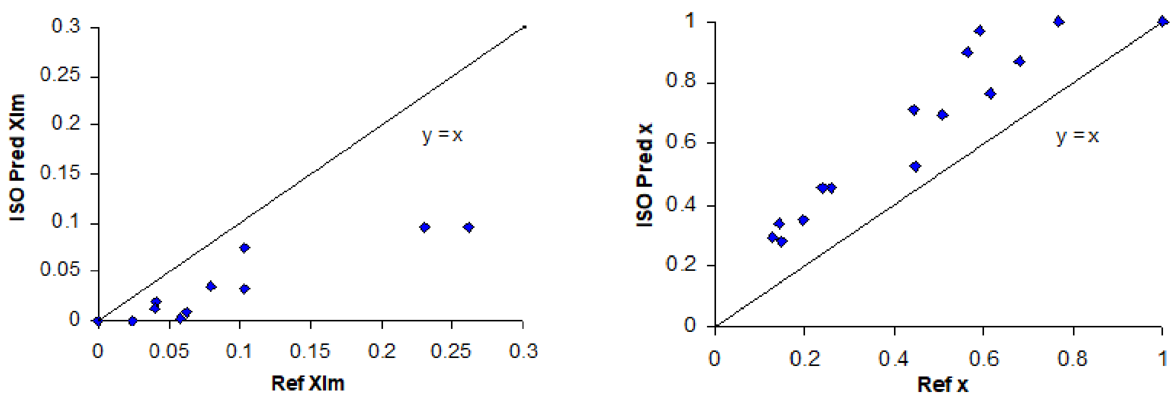

Fig 27. 14", 0.48β ISO TR 11583 X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

Fig 27 shows the 0.48β orifice meter X_{LM} and '*x*' results when using the ISO TR 11583's $X_{LM} = f(PLR, DR, \beta)$ prediction, i.e. equation set 11 thru 13. Again, extrapolation of ISO TR 11583 leads to the Lockhart Martinelli parameter and quality predictions having significant negative and positive bias respectively.

It is clear from Fig 26 that there is a relationship between these meter's saturated wet steam over-reading and quality. Hence, again it was possible for TDFS to fit a saturated steam $OR\% = f(X_{LM}, DR, Fr_g)$ correlation. Fig 28 show the 0.48β orifice meter uncorrected results when applying a TDFS $OR=f(X_{LM},DR,Fr_g)$ data fit for *a known* quality. As expected with a data fit there is no significant bias, but some scatter is evident.

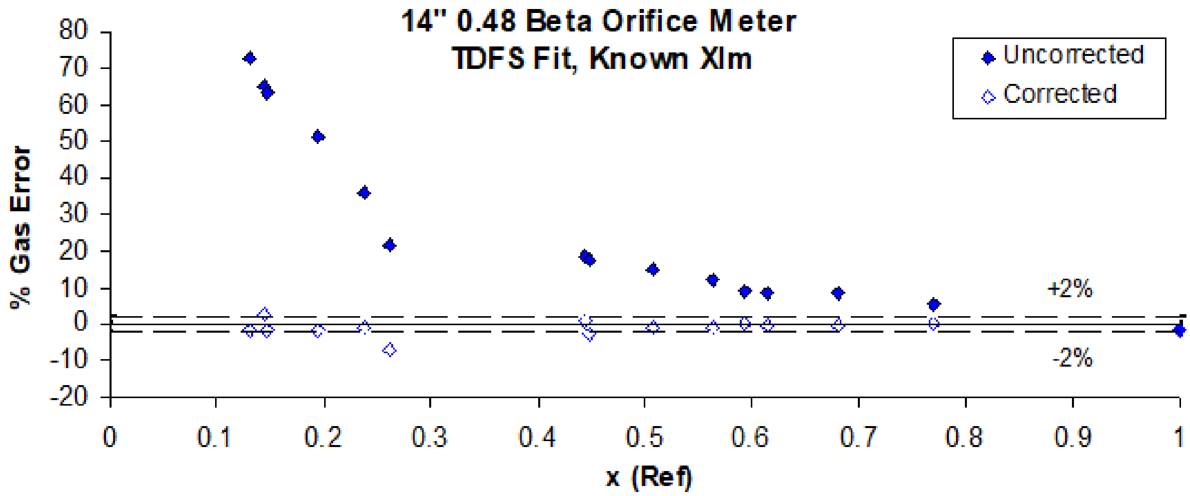

Fig 28. 14" 0.48β Orifice Meter Steam OR% & TDFS Correction for Known 'x'.

It is clear from Fig 27 that although there is an ISO TR 11583 correlation bias, there is a relationship between these meter's PLR and steam quality / Lockhart Martinelli parameter. Hence, it was possible for TDFS to fit their own $X_{LM} = f(PLR, DR, \beta)$ equation. Fig 29 shows the results of the ISO correlation and a TDFS $X_{LM} = f(PLR, DR, \beta)$ prediction.

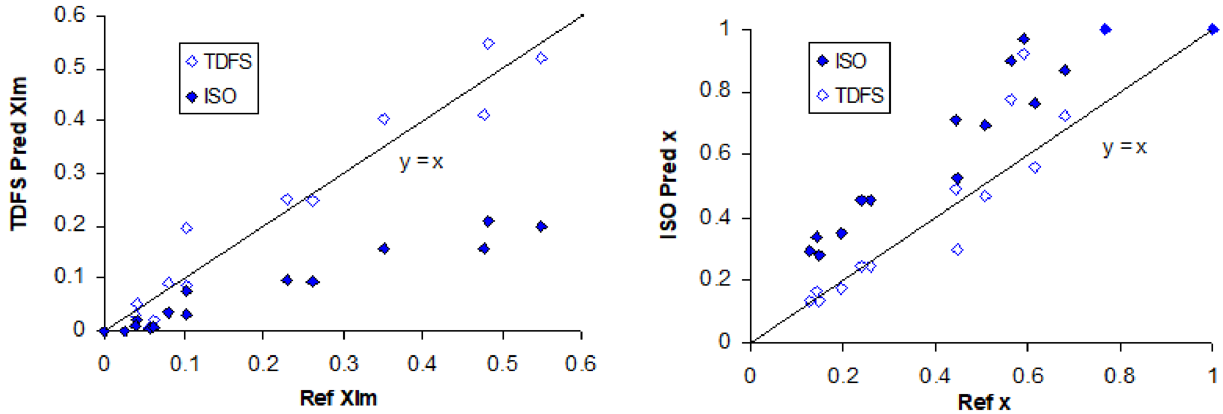

Fig 29. 14", 0 .48β TDFS X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

Fig 30 shows the uncorrected 0.48β steam flow predictions with the full TDFS 0.48β correlation results, i.e. using the TDFS $OR\% = f(X_{LM}, DR, Fr_g)$ and $X_{LM} = f(PLR, DR, \beta)$ predictions. The steam flowrate is predicted to 5% uncertainty. Fig 31 shows that the TDFS data fit give approximate predictions of the water flow (via Equation 17).

This performance matches the hydrocarbon industry's rule of thumb for acceptable wet gas meter performance. The 0.48β meter was tested over a much wider liquid loading range than the 0.7β meters. The published hydrocarbon industry R&D concentrates on $X_{LM} < 0.15$. Fig 32 reproduces CEESI JIP orifice meter $X_{LM} = f(PLR,DR)$ graphs, where the $X_{LM} < 0.15$ range is in line with the 0.7β geothermal steam data of x > 0.4 presented here. Nevertheless, the 14" 0.48β orifice meter can still be made to approximate the steam and water flow across the wider liquid loading range with no external liquid flowrate information required.

Comparing Figs 23 and 29 shows that the 0.48β meter's Lockhart Martinelli parameter / quality prediction has more scatter than the 0.7β meters. This is a natural consequence of the lower orifice meter beta producing a shallower X_{LM} vs. ΔPLR gradient, i.e. the lower beta orifice meter has a PLR less sensitive to liquid loading (e.g. see Fig.32). This is shown for this current saturated steam data in Figs 33 and 34. Hence, when using such a two-phase flow orifice meter method it is advisable to use a higher beta, e.g. 0.7β. The geothermal saturated wet steam flow conditions tested are such that reasonable DPs are produced across a high beta orifice meter. This coupled with suitable DP transmitter range availability makes this a practical and reasonable stipulation.

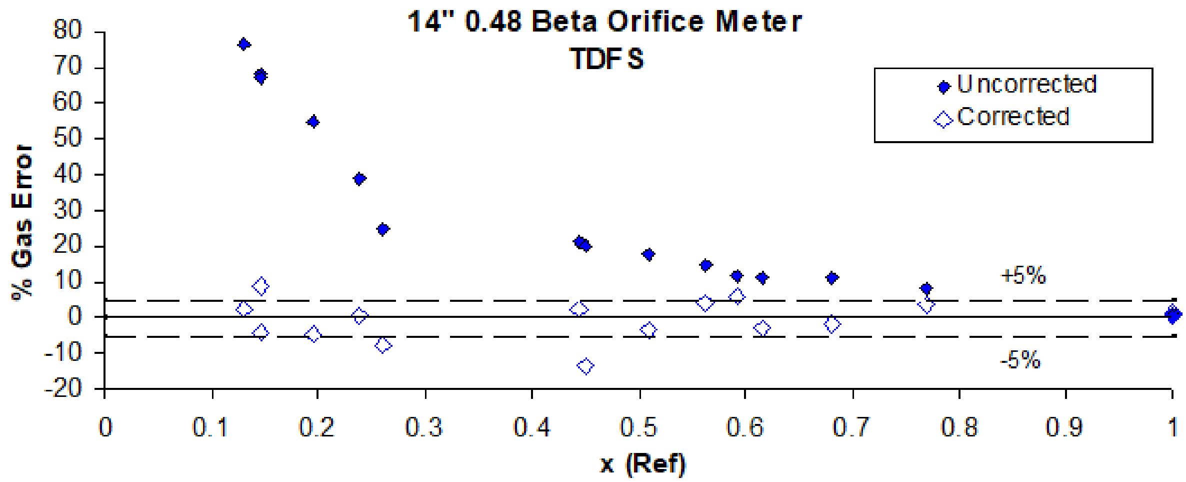

Fig 30. Gas Mass Flow % Error vs 'x' for 0.48β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits.

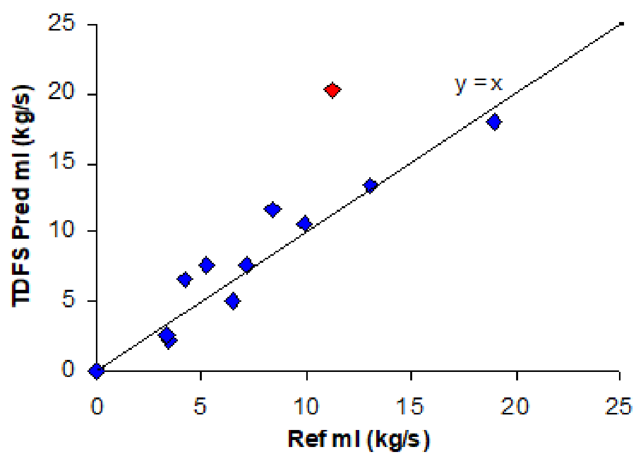

Fig 31. 14" 0.48β TDFS Data Fit Predicted to Reference Water Mass Flowrate Results.

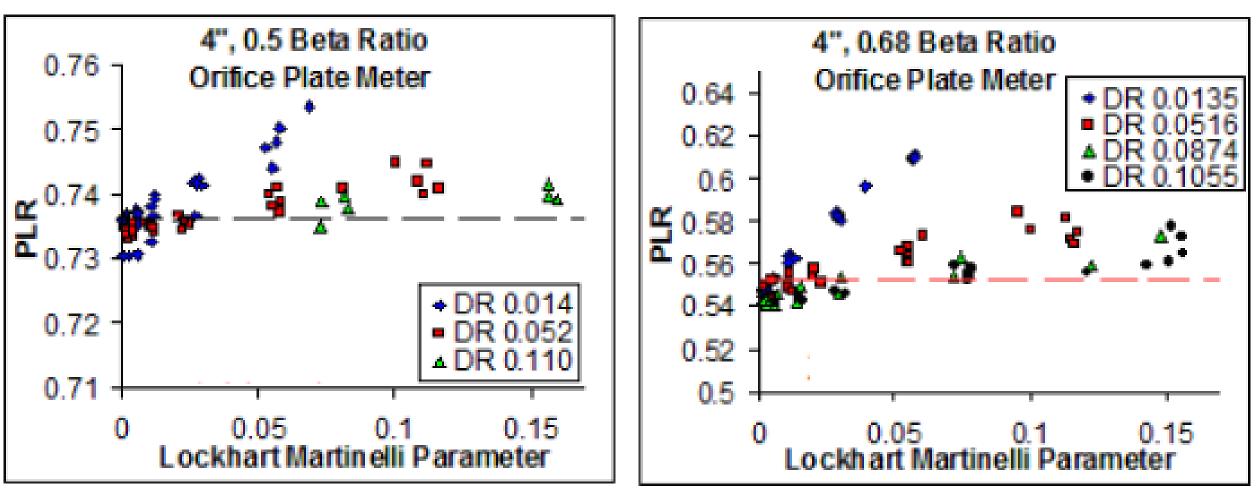

Fig 32. 4" Orifice Meter Beta Dictated PLR vs. X_{LM} Sensitivity.

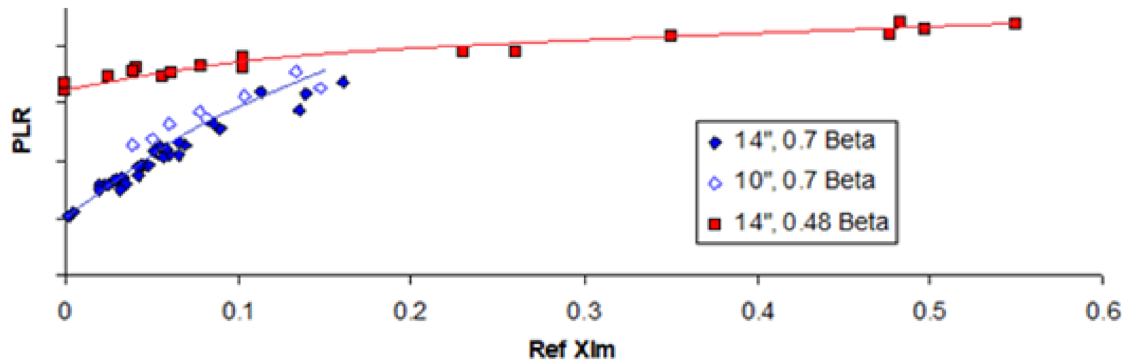

Fig 33. 0.48β and 0.7β Saturated Wet Steam PLR vs. X_{LM} Data.

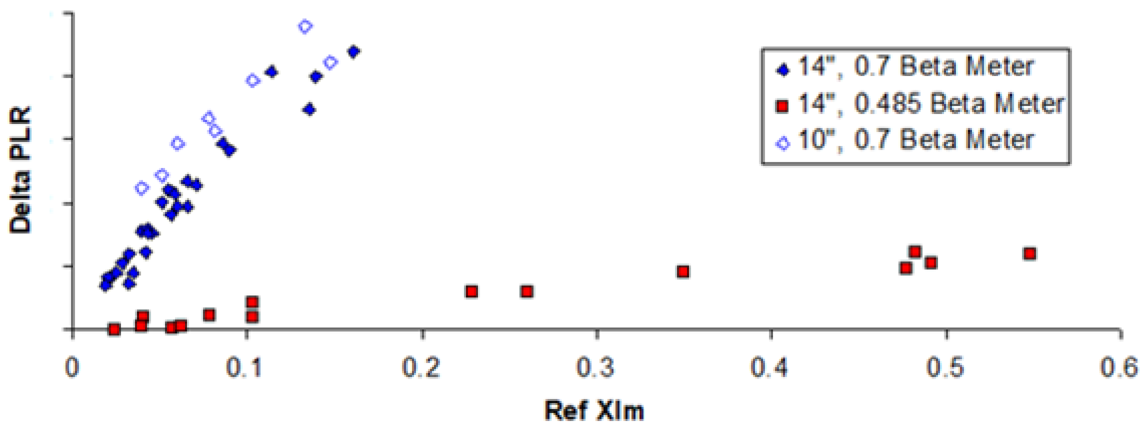

Fig 34. 0.48β and 0.7β Saturated Wet Steam PLR vs. X_{LM} Relative Relationship.

9 ORIFICE METER AXIAL PRESSURE PROFILE ANALYSIS DIAGNOSTIC SYSTEM

The Appendix describes the orifice meter Axial Pressure Profile Analysis diagnostic operating principle (called 'Prognosis'). Such a system can be used to either track known phenomena (e.g. varying steam quality) or show the presence of unexpected issues.

Fig 35 shows Axial Pressure Profile Analysis results from the 14", 0.48β orifice meter running with single phase steam flow. All diagnostic points are inside the Normalized Diagnostic Box (NDB), indicating a correctly operating meter.

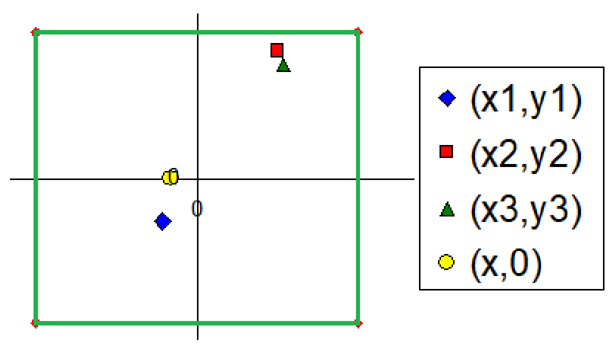

Fig 35. Correctly Operating Single Phase Flow Orifice Meter

9.1 Prognosis as an Active Steam Quality Tracking System

The 14", 0.48β orifice meter was tested with steam qualities between $0.14 \leq x \leq 1$. The 14" and 10" 0.7β orifice meters were tested with steam qualities between $0.3 \leq x \leq 1$. Lowering steam quality, i.e. raising the relative amount of liquid, makes the diagnostic points move away from the NDB. Fig 36 shows the 0.48β and 0.7β orifice meter Prognosis responses to saturated wet steam flow.

For orifice meter's with $\beta \geq 0.5$, the Axial Pressure Profile Analysis ('Prognosis™') clearly tracks steam quality. This can be useful for monitoring geothermal steam flows.

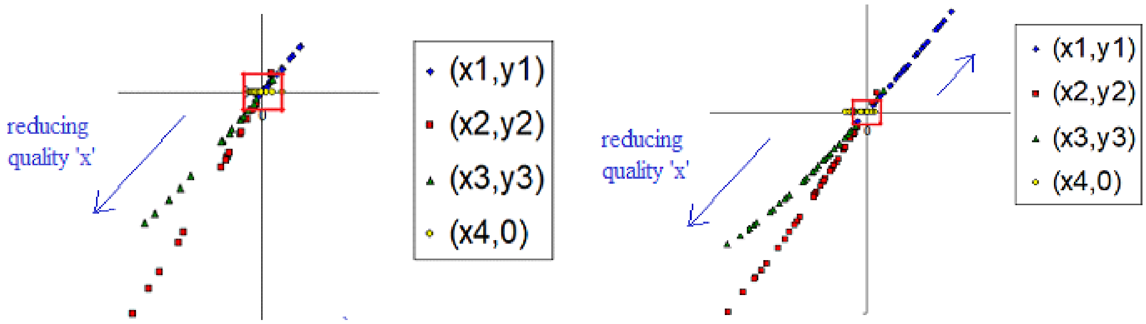

Fig 36. 0.48β Meter (Left) and 0.7β Meter (Right) Tracking Steam Quality.

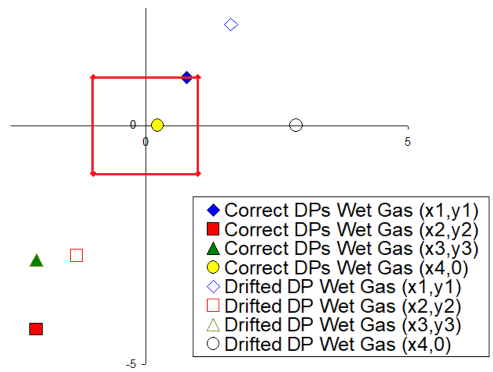

Fig 37. 14", 0.48β Steam Orifice Meter With / Without DP_t Drift.

The Axial Pressure Profile Analysis orifice meter diagnostic technique is useful for more than tracking steam quality. It can also monitor for erroneous DP readings. Say during saturated wet steam flow the primary DP reads 0.514 Bar instead of the actual 0.541 bar, i.e. -5% DP bias. Fig 37 shows the Prognosis result if the DPs are correct, i.e. a saturated wet steam pattern. However, it also shows the results for the case of a saturated steam flow with an erroneous primary DP reading. With the exception of the respective (x_3,y_3) points, the pattern is different. With a DP error x_4 leaves the box specifically showing that there is a DP issue, regardless of the wet saturated gas. Hence, the 'Prognosis' orifice meter diagnostic system can monitor steam quality and the health of the DP readings in a saturated steam flow service.

10 REDUNDANT DP TRANSMITTER USE

TDFS has developed the use of the axial pressure profile analysis (Prognosis) three DP transmitters, i.e. primary, recovered, and permanent pressure loss, to offer DP transmitter redundancy in wet gas / saturated steam orifice metering systems. A DP transmitter can be off-line for various reasons, e.g. electro-mechanical failure, ineffective temperature isolation, a plugged impulse line, over-ranging etc. If one of the three DP transmitters is off line it is possible to continue to operate as a wet gas / saturated steam meter using the remaining two DP transmitters. The missing DP can be inferred from the other two DP readings, i.e. see equations 18, 19, and 20.

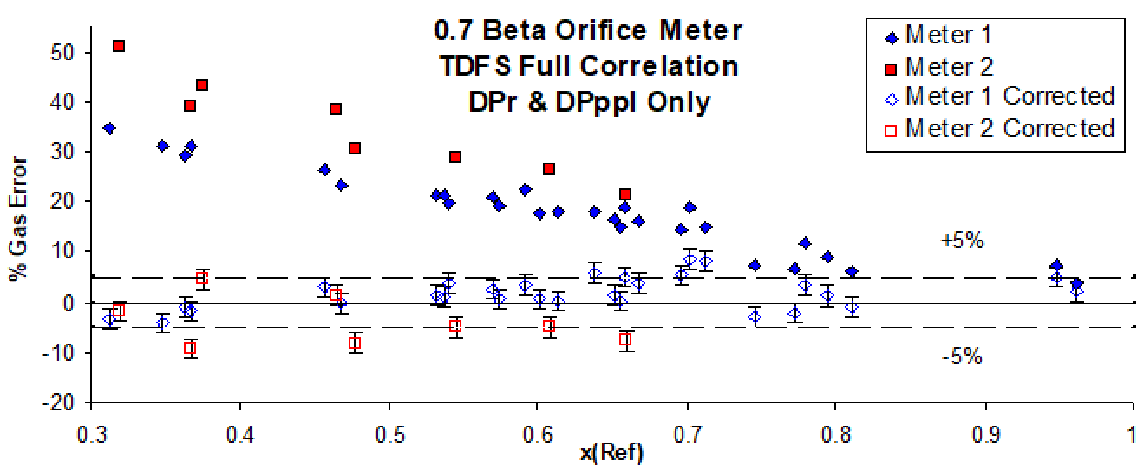

Fig 38. Gas Mass Flow % Error vs 'x' for 0.7β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits, Using ΔP_r and ΔP_{PPL} Only.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \tag{18}$$

$$\Delta P_{PPL} = \Delta P_t - \Delta P_r \tag{19}$$

$$\Delta P_r = \Delta P_t - \Delta P_{PPL} \tag{20}$$

Fig 38 - 40 show the 14" and 10" 0.7β meter performances if the primary DP transmitter fails, and only the recovered and PPL DPs are available. Failure of the primary DP reading on a standard orifice meter with a PPL reading would stop that meter's operation as a two-phase meter. However, with these three DP readings, when switching to using any two of the three DPs, there is no noticeable wet gas / saturated steam flow metering performance degradation.

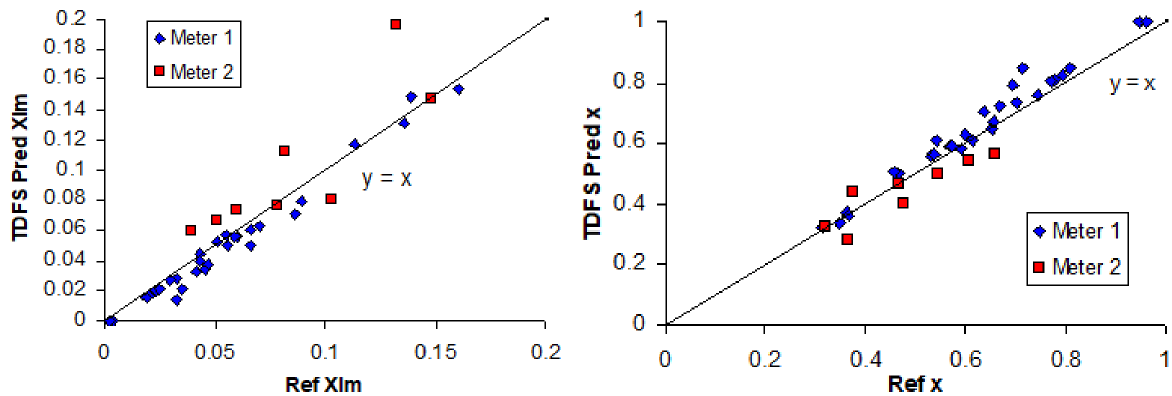

Fig 39. 14" and 10" 0.7β Two-Phase Orifice Meter TDFS Data Fit X_{LM} and 'x' Prediction Using ΔP_r and ΔP_{PPL} Only.

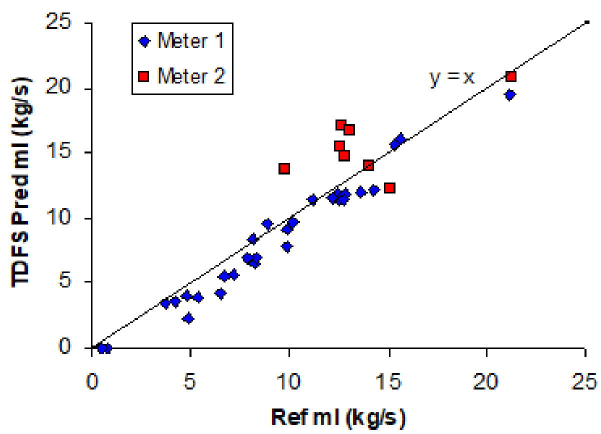

Fig 40. 14" and 10" 0.7β Two-Phase Orifice Meter TDFS Data Fit Water Flowrate Prediction

11 CONCLUSIONS

The hydrocarbon production industry's wet natural gas metering technology can be utilized by the geothermal power industry. Wet natural gas and saturated steam are both two-phase flows. Both metering requirements can potentially be met by the same methodologies.

Live geothermal well saturated steam flowrate and quality metering can be obtained by adopting the hydrocarbon industry's wet gas orifice meter design. Specifically, an orifice meter with a downstream pressure tap reading primary, permanent pressure loss, and optional recovered DPs can predict steam quality and flowrates. The geothermal saturated steam applications generally have larger orifice meters, different pressure tap locations, lower gas to liquid density ratios, and low liquid surface tension, than the hydrocarbon production industry. Therefore, although the same two-phase flow performance trends are there, dedicated geothermal saturated steam data fits are required. The same form of OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) fits as published in ISO TR 11583 are applicable, but saturated steam data is required to modify the constants used in these equations.

Use of such a wet gas orifice meter would allow the geothermal well operator to have real time / live tracking of each pipeline's steam flow and quality, without the need for tracer dilution tests or taking the pipeline off-line for test separator work. This would give optimum control and efficiency of the well, allowing the operator to choose to maximize revenue, minimize fluid extraction, minimize CO_2 or Non-Condensable Gas extraction, minimize pressure loss etc., while keeping Well Head Pressure above the level required to avoid pipe component scaling.

It has also been shown that the 'Axial Pressure Profile Analysis' validation system ('Prognosis') is directly applicable to geothermal well orifice meter operation. Furthermore, the three DPs that it requires offer valuable DP redundancy, meaning if an orifice meter was to lose a DP transmitter, e.g. due to over-ranged transmitter, ineffective thermal isolation, drifting transmitter etc. then the system has the redundancy to continue operating correctly.

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APPENDIX: ORIFICE METER VALIDATION SYSTEM 'PROGNOSIS'

A comprehensive diagnostic system (or 'suite') is a prerequisite for a flow meter to be considered a cutting edge, state-of-the-art, modern flow meter. Whereas the orifice meter is a beautifully simple traditional technology, quite counter-intuitively, it also has arguably the most modern, comprehensive, and beautifully simple, easy to understand diagnostic suite. An overview of these 'axial pressure profile monitoring' diagnostics is now given. (See Skelton et al [9] & Rabone et al [10] for more details.)

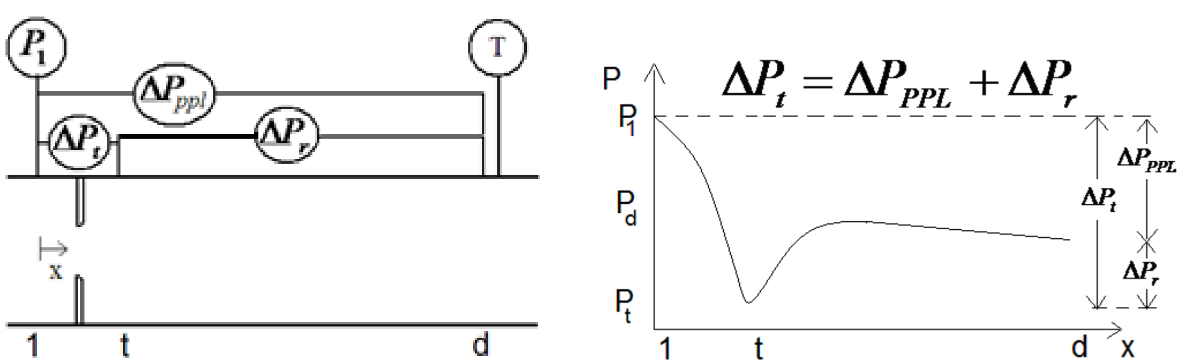

Fig A1. Orifice Meter with Instrumentation Sketch and Pressure Field Graph.

Fig A1 shows a sketch of an orifice meter and its axial pressure profile. The meter has a 3rd pressure tap downstream of the two standard taps. This allows three DPs to be read, i.e. the primary, aka 'traditional' (ΔP_t), recovered (ΔP_r), and permanent pressure loss (ΔP_{PPL}) DPs.

These DPs are related by equation A1.1. The percentage difference between the inferred primary DP (i.e. the sum of the recovered & PPL DPs) and the read primary DP can be checked against a set maximum allowable variance.

Each DP can be used to independently meter the flow rate, as shown in equations A1.2, A1.3 & A1.4. Here m_t, m_r, and m_{PPL} are the mass flow rate predictions of the traditional, expansion & PPL flow rate calculations. Symbols x%, y%, and z% represent the uncertainties of each of these flow rate predictions respectively. Inter-comparison of these flow rate predictions produces three diagnostic checks.

Reading these three DPs produces three DP ratios, the 'PLR' (i.e. the PPL to traditional DP ratio), the PRR (i.e. the recovered to traditional DP ratio), the RPR (i.e. the recovered to PPL DP ratio). DP meters have predictable DP ratios. Therefore, comparison of each read to expected DP ratio produces three diagnostic checks. The correct DP ratios for a given correctly operating orifice meter are derivable from ISO 5167 and / or published orifice meter $PLR = f(\beta)$ fits. Reasonable variances for these baselines can be set by experience as a% for the PLR baseline, b% for the PRR baseline, and c% for the RPR baseline. Comparing the percentage differences between the 'as found' and baseline DP ratios with their respective allowable variances produces three diagnostic checks.

DP Summation:	$\Delta P_t = \Delta P_r + \Delta P_{PPL}$,	uncertainty $\pm\ \theta$ %	(A1.1)
Traditional flow calculation:	$m_t = f(\Delta P_t)$,	uncertainty ± x%	(A1.2)
Expansion flow calculation:	$m_r = f\ (\Delta P_r)$,	uncertainty ± y%	(A1.3)
PPL flow calculation:	$m_{PPL} = f(\Delta P_{PPL})$,	uncertainty ± z%	(A1.4)

These seven diagnostic results are often plotted on a display. The seven checks can be represented as four co-ordinates, as shown in Fig A2. Inside the box represents acceptable performance; if all points are inside the box then the meter is operating correctly. If one or more points are outside the box there is a meter malfunction. Stability checks on the three DPs and the associated diagnostic parameters are sometimes called the eighth diagnostic check. The pattern of a meter malfunction can indicate the source of the problem.

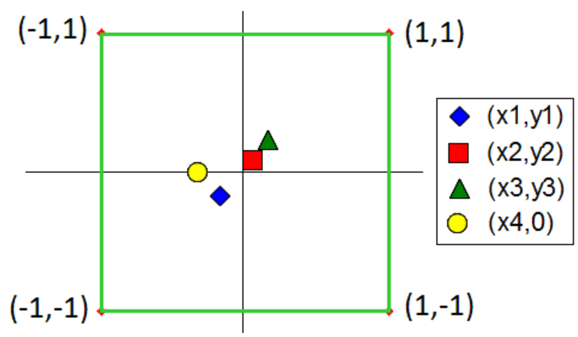

Fig A2. Prognosis Orifice Meter Display.