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Saturated Wet Steam Orifice Meter Tests at a Geothermal Power Station

Richard Steven, Tek DPro Flow Solutions
Egill Juliusson, formerly Landsvirkjun

1 INTRODUCTION

The nuclear and geothermal power industries started publishing saturated steam flow metering R&D as of the 1950's. The hydrocarbon production industry started to become more interested in wet natural gas metering R&D in the 1990s. With both saturated steam and wet natural gas flows being two-phase flow metering challenges, initial wet natural gas flow metering research incorporated the existing saturated steam metering methodologies. However, the subsequent direction of the hydrocarbon industry's R&D was somewhat different to that of the steam industries. The hydrocarbon industry's two-phase metering developments did not tend to permeate back to, or at least were not generally adopted by, the steam industries.

There is often a lack of communication and idea transfer between independent industries. The hydrocarbon production industry has developed flow metering technology which could potentially benefit other industries, including the renewable energy sector, 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 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, and with hydro, wind, and geothermal power generation is Iceland's largest electricity producer. Landsvirkjun strives to improve the efficiency of its three geothermal power stations, and as such conducted saturated steam flow meter R&D between 2020 and 2021.

Geothermal power stations (Fig 3) are 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 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 curve is WHP vs. water and steam flows, or WHP vs. total flow and enthalpy. Such control allows the choice between maximizing revenue, minimizing fluid extraction, minimizing CO_2[1] or Non-Condensable Gas extraction, minimizing pressure loss etc., while keeping WHP above the level required to avoid scaling, and providing the required quantity of water (i.e. 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 meter tests between 2020 and 2021.

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 seasons Landvirkjun conducted three orifice meter saturated steam flow field tests using various wells at the Theistareykir power station.

3 GEOTHERMAL POWER STATION ORIFICE METER FIELD TESTS

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

Test 1: 5^{th} thru 9^{th} July 2021, 14" 0.7β orifice meter
Test 2: 5^{th} thru 9^{th} July 2021, 10" 0.7β orifice meter
Test 3: 1^{st} thru 9^{th} 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. 5). 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

[1] GeoThermal Steam flows do contain CO_2, i.e. they are not entirely carbon neutral. The quantity of CO_2 produced by a geothermal power plant is dependent on geological factors. However, many geothermal wells, such as those in Iceland, produce between 1% and 10% of the CO_2 per unit power output of a conventional fossil fuel power station. Some geothermal power plant operators such as Landsvirkjun are aiming towards 'net zero' by investigating carbon capture and reinjection techniques.

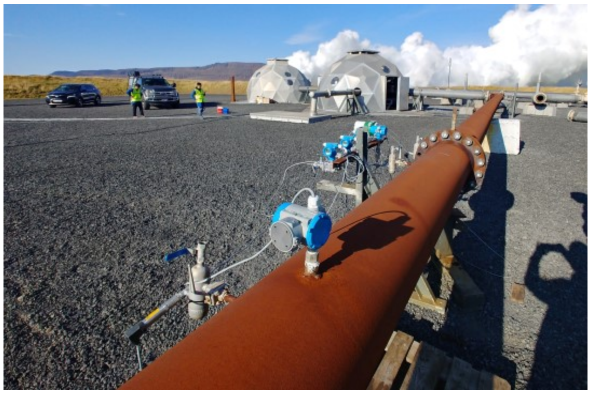

Fig 5. Orifice Meter Downstream of Well Head.

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.

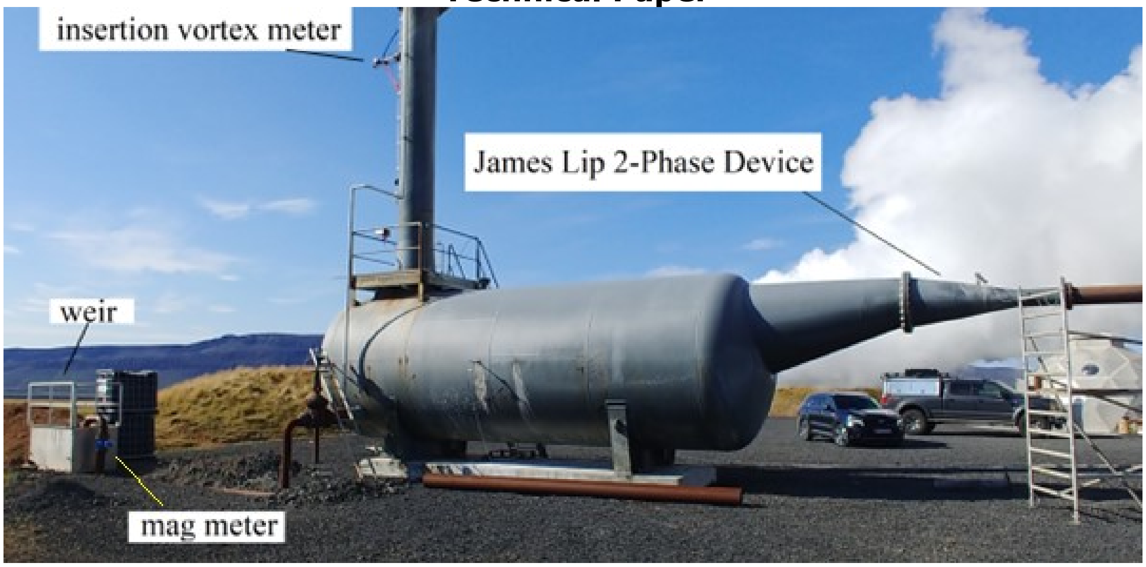

Fig 10. Atmospheric Separator (aka Silencer), with James Lip Pressure Two-Phase Device, Single Phase Steam Flow Vortex Meter, Water Magnetic Meter, and Weir.

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 James Lip Pressure Device is well known and trusted in the geothermal industry. It is described in Appendix 1. 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 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 testing of the orifice meter diagnostics system 'Prognosis', as well as the flowrate prediction uncertainty reducing Data Validation And Reconciliation System 'Oculus'.

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 gas. 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 $0 \le x \le 1$, ($0\% \le x \le 100\%$). 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. $X_{LM} \le 0.3$. 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.

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

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

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.

$$DR = \frac{\rho_g}{\rho_l} \tag{3}$$

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

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%*). Correction of this over-reading is the basis for orifice meter 'wet gas corrections'.

$$OR = \frac{m_{g\ Apparent}}{m_g} \cong \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} \tag{5}$$

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, drag 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.

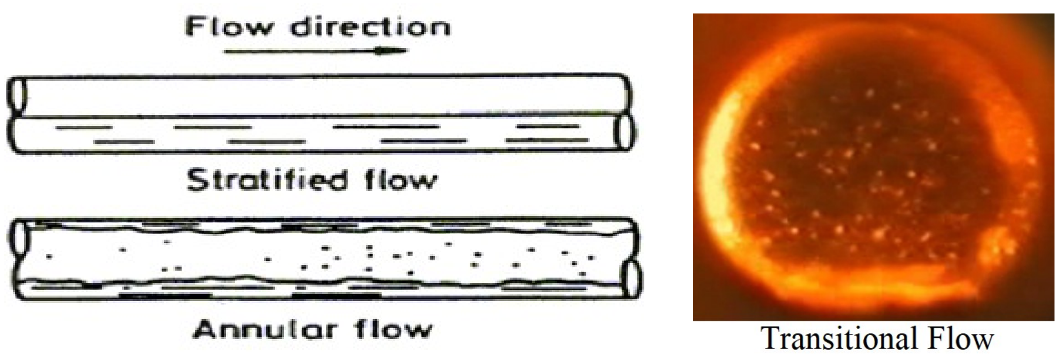

Fig 15. Horizontal Wet Gas Flow Patterns.

5a. Wet Gas Flow, Orifice Meters, Liquid Damming, Slugging and Instability

Wet natural gas flows and saturated wet steam flows are inherently pseudo-steady flows. Liquid loading and the instrument values fluctuate around average values. Instrument standard deviations are higher for two-phase flows than single phase flows.

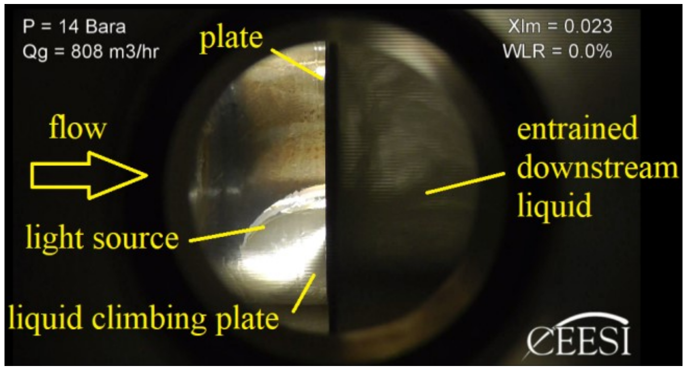

Fig 16. Photograph of a 8" 0.6β Plate
with Stratified Flow 'Climbing' the Plate

Nevertheless, most wet gas flow result can be averaged over time to be reproducible; hence the existence of ISO TR 11583 wet gas orifice meter correlations.

Wet gas flow is inherently pseudo-steady. Liquid loading can change second by second. Liquid can get 'held up' at low level pipework, or at valves etc., gather and then be pushed downstream. This is slugging. Such slugging can cause spikes in instrument readings.

It is often assumed an orifice plate used with two-phase flow *will* dam liquid. However, this is not inevitable, and is dictated by liquid loading, the balance of forces on the liquid, and the size of the 'wall' the plate represents to the oncoming flow. Two-phase flow finds an equilibrium. If there is annular mist flow the liquid does not get dammed. If there is stratified flow it may dam. For a given two-phase flow, as liquid starts to dam the upstream cross sectional flow area reduces, the gas velocity increase, thereby increasing the gas dynamic pressure, i.e. increasing the energy available to drive the liquid through the orifice. A pseudo-steady stratified two-phase flow will settle to an upstream liquid depth where the gas dynamic pressure is usually enough to drive the liquid up the wall of the plate and through the orifice (see Fig 16).

Nevertheless, some photographs of removed plates show 'tide marks'. This occurs for three reasons. The first trivial reason is the pipework was partially flooded during shut down, leaving a high liquid mark. The second reason is the natural stratified flow liquid depth, which exists with stratified two-phase flow with or without an orifice plate, leaves a mark. The third reason is, the flow does not have enough gas dynamic pressure to drive the liquid up the plate, even by the time the liquid depth reaches the base of the orifice. The liquid then spills over like a weir, the height of the 'river' leaves a mark.

For example, consider a 4", sch 80, 0.65β orifice meter, with a gas flow conditions at 50 kg/m^3 and 20 m/s. The orifice plate 'wall' is < 1" in height and the gas dynamic pressure is 10,000Pa. Now consider a 24", sch 80, 0.2β orifice meter, with a gas flow conditions at 3 kg/m^3 and 2 m/s. The orifice plate 'wall' is > 8" in height and the gas dynamic pressure is 6Pa. The second scenario has > 8 times the wall height but only 0.06% of the gas dynamic pressure. The first scenario will not dam liquid. The second example probably will dam liquid. Nevertheless, *most* orifice meter wet gas applications have enough gas dynamic pressure to avoid liquid damming.

With moderate dynamic pressures and plate wall heights significant liquid damming would be unusual in geothermal saturated steam applications. Nevertheless, intermittent slugging from the well and / or liquid hold up upstream of the meter is a more likely phenomenon. This is identifiable by DP fluctuations as the slug passes. This project's geothermal steam flow data does exhibit periodic slugging. In this analysis these were not removed, but absorbed into the massed data averaging.

6 WET NATURAL GAS / SATURATED STEAM ORIFICE METER CONCEPTS

From the 1960s to early 1980's technical papers on orifice meter reaction to 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.

Post 1980's geothermal saturated steam orifice metering R&D tends to discuss 'sustaining innovation' techniques, i.e. the improvement of existing methods. The hydrocarbon industry's wet natural gas orifice metering R&D tended to aim for 'disruptive innovation' techniques, i.e. fundamental changes to the technology that potentially changes how the technology can be used.

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 by 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.

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

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

In this industry this water flowrate information tends to come from either periodic tracer dilution tests or a separator water outlet metering system. However, under normal operation each well does not have a separator and weir 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 flow's quality is assumed from such historical data and commingled with other such flows from different wells, such that a communal saturated steam flow of *assumed* quality is sent to the power plant.

The geothermal industry's R&D on 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 redundancy, 3) for a comprehensive validation system to be in place, and 4) for orifice meter specific Data Validation and Reconciliation (DVR) techniques to further improve the meter's capabilities.

6.2.1 A Hydrocarbon Industry Wet Natural Gas Orifice Meter Correlation

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 data fitted Chisholm exponent '*n*' of ¼ in Equation 7 was an average value for all the orifice meter data across the flow pattern spectrum.

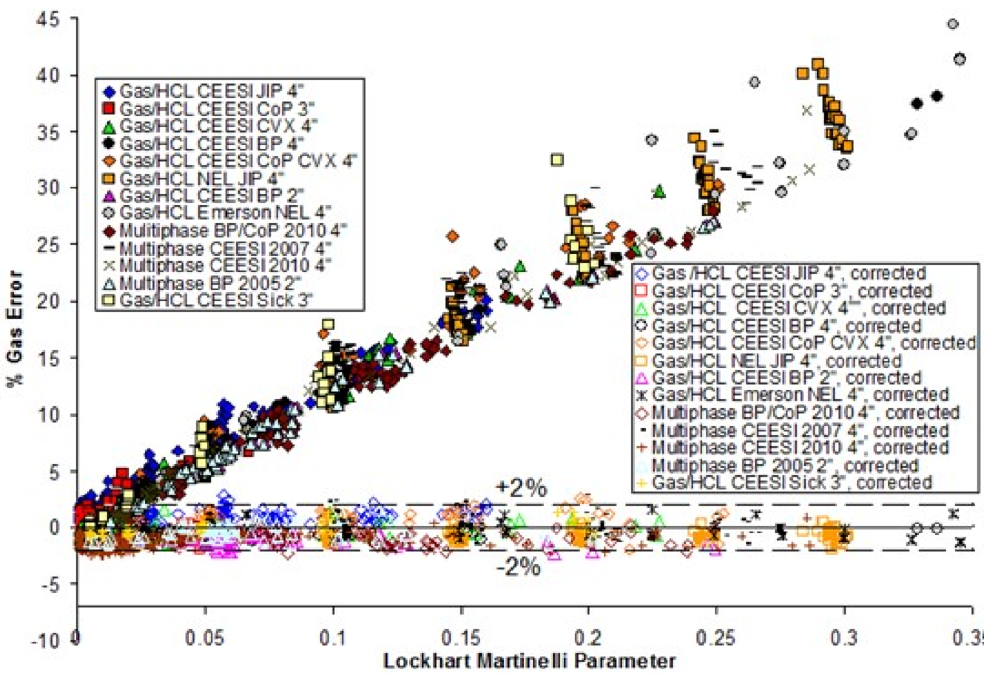

Fig 17. ISO 2" to 4" Flange Tap Orifice Meter Multiphase Wet Gas Data Set With & Without ISO Correction for Known Liquid Flow Rate.

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 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.

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

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

$$Fr_{g,tran} = 1.5 \tag{8}$$

for $Fr_g \leq Fr_{g,tran}$ stratified flow: $$n_{strat} = 0.214 \tag{9}$$

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

Note, $Fr_{g,tran}$ 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 17 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 gas correlation (see TR 11583 [5]). This correlation’s limits are stated to be $0.24 \leq \beta \leq 0.73$, $X_{LM} \leq 0.3$, $Fr_g > 0.2$, and meter inlet diameter > 50mm, although no data was available for > 200mm.

Use of the ISO wet 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 much lower surface tension than water and light oil at ambient conditions, see Fig 18. Very low surface tension liquids facilitate annular / homogenous flow. Furthermore, unlike natural gas with hydrocarbon liquid, saturated steam is a single component flow, and thermodynamic changes through the meter do cause modest phase change. The form of the ISO correlation should work, but saturated steam flow would certainly require different parameter values.

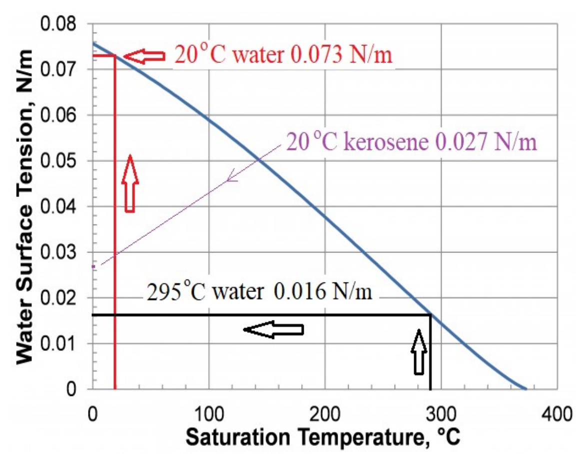

Fig 18. Liquid Surface Tensions.

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, e,g. Lockhart Martinelli parameter (X_{LM}), $X_{LM} = f(PLR)$. This idea was subsequently tested on orifice meter by a 1999-2002 Joint Industry Project (JIP) on wet natural gas metering.

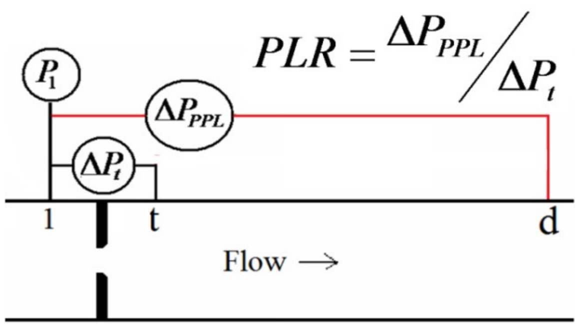

Fig 19. Orifice Meter with PPL DP (ΔP_{PPL}) and Traditional (ΔP_t) DP Read.

Fig 19 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 16. Fig 20 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 $\beta < 0.5$.

Whereas, 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, Steven [4] subsequently showed that these limits were only partly 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.

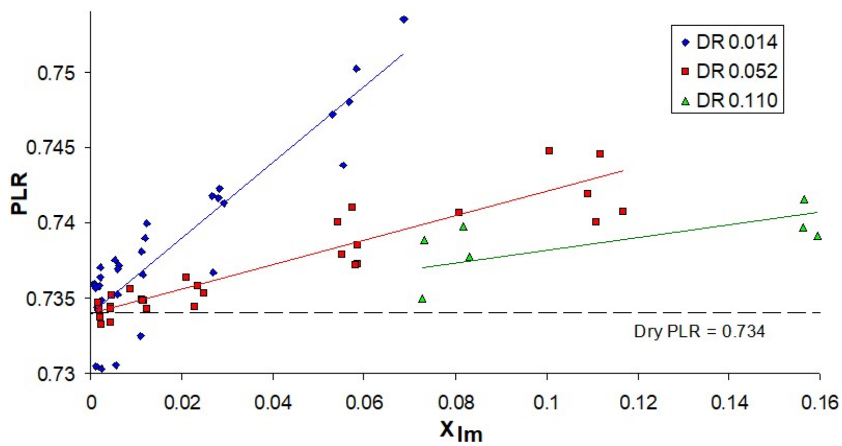

Fig 20. Sample JIP 4", 0.5β Orifice Meter PLR vs. X_{LM} Data.

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

$$Y = \left(PLR_{wet}\right) - \left(PLR_{dry}\right) \quad (12)$$

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

$$X_{LM} < 0.45\left(DR\right)^{0.46} \quad (14)$$

$$DR \leq \left(0.21\beta\right) - 0.09 \quad (15)$$

Optional for $\beta \geq 0.55$:
$$PLR_{dry} = 1.033 - \left(0.8552 * \beta^{1.5}\right) \quad (16)$$

$$m_l = m_g X_{LM}\sqrt{1/DR} \quad (17)$$

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 Aimed Orifice Meter Validation System

A comprehensive orifice meter 'axial pressure profile analysis' diagnostic tool (called 'Prognosis') was developed for the hydrocarbon industry (see Appendix 2). 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. E.g., with two-phase / wet gas flows the liquid loading 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.

6.2.4 Data Validation and Reconciliation ('DVR')

In 2019 Wilson et al [13] introduced the concept of applying pipe system wide Data Validation and Reconciliation ('DVR') techniques to a standalone flow meter system.

Many industries operate large complex pipework systems with numerous and varied equipment. Due to inherent uncertainty in each equipment setting and instrumentation output, the resulting massed raw data can be somewhat inconsistent. As such industry may apply 'data reconciliation' techniques on the macro overall pipe system. Such techniques involve mathematical procedures that combine a pipework's multiple instrumentation readings, equipment settings, associated uncertainties, and governing physical laws, to automatically validate data and reconcile measurements such that the whole makes physical sense. The technique can improve best estimates of variables. The technique transforms raw and sometimes inconsistent data sets into a single consistent data set representing the most likely truth. Such is the acceptance of this methodology that German industry has a standard [14].

Wilson [13] showed that such DVR techniques can be applied inside a control volume consisting of a flow meter and its internal associated diagnostic suite. One such example was the use of an orifice meter and it's diagnostic suite, i.e. 'Prognosis™' (see Section 6.2.3). Whereas Wilson states these techniques can be developed for two-phase flow, e.g. saturated steam, as yet only single phase methodologies have been published. Nevertheless, this research has single phase steam data with the Prognosis system, and the DVR technique can therefore be applied.

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 21 shows the 14" (meter 1) and 10" (meter 2) 0.7β saturated steam results. The solid points are the uncorrected steam flowrate biases. The hollow points are the ISO TR 11583 equation set 6 thru 9 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 flowrate prediction. The data range was $5.9 < P$ (Bar a) < 12.7, $0.003 < DR < 0.0074$, $0.6 < Fr_g < 3.5$, $0 \le X_{LM} < 0.17$, and $0.31 < x \le 1$.

Fig 22 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.

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 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 23 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 22 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 24 shows the results of such a TDFS $X_{LM} = f(PLR, DR, \beta)$ prediction.

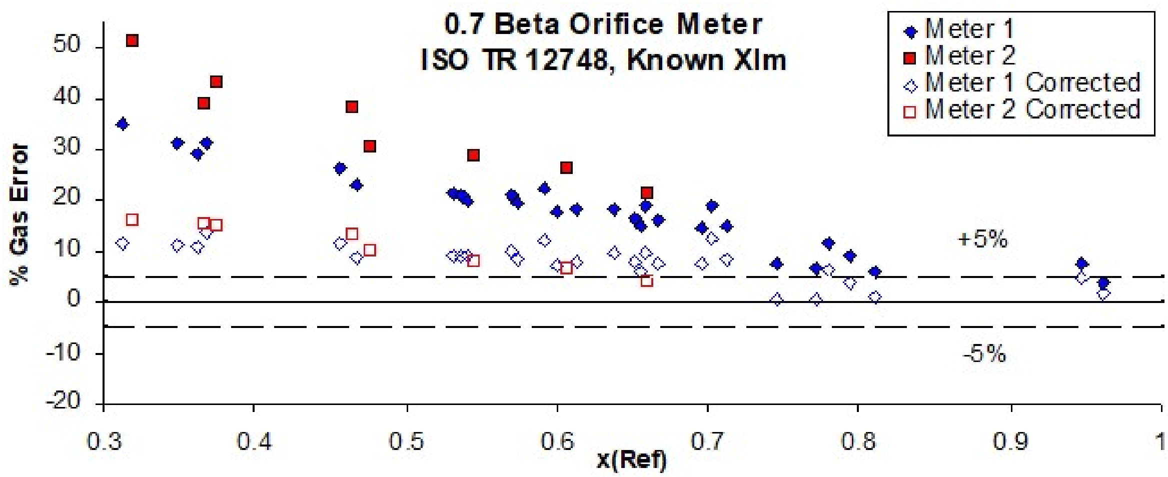

Fig 21. 14" (Meter 1) and 10" (Meter2) 0.7β Steam OR% and ISO Correction (Known 'x').

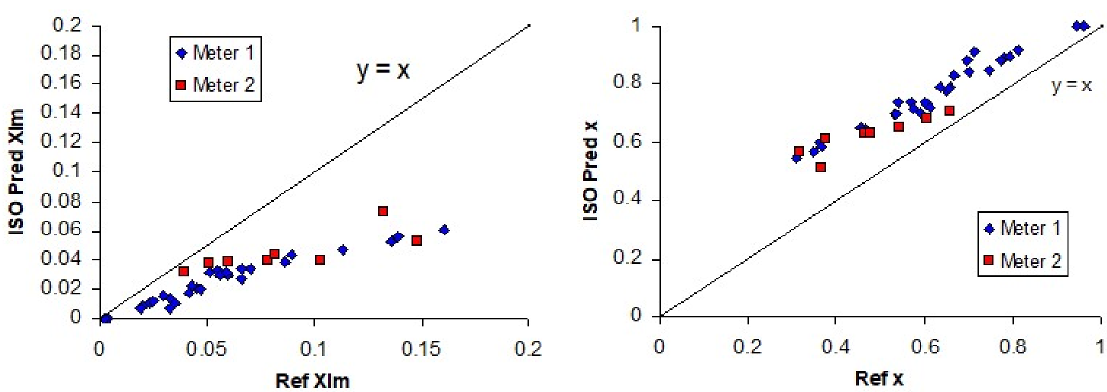

Fig 22. 14" (Meter 1) and 10" (Meter 2) 0.7β ISO X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

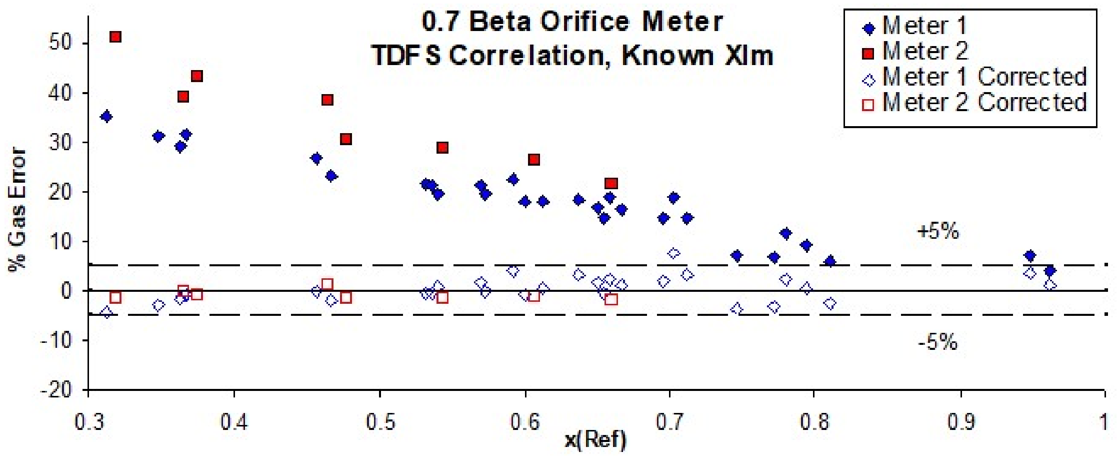

Fig 23. 14” (Meter 1) and 10” (Meter 2) 0.7β Steam OR% & TDFS Correction (Known ‘x’).

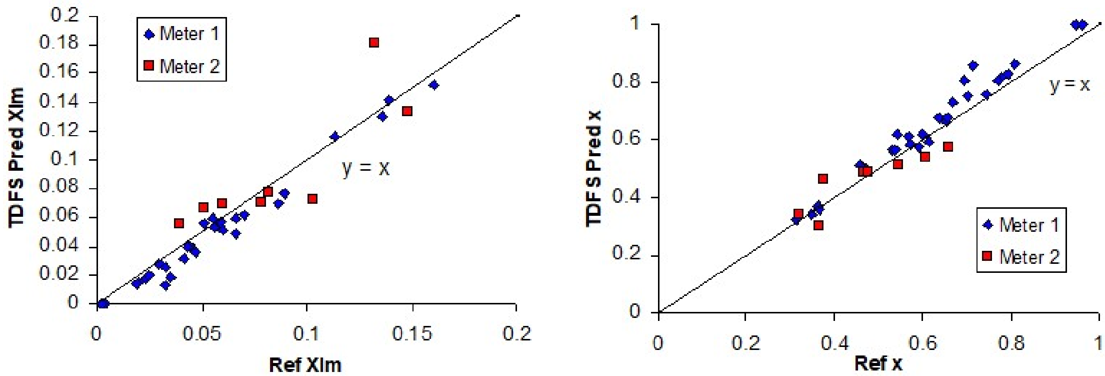

Fig 24. 14” (Meter 1) and 10” (Meter 2) 0.7β TDFS X_{LM} = f(PLR, DR, β) ‘X_{LM}’ and ‘x’ Prediction Performance.

Fig 25 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 26 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.

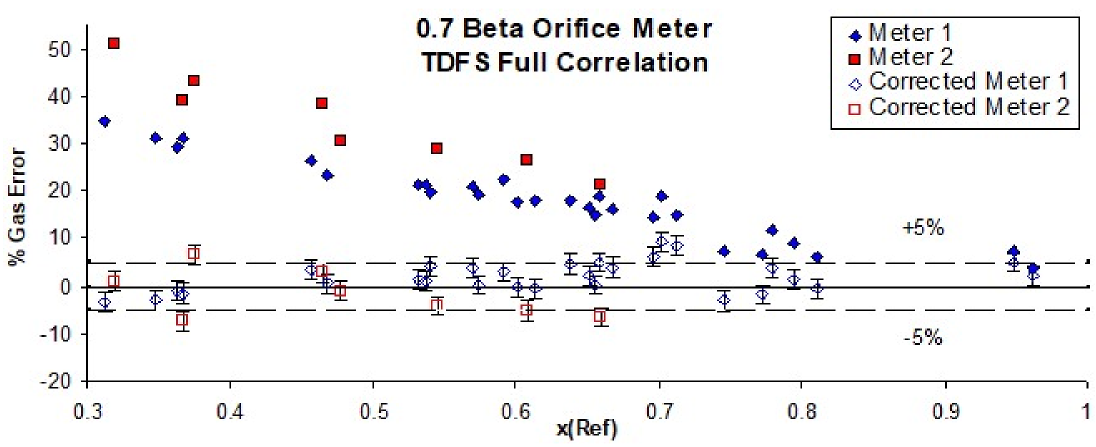

Fig 25. Gas Mass Flow % Error vs ‘x’ for 0.7β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits.

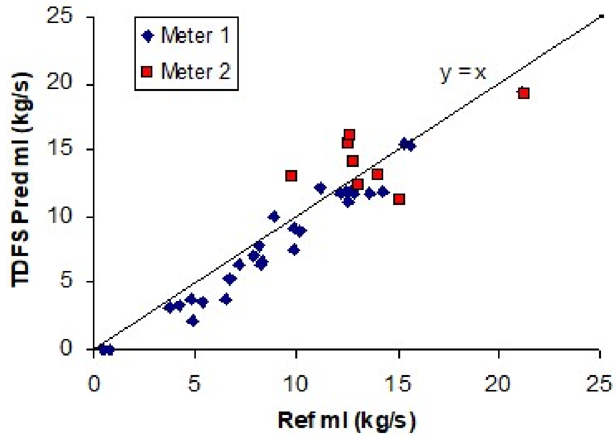

Fig 26. 14” (Meter 1) and 10” (Meter2) 0.7β Orifice Meter TDFS Data Fit Predicted to Reference Water Mass Flowrate Results.

8. LANDSVIRKJUN 14” 0.48β ORIFICE METER SATURATED STEAM RESULTS

A 14”, sch 20, 0.48β, D and D/2 tap orifice flange union meter was tested in 2021. Fig 27 shows routine maintenance on the insertion vortex meter before the tests. Various pseudo-steady flow conditions were held for long periods, and then the data was averaged.

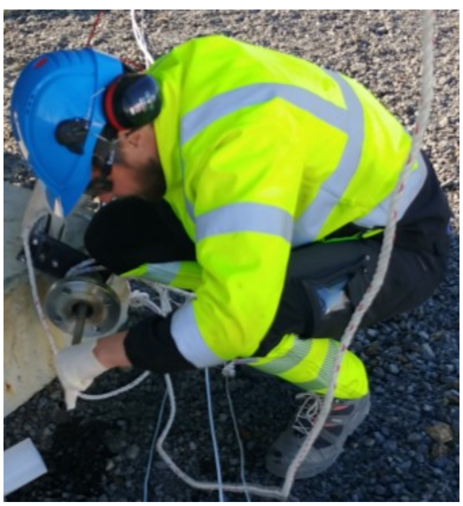

Fig 27.Insertion Vortex Meter Inspection.

During this test saturated single phase flow conditions were logged (i.e. x=1). The single phase flow orifice and reference meters have 1% and 3% uncertainty respectively. The maximum difference expected is the root sum square of 3.16%. Of seven single phase steam flows, the meters agreed to <3.16% five times, and <6% twice. Fig 28 shows these results. However, Fig 38 shows the orifice meter’s corresponding Prognosis results (see Appendix 2). This orifice meter validation system indicates that the orifice meter is working correctly. Furthermore, the saturated steam OR vs. X_{LM} trends are correct, e.g. see Fig 29.

The two single phase outliers were treated as anomalies, probably caused by unsteady flow during logging. The over-all evidence shows the meter is operating correctly.

Fig 29 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 7 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 (Bar a) < 12.4, 0.0045 < DR < 0.0065, 0.27 < Fr_g < 1.1, 0 ≤ X_{LM} < 0.55, and 0.13 < x ≤ 1.

Fig 30 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

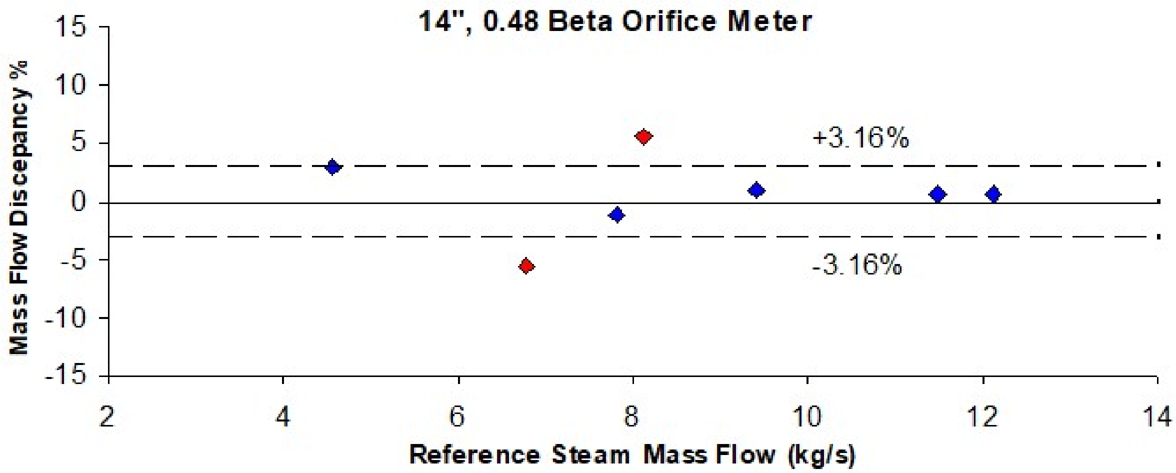

Fig 28. 14”, 0.48β Orifice Meter vs. Single Phase Reference Flow.

TR 11583 leads to the Lockhart Martinelli parameter and quality predictions having significant negative and positive bias respectively.

It is clear from Fig 29 that there is a relationship between these meter’s saturated 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 31 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 scatter is evident.

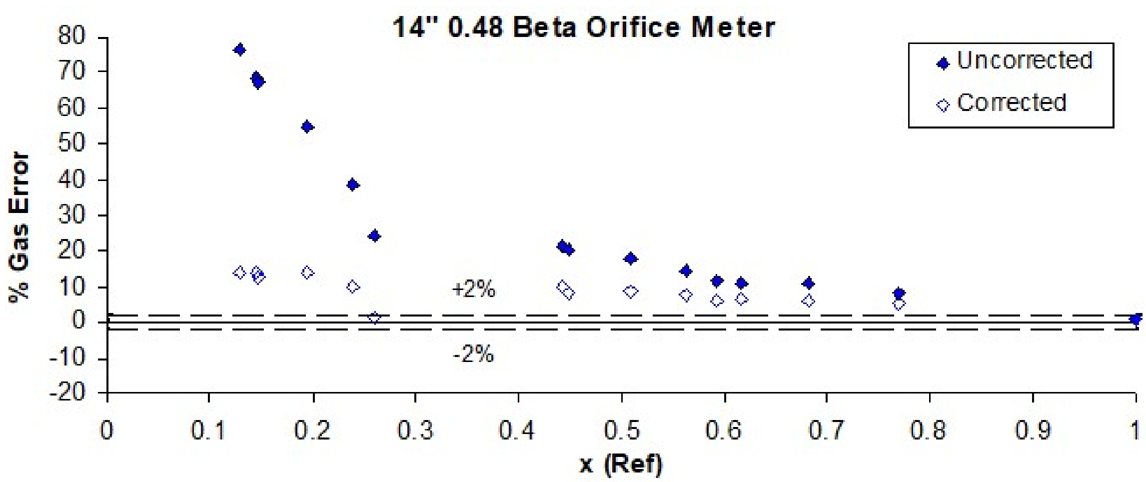

Fig 29. 14” 0.48β Steam OR% and ISO TR 11583 Correction for Known ‘x’.

It is clear from Fig 30 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 32 shows the results of such a TDFS $X_{LM} = f(PLR, DR, \beta)$ prediction.

Fig 33 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 34 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.

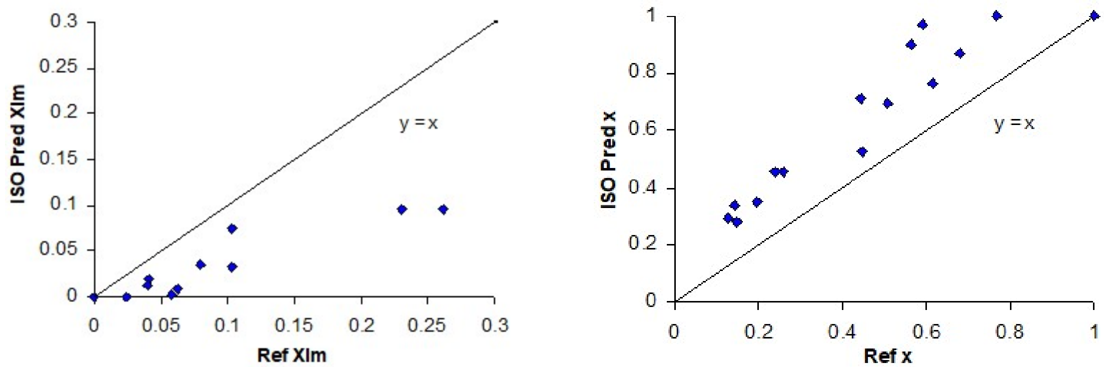

Fig 30. 14", 0.48β ISO TR 11583 X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

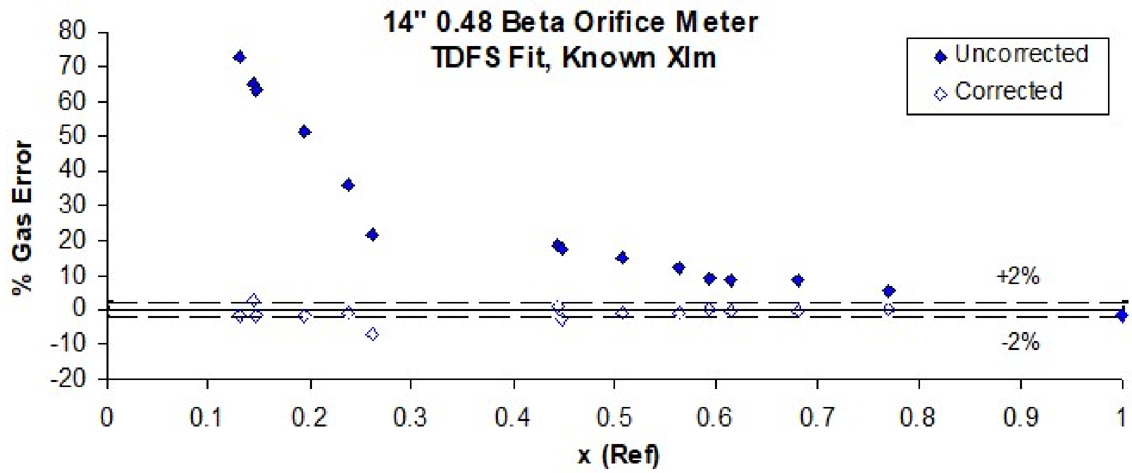

Fig 31. 14" 0.48β Orifice Meter Steam OR% & TDFS Correction for Known 'x'.

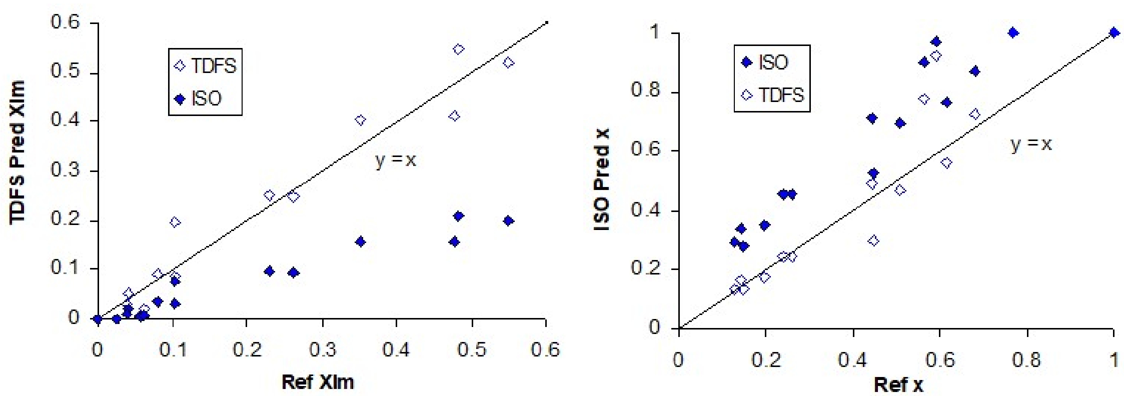

Fig 32. 14", 0 .48β TDFS X_{LM} = f(PLR, DR, β) 'X_{LM}' and 'x' Prediction Performance.

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 35 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.

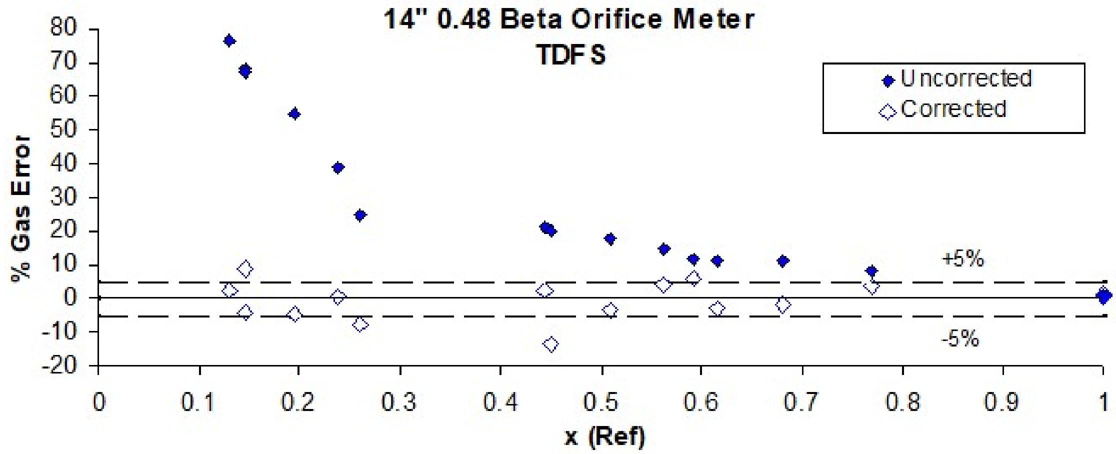

Fig 33. Gas Mass Flow % Error vs 'x' for 0.48β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits.

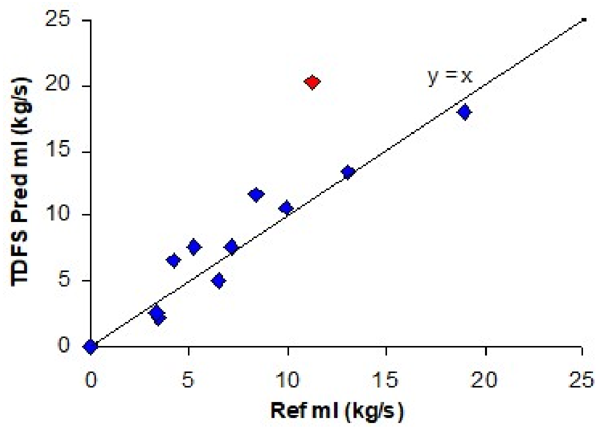

Fig 34. 14" 0.48β TDFS Data Fit Predicted to Reference Water Mass Flowrate Results.

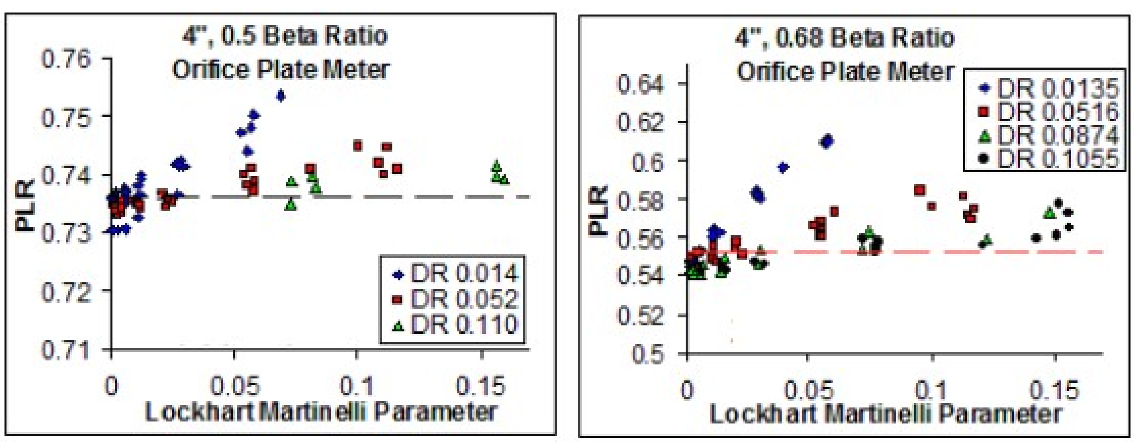

Fig 35. 4" Orifice Meter Beta Dictated PLR vs. X_{LM} Sensitivity.

Comparing Figs 24 and 32 shows that the 0.48β meter's Lockhart Martinelli parameter / quality prediction has somewhat more scatter than the 0.7β meters. This is a natural consequence of the lower beta producing a shallower X_{LM} vs. ΔPLR gradient, i.e. the lower beta orifice meter has a PLR less sensitive to liquid loading. This is shown for this current saturated steam data in Figs 36 and 37.

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.

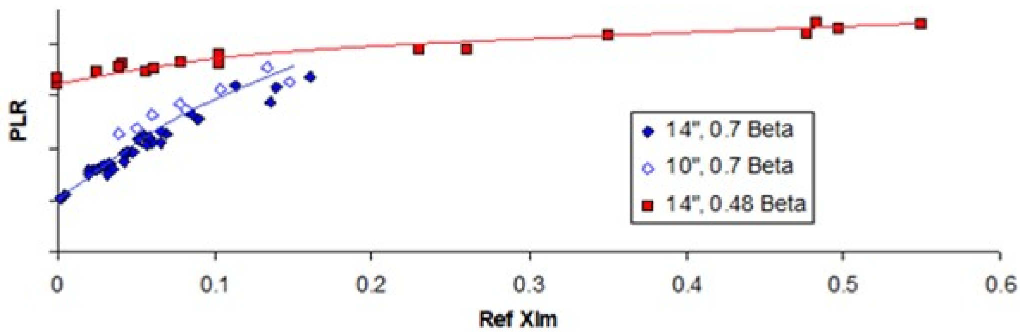

Fig 36. 0.48β and 0.7β Saturated Wet Steam PLR vs. X_{LM} Data.

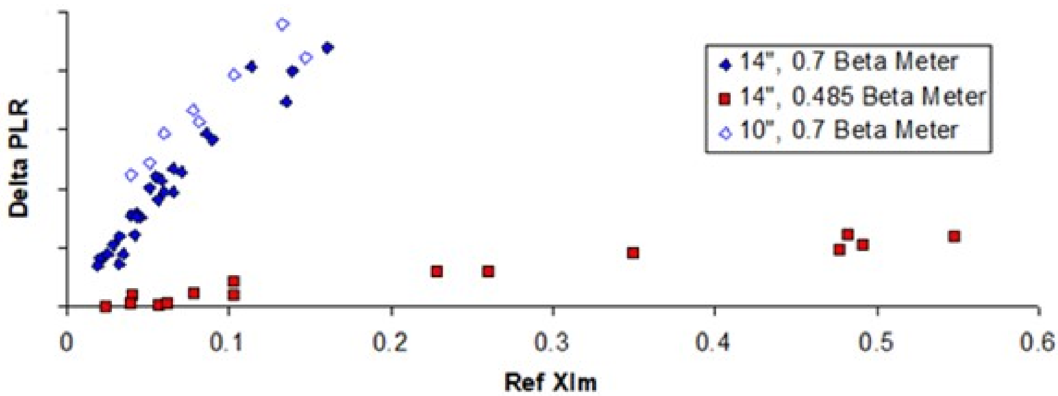

Fig 37. 0.48β and 0.7β Saturated Wet Steam PLR vs. X_{LM} Relative Relationship.

9 ORIFICE METER AXIAL PRESSURE PROFILE ANALYSIS DIAGNOSTIC SYSTEM

Appendix 2 describes the Axial Pressure Profile Analysis 'Prognosis' operating principle. Such a system can be used to either track known phenomena (e.g. varying steam quality) or show the presence of unexpected issues.

Fig 38 shows results from the 14", 0.48β orifice meter running with single phase flow steam. All diagnostic points are inside the Normalized Diagnostic Box (NDB), indicating a correctly operating meter.

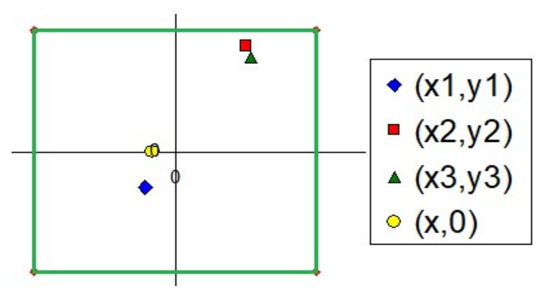

Fig 38. Prognosis Result for Correctly Operating Single Phase Flow Orifice Meter.

9a Prognosis as an Active Steam Quality Tracking System

The 14", 0.48β orifice meter was tested with steam qualities between $0.14 \le x \le 1$. The 14" and 10" 0.7β orifice meters were tested with steam qualities between $0.3 \le x \le 1$. Lowering steam quality, i.e. raising the relative amount of liquid, makes the Prognosis points move away from the NDB. Fig 39 shows the 0.485β and 0.7β orifice meter Prognosis responses to saturated wet steam flow.

Fig 39. 0.48β Meter (Left) and 0.7β Meter (Right) Tracking Steam Quality.

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

9b General Use of Prognosis to Identify Orifice Meter Problems

The following examples use the 14", 0.48β orifice meter single phase steam flow data as a baseline for hypothetical Axial Pressure Profile Analysis ('Prognosis ™') examples.

Example 1: Inlet Diameter Keypad Entered Positive Bias

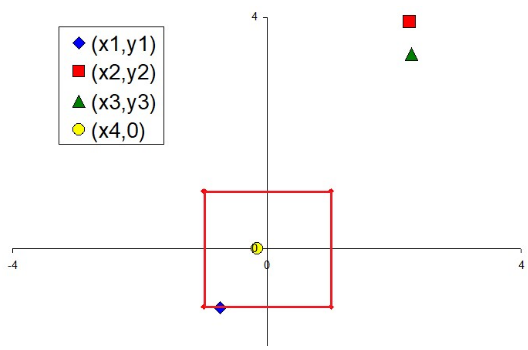

Fig 40. Inlet Diameter Entered High

Say the inlet diameter of 0.34m was erroneously entered as 0.3**6**m, inducing a -0.7% flow prediction bias. Traditionally orifice meter systems have no diagnostics and cannot see this issue. Fig 40 shows the Prognosis result.

Example 2: Throat Diameter Keypad Entered Positive Bias

Say the orifice bore diameter of 0.1649m was erroneously entered into the flow computer as 0.1**7**49m. This would induce a +13.4% flow prediction bias on the single phase steam flow. Traditionally orifice meter systems have no diagnostics and cannot see this issue. Fig 41 shows the Prognosis pattern.

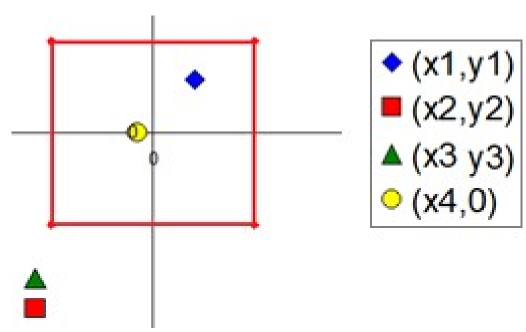

Fig 41. Throat Diameter Entered High.

Example 3: Primary DP Negative Drift

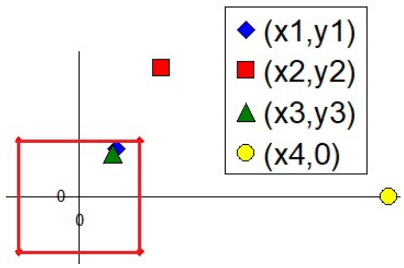

Fig 42. Primary DP Negative Drift

Say the primary transmitter DP read an erroneous DP of 0.7221 Bar instead of the actual DP of 0.7601 Bar, i.e. a -5% bias. This would induce a -2.5% flow prediction bias on the single phase steam flow. Traditionally orifice meter systems have no diagnostics and cannot see this issue. Fig 42 shows the Prognosis pattern.

Example 4: PPL DP Negative Drift

Say the PPL transmitter read 0.5297 Bar instead of the actual DP of 0.5576 Bar, i.e. a -5% bias. This would not induce a primary flow prediction bias, but it does constitute an orifice meter diagnostic system malfunction. Fig 43 shows the Prognosis pattern. It is important that a diagnostic system monitors itself as well as the meter.

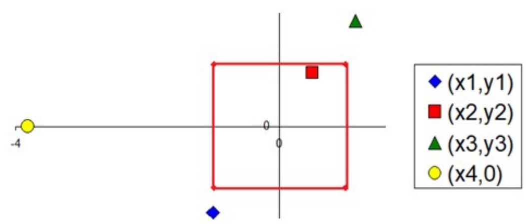

Fig 43. PPL DP Negative Drift

Example 5: Saturated Steam Gas Flow with Primary DP Drift

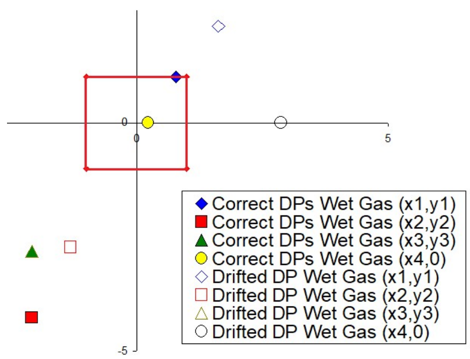

Fig 44. 14”, 0.48β Orifice Meter Wet Steam Flow and Wet Steam Flow with DP_t drift.

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 44 shows the Prognosis result if the DPs are correct, i.e. a saturated wet steam pattern, and if the meter also has an erroneous primary DP reading. With the exception of the respective (x_3,y_3) points, the patterns are different. With a DP error x_4 leaves the box specifically showing that there is a DP issue, regardless of the wet saturated gas.

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.:

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \tag{18}$$
$$\Delta P_{PPL} = \Delta P_t - \Delta P_r \tag{19}$$
$$\Delta P_r = \Delta P_t - \Delta P_{PPL} \tag{20}$$

Fig 45 - 47 show the 14" and 10" 0.7β meter performances if the primary DP transmitter fails, and only the recovered and PPL DPs are available. Whereas standard orifice meters with a PPL reading would stop operating as a two-phase meter, 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.

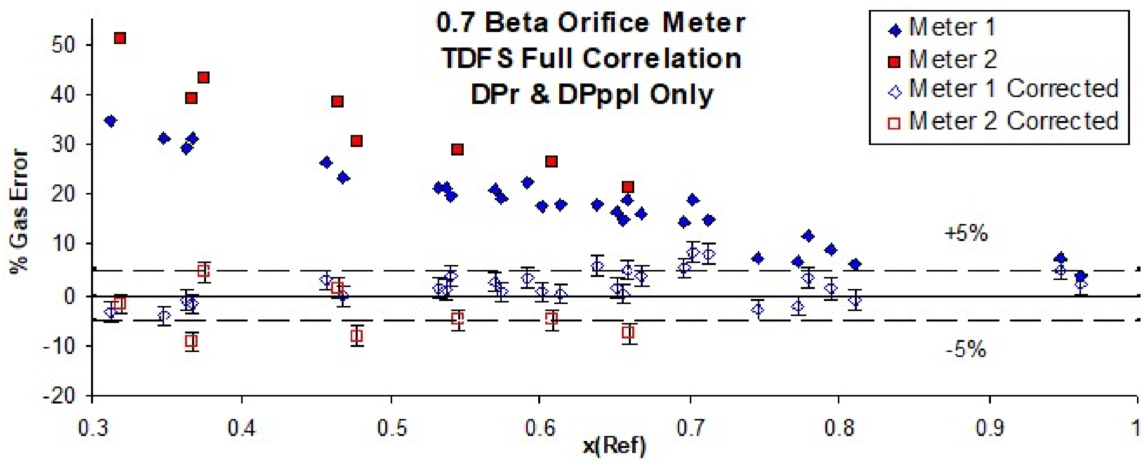

Fig 45. Gas Mass Flow % Error vs 'x' for 0.7β Apparent and Corrected Steam Flow Using TDFS OR% = f(X_{LM}, DR, Fr_g) and X_{LM} = f(PLR, DR, β) Fits, Using ΔP_r and ΔP_{PPL} Only.

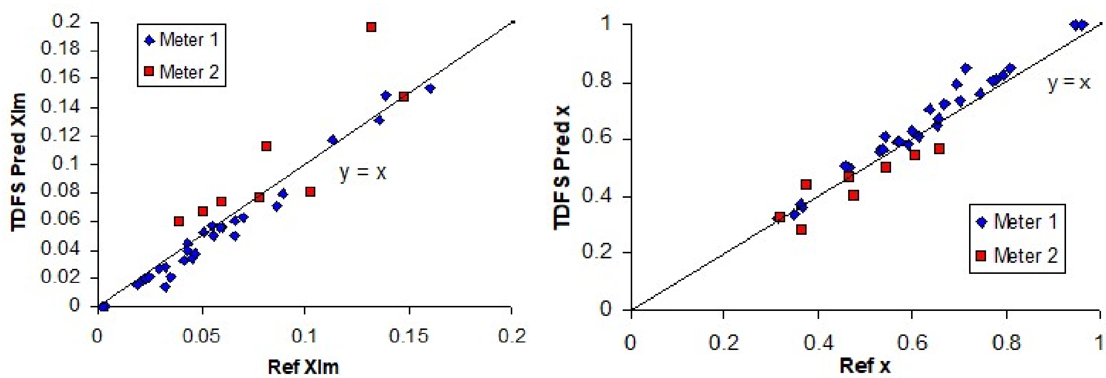

Fig 46. 14" and 10" 0.7β Two-Phase Orifice Meter TDFS Data Fit X_{LM} and 'x' Prediction Using ΔP_r and ΔP_{PPL} Only.

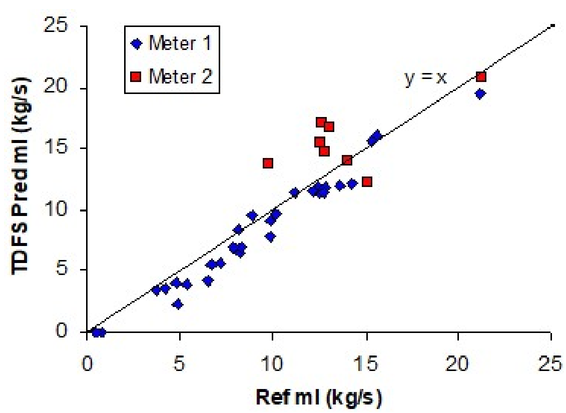

Fig 47. 14" and 10" 0.7β Two-Phase Orifice Meter TDFS Data Fit Water Flowrate Prediction

11 DATA VALIDATION AND RECONILIATION (DVR) 'OCULUS' TECHNIQUE

When used with single phase steam flow the 14", 0.485β orifice meter had a relatively low flowrate prediction uncertainty. The primary DP was read by a new digital DP transmitter where it was zeroed to the applications pressure and temperature. Relative to the DP transmitter span and Upper Range Limit the primary DPs were high to moderate across the flow range, and therefore the DP uncertainties were low. With the steam density uncertainty found via the relatively low uncertainty pressure and temperature readings and steam tables IW97 code, the steam density is also of low uncertainty. The largest uncertainty contribution comes from the ISO discharge coefficient value of 0.5%. Therefore, using the AGA 3 orifice meter uncertainty calculation template produces a steam flowrate prediction uncertainty of 0.58% at the highest single phase steam flowrate (see Fig 48). This uncertainty rises to 0.77% at the lowest flowrate.

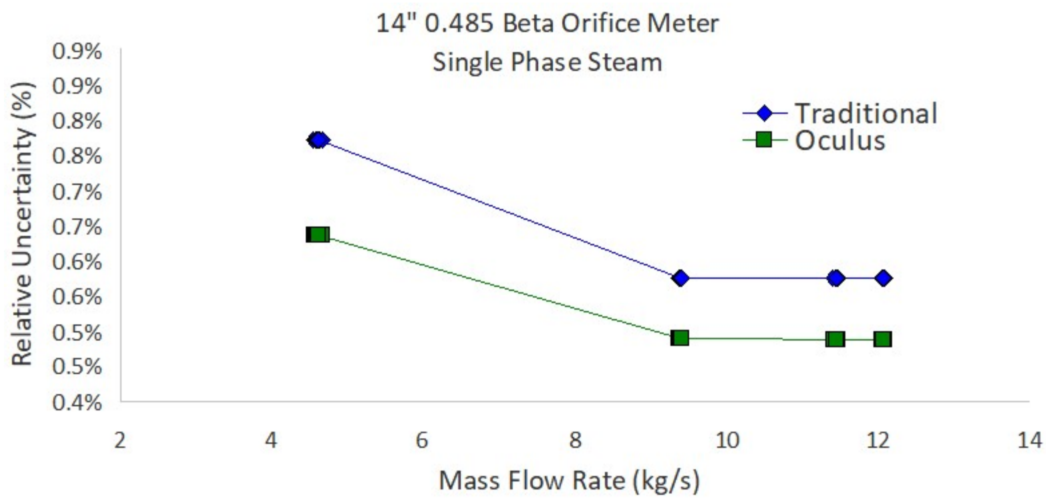

Fig. 48. Single Phase Steam Flow Orifice Meter Standard and Oculus 'DVR' Flowrate Prediction Uncertainty.

Once the orifice meter axial pressure profile analysis diagnostic suite 'Prognosis' shows the meter is working correctly, the system's three DPs (see Fig. A2) can then be further utilized to apply 'Oculus' (see Wilson et al [13] for technical details). This is the application of data validation and reconciliation techniques internal to the metering system. Fig 48 shows that this method reduces the steam flowrate uncertainty of the highest flowrate from 0.58% to 0.49%, and of the lowest flowrate from 0.77% to 0.64%. That is, even for this low flowrate prediction uncertainty meter 'Oculus' still reduces the absolute uncertainty in the order of 0.1%, which is a 15% relative reduction.

12 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.

Saturated steam metering requirements of geothermal well operation could be met 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 was 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 a 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.

Finally, it has been shown that for single phase steam flow at least, use of the 3 DP configuration as used by the diagnostic system 'Prognosis™', can also facilitate the application of the DVR technique 'Oculus'. This produces a noticeable reduction in steam flowrate prediction uncertainty.

Appendix 1: James Lip Pressure Device

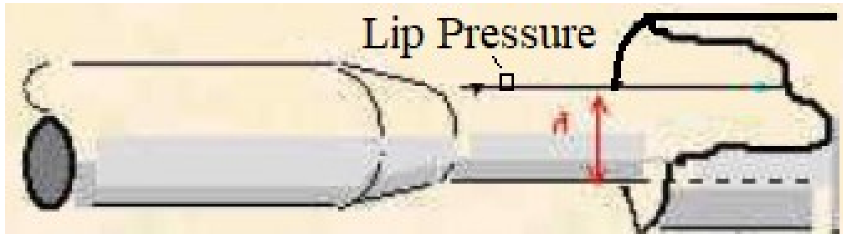

Fig A1. The James Lip Pressure Device

The James Lip Pressure method is a two-phase saturated steam metering method developed in New Zealand for the geothermal power industry by Russel James, circa 1962. For a known water flowrate the method predicts total mass flow rate, enthalpy, steam flowrate, and quality.

A pipe of cross sectional area 'A' discharges into an atmospheric separator, aka 'silencer', entrance (see Fig A1). The pressure, P, is read at the exit (or 'lip') of the discharge into the atmospheric separator. Fig 10 shows a separator with a James Lip Pressure Device at its entrance. Fig 12 show the James Lip pipe that is inserted into the entrance of the separator. James noted that there was a relationship between the total mass flow (m_t), i.e. the sum of the water mass flow (m_l) and steam mass flow (m_g), the total flow enthalpy (h), the cross sectional area (A), and the pipe pressure (P). James stated:

$$\frac{m_t h^{1.102}}{3600 A P^{0.96}} = 0.184 \quad \text{(A1.1)}$$

where m_t is in tons/hour, h is flowing enthalpy (kJ/kg), A is lip pipe area (cm2) and P is 'lip pressure' (bar absolute).

The definition of steam quality is such that:

$$x = \frac{m_g}{m_g + m_l} = \frac{m_g}{m_t} \quad \text{(A1.2)}$$

$$1 - x = \frac{m_l}{m_g + m_l} = \frac{m_l}{m_t} \quad \text{(A1.3)}$$

The relationship between steam (h_g), water (h_l), and latent enthalpy (h_{lg}) is:

$$h = xh_g + (1-x)h_l = h_l + xh_{lg} \quad \text{(A1.4)}$$

where

$$h_{lg} = h_g - h_l \quad \text{(A1.5)}$$

And therefore:

$$x = \frac{h - h_l}{h_{lg}} \quad \text{(A1.4a)}$$

And therefore:

$$(1-x) = 1 - \frac{(h - h_l)}{h_{lg}} = \frac{h_{lg} - (h - h_l)}{h_{lg}} = \frac{(h_g - h_l) - (h - h_l)}{h_{lg}} = \frac{h_g - h}{h_{lg}} \quad \text{(A1.5)}$$

From equations A1.3 and A1.5:

$$m_t = \frac{m_l}{1-x} = \frac{m_l h_{lg}}{h_g - h} \tag{A1.6}$$

Hence, the James equation A1.1 becomes:

$$\frac{m_t h^{1.102}}{3600\,AP^{0.96}} = \frac{m_l h_{lg} h^{1.102}}{3600\,AP^{0.96}\left(h_g - h\right)} = \frac{Y h_{lg} h^{1.102}}{3600\left(h_g - h\right)} = 0.184 \tag{A1.7}$$

Let Y be defined as:

$$Y = \frac{m_l}{AP^{0.96}} \tag{A1.8}$$

If the water flow (m_l) is known from the separator exit flow reference meters, and lip pressure *P* is read, and lip area *A* is known, then *Y* is a known parameter. As the separator is at atmospheric conditions (1.0125 Bar abs) the steam enthalpy h_g, water enthalpy *hl*, latent enthalpy h_{lg} are known as 2676kJ/kg, 419kJ/kg, and 2257kJ/kg respectively. Hence:

$$Y = \frac{(0.184)(3600)(2676-h)}{2257h^{1.102}} = \frac{0.293(2676-h)}{h^{1.102}} \tag{A1.9}$$

Hence, for a known Y, the total flow enthalpy *h* can be found by iteration of equation A1.9. With total enthalpy *h* found, the total mass flow and quality are found via equations A1.6 and A1.4 respectively:

$$m_t = \frac{m_l}{1-x} = \frac{m_l h_{lg}}{h_g - h} = \frac{m_l(2257)}{2676-h}$$

$$x = \frac{h-h_l}{h_{lg}} = \frac{h-419}{2257}$$

And with total flowrate *m* and quality *x* found, equations A2a and A3a give the steam (m_g) and water (m_l) flows respectively:

$$m_g = x m_t \tag{A1.2a}$$

$$m_l = (1-x) m_t \tag{A1.3a}$$

Appendix 2: 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 isnow given. For details, refer to the descriptions given in by Skelton et al [9] & Rabone et al [10].

Fig A2 shows a sketch of an orifice meter and it's 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 A2.1. 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 variance.

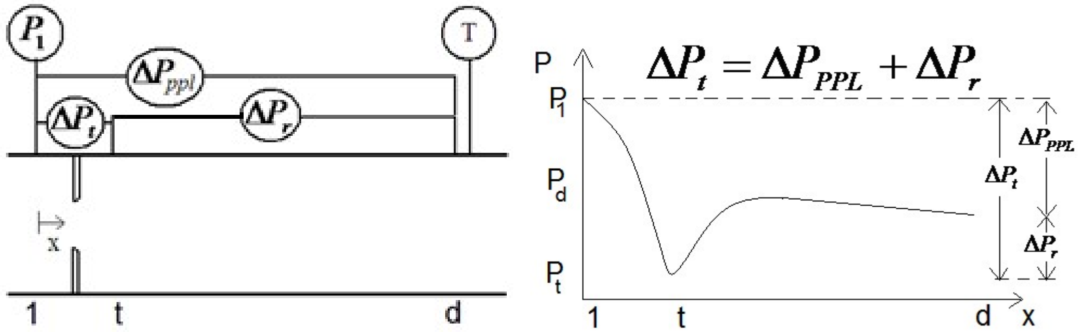

Fig A2. Orifice Meter with Instrumentation Sketch and Pressure Field Graph.

DP Summation:	$\Delta P_t = \Delta P_r + \Delta P_{PPL}$,	uncertainty ± θ%	(A2.1)
Traditional flow calculation:	$m_t = f(\Delta P_t)$,	uncertainty ± x%	(A2.2)
Expansion flow calculation:	$m_r = f(\Delta P_r)$,	uncertainty ± y%	(A2.3)
PPL flow calculation:	$m_{PPL} = f(\Delta P_{PPL})$,	uncertainty ± z%	(A2.4)

Each DP can be used to independently meter the flow rate, as shown in equations A2.2, A2.3 & A2.4. 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 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.

These seven diagnostic results can be plotted on a display. The seven checks can be represented as four co-ordinates, as shown in Fig A2.1. 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. The pattern of a meter malfunction can indicate the source of the problem.

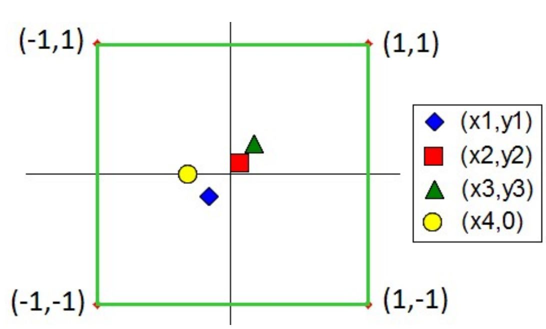

Fig A2.1. Prognosis Orifice Meter Display.

Technical Paper

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