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Research Article

Modelling of Multiphase Flow Metering for Crude Oil Production Monitoring

Ego C. Obukohwo†, Okologume C. Wilfred‡#*, Dulu Appah‡ and Marcus B. Umeleuma†

†#Department of Petroleum and Gas Engineering, University of Port Harcourt, Port Harcourt, Nigeria
‡Department of Petroleum and Natural Gas Engineering, Federal University of Petroleum Resources, Effurun Delta State, Nigeria

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Abstract

Multiphase flow metering (MPFM) use has seen considerable growth and adoption in the oil and gas industries. The real time multiphase flow metering is an advanced technology for production allocation and monitoring. It is a virtual metering technology that is located either remotely in a control room or on the MPFMs. The challenge of real-time MPFM in exploration well monitoring and optimization is to resolve the uncertainty of the well conditions so that the monitoring operation maybe carried out in a controlled and safe manner. In this study, a computer program was developed to show a real-time (MPFM) model utilizing Coriolis meter principle to convert volumetric rates and faction at test condition to standard condition. The systems have mostly been pipeline model enabling it to simulate process state in pipeline in real time reaching from well to inlet facilities on a production unit. The study result generated by the real-time MPFM for the inputted parameters was observed to be a steady state flow rate at standard condition of pressure and temperature measurements. A deterministic economic model was also developed to consider the economic viability to install the multiphase flow meter (MPFM) as an effective alternative to test separators, test lines and offshore test barges for production monitoring, allocation and well testing operation. Analysis of the economic evaluation model was performed by calculating the production life of the well, which is directly linked with the working duration of the MFPM to give reliable analysis as production declines and new flow regimes prevail. Capital expenditures (CAPEX) and operating expenditures (OPEX) for the brand of MFPM to be installed is provided and the depreciating service life of the MPFM is calculated using a straight-line depreciation method. The NPVs calculated shows that it was economically viable to install the multiphase flow meter (MPFM) considered.

Keywords: *OPEX, CAPEX, Coriolis meter, MPFM, Multiphase flow, Metering.*

1. Introduction

Multiphase flow is the flow of two or more phases flowing simultaneously in a closed conduit. This work deals in particular with multiphase flows of oil, water and gas, hence the importance of measuring the multiphase flow rate and its separate variables lead to the manufacturing of the Multiphase Flow Meters known as (MPFM). The multiphase flow meter (MPFM) is a device for measuring the individual oil, water and gas phase fractions in a multiphase flow. The term "Multiphase Flow Metering" in its broadest interpretation can be used to refer to both wet gas metering as well as the measurement of oil, water, and gas portions of commingled streams which is commonly referred to as multiphase metering (Mehdizadeh *et.al*, 1997-1998). Production test are run routinely to measure oil, gas and water produced by a well under normal producing conditions. The test results are needed for reservoir management, forecasting purposes and for the monitoring of individual well and total field production. Production test provide periodic physical evidence of well conditions. Selecting the proper testing equipment for production testing is of preeminent important if the best possible results are to be obtained.

Multiphase Flow Metering (MPFM) have been recognized to provide the critical need to alleviate production decline, optimization of production operation and reduce capital and operating costs for companies managing and optimizing their upstream oil and gas business (Mehdizadeh *et.al*, 2003-2004). The multiphase meters for simultaneous measurement of gas, oil and water flow rates are now finding increasing acceptance in onshore and offshore fields in which the phases are separated and then metered using single phase meters before being recombined into a multiphase steam (Hatton, 2013).

The development of multiphase metering technology for oil/gas/water flow started in the early eighties (Jamieson, 1998). Several multiphase testing

*Corresponding author: **Okologume C. Wilfred**

units have been introduced in the past years to measure oil, gas and water rates and it has been said that "the application of multiphase flow meters in company operations if successful will provide continuous online well production and monitoring and will also eliminate large conventional test separators, portable test units and well test lines (Al-Taweel and Barlow, 1997-1998). The real-time model based multiphase flow metering is an advanced technology for production allocation and monitoring for smaller and marginal fields. These real-time MPFMs technology have been around for about two decades and most of them are on a steady state approach but some are also dynamic, meaning that the system could have a solution also in transient conditions. This technology goes under lots of different names, but virtual metering seems to be the most common term (Patel et. al, 2014).

The real-time metering systems have computers which are located either on the multiphase flow meters (MPFMs) or located remotely in a control room (Hamoud and Al-Ghamdi, 2008). The basic principle of such systems is that they are mostly been pipeline model reaching from well to inlet facilities on a production unit enabling it to simulate process states in the pipeline in real time (Patel et. al, 2014).This work is intended to serve as a guide for users of multiphase flow meters to enable the user evaluates their suitability for use in specific applications. The study is limited to the measurement accuracy and performance of the total flow rate (gas/oil/water) for multiphase flow meters (MPFM).

2. Methodology

2.1 Model for Real-Time Multiphase Flow Metering Unit

A computer program was developed using virtual basic (Vb.net*)* to first convert the mass flow rate data into volumetric rates and fractions at test conditions.

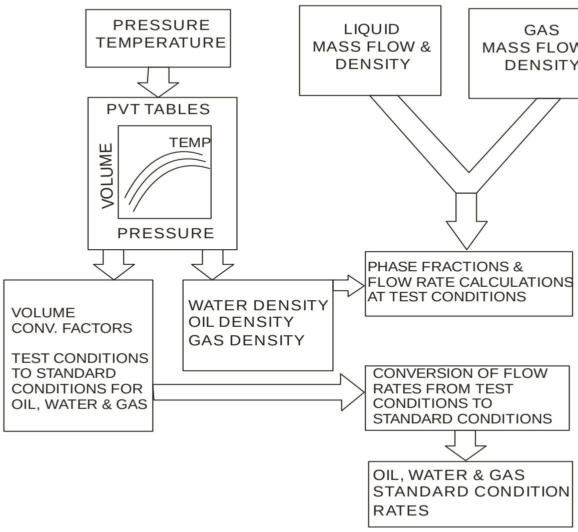

Fig. 1: Conversion of Mass flow rate from test condition to standard condition

The program then converts the rates from test conditions to standard conditions. These calculations depend on input PVT property data that is specific to the crude being tested (see figure 1).

2.1.1 Multiphase Flow Metering (MPFM) Model

The start-up interfaces of the Christometer consist of Real-Time Fluid Flow Metering module and the Deterministic Economic Evaluation Model (Flow Meter Design Economics) module as shown in figure 2. The Real-Time Fluid Flow Metering and Flow Meter Design Economics module calculates the real-time fluid flow rates at standard condition and the economic analysis of MPFMs respectively. Each module analyses the input data and gives the summary of results and graphical presentations.

Fig 2: Loading interface of the MPFM model

The technology has numerous names, but the virtual metering seems to be the most common term been used. The basic principle of such systems is that the pipeline model is fed with real time measurements from the Supervisory Control and Data Acquisition (SCADA) into model boundaries enabling it to simulate process state in the pipeline at real time. During the development of the real-time fluid flow metering model, a number of down-hole crude oil samples were obtained for PVT analysis. This determines oil, gas and water densities, formation volume factors of oil, gas and water, specific gravity of gas and API of oil, and solution gas oil ratio (Rs) at different temperature and pressure. Table 1 and 2 shows the input parameters and PVT values for the real-time multiphase metering model; for converting actual volumetric flow rates and factions into standard flow rate condition. These data are the input PVT tables for the program to calculate the rates at standard conditions.

The following equations were used to calculate the flow rates at standard conditions:

(A) Liquid Calculations:

Specific gravity of water @ test conditions;

$$\gamma wt = \frac{\gamma ws}{\left(2.718^{(0.00022*(LT-60))}\right)*(1-(0.0000032*LP)} \quad (1)$$

Water cut at test conditions;

$$Wct = \frac{\gamma ml - \gamma ot}{\gamma wt - \gamma ot} \quad (2)$$

Oil rate at standard conditions (stb/sec);

$$Qos = \frac{(1-Wct)*MF\ ibs/sec*4.1085}{Bot*\gamma ml} \quad (3)$$

Water rate at standard conditions (*stb/sec*);

$$Qws = \frac{Wct**MF\ ibs/sec*4.1085}{\gamma ml*(2.78^{(0.00022*(LT-60))})*(1-(0.0000032*LP)} \quad (4)$$

Total Oil rate at standard conditions (*stb/sec*);

$$Q_{ots} = Q_{os} + Q_{oc} \quad (5)$$

Where,
Q_{oc} is the oil carry over from gas corlolis meter.

Oil Fraction at Standard condition;

$$F_0 \frac{Qots}{Qots + Qws + (\frac{Qgs\,t*1000}{GOR})} \quad (6a)$$

Water cut at standard conditions;

$$F_w = W_{cs} = \frac{Qws}{Qots + Qws + (\frac{Qgst*1000}{GOR})} \quad (6b)$$

(B) Gas Calculations:

Gas fraction at test conditions;

$$G_{ft} = \frac{\gamma mg - \gamma ot}{\gamma gt - \gamma ot} \quad (7)$$

Where,
γ_{gt} is specific gravity of free gas relative to standard conditions fresh water.

Oil carryover at standard conditions;

$$Q_{oc} = \frac{(1-Gft)*MF\ IBS/sec*4.1085}{\gamma ml*Bot} \quad (8)$$

Note: All liquid carryover is assumed to be oil.

Free gas at standard conditions (scf/sec);

$$Q_{gs} = \frac{Gft*MF\ IBS/sec*23.0676}{\gamma mg*Bot} \quad (9)$$

Total gas rate at standard conditions (Mscf/sec);

$$Q_{gts} = \frac{Qgs + Rs*Qots}{1000} \quad (10a)$$

$$R_s = \gamma_{gt}\left(\left(\frac{P}{18.2} + 1.4\right)10^X\right)^{1.2048} \quad (10b)$$

$$X = 0.0125API - 0.00091(T - 460) \quad (10c)$$

Gas Oil ratio (scf/stb);

$$GOR = \frac{Qgst*1000}{Qots} \quad (11a)$$

Oil Fraction at Standard condition;

$$F_g = GVFs = \frac{(\frac{Qgst*1000}{GOR})}{Qots + Qws + (\frac{Qgst*1000}{GOR})} \quad (11b)$$

Table 1: Inputted parameters and values for Real-Time Multiphase flow metering model (*Case 1*)

Parameters	Values	S.I Unit
Specific Gravity of Water (Y_{ws})	1.092	Frac.
Liquid Temp.	154	^{0}F
Liquid Pressure	2879.3	Psi
Mass Flow Rate (MF, ibs/min)	200	Ibs/min
Specific gravity of oil @test condition (Y_{ot})	0.800	Frac.
Oil formation volume factor (B_{ot})	1.268	bbl/stb
Specific gravity of oil + water @ test condition (Y_{ml})	0.889	Frac.
Specific gravity of gas + any oil carryover @ test condition (Y_{mg})	0.730	Frac.
Specific gravity of gas @ test condition (Y_{gt})	0.650	Frac.
Gas formation volume factor (B_{gt})	0.005	bbl/scf
Solution gas oil ratio	540	Scf/stb
Fluid API Gravity	45.6	^{0}API

Table 2: Inputted parameters and values for Real-Time Multiphase flow metering model (*Case 2*)

Parameters	Values	S.I Unit
Specific Gravity of Water (Y_{ws})	1.092	Frac.
Liquid Temp.	250	^{0}F
Liquid Pressure	3885.64	Psi
Mass Flow Rate (MF, ibs/min)	850	Ibs/min
Specific gravity of oil at test condition (Y_{ot})	0.830	Frac.
Oil formation volume factor (B_{ot})	1.32	bbl/stb
Specific gravity of oil + water at test condition (Y_{ml})	0.8942	Frac.
Specific gravity of gas + any oil carryover at test condition (Y_{mg})	0.8083	Frac.
Specific gravity of gas at test condition (Y_{gt})	0.800	Frac.
Gas formation volume factor (B_{gt})	0.005	bbl/scf
Solution gas oil ratio	500	Scf/stb
Fluid API Gravity	39	^{0}API

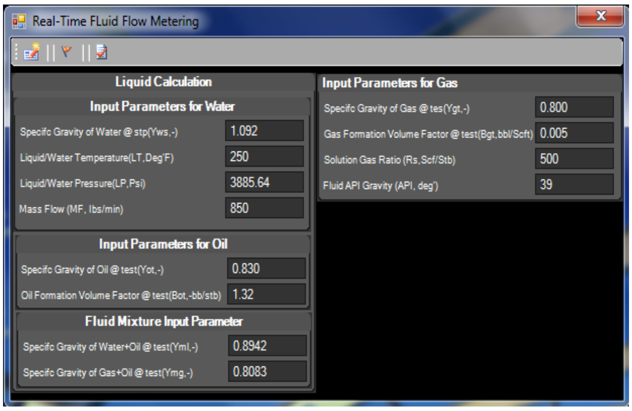

Fig 3: Input interface for the inputted parameter of real-time fluid flow metering model

2.1.2 Development of Economic Evaluation Model

A general economic model is proposed to enable management compare the costs of investment on the multiphase flow meter and test separator and take decision. This model considers all costs involved in the evaluation life of the meters. The following were the assumptions made in this study:

1. The production life of the well is calculated using decline curve analysis to determine the economic life of the well which is directly linked with the working duration of the MFPM.
2. Multiphase meters depreciating service life is considered using a straight line depreciation method;
3. The price value of crude oil is considered;
4. Tax implication to the investment may be consider if it is implemented;
5. Base case of 15% discount is considered.

In calculating the production decline rate of a producing well, the effective decline rate is commonly used. The effective decline rate per unit time (d) is the drop in production rate from q_i to q over a period of time divided by the production rate at the beginning of the period:

$$d = \frac{q_i - q}{q_i} \tag{12}$$

The effective decline rate is expressed as a fraction and it is often expressed as a percentage (%) in practice. The mathematical treatment of production decline curves is greatly simplified if the instantaneous or continuous decline rate is introduced. The differential equation that describes the constant percentage decline is:

$$d = -\frac{1}{q}\frac{dq}{dt} \quad \text{(d=constant)} \tag{13}$$

This states that the instantaneous or nominal decline rate is a constant percentage of the instantaneous production rate. The rate-time relation can be derived by integrating Eq. 13:

$$\int_{q_i}^{q} \frac{dq}{q} = -d\int_0^1 dt \tag{14}$$

$$q = q_i\, e^{-dt} \tag{15}$$

Thus, the production life to abandonment time may be obtained by solving for time from Eq. 15;

$$t_a = \frac{1}{d}\ln\left(\frac{q_i}{q_a}\right) \tag{16}$$

The time calculated is the used as the estimated asset life of the equipment in years. The total cost for the MPFM is obtained separately using the equation:

$$\text{Total Cost, (TC)} = -(\text{CAPEX} + \text{OPEX}) \tag{17}$$

i.e., the total cost for Multiphase Flow Meter (MPFM):

$$TC\ for\ MPFM = -(\text{CAPEX} + \text{OPEX})_{\text{MPFM}} \tag{18}$$

The total cost, TC is then discounted at 15% to btain the net present value (PV) given by:

$$\text{NPV} = \Sigma\left[\frac{TC}{(1+d)^n}\right] \tag{19}$$

i.e., net present value for MPFM:

$$NPV_{MPFM} = \Sigma\left[\frac{TC}{(1+d)^n}\right]_{MPFM} \tag{20}$$

The procedure for estimating depreciating value of the equipment is by using the straight-line depreciation ''*D*'' allowance per year:

$$D = \frac{C-S}{n} \tag{21}$$

Where;
C = capital investment on equipment ($)
S = estimated salvage value
n = estimated asset life of the equipment in years (*using the production years of the well*)

When the NPV* is calculated, decision is made as follows:

- If NPV* is negative for the MPFM, reject the investment;
- If NPV* is zero for the MPFM, either accept or reject the investment;
- If NPV* is positive for the MPFM, accept the investment;

Table 3: Inputted parameters and values for economic analysis of *Case A*

Parameters	Values	S.I Unit
Initial Flow Rate	547500	bbl/yr
Abandonment Rate	73000	bbl/yr
Effective Decline Rate	0.05	faction
Average Oil Price Per Year	70	$
Inflation rate	0	%
Royalty Rate	0	%
CAPEX	350,000	$
OPEX	12,500	$
Depreciation	8,750	$
Income Tax Rate	0	%

Table 4: Inputted parameters and values for economic analysis of *Case B*

Parameters	Values	S.I Unit
Initial Flow Rate	547500	bbl/yr
Abandonment Rate	73000	bbl/yr
Effective Decline Rate	0.05	faction
Average Oil Price Per Year	70 (1yr-15yr), 55 (16yr-25yr), 80 (26yr-32yr), 70 (33yr-40yr)	$/bbl
Inflation rate	10%	%
Royalty Rate	8	%
CAPEX	350,000	$
OPEX	12,500	$
Depreciation	8,750	$
Income Tax Rate	10	%

2.1.3 Deterministic Economic Evaluation Model for MPFMs

This model considers costs involved in the evaluation life of a multiphase flow metering (MPFM) unit. The parameters to be inputted for calculating the Net Present Value (NPV) for the investment is shown in fig.4.

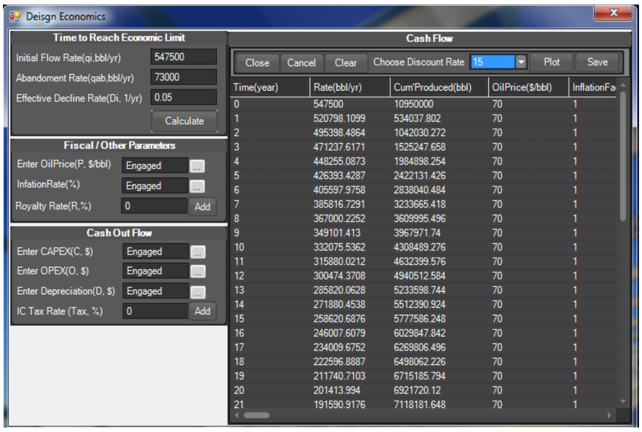

Fig 4: Interface for the inputted parameter of the Economic Evaluation Model

In achieving this analysis, vendors of multiphase flow meter (MPFMs) must present capital expenditures (CAPEX) and operating expenditures (OPEX) for the brand of MFPMs to be designed or installed. Depending on the application, the average cost for MPFMs ranges from $200,000 to $350,000 (Hatton, 2013). The operators of the flow meter must also present the initial and abandonment flowing rate of the producing-well as well as its effective decline rate in other to calculate the production life of the well, which is directly linked with the working duration of the MFPM.

3. Result and Discussion

3.1 Data analysis and discussion of the Flow-Metering Model

The real-time MPFM measurements are taken at the pressure and temperature of the fluid passing though the metering system. The measurement at actual conditions is the principle behind the real-time metering system measurement technologies and techniques.

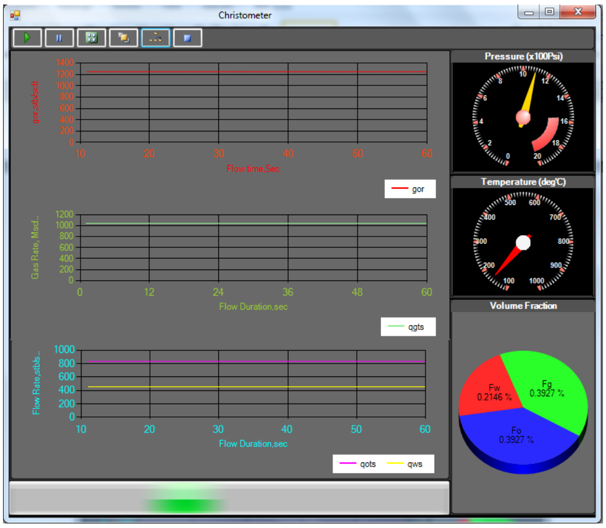

Fig 5: Real-time Production Value against Production Time for Case 1

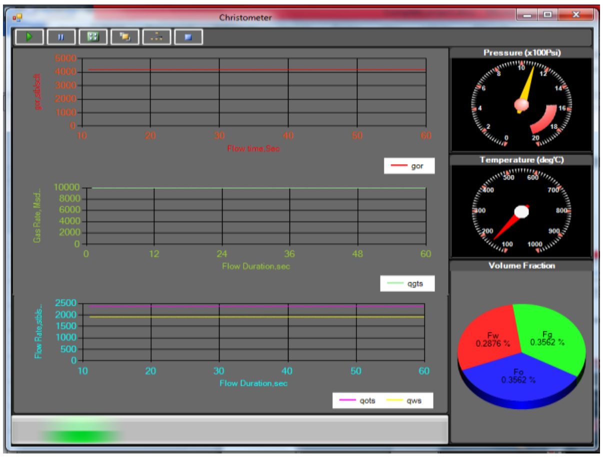

Fig 6: Real-time Production Value against Production Time for Case 2

From the result generated by the real-time MPFM for the inputted parameters and PVT values as shown in table 1 and 2 for case 1 and case 2, it was observed to be a steady state flow rate at standard condition of pressure and temperature measurements as shown by the graphs in fig. 5 and 6; the pie chats shows the fraction of the oil, water and gas phases at real-time production. The challenge of real-time MPFM in exploration well monitoring and optimization is to resolve the uncertainty of the well conditions so that the monitoring operation maybe carried out in a controlled and safe manner. Measurement of pressure, temperature, fluid properties, fluid flow rate and volume can provide the needed information to resolve much of the uncertainty. Hence having this information available for use during well test enables one to safely and confidently conduct the well test operations.

3.2 Data analysis and discussion of the Economic Evaluation Model for MPFMs

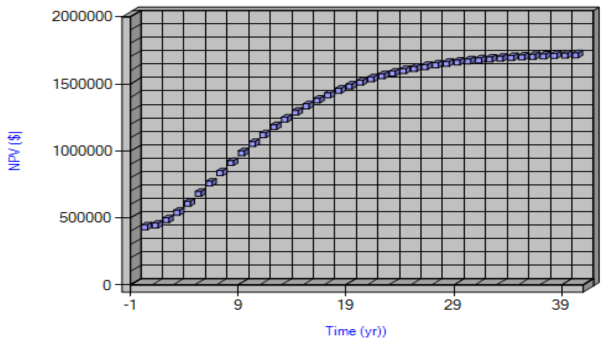

Fig. 7: Graph of NPV vs Production-Time for Case A at 15% discount rate

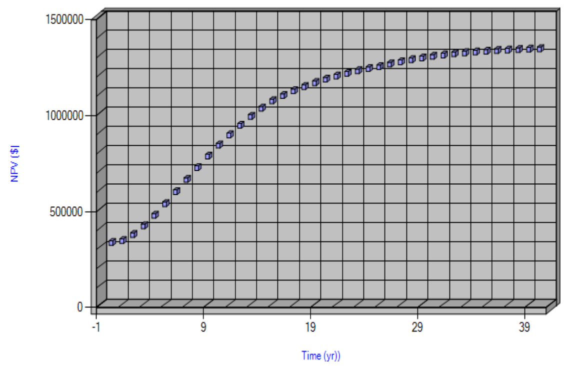

Fig 8: Graph of NPV vs Production-Time for Case B at 15% discount rate

Considering the production life of the well which is directly linked to the working life of the MPFM and an assumed base case of 15% discount rate, a two cases scenario were considered; case A and case B. Case A did not consider a change in the price of crude oil, inflation rate on crude oil price, tax implication to the investment and royalty payment on equipment installation. While case B considers a change in the price of crude oil over time, inflation rate on crude oil price, tax implication to the investment and royalty payment on equipment installation. From the figures 7 and 8, the graphs for the economic analysis of Case A and Case B, it was observed that the Net Present Values (NPVs) calculated at 15% discount factor were positive for both cases. Hence, we can accept the installation of the Multiphase Flow Meter (MPFM) for both investments considered.

Conclusions

The following conclusions are benefits observed during the series of the multiphase flow metering performance flow rate measurements.

a) The real-time multiphase test results are proven to be very accurate because of the continuous flow rates recording with all the instantaneous flow variations revealed. It is proved to be more informative than the discontinuous and detail lacking separator measurement.
b) The MPFM technologies have been recognised to provide the critical need to alleviate production decline, production optimization and reduce capital and operating cost than bulky test separators, test-lines and test barges.
c) The continuous and real-time MPFM data has also enhanced monitoring of well performance, production optimization and reservoir management which has led to improved total recovery.

Recommendations

The following recommendations are made for the study of multiphase flow metering system and its performance:

a) Rapid accurate production diagnosis should be ensured to enable timely decisions to optimize a well's production.
b) Generally, it is recommended to use the continuous and real-time MPFM because it measures well production rates quicker with more accuracy of data and less human intervention than the conventional well test system. In addition to performing well rate metering faster than conventional test separators, some MPFMs provide additional information of great value to the operators as well as changes in the well performance can be observed in real time.

Nomenclature

Y_{wt} = Specific gravity of water at test conditions.
Y_{ws} = Specific gravity of water at standard conditions 1.092.
LT = Liquid temperature in degrees F measured by coriolis meter.
LT = Liquid pressure measured by the coriolis meter.
Wet = Water cut at test conditions.
Y_{ml} = Specific gravity of liquid (oil & water) at test conditions measured by the liquid coriolis meter.
Y_{ot} = Specific gravity of oil at test conditions.
Qo_s = Oil rate at standard conditions.
MF lbs/sec = Mass flow rate measured by the liquid or the gas coriolis meter.
B_{ot} = Oil formation volume factor at test condition.
Q_{ws} = Water rate at standard conditions.
Q_{ots} = Total oil rate at standard conditions.

Q_{oc} = Oil carry over from gas coriolis meter at standard conditions.
W_{cs} = Water cut at standard conditions
Y_{mg}= Specific gravity of gas and any oil carry over at test conditions measured by the gas coriolis meter.
G_{ft} = Gas fraction at test conditions.
y_{gt} = Specific gravity of gas at test condition.
Q_{gs} = Free gas at standard conditions.
B_{gt} = Gas formation volume factor at test condition.
Q_{gts} = Total gas rate at standard conditions.
Rs = Solution gas oil ratio from input PVT table.
GOR = Gas oil ratio.
d = Effective decline rate per unit time
q_i= Initial Production Rate
q = Production Rate at time (t)
C = capital investment on equipment ($)
S = estimated salvage value
n = estimated asset life of the equipment in years (using the production years of the well)
PVT = Pressure Volume Temperature
GVF = Gas Volume Fraction
WLR = Water Liquid Ratio
STBD = Stock Tank Barrel per Day
MSCFD = Thousand Standard Cubic Foot per Day
MPFM = Multiphase Flow Meter
SCADA = Supervisory Control and Data Acquisition
NCF = Net Cash Flow
NPV = Net Present Value

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