Water Content of Sweet Natural Gas: A Simplified Formula-Based Approach

Uwaezuoke, N.[a],*; Izuwa, N. C.[a]; Onwukwe, S. I.[a]

[a]Department of Petroleum Engineering, Federal University of Technology, P.M.B 1526, Owerri, Imo State, Nigeria.
*Corresponding author.

Abstract

Gas with negligible or zero composition of hydrogen sulphide is sweet natural gas. During production, transportation and processing, the presence of traces of water can cause problems such as ice formation and/0r the problem of gas hydrates, increase in corrosion potential of the gas and two-phase flow problems if condensation occurs. Calculation of the water content at specified temperature and pressure conditions is the first step. A formula based approach of the calculation is proposed, and comparison with existing formulas presented. Application of the proposed formula in the specified ranges of temperature and pressure conditions of 15°C (59°F) to 48.8°C (119.84°F) and 1.07MPa (155.19 psia) to 10MPa (1450.38 psia) is recommended for sweet natural gases. A calculated Mean Absolute Percentage Deviation (MAPD) of 16.4077% from the experimental data is the statistical indicator used for validity check. It predicted better than some existing models which are adaptable under certain conditions. Only a hand-held device is required as the proposed model is highly simplified.

Key words: Mean Absolute Percentage Deviation; Natural Gas; Pressure; Temperature; Water Content

INTRODUCTION

During production, transportation and processing of natural gas, the presence of traces of water can cause problems such as ice formation and/0r the problem of gas hydrates, increase in corrosion potential of the gas and two-phase flow problems if condensation occurs. Charts, models and computer programs have been used to estimate the water content of natural gas at different conditions and mixtures.

Many authors have developed correlations that represent the curves in the charts such as in the McKetta and Wehe chart (Mcketta and Wehe, 1958) chart, in order to reduce the time and tediousness associated with graphical based calculations such as interpolation. Formulas for water content of sweet natural gases, typical of gases found in the Niger delta, have also been evaluated (Lin, *et al*., 2015). These formulas are adaptable under certain conditions of pressure and temperature (Lin, *et al*., 2015), hence, generalized accurate natural gas water content prediction formula remains a problem even after equations of state and computer programs were introduced.

This work re-examined the McKetta and Wehe (Mcketta and Wehe, 1958) chart and the aim was to propose a simplified formula for water content of sweet natural gas that also requires only pressure and temperature values. Validity was checked by comparing with other formula calculation methods, by the use of an experimental data with the aid of a statistical indicator. A range of temperature and pressure conditions where the formula predicts most accurately was recommended.

1. LITERATURE REVIEW

Several methods have been proposed for estimation of water content of natural gas. McKetta and Wehe (Mcketta and Wehe, 1958) developed a chart empirically

for estimation of water content of a sweet gas, with corrections for salinity and gas gravity. An improved chart has also been developed (Guo and Ghalambor, 2005), with duplicated data of McKetta and Wehe nomographic chart.

Water content can also be determined from commercial softwares and models based on phase-equilibria (Alireza *et al.,* 2016, Haridy *et al.*, 2002, Mohammadi and Richon,

2008) at different conditions of temperature, pressure and mixtures. Some formula calculation methods have also been evaluated based on mean absolute percentage deviation (MAPD) (Equation 1), and ranges of temperature and pressure of adaptability recommended (Lin *et al.*, 2015).

$$\text{MAPD} = \frac{1}{n}\left(\sum_{i-1}^{n}\left(\frac{\left|\left(a_{e,i} - a_{p,i}\right)\right|}{a_{e,i}}\right)\right) * 100 \quad (1)$$

Other statistical indicators include R, predicted R^2 and adjusted R^2 (Equation 2, Equation 3 and Equation 4)

$$R = \frac{\sum_{i-1}^{n}\left(a_{p,i} - a_{p,ave}\right)\left(a_{e,i} - a_{e,ave}\right)}{\sqrt{\left[\sum_{i-1}^{n}\left(a_{p,i} - a_{p,ave}\right)^2\right]\left[\sum_{i-1}^{n}\left(a_{e,i} - a_{e,ave}\right)^2\right]}} \quad (2)$$

$$\text{Predicted } R^2 = 1 - \frac{\sum_{i-1}^{n}\left(a_{e,i} - a_{p,i}\right)^2}{\sum_{i-1}^{n}\left(a_{e,i} - a_{e,ave}\right)^2} \quad (3) \qquad \text{Adjusted } R^2 = 1 - \left[\left(1 - R^2\right)* \frac{n-1}{n-j-1}\right] \quad (4)$$

Where n is the number of experimental data, $a_{e,i}$ is the experimental values, $a_{p,i}$ is the predicted values, $a_{e,ave}$ is the average experimental values, $a_{p,ave}$ is the average predicted values and j is the number of input variables.

Several methods have been developed to determine the water content of acid gases (carbon hydroxide and hydrogen sulphide) and sour natural gases (significant amount of acid gas). A chart based method that provides good estimates for sour gases for a range of conditions exists (Wichert and Wichert, 2003).

Also, the Peng Robinson (PR-EoS), Soave-Redlich-Kwong (SRK-EoS) and Cubic-Plus-Association (CPA-EoS) equations of state and their combinations and improvements have also been used to estimate water content (Palma *et al.*, 2017, Chapoy *et al.*, 2016, Li and Firoozabadi, 2009). Whereas the PR-EoS and SRK-EoS are the classic equations of state, the addition of CPA-EoS over twenty years ago was to account for contribution from hydrogen bonding in the form of association and solvation (Equation 5).

$$Z = \underbrace{\frac{v_m}{v_m - b} - \frac{a(T)}{\mathbb{R}\,(v_m + b)}}_{SRK} - \underbrace{\frac{1}{2}\left(1 + \frac{\tilde{n}\partial \ln g}{\partial \tilde{n}}\right)\sum_{i} x_i \sum_{A_i}\left(1 - X_A\right)}_{\text{association and solvation}} \quad (5)$$

Other methods that have been used to predict water content of natural gas, with reliable data, a wide range of temperatures and pressures and mixtures of acid and natural gases have been highlighted (Haridy et al., 2002) to include; MacCarthy, et al. chart (1950), Katz chart (1956), Sharma

and Campbell (1969), Campbell chart (1970), GPSA (1972), Robinson, et al. (1976), Sloan (1986), Gordon chart (1993), Kasim (1996) and Dalton's Law.

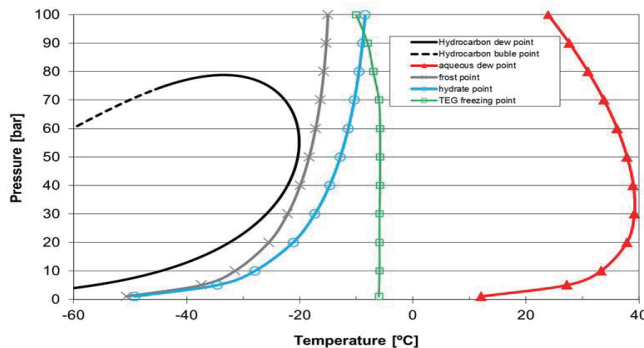However, the phase behavior of a natural gas stream with traces of water is shown in Figure 1.

Figure 1
Phase behavior of natural gas with traces of water (Christensen *et al.*, 2004)

It is observed (Figure 1) that the gas phase and dissolved water (as vapor) can form a condensate (liquid water), ice/frost, or gas hydrate at the liquid water-gas, ice-gas, or hydrate-gas boundaries, respectively.

i. Sloan's formula;

$$W_{H_2O} = 16.02 \times \exp[a_1 + a_2\ln p + (a_3 + a_4\ln p)(T + 273.15) + a_5/(T + 273.15)^2 + a_6(\ln p)^2] \tag{6}$$

It is based on nomographic chart and was derived based on low temperature data (15°C and 0.101325 MPa).

ii. Ning Yingnan's formula;

$$W_{H_2O} = (1015.32 + 1.1T - 18.2d - 1.42Td) \times (1 - 0.02247S) \times \exp(a_0 + a_1T + a_2T^2) \tag{7}$$

Its derivation was based on the calibrated and McKetta-Wehe nomographic charts.

iii. Khaled's formula;

$$W_{H_2O} = 16.02\left[\frac{\sum_{i=1}^{5} a_i(T + 273.15)^{i-1}}{p} + \sum_{i=1}^{5} b_i(T + 273.15)^{i-1}\right] \tag{8}$$

It was derived based on high temperature data fit of the nomographic chart.

iv. Bahadori's formula;

$$W_{H_2O} = \emptyset \sum_{i=0}^{3} \sum_{j=0}^{3} a_j T_j (\log p + 3)^i \tag{9}$$

Derivation was based on numerical fitting.

v. Zhu Lin's formula;

$$W_{H_2O} = 101.325 \frac{\sum_{i=0}^{7} a_i T_i}{T} + \sum_{i=0}^{7} b_i T_i \tag{10}$$

Derivation was based on the conclusion that sweet natural gas water content is inversely proportional to pressure and directly proportional to temperature.

vi. Behr's formula;

$$W_{H_2O} = a_0\exp\left[a_1 + \frac{a_2 + a_3\ln p + a_4(\ln p)^3}{(T + 273.15)^2} + a_5\ln p\right.$$
$$\left. + a_6(\ln p)^2 + a_7(\ln p)^3 + \frac{a_8 + a_9\ln p + a_{10}(\ln p)^2 + a_{11}(\ln p)^3}{(T + 273.15)^3}\right] \tag{11}$$

The work regarded water content as a function of natural log of pressure and reciprocal of Kelvin temperature unit.

vii. Kazim's formula;

$$W_{H_2O} = 16.02 A_1 A_2^{(1.8T+32)} \tag{12}$$

$$A_i = \sum_{j=1}^{4} a_j \left(\frac{145p - 350}{600}\right)^{j-1} \tag{13}$$

It was based on low temperature (T<37.78°C) and high temperature (37.78°C≤T≤82.22°C) data fitting.

viii. Saturated Vapour Pressure Model (SVPM);

$$W_{H_2O} = 761900.42 \frac{p_{sv}}{p - p_{sv}} \tag{14}$$

1.1 Some Existing Formulas

Equations 6 to 23 are the existing formulas for water content of sweet natural gas. They have been tested for conditions of adaptability (Lin et al., 2015) in terms of temperature, pressure and phase equilibria conditions.

$$p_{sv} = p_c \exp\left[\frac{\ddot{e}-1}{\ddot{e}} f(\ddot{e})\right] \quad (15)$$

$$f(\lambda) = 7.21275 + a(0.745 - \lambda)^2 + b(0.745 - \lambda)^c \quad (16)$$

It estimates water content based on the law of partial pressures.

ix. Modified Ideal Model (MIM);

$$W_{H_2O} = 761900.42 \frac{p^{sv}}{p} \exp\left[11.81479 \frac{p^{0.92951}}{(T + 273.15)}\right] \quad (17)$$

This is for gas-liquid equilibrium state

$$p_{sv} = 0^{-6} \exp\left[73.960 - \frac{7258.2}{T + 273.15} + 2.276 \times 0^{-3} T - 7.3073 \times h(T + 273.15) + 4.1653 \times 0^{-6} T^2\right] \quad (18)$$

This is for gas-liquid equilibrium state
This formula is a correction for the ideal model and valid at low pressure of p<1.38MPa.

x. Simplified Thermodynamic Model (STM);

$$W_{H_2O} = 761900.42 \frac{p_{sv}}{\varphi_{H_2O} p} \exp\left[\frac{(p - p_{sv})V_{H_2O}}{R(T + 273.15)}\right] \quad (19)$$

$$\varphi_{H_2O} = \exp\left[\left(0.069 - \frac{30.905}{T + 273.15}\right)p + \left(\frac{0.3179}{T + 273.15} - 0.0007654\right)p^2\right] \quad (20)$$

These are simplified models based on thermodynamic gas-liquid and gas-solid equilibrium.

xi. Bukacek's formula;

$$W_{H_2O} = 761900.42 \frac{p_{sv}}{p} + 16.016 \times 0^{\left(\frac{-1716.26}{T + 273.15} + 6.69449\right)} \quad (21)$$

$$p_{sv} = p_c \times \exp[(-7.858\hat{o} + 1.83991\hat{o}^{1.5} - 11.7811\hat{o}^3 + 22.6705\hat{o}^{3.5} - 15.9393\hat{o}^4 + 1.77516\hat{o}^{7.5})(1 - \hat{o})] \quad (22)$$

$$\hat{o} = \frac{T_c - T}{T_c + 273.15} \quad (23)$$

This is a modification of ideal models of Behr's and STM.

In Equations 6 to 23, W_{H2O}=water content mg.m^{-3}, a_{ij}, a_0 to a_{11} are coefficients, P = absolute pressure of the gas, T = temperature of the gas, d = relative density, S = salt content, V_{H2O} = m^3/mol and a function of temperature, P_c = critical pressure of water (22.064 MPa), T_c = critical temperature of water (393.99^{o}C), φ_{H_2O} is the fugacity coefficient of water, λ is a function of temperature and critical temperature, R is the universal gas constant of 8314 (m^3.MPa) per (mol.K).

2. MATERIALS AND METHOD

2.1 Materials

Table 1 was created from some readings taken from McKetta and Wehe nomographic chart and used to duplicate the chart (Figure A.1). An MSExcel (version 2010) based regression tool from Data Analysis ToolPak under the add-ins was used to generate the formula (Equation 25). However, other commercial regression tools and statistical software packages such as Minitab® and Design Expert® exist.

An experimental data from literature (Lin *et al.*, 2015) was used to test the validity of the proposed formula, by the application of the statistical indicator, mean absolute percentage deviation (MAPD) (Equation

1). Simulation runs in Table 1 were generated by the use of the Design Expert.

Table 1
Simulation Runs of Water Content Readings From Table 2 for an Experiment (Lin, et al., 2015)**, analogous to McKetta and Wehe nomographic chart** (Guo and Ghalambor, 2005, Mokhatab et al., 2006) **at Standard Conditions of Temperature and Pressure**

Run	Factor 1 A:T deg. F	Factor 2 B:P psia	Response 1 R1 lb/MMscf
1	116.036	1127.41	71.46
2	165.2	73.97	1949.43
3	59.63	73.97	128.48
4	165.2	1119.35	195.17
5	87.575	2552.66	17.85
6	59.63	73.97	128.48
7	165.2	2180.86	110.93
8	121.73	2007.35	52.68
9	111.794	86.3634	603
10	41	2552.66	2.35
11	165.2	2180.86	110.93
12	87.575	2552.66	17.85
13	68.324	941.511	21.42
14	118.036	1127.41	72.46
15	41	1660.33	3.39
16	113.036	1132.41	69.46

2.2 Method

The oil and gas industry have existing formulas for water content of sweet natural gas developed using different experimental data sets, extracts from McKetta and Wehe nomographic chart (Guo and Ghalambor, 2005, Mokhatab *et al.*, 2006) and software packages. Similarly, in this work, the McKetta and Wehe nomographic chart and experimental results of water content of sweet gas were all applied. The independent variables, temperature and pressure were used as explanatory or predictor variables, while the dependent variable, the water content of sweet natural gas is the criterion variable. The logarithms of both the predictor and criterion variables

were determined. The undefined values thereafter, due to negative or zero values of temperature read from the nomographic chart were eliminated. The model was build based on non-linear regression similar to the approach used in developing a proxy model for critical rate and optimum well placement (Onwukwe *et al.*, 2012). The proposed formula was applied to estimate the water content from the experimental data presented at different temperature and pressure conditions without consideration of the gas gravity and salinity, in accordance with adaptability analysis performed with experimental data (Lin *et al.*, 2015). The predicted values were compared with calculated water content values of eleven existing formulas (Table 2) for validation. Comparison of the results was made on the basis of mean absolute percentage deviation (MAPD) as used for the other formulas. Other statistical indicators applied include R, predicted R^2 and adjusted R^2. Applicable ranges of temperature and pressure conditions have been recommended.

3. RESULTS AND DISCUSSION

3.1 Results and Comparison

With the protocol, using the non-linear least-squares fitting, with the sum of squared residuals computed and minimized, the temperature and pressure values that best represent the experimental data (Figure A.1) were used to generate the formula.

The new proposed formula is summarized and presented as Equation 25.

$$V_{H_2O} = 10^{-1.04624} T^{2.6688} P^{-0.8471} \quad (24)$$

This equation reduces to;

$$V_{H_2O} = k T^{\alpha} P^{\beta} \quad (25)$$

where V_{H2O} is the water content in lb/MMcf standard conditions, k is 8.99E-2, α is 2.6688, β is -0.8471, T is the temperature in ^oF and P is the pressure in psia.

Presented in Table 2 are the experimental values and the predicted values from existing formulas and the **proposed formula** (column #1) in mg.m^{-3}.

From the statistical indicators applied, based on the procedures[2], the R, predicted R^2 and adjusted R^2 are 0.9897, 0.7848, and 0.7669 respectively.

Table 2
Calculated and Experimental Water Contents (Lin, et al., 2015)

| S/N	Temperature °C	°F	Pressure MPa	Psia	Experimental value [mg.m⁻³]	1 Proposed formula	2 Sloan	3 Ning Yingman	4 Khaled	5 Bahadori	6 Zhu Lin	7 Behr	8 Kazim	9 SVPM	10 MIM	11 STM	12 Bukacek
1	5	41.00	1.5	217.56	476.19	303.68	494.2	527.84			518.89	344.22		442.96	442.73	470.92	
2	15	59.00	4	580.15	387.81	349.49	415.63	445.33		410.11	437.92	412.64	415.99	324.96	324.86	375.95	414.62
3	15	59.00	6	870.23	281.14	247.89	304.76	324.38		303.32	327.86	281.23	301.59	216.61	216.57	268.55	306.35
4	15	59.00	8	1160.30	228.57	194.28	246.42	268.79		249.41	272.84	206.38	279.21	162.45	162.43	215.23	252.22
5	15	59.00	10	1450.38	198.09	160.82	209.9	236.96		216.8	239.82	160.56		129.95	129.94	183.49	219.73
6	15	59.00	6.02	873.13	239.24	247.20	304	268.99		302.61	327.13	280.26	300.85	215.89	215.85	267.84	305.63
7	24.8	76.64	6	870.23	540.95	498.26	532.04	543.96		536.8	543.82	498.45	523.31	398.02	397.88	483.64	538.49
8	24.8	76.64	10	1450.38	318.47	323.24	364.03	317.88		379.58	382.27	283.29		238.76	238.73	326.59	379.45
9	30	86.00	0.51	73.97	6453.3	5468.86		4999.1			6596.8			6399.4	6347.6	6451.9	6518.7
10	30	87.44	1.07	155.19	3276.2	3051.65		2444.9		3222.6	3406.9	1468.2		3209.8	3197.2	3306.7	3377.2
11	30	86.00	2.42	350.99	1508.6	1462.34	1466.9	1358.5		1480.4	1524.2	1364.3	1678.9	1345.3	1343.3	1450.3	1518.9
12	29.9	85.82	3.66	530.84	967.61	1024.30	1034.4	1092.5		1041	1053.6	1041.5	1045.9	880.24	879.43	986.98	1054.7
13	30	86.00	17.6	2552.66	338.28	272.34	323.2	406.08		362.13	350.16	202.39		184.99	184.99		361.63
14	35	95.00	17.5	2538.16	430.47	356.91	416.73	508.76		466.92	442.17	265.26		245.21	245.2		463.34
15	40	104.00	10	1450.38	861.71	730.04	801.24	1099.9	841.55	847.66	812.09	640.37		566.19	566	739.75	834.36
16	40	104.00	17.5	2538.16	592	454.43	532.88	636.17	594.88	597.15	546.02	343.74		321.72	321.71		589.26
17	48.9	120.02	0.53	76.87	17219	12884.51		14232	17266		17685			17527	17143	17371	17502
18	48.7	119.66	1.1	159.54	8076.1	6885.83		6357.5	8281.8	7984.4	8464.9			8104	8023.4	8255.3	8390.5
19	48.9	120.02	1.92	278.47	4906.6	4330.29	4676.41	5570.4	4955.5	4840.7	5052.1	3880.4		4668.7	4643	4879.5	5016.9
20	48.8	119.84	3.11	451.07	3017.1	2866.45	3073.81	2523	3190.4	3168.5	3240.6	3074.3	3868.7	2861.1	2852.1	3090	3226.7
21	48.7	119.66	4.17	604.81	2323.8	2226.91	2398.22	2150.1	2464.6	2474.8	2495.6	2438.2	2659.7	2121.1	2116.5	2355	2490.6
22	59.5	139.10	0.51	73.97	30247	19734.16		22394	29404		30064			30263	29134	29458	29657
23	59.6	139.28	1.52	220.46	10210	7851.64		7132.2	10289	9970.8	10517	6528.1		9939.7	9820.7	10164	10371
24	59.9	139.82	2.92	423.51	5500.9	4563.09		6948.3	5723	5650.7	5848.7	5342	8502.5	5211.2	5180.6	5533.2	5741.6
25	59.8	139.64	4.9	710.68	3451.4	2933.10		4047	3615.1	3642.1	3693.3	3508.2	4302.9	3084.4	3074.8	3430.8	3637.6
26	74.2	165.56	0.57	82.67	52495	28584.88		49088	51464	50512	52603			54358	50819	51296	51664
27	74	165.20	1.53	221.91	19276	12312.97		13002	19266	18724	19677	11979		18871	18444	18971	19335
					MAPD	16.4077	7.073	16.676	2.524	6.145	7.911	19.255	18.819	15.067	15.402	3.4671	4.635
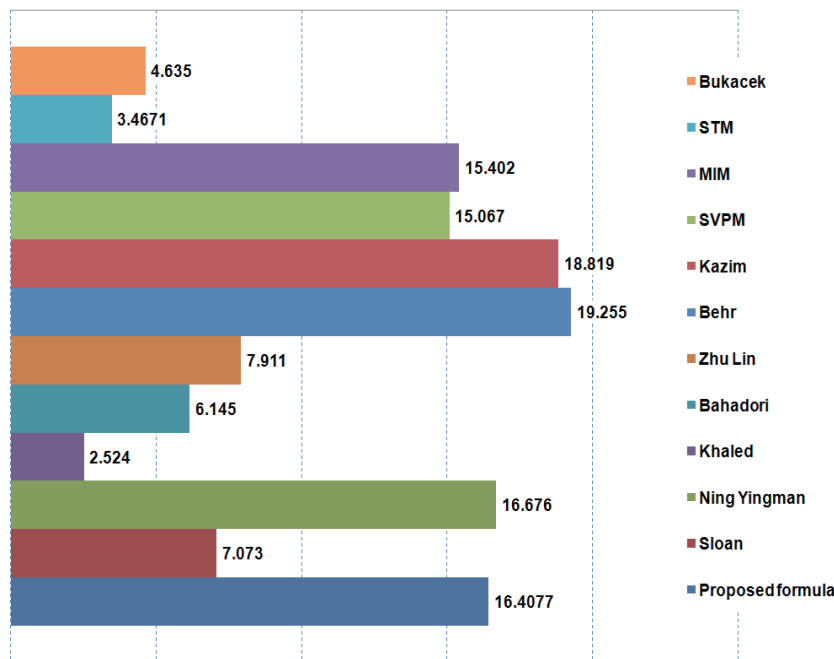
Figure 2
Comparison of the mean absolute percentage deviation (MAPD) of the models from the experimental data
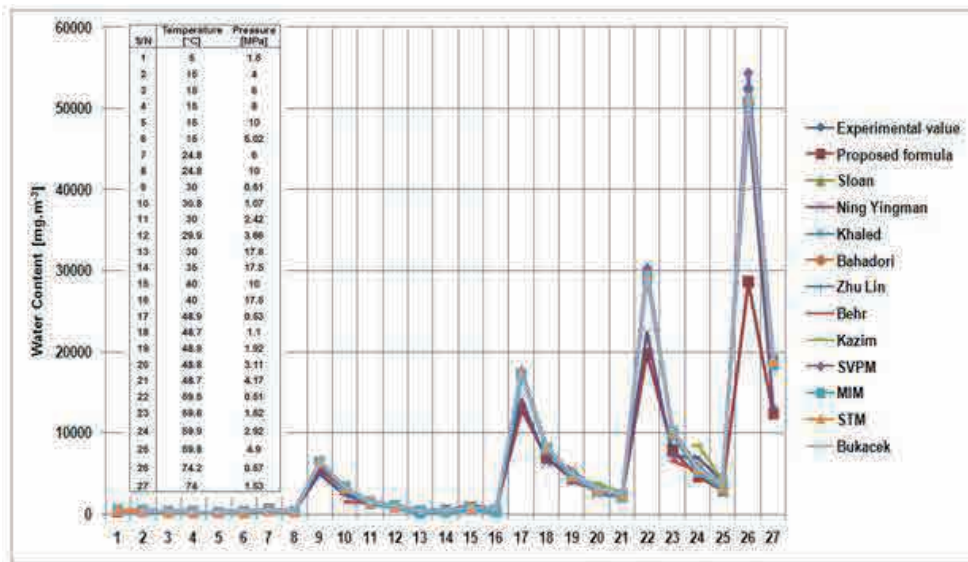
Figure 3
Comparison of water content values of the proposed and existing formulas with the experimental data of twenty seven sets of pressure and temperature variations

3.2 Discussion and Model Validation

It was observed that increasing the temperature increases the water content, while increasing the pressure decreases the water content. The reverse is the case for both parameters. The predicted values of water content of the proposed formula with data (Lin *et al*., 2015) compared quite fine with other existing formulas (Table 2). The MAPD from the experimental data was 16.4077%. The new formula performed better than Ning Yingman, Behr and Kazim's formulas. The proposed formula predicted best under specified ranges of 15°C (59°F) to 48.8°C (119.84°F) and 1.07MPa (155.19 psia) to 10MPa (1450.38 psia) conditions. Also, by application of the analysis of variance statistics (ANOVA), the predicted R² of 0.7848 is in reasonable agreement with the adjusted R² of 0.7669, since the difference is less than 0.20.

Shown in Figure 3 are the predictions of the proposed and existing formulas in comparison with the experimental values. Different conditions of temperature and pressure were used in the predictions, based on similar conditions used in the experimental data provided. The conditions are shown in the insert in Figure 3. The points are represented on the abscissa, while the water content is the ordinate. The trends are similar, but some formulas are more adaptable in some conditions where they predict better (Lin *et al*., 2015).

Methods with MAPD value of less than 10% include STM, Bahadori, Khaled, Sloan, Bukacek and Zhu Lin. Zhu Lin's formula is the most precise from -50 to -40 $^{\circ}$C, Sloan's formula for -40 to 0 $^{\circ}$C, STM for 0 to 37.78 $^{\circ}$C, Khaled's formula for 37.78 to 171.11 $^{\circ}$C, and Bukacek's formula for 171.11 to 237.78 $^{\circ}$C temperature ranges.

The proposed formula adaptable range of temperature is within the STM and Khaled's formulas, though the points where they performed poorly have been neglected in determining the MAPD as shown in columns #4 and #11 in Table 2; whereas no point was neglected in calculating the MAPD for the proposed formula.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

The formula is very simple as water content could be obtained with a hand-held device. It predicted water content of a sweet gas, and compared with the experimental data with the mean absolute percentage deviation of 16.4077%. The value is within the range of other formulas evaluated and predicts better than Ning Yingman, Behr and Kazim's formulas. Application of the proposed formula in the specified ranges of temperature and pressure conditions of 15°C (59°F) to 48.8°C (119.84°F) and 1.07MPa (155.19 psia) to 10MPa (1450.38 psia) would yield MAPD value less than 10%. Only a hand-held calculator is required as the proposed model is highly simplified.

4.2 Recommendation

It is recommended to apply the proposed formula in the combined ranges of temperature and pressure conditions of {15oC (59oF) ≤ T ≤ 48.8oC (119.84oF)} and {1.07MPa (155.19 psia) ≤ P ≤ 10MPa (1450.38 psia)}. This is in line with the other recommendations made after making an evaluation of the other eleven existing correlations/ formulas, and their adaptability analyses.

REFERENCES

Alireza, B., Tomoaki, K., Meysam, B., Zainal, A., & Alireza, B. (2016).Estimation of natural gases water content using adaptive neuro-fuzzy inference system. *Journal of Petroleum Science and Technology, 34*(10), 891-897; DOI: 10.1080/10916466.2016.1176039

Chapoy, A., Burgass, R., Terrigeol, A., & Coquelet, C. (2016). Water content of CO2 rich mixtures: measurement and modeling using the cubic-plus-association equation of state. *Journal of Natural Gas Engineering, John Carroll, 1*(13), 85-97. <10.7569/JNGE.2015.692505>.<hal-01305689>

Christensen, K. O., Lokken, T. V., Solbraa, E., Nygaard, C. F., & Bersas, A. (2004). *Water content of high pressure natural gas: data, prediction and experience from field* (pp.1979-2021). International gas union research conference, Paris.

Guo, B., & Ghalambor, A. (2005). *Natural gas engineering handbook* (p.126). Houston, USA: Gulf Publishing Company.

Haridy, A., Awad, M. E., Abd-el-Fatah, & Kenawy, F. (2002). New model estimates water content in saturated natural gas. *Oil and Gas Journal Online*.

Li, Z., & Firoozabadi, A. (2009). Cubic-Plus-Association equation of state for water-containing mixtures: is "cross association" necessary? *American Institute of Chemical Engineers AIChE Journal, 55*(7), 1803-1813.

Lin, Z., Junming, F., Jia, Z., Li, Q., & Luling, L. (2015). Formula calculation methods of water content in sweet natural gas and their adaptability analysis. *Natural Gas Industry B*, 144-149; http://dx.doi.org/10.1016/j.ngib.2014.11.004

McKetta, J. J., & Wehe, A. H. (1958). Use this chart for water content of natural gas. *Petroleum Refiner, 37,* 153-154.

Mohammadi, A. H., & Richon, D. (2008). Determination of water content of natural gases. *Natural Gas Research Progress*. NY, USA: Nova Science Publishers.

Mokhatab, S., Poe, W. A., & Speight, J. G. (2006). *Handbook of natural gas transmission and processing*. Burlington, USA: Gulf Professional Publishing.

Onwukwe, S. I., Obah, B., & Uwaezuoke, N. (2012). A model approach of controlling coning in oil rim reservoirs. *Journal of Petroleum Engineering and Technology, 2*(1), 1-10.

Palma, M. P, Oliveira, M. B., Queimada, A. J., & Coutinho, J. A. P (2017). Re-evaluating the CPA EoS for improving critical points and derivative properties description. *Fluid Phase Equilibria, 436*, 85-97; https://doi.org/10.1016/j.fluid.2017.01.002

Wichert, G. C., & Wichert, E. (2003). New charts provide accurate estimations for water content of sour natural gas. *Oil Gas Journa, 101*(41), 64–66.
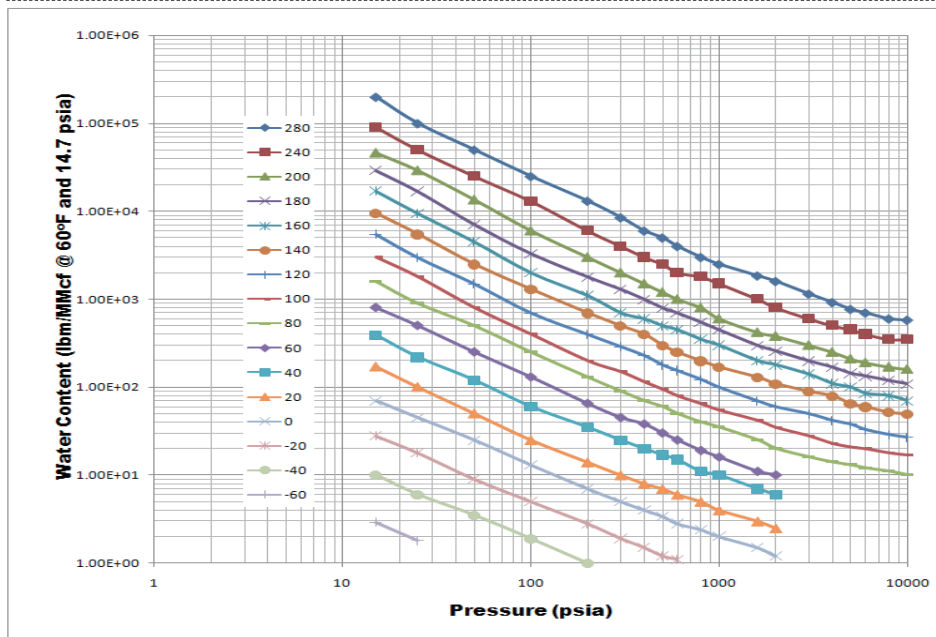
APPENDIX

Figure A. 1
Water content of sweet natural gases (duplicated by authors with data of McKetta and Wehe (McKetta and Wehe, 1958)