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Research article

Formula calculation methods of water content in sweet natural gas and their adaptability analysis

Zhu Lin [a,*], Fan Junming [a], Zhu Jia [a,b], Qin Li [c], Li Luling [a]

[a] *School of Chemistry & Chemical Engineering, Chengdu, Sichuan 610500, China*
[b] *Suining Operation Zone, Chuanzhong Division of PetroChina Southwest Oil & Gas Field Company, Suining, Sichuan 629000, China*
[c] *Luzhou Carbon Black Plant, PetroChina Southwest Oil & Gas Field Company, Luzhou, Sichuan 646000, China*

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Abstract

Estimation of water content is the foundation of natural gas processing and designing, and a formula calculation method provides a solution simple and easy to be programmed by computers. In this regard, several main formula calculation methods of water content in sweet natural gas were reviewed and evaluated individually. There are formulas fitted with nomographic data (e.g. Sloan formula, Ning Yingnan formula, Khaled formula and Bahadori formula), empirical formulas fitted with experimental data (e.g. Zhu Lin formula, Behr formula and Kazim formula) and formulas generated based on water-hydrocarbon phases equilibrium (e.g. Saturated Vapor Pressure Model, Modified Ideal Model, Simplified Thermodynamic Model and Bukacek formula). The comparison of calculated and experimental values of each above formula calculation method indicates that, the Khaled formula provided the minimum average absolute deviation (AAD) − 2.524 0%, while the Behr method achieved the maximum AAD − 19.255%. After the analysis of the AAD results calculated by the methods at different temperature ranges, the Zhu Lin formula is recommended for −50 to −40 °C, the Sloan formula for −40 to 0 °C, the Simplified Thermodynamic Model for 0 to 37.78 °C, the Khaled formula for 37.78 to 171.11 °C, and the Bukacek formula for 171.11 to 237.78 °C.

Keywords: Natural gas; Sweet natural gas; Water content; Formula calculation method; Average absolute deviation (AAD); Evaluation; Method

1. Introduction

Estimation of water content is the foundation of natural gas processing, storage, transmission, utilization and other processes. With no or a trace of acidic components (CO_2 and some sulfides) [1], water content sweet natural gas in could be estimated nomographic methods [2] or formula methods [3–5]. The latter has been widely used due to their simplicity and routinization. This paper listed and analyzed the formula calculation methods commonly used to predict water content in sweet natural gas.

* Corresponding author.
E-mail address: zhulinswpi@gmail.com (Z. Lin).
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2. Formula calculation methods

Formula calculation methods include semiempirical formulas fitted with nomographic data or experimental data and formulas generated based on water-hydrocarbon phases equilibrium.

2.1. Semiempirical formulas based on nomographic data

Some semiempirical formulas were derived from Mcketta-Wehe nomographic chart [6,7] published in 1958.

2.1.1. Sloan's formula

Sloan treated the water content in sweet natural gas as the function of $1/(T + 273.15)$ and $\ln p$ and derived Equation (1) based on the low-temperature data of the nomographic chart [8–10].

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$$W_{H_2O} = 16.02 \times \exp\left[a_1 + a_2 \ln p + \left(a_3 + a_4 \ln p\right)/\left(T + 273.15\right) + a_5/(T + 273.15)^2 + a_6\left(\ln p\right)2\right] \quad (1)$$

where, W_{H_2O} is the water content in sweet natural gas in mg/m^3 (15 °C, 0.101325 MPa, the same below); T denotes the temperature of the gas in °C, and p is the absolute pressure of the gas in MPa; parameters of a_1 to a_6 are the coefficients and their values are shown in Table 1.

2.1.2. Ning Yingnan's formula

Ning Yingnan developed Equation (2) [11] based on the Mcketta-Wehe nomographic chart and the calibrated chart.

$$W_{H_2O} = \left(1015.32 + 1.1T - 18.2d - 1.42Td\right) \times \left(1 - 0.02247S\right) \times \exp\left(a_0 + a_1 T + a_2 T^2\right) \quad (2)$$

$$d = \frac{\sum M_j y_j}{28.966} \quad (3)$$

where, d is the relative density; S is the salt content; M_j and y_j denote the relative molecular mass and the mole fraction in the gas phase of the jth component separately; parameters of a_0 to a_2 are the coefficients and their values are shown in Table 2.

2.1.3. Khaled's formula

Khaled proposed that the water content in sweet natural gas was in direct proportion to the temperature T and in inverse proportion to the pressure p and derived Equation (4) by fitting the high-temperature data on the nomographic chart [12].

$$W_{H_2O} = 16.02\left[\frac{\sum_{i=1}^{5} a_i (T + 273.15)^{i-1}}{p} + \sum_{i=1}^{5} b_i (T + 273.15)^{i-1}\right] \quad (4)$$

The values of coefficients a_i and b_i ($i = 1, 2, \ldots, 5$) in above equation are shown in Table 3.

2.1.4. Bahadori's formula

Bahadori presented that the water content in sweet natural gas was the function of the temperature T and lg$p$ and derived Equation (5) through numerical fitting [13].

$$W_{H_2O} = 10 \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} T_j (\lg p + 3)^i \quad (5)$$

The values of coefficients a_{ij} ($i = 0, 1, 2, 3$ and $j = 0, 1, 2, 3$) are shown in Table 4.

Table 1
Coefficients in Equation (1).

Coefficient	Value	Coefficient	Value
a_1	21.58610805	a_4	113.0735222
a_2	−1.280044975	a_5	−40377.6358
a_3	−4808.426205	a_6	3.8508508×10^{-2}

Table 2
Coefficients in Equation (2).

p/MPa	a_0	a_1	a_2
0.1	1.544412	0.0681	-1.7452×10^{-4}
0.2	0.913996	0.0651	-1.4347×10^{-4}
0.3	0.481486	0.0648	-1.4216×10^{-4}
0.4	0.259524	0.0636	-1.3668×10^{-4}
0.5	0.107676	0.0618	-1.2643×10^{-4}
0.6	−0.164630	0.0612	-1.1875×10^{-4}
0.8	−0.387960	0.0630	-1.2884×10^{-4}
1.5	−0.945970	0.0607	-1.1534×10^{-4}
2	−1.172380	0.0581	-1.0108×10^{-4}
3	−1.499380	0.0576	-1.0113×10^{-4}
4	−1.649210	0.0569	-1.0085×10^{-4}
5	−1.913820	0.0597	-1.1618×10^{-4}
6	−1.963050	0.0567	-1.0264×10^{-4}
8	−2.162460	0.0576	-1.0912×10^{-4}
15	−2.326270	0.0513	-8.4136×10^{-5}
20	−2.395928	0.0499	-8.1751×10^{-5}
30	−2.447437	0.0467	-7.0353×10^{-5}
40	−2.620645	0.0474	-7.4510×10^{-5}
50	−2.627157	0.0457	-6.9094×10^{-5}
60	−2.601997	0.0436	-6.1641×10^{-5}
70	−2.727667	0.0456	-7.1151×10^{-5}

2.2. Semiempirical formulas based on experimental data

2.2.1. Zhu Lin's formula

Zhu Lin derived Equation (6) based on the conclusion that the water content in sweet natural gas was in direct proportion to the temperature T and in inverse proportion to the pressure p [1,14].

$$W_{H_2O} = 101.325 \frac{\sum_{i=0}^{7} a_i T_i}{p} + \sum_{i=0}^{7} b_i T_i \quad (6)$$

The values of coefficients a_i and b_i ($i = 1, 2, \ldots, 7$) are shown in Table 5.

2.2.2. Behr's formula

Behr regarded the water content in sweet natural gas as the function of ln$p$ and 1/(T +273.15) and developed Equation (7) through numerical fitting [15].

$$W_{H_2O} = a_0 \exp\left[a_1 + \frac{a_2 + a_3 \ln p + a_4 (\ln p)^2}{(T + 273.15)^2} + a_5 \ln p + a_6 (\ln p)^2 + a_7 (\ln p)^3 + \frac{a_8 + a_9 \ln p + a_{10} (\ln p)^2 + a_{11} (\ln p)^3}{(T + 273.15)^3}\right] \quad (7)$$

Table 3
Coefficients in Equation (4).

Coefficient	Value	Coefficient	Value
a_1	706652.14	b_1	2 893.11193
a_2	−8915.814	b_2	−41.86941
a_3	42.607133	b_3	0.229899
a_4	−0.0915312	b_4	-5.68959×10^{-4}
a_5	7.46945×10^{-5}	b_5	5.36847×10^{-7}