Determination of Bubble-Point and Dew-Point Pressure Without a Visual Cell

R. Hosein, and R. Mayrhoo, The University of The West Indies; W. D. McCain Jr., Texas A&M University

Abstract

Bubble-point and dew-point pressures of oil and gas condensate reservoir fluids are used for planning the production profile of these reservoirs. Usually the best method for determination of these saturation pressures is by visual observation when a Constant Mass Expansion (CME) test is performed on a sample in a high pressure cell fitted with a glass window. In this test the cell pressure is reduced in steps and the pressure at which the first sign of gas bubbles is observed is recorded as bubble-point pressure for the oil samples and the first sign of liquid droplets is recorded as the dew-point pressure for the gas condensate samples.

The experimental determination of saturation pressure especially for volatile oil and gas condensate require many small pressure reduction steps which make the observation method tedious, time consuming and expensive. In this study we have extended the Y-function which is often used to smooth out CME data for black oils below the bubble-point to determine saturation pressure of reservoir fluids. We started from the initial measured pressure and volume and by plotting log of the extended Y function which we call the Y_{EXT} function, with the corresponding pressure, two straight lines were obtained; one in the single phase region and the other in the two phase region. The point at which these two lines intersect is the saturation pressure.

The differences between the saturation pressures determined by our proposed Y_{EXT} function method and the observation method was less than $\pm$ 4.0 % for the gas condensate, black oil and volatile oil samples studied. This extension of the Y function to determine dew-point and bubble-point pressures was not found elsewhere in the open literature. With this graphical method the determination of saturation pressures is less tedious and time consuming and expensive windowed cells are not required.

Introduction

In the hydrocarbon industry, bubble point is known as the pressure at which gas begins to evolve from oil and dew point as the pressure at which liquid begins to condense from natural gas (McCain, 1990). Oil production will decrease from oil reservoirs that are at the bubble point or below due to the preferential flow of gas that escape from the oil. This is because gas has a lower viscosity than oil and therefore a higher mobility. In the case of gas reservoirs at the dew point pressure or below, liquid condensation occurs, initially near the wellbore region. Some of this liquid condensate flows to the surface with the
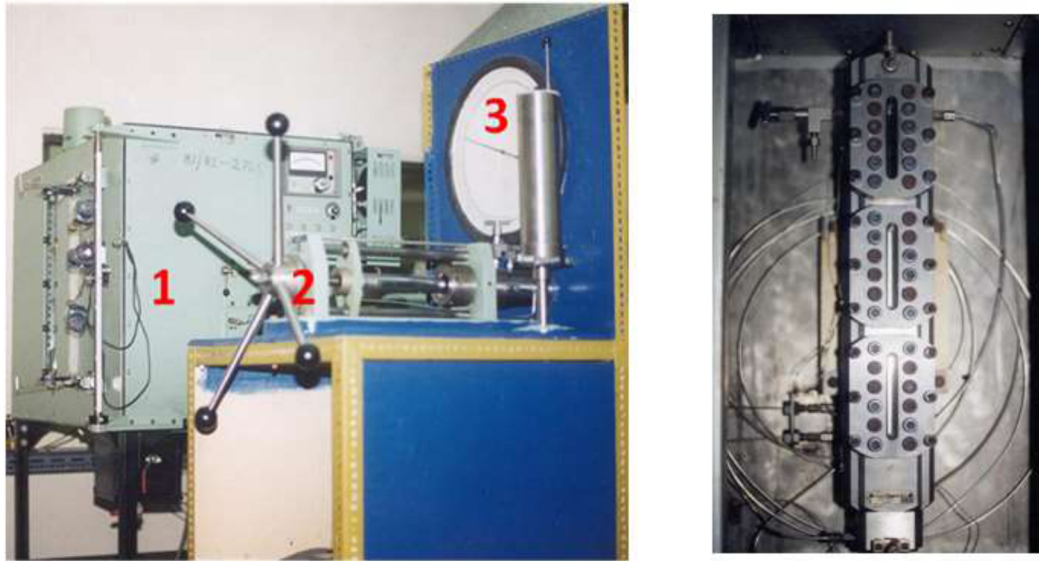
Figure 1—PVT Equipment and Three Windowed PVT Cell

flowing gas whilst the remainder is trapped in the reservoir by interfacial forces and reduces the gas flow rate (Craft and Hawkins, 1959; Smith, Dawe and Kydd, 2007). With time a liquid condensate bank builds up which can eventually "kill" the well. In many cases, from knowledge of bubble point and dew point pressures, pressure maintenance schemes are applied to oil and gas reservoirs to sustain oil and gas production rates.

Saturation Pressures from Constant Mass Expansion (CME) Test

The determination of bubble point and dew point pressure (also known as saturation pressure) is important to predict, design and manage oil and gas production from reservoirs (Coats and Smart, 1986; Hosein and Dawe, 2011). Experimental observation during a CME test is the common route and is a standard test that is performed during Pressure-Volume-Temperature (PVT) analyses on oil and gas samples taken very early from an exploratory well while reservoir pressure is still above the saturation pressure (Danesh, 1998; Hosein, 2004). This test is conducted in a windowed cell (Figure 1), at reservoir temperature and with reservoir pressure or higher as the starting point. The cell pressure is reduced in several pre-determined steps down to abandonment pressure with the change in the total hydrocarbon volume for each pressure reduction step measured. During this process a second phase evolves – gas from an oil sample and retrograde liquid (McCain, 1990) from a gas sample. The pressure at which the first bubble of gas is observed from the oil sample and droplet of liquid from the gas sample is reported as the saturation or bubble point and dew point pressure respectively (Danesh, 1998). The hydrocarbon volume at saturation pressure is used as a reference volume and the total hydrocarbon volume measured for each pressure depletion step is reported relative to this volume (Danesh, 1998; Hosein, 2004).

This method for determining bubble point for some black oils, volatile oils and dew point pressures for gas condensates, especially lean gases (McCain, 1990) (C_{7+} composition of less than 4.0 mole percent) can be difficult and errors greater than $\pm$ 500 psia are possible (Mesingset, 1998). In some cases, small pressure reduction steps of less than 100 psia are needed in order to see the first sign of a change in phase (Hosein, 2004) which make the observation method extremely tedious, time consuming and expensive (Danesh, 1998). PVT cells equipped with optical devices for detecting a phase change further add to the cost for this test.

Dew Point Pressure from Correlations

An outline of correlations and genetic programming models developed over the years for determining dew point pressures for gas condensates have been documented by Eissa (2008). Basic data required for the

correlations are condensate gas ratio (CGR) (Eilerts and Smith, 1942), composition and physical properties of the heptanes-plus fraction (Organic and Golding, 1952; Nemeth and Kennedy, 1967; Elsharkawy, 2002). The correlations themselves have been developed using data from specific geographical regions and depends on the accuracy of the measured input data for example CGR at the time of sampling, gas chromatography (GC) for compositional analysis and True Boiling Point Distillation (TBP) for the properties of the heptanes-plus fraction (Hosein 2004). Genetic programming models depend on the accuracy of the compositional analysis and require a large data set of experimental dew point pressures for modeling (Eissa, 2008). CME experiments are therefore the preferred method compared to correlations.

Bubble Point Pressure from Correlations
A comparison of correlations that were developed over the years for determining bubble point pressure for black oils have been documented by Mc Cain et al (2010). Many of these correlations were developed for specific regions for more accurate prediction of bubble point pressure, by using Standing's (1947) correlation as a base. This difficulty of producing an accurate universal bubble point correlation for black oils and the non-existent of a bubble point correlation for volatile oil also make CME experiments the preferred method for determining bubble point pressure of these reservoir fluids. A Y function (Standing, 1952; Craft and Hawkins, 1959; Amyx et. al., 1960) is commonly used by PVT analysts to smooth out data below the bubble point so as to obtain an almost linear relationship with CME data (pressure and volume) as follows:

The Y Function
The Y function is linear with pressure and is related to the two phase relative volume and pressure as follows:

$$Y = (P_b - P) / (P \times (V/V_b - 1)), \tag{1}$$

Where P_b = bubble point pressure, psia
       P = pressure at any point.
       V_b = bubble point volume, cc
       V = two-phase volume at pressure P
       V/V_b = relative volume, V_t
It was derived from the compressibility equation (Standing 1952)

$$\beta = - (1 / V) \times (\delta V / \delta P)_T, \tag{2}$$

Where β = compressibility, 1/psi
V = volume, cc
$\delta V / \delta P$ = change in volume due to change in pressure at constant temperature T.

This Y function, which is dimensionless, is applied to CME data below the bubble point from black oil PVT studies (Standing, 1952; Craft and Hawkins, 1959; Amyx et. al., 1960). In this study we have extended the Y function in a new way to determine dew-point pressure for gas condensates and also bubble point pressures for black oils and volatile oils.

Source of Constant Mass Expansion Data

The samples for this study were selected from different regions worldwide and were classified by composition as follows (summarized in Table 4) (McCain, 1990):

- Samples with C_{7+} composition of < 4.0 mole percent are classified as lean gas condensates.
- Samples with C_{7+} composition ≥ 4.0 mole percent but < 12.5 mole percent are classified as rich gas condensates.

- Samples with C_{7+} composition $\geq$ 12.5 mole percent but $<$ 20.0 mole percent are classified as volatile oils.
- Samples with C_{7+} composition $\geq$ 20.0 mole percent are classified as black oils.

CME data for samples LS1 to LS7 were obtained from published literature and for RS1 to RS4 from PVT reports analyzed by commercial PVT laboratories. Sample TS2 (Hosein and Dawe, 2011) was obtained by recombination using the PVT laboratory (Figure 1) at UWI. The gas and liquid condensate samples for the recombination were taken from a surface test separator located on one of the gas production platforms offshore the Southeast coast of Trinidad.

Sample TS2 has a C_{7+} composition lesser than 4.0 mole percent (Hosein and Dawe, 2011) which suggests that it is a lean gas condensate (McCain, 1990). Details of the sampling procedures, sample quality test conducted, recombination calculation and composition analysis have been outlined by Hosein (2004). A CME test was conducted on sample TS2 using the PVT apparatus at the UWI (Mayrhoo, 2012). Sample LS2 has a C_{7+} composition greater than 4.0 mole percent (Coats and Smart, 1986) which suggest that it is a rich gas condensate (McCain, 1990). Samples TS2 and LS2 were used to establish a method for determining dew point pressure without a visual cell. The method was tested with the other lean and rich gas samples and also for determining bubble point of black oils and volatile oils. CME data for Sample LS2 was taken from Coats and Smart (1986).

PVT Equipment

A photograph of the PVT equipment used in this study is shown in Figure 1. Basically it can be divided into three sections as follows:

1. A three windowed high pressure cell enclosed in a temperature controlled air oven (Figure 1).
2. A high pressure mercury injection system.
3. Pressure gauge

The operating procedures followed were outlined by Hosein (2004).

Constant Mass Expansion Test

Determination of Dew Point Pressure by Observation

A Constant Mass Expansion (CME) test was performed on the recombined Trinidad sample TS2 to simulate pressure-volume relations and to determine:

1. Dew point pressure by the observation method
2. Hydrocarbon volume as a function of pressure.

This test was conducted in the windowed PVT cell (Figure 1), at reservoir temperature, with reservoir pressure as the starting point. Mercury was removed from the cell and the change in the hydrocarbon volume was measured for each pressure reduction step (Table 1). During this process a second phase evolved – retrograde liquid (McCain, 1990). The pressure at which the first droplet of liquid was observed (with the aid of a cathetometer) was reported as the saturation or dew point pressure (Table 1). The volume occupied by the saturated fluid, at dew point pressure, V_d was used as a reference volume and the total hydrocarbon volume measured for each pressure depletion step was reported relative to this volume (Table 1). The volume of the liquid condensate at each pressure step was recorded and expressed as a percentage of the hydrocarbon volume at dew point (saturation) pressure. The pressures and volumes were read to within $\pm$ 0.5 psia and $\pm$ 0.1 cc respectively. Further details of the experimental procedures involved were outlined by Hosein (2004). It should be noted that this is a standard laboratory test that is conducted for gas condensate samples and can be found in PVT reports (Amyx et. al., 1960). In this test,

Table 1—Constant Mass Expansion Data for Trinidad Sample TS2 (lean gas)

Pressure psia	Liquid Vol. in Cell, cc	Gas Vol. in Cell, cc	Total Vol. in Cell., cc	Relative Volume (1)
7515 (Pi)		**75.0 (Vi)**	**75.0 (Vi)**	**0.943(Vi)**
7115		76.6	76.6	0.964
7043		76.9	76.9	0.968
6995		77.1	77.1	0.971
6895		77.6	77.6	0.977
6745		78.3	78.3	0.986
6645		78.9	78.9	0.992
6545 (Pd)	**0.0**	**79.5(Vd)**	**79.5(Vd)**	**1.000**
6295	0.3	80.6	80.9	1.018
5995	1.2	81.7	82.8	1.042
5645	2.2	83.2	85.4	1.075
5245	3.3	85.7	89.0	1.120
4765	4.0	90.4	94.4	1.188
4265	4.3	97.3	101.7	1.279
3715	4.3	108.3	112.6	1.418
3215	4.1	122.7	126.7	1.595
2895	3.9	135.1	138.9	1.748

Notes: Relative Volume, $V_t = V/V_d$

no hydrocarbon is removed from the cell. The observed dew point pressure was 6545 psia as shown in Table 1.

Results and Discussion

Dew Point Pressure by Observation
Dew point pressures are recorded during pressure reduction when the first sign of liquid droplets is observed and again when pressure is increased, at the point when the last few remaining liquid droplets vaporize. The average of these two pressure readings are taken as the dew point. The above method for determining dew point pressures for lean gases (C_{7+} composition of less than 4.0 mole percent) is rather difficult and errors greater than $\pm$ 500 psia are possible. To attempt to reduce this error, small pressure reduction steps of less than 100 psia are needed in order to observe the first sign of liquid droplets. Because of these small pressure steps, the small sample size (cell volume is usually less than 600 cc) and the small amount of heavy components that condenses during pressure reduction, the determination of dew point pressures by the observation method become tedious, time consuming and expensive.

Dew Point Pressure by Pressure – Volume (PV) Relations
Most often a pressure - relative volume (defined earlier) plot for gas condensates is a continuous curve as obtained in Figure 2 from the CME data in Table 2, for samples TS2 (Mayrhoo, 2012) and LS2 (Coats and Smart, 1986). A change in trend indicating single phase (gas) above dew point and two phases (gas and liquid condensate) below dew point is not noticeable as with black oil samples above and below the bubble point (Standing 1952).

In PVT reports a backup for the visual reading is included from a plot of liquid condensate volume against pressure. This plot is extrapolated to zero liquid volume and the pressure at this point is recorded as the dew point pressure. However a visual cell is needed to determine separately the liquid volume from the total hydrocarbon (gas plus liquid condensate) for each pressure depletion step.

The difficulty of measuring liquid condensate volume was documented by Eyton (1987). Because of the small sample size and the small amount of heavy components present (< 4.0 % for lean gases), the first pressure reduction step below dew point can be greater than 200 psia in order to measure only less than 0.3 cc of liquid condensate (Table 1). Another 0.5 cc to 1.0 cc can be lost due to wetting of the
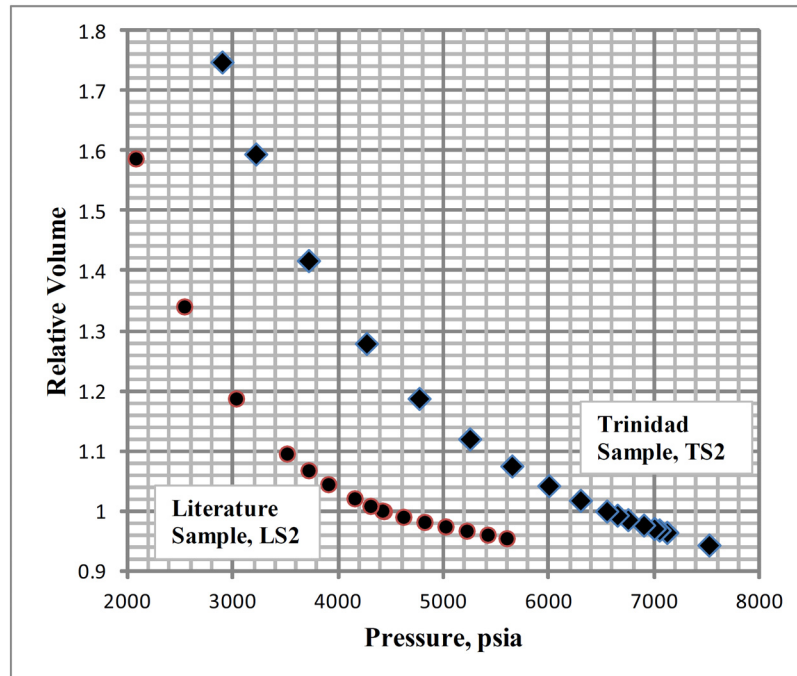
Figure 2—Graphical Plot of Relative Volume and Pressure for Trinidad Sample TS2 (lean gas) and Literature Sample LS2 (rich gas) (Source: Coats and Smart, 1986)

Table 2—Constant Mass Expansion Data

Trinidad Sample TS2 (lean gas)		Literature Sample LS2 (rich gas),(Coats and Smart, 1986).	
Pressure psia	Relative Volume (1)	Pressure psia	Relative Volume (1)
7515 (Pi)	**0.943(Vi)**	**5595 (Pi)**	**0.955(Vi)**
7115	0.964	5415	0.961
7043	0.968	5215	0.967
6995	0.971	5015	0.974
6895	0.977	4815	0.982
6745	0.986	4615	0.991
6645	0.992	**4430(Pd)**	**1.000**
6545 (Pd)	1.000	4415	1.001
6295	1.018	4302	1.009
5995	1.042	4152	1.021
5645	1.075	3902	1.045
5245	1.120	3715	1.068
4765	1.188	3510	1.096
4265	1.279	3027	1.188
3715	1.418	2536	1.341
3215	1.595	2075	1.588

internal walls of the condensate cell (Eyton 1987) after allowing a drainage time of 0.5 hours (Hosein, 2004; Mayrhoo, 2012) between readings. Hence liquid volumes measured just below dew point could have errors of over 50 %. Such measurements cannot be recommended for extrapolation.

A New Method of Determining Dew Point Pressure using the Y Function
In this study the Y function was modified (Y_{EXT}) and applied to determine dew-point pressure graphically as follows:

Table 3—Calculated Y_{EXT} and Log Y_{EXT} Data for Trinidad Sample TS2 (lean gas) and Literature Sample LS2 (rich gas).

Trinidad sample TS2 (lean gas).			Literature Sample LS2 (rich gas) (Source: Coats and Smart, 1986).		
Pressure psia	Y_{EXT} Function	Log Y_{EXT} Function	Pressure psia	Y_{EXT} Function	Log Y_{EXT} Function
7515 (Pi)			**5595 (Pi)**		
7115	2.403	0.381	5415	5.297	0.724
7043	2.370	0.375	5215	5.230	0.719
6995	2.374	0.375	5015	5.076	0.706
6895	2.344	0.370	4815	4.930	0.693
6745	2.291	0.360	4615	4.685	0.671
6645	2.247	0.352	**4430(Pd)**	4.409	0.644
6545 (Pd)	2.151	0.333	4415	4.378	0.641
6295	2.056	0.313	4302	4.094	0.612
5995	1.929	0.285	4152	3.703	0.569
5645	1.781	0.251	3902	3.207	0.506
5245	1.612	0.207	3715	2.834	0.452
4765	1.413	0.150	3510	2.522	0.402
4265	1.214	0.084	3027	1.882	0.275
3715	1.006	0.003	2536	1.351	0.131

Table 4—Comparison of Dew Point and Bubble Point Pressures Obtained by Observation and by the Y_{EXT} Graphical Method from this Study.

Samples	Mole %C7+	Classification	ExperimentalSat. P., (Psia) (Observed)	Y_{EXT}Sat. P., (Psia) (Graphical)	Difference (%)
LS1, (Amyx et al, 1960)	2.24	lean gas	3845 (dew point)	3875 (dew point)	0.8
RS1, (PVT Report)	3.9	lean gas	5006 (dew point)	5100 (dew point)	1.9
TS2 (Expt., this study)	3.92	lean gas	6545 (dew point)	6600 (dew point)	0.8
LS2, (Coats and Smart, 1986)	11.45	rich gas	4430 (dew point)	4500 (dew point)	1.6
LS3, (Pedersen et al, 1989)	5.69	rich gas	5820 (dew point)	5950 (dew point)	2.2
RS2, (PVT Report)	7.54	rich gas	6090 (dew point)	6100 (dew point)	0.2
LS4, (Coats and Smart, 1986)	35.97	black oil	1694 (bubble point)	1750 (bubble point)	3.3
LS5, (McCain, 1990)	33.29	black oil	2620 (bubble point)	2700 (bubble point)	3.1
RS3, (PVT Report)	36.49	black oil	4750 (bubble point)	4900 (bubble point)	3.2
LS6, (Coats and Smart, 1986)	18.51	volatile oil	2115 (bubble point)	2140 (bubble point)	1.2
LS7, (Coats and Smart, 1986)	16.92	volatile oil	4460 (bubble point)	4480 (bubble point)	0.4
RS4, (PVT Report)	15.66	volatile oil	7437 (bubble point)	7480 (bubble point)	0.6

Note: Difference, % = (Z $_{YEXT.}$ - Z$_{observed.}$ / Z $_{observed}$) × 100, where Z observed is the observed saturation pressure value and Z $_{YEXT}$ is the estimated value from our Y_{EXT} Function Method.

$$Y_{EXT} = (P_i - P) / (P_i \times (V/V_i - 1)) \quad\quad\quad (3)$$

Where P_i = initial pressure (psia) at the start of the CME test

P = pressure (psia) at any point.

V = total hydrocarbon volume at pressure P

V_i = initial volume of hydrocarbon in the cell at P_i.

The values of Y_{EXT} obtained at each pressure step for samples TS2 and LS2 are given in Table 3. When Y_{EXT} was plotted against pressure, a concave up and concave down plot was obtained as shown in Figure 3 for Sample LS2. When log Y_{EXT} (Table 3) was plotted against pressure two straight lines were obtained, one above and one below the observed dew point. These lines were extended and the pressure at the point where they met was recorded as the dew point pressure (Figures 4 and 5). The differences between the observed and graphical values for both the lean and rich gas samples were less than ± 2.0 %.
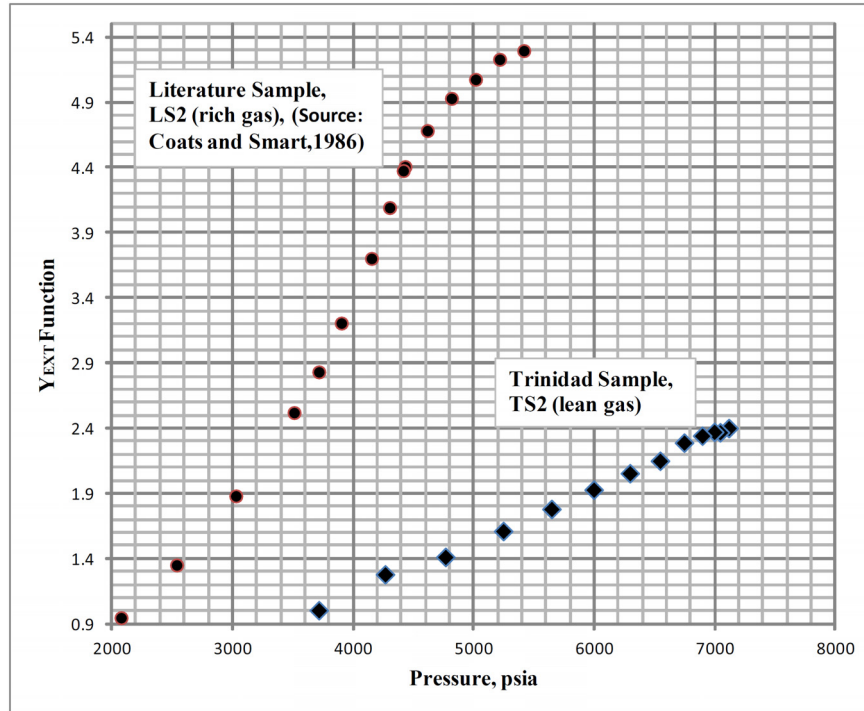
Figure 3—Graphical Plots of the Y_{EXT} Function and Pressure for Trinidad Sample TS2 (lean gas) and Literature Sample LS2 (rich gas), (Coats and Smart, 1986)
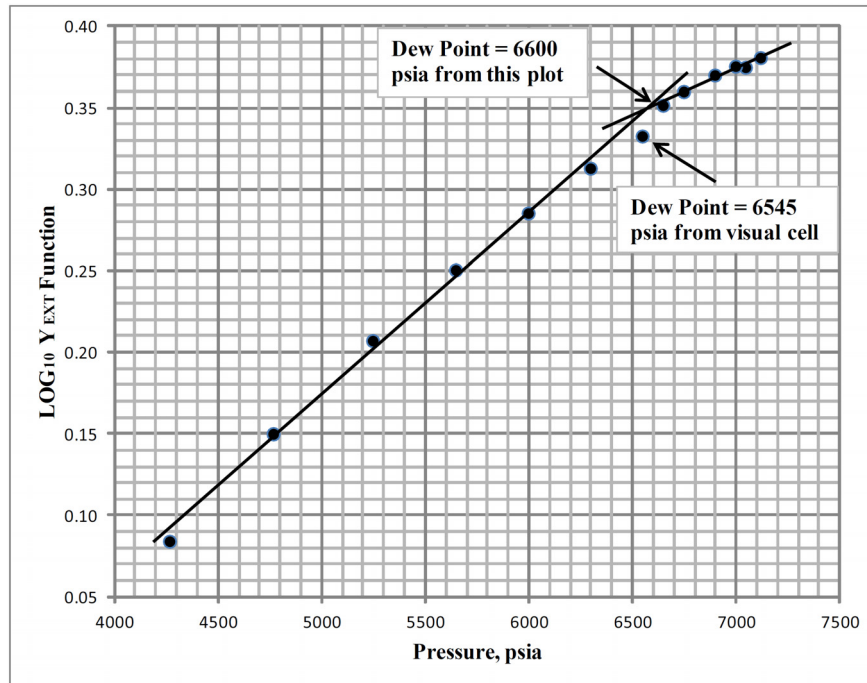

Figure 4—Graphical Plot to Determine Dew Point Pressure by the Y_{EXT} Function Method for Trinidad Sample TS2 (lean gas)

This proposed Y_{EXT} function method was tested with CME data shown in Appendix Tables A1 to A4 for these lean and rich gas condensate samples. Similar plots shown in Figures A1 to A4 were made to obtain graphical dew point pressures for these gas condensate samples by this method.
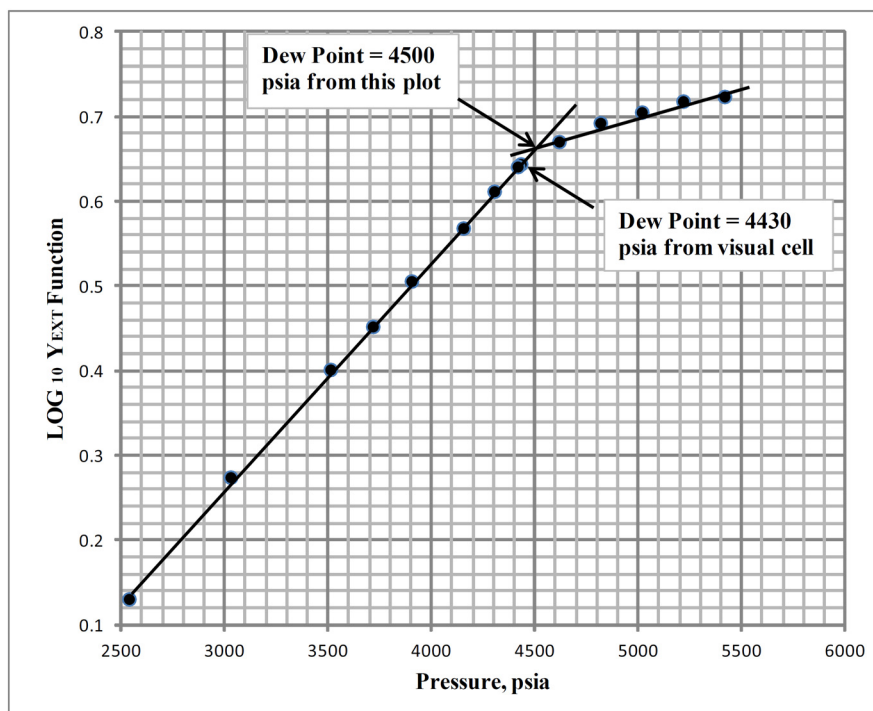
Figure 5—Graphical Plot to Determine Dew Point Pressure by the Y_{EXT} Function Method for Literature Sample LS2 (rich gas) (Source: Coats and Smart, 1986)

Application of the Y_{EXT} Function Method to Determine Bubble Point Pressure.
The proposed Y_{EXT} function method was tested with CME data for black oils and volatile oil samples shown in the Appendix Tables A5 to A10. Similar plots shown in Figures A5 to A10 were made to obtain graphical bubble point pressures for these oil samples by this method.

Comparison of Saturation Pressure (Sat. P.) from Observation and the Y_{EXT} Function Method
The observed dew point and bubble point pressures (Sat. P.) for the twelve samples can be seen in Table 4. These were compared to the graphical values obtained by the proposed Y_{EXT} function method. The differences between the observed and graphical values for the lean and rich gas samples, black oil and volatile oil samples were less than ± 4.0 %. These results show that with this new Y function method, dew point and bubble point pressures can be determined quickly and accurately without the use of a visual cell.

Conclusions

1. A technique using an $_{EXT}$ended Y function and called the Y_{EXT} function was developed to determine dew point and bubble point pressures graphically.
2. The differences between the dew point and bubble point pressures determined by the proposed Y_{EXT} function method and the observation method were less than ± 4.0 % for the lean and rich gas condensate and oil samples tested.
3. A visual cell is not needed to determine dew point and bubble point pressures by the proposed Y_{EXT} function method. This new method is less tedious and time consuming when compared to the visual method.
4. This application of the Y function to determine dew point and bubble point pressures for reservoir fluids was not found elsewhere in the open literature.

Acknowledgements

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Appendix

Table A1—CCE Data and Calculated Y_{EXT} Data for Literature Sample LS1 (lean gas),

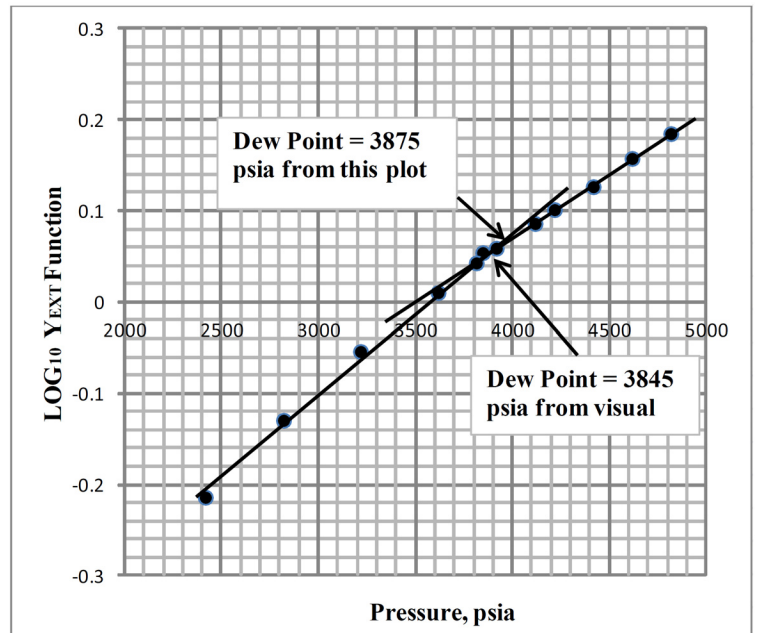| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
5015 (Pi)	**0.829(Vi)**		
4815	0.851	1.531	0.185
4615	0.875	1.438	0.158
4415	0.903	1.339	0.127
4215	0.934	1.264	0.102
4115	0.951	1.220	0.086
3915	0.988	1.146	0.059
3845 (Pd)	**1.000**	1.133	0.054
3812	1.009	1.105	0.043
3615	1.055	1.025	0.011
3215	1.166	0.884	−0.054
2818	1.319	0.743	−0.129
2415	1.533	0.611	−0.214
2015	1.842	0.490	−0.310

(Source: Amyx et. al., 1960).

Figure A1—Graphical Plot to Determine DPP by the Y_{EXT} Function Method for Literature Sample LS1 (lean gas).

Table A2—CCE Data and Calculated Y_{EXT} Data for Worldwide Sample RS1 (lean gas),

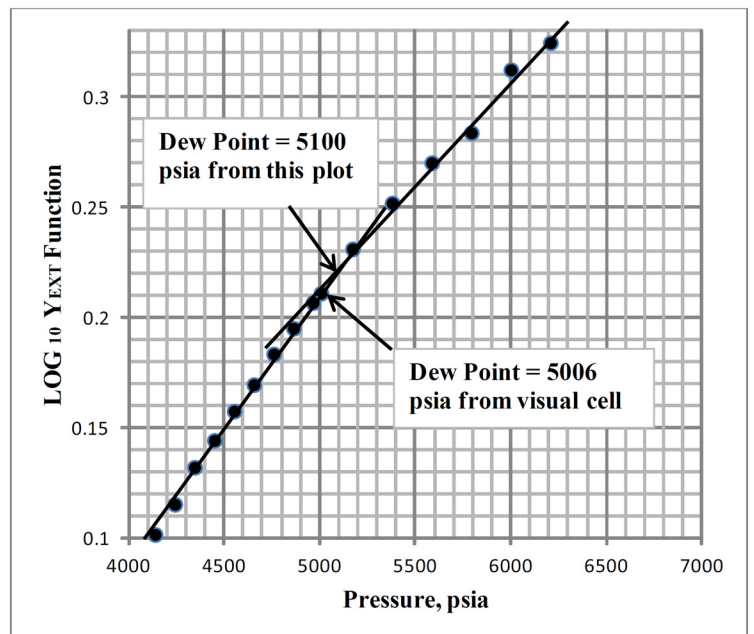| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
6692 (Pi)	**0.866(Vi)**		
6206	0.896	2.112	0.325
5999	0.910	2.053	0.312
5792	0.926	1.923	0.284
5585	0.943	1.863	0.270
5378	0.961	1.786	0.252
5171	0.981	1.703	0.231
5006 (Pd)	**1.000**	1.626	0.211
4964	1.005	1.610	0.207
4862	1.017	1.567	0.195
4758	1.030	1.526	0.183
4655	1.044	1.478	0.170
4551	1.059	1.437	0.158
4448	1.074	1.394	0.144
4344	1.090	1.356	0.132
4241	1.109	1.304	0.115
4137	1.127	1.264	0.102

(Source: PVT Report).

Figure A2—Graphical Plot to Determine DPP by the Y_{EXT} Function Method for Worldwide Sample RS1 (lean gas).

Table A3—CCE Data and Calculated YEXT Data for Literature Sample LS3 (rich gas),

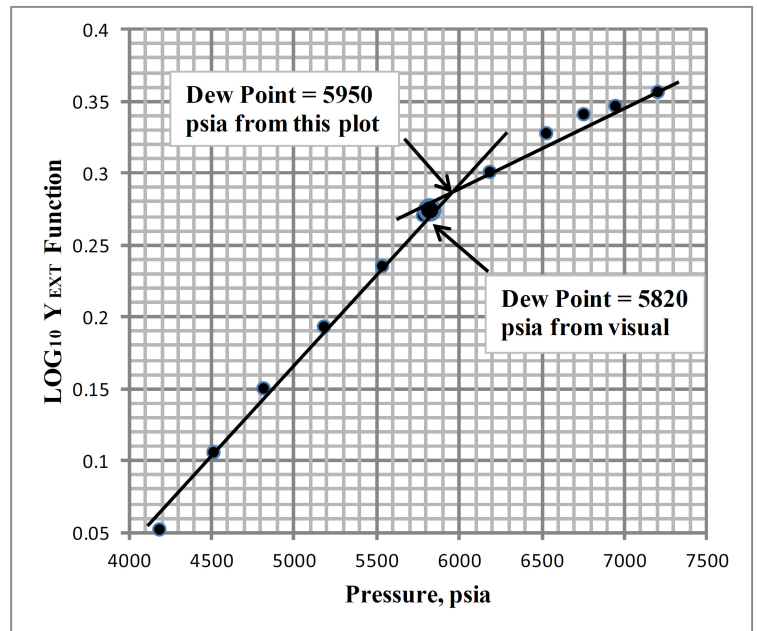| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
7427 (Pi)	**0.897(Vi)**		
7197	0.909	2.276	0.357
6941	0.923	2.225	0.347
6749	0.934	2.196	0.342
6522	0.948	2.130	0.328
6180	0.972	2.002	0.302
5895	0.996	1.867	0.271
5820 (Pd)	**1.000**	**1.880**	**0.274**
5777	1.004	1.868	0.271
5529	1.030	1.722	0.236
5177	1.071	1.563	0.194
4811	1.120	1.415	0.151
4508	1.173	1.278	0.106
4181	1.244	1.129	0.053
3834	1.325	1.013	0.006
3579	1.402	0.920	−0.036

(Source: Pedersen et. al., 1989).

Figure A3—Graphical Plot to Determine DPP by the Y_{EXT} Function Method for Literature Sample LS3 (rich gas).

Table A4—CCE Data and Calculated Y_{EXT} Data for Worldwide Sample RS2 (rich gas),

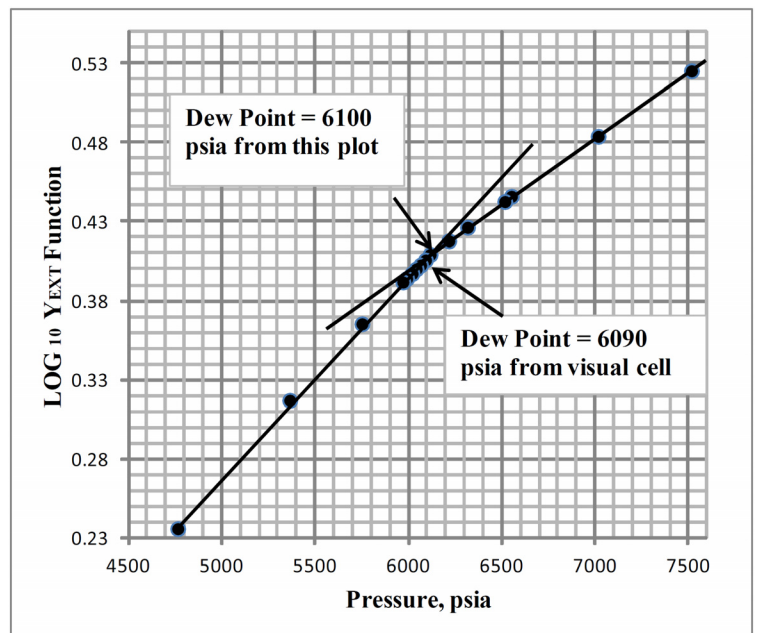| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
8015 (Pi)	**0.914(Vi)**		
7515	0.931	3.353	0.525
7015	0.951	3.048	0.484
6550	0.974	2.793	0.446
6515	0.976	2.772	0.443
6315	0.986	2.670	0.426
6215	0.992	2.618	0.418
6115	0.998	2.567	0.409
6090 (Pd)	**1.000**	**2.546**	**0.406**
6064	1.002	2.528	0.403
6040	1.003	2.513	0.400
6018	1.005	2.496	0.397
5989	1.007	2.478	0.394
5969	1.008	2.466	0.392
5750	1.025	2.320	0.366
5363	1.060	2.075	0.317
4763	1.129	1.721	0.236

(Source: PVT Report).

Figure A4—Graphical Plot to Determine DPP by the Y_{EXT} Function Method for Worldwide Sample RS2 (rich gas).

Table A5—CCE Data and Calculated Y_{EXT} Data for Literature Sample LS4 (Black Oil),

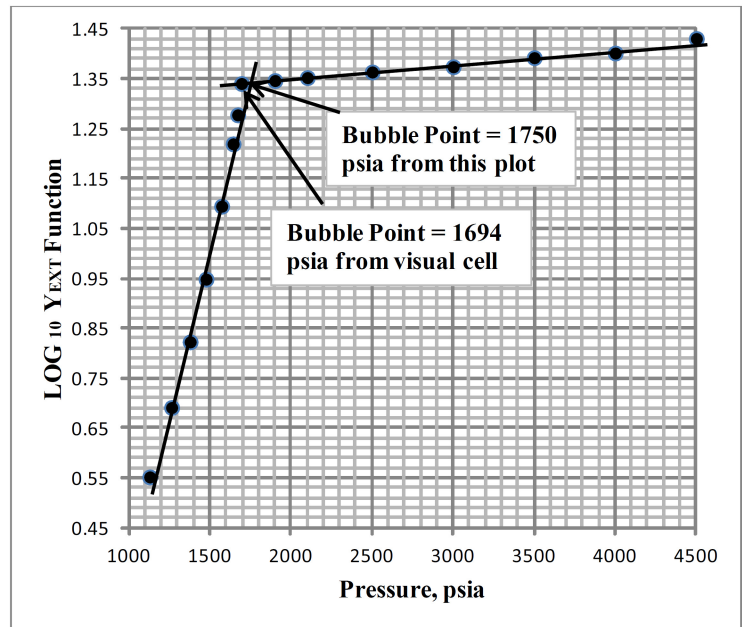| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
5000 (Pi)	**0.971(Vi)**		
4500	0.974	26.964	1.431
4000	0.978	25.213	1.402
3500	0.983	24.679	1.392
3000	0.987	23.676	1.374
2500	0.992	23.112	1.364
2100	0.996	22.520	1.353
1900	0.998	22.208	1.347
1694 (Pb)	**1.000**	21.905	1.341
1670	1.005	18.959	1.278
1642	1.010	16.588	1.220
1572	1.024	12.439	1.095
1475	1.048	8.888	0.949
1377	1.076	6.654	0.823
1263	1.118	4.915	0.692
1128	1.181	3.568	0.552

(Source: Coats and Smart, 1986).

Figure A5—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Literature Sample LS4 (Black Oil).

Table A6—CCE Data and Calculated Y_{EXT} Data for Literature Sample LS5 (Black Oil)

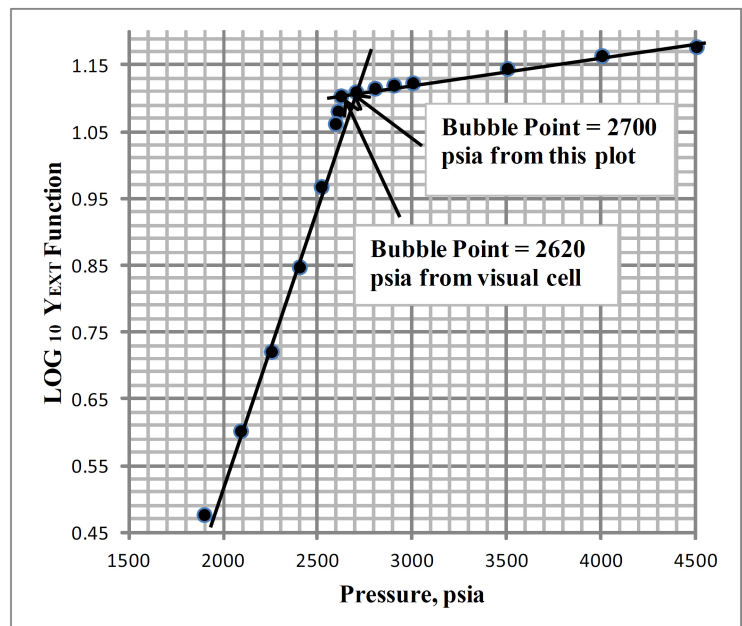| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
5000 (Pi)	**0.964(Vi)**		
4500	0.970	15.061	1.178
4000	0.977	14.605	1.164
3500	0.985	13.970	1.145
3000	0.993	13.295	1.124
2900	0.995	13.187	1.120
2800	0.996	13.050	1.116
2700	0.998	12.889	1.110
2620 (Pb)	**1.000**	12.710	1.104
2605	1.002	12.055	1.081
2591	1.004	11.552	1.063
2516	1.015	9.298	0.968
2401	1.035	7.047	0.848
2253	1.065	5.264	0.721
2090	1.104	4.004	0.603
1897	1.163	3.000	0.477

(Source: McCain, 1990).

Figure A6—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Literature Sample LS5 (Black Oil).

Table A7—CCE Data and Calculated Y_{EXT} Data for Worldwide Sample RS3 (Black Oil),

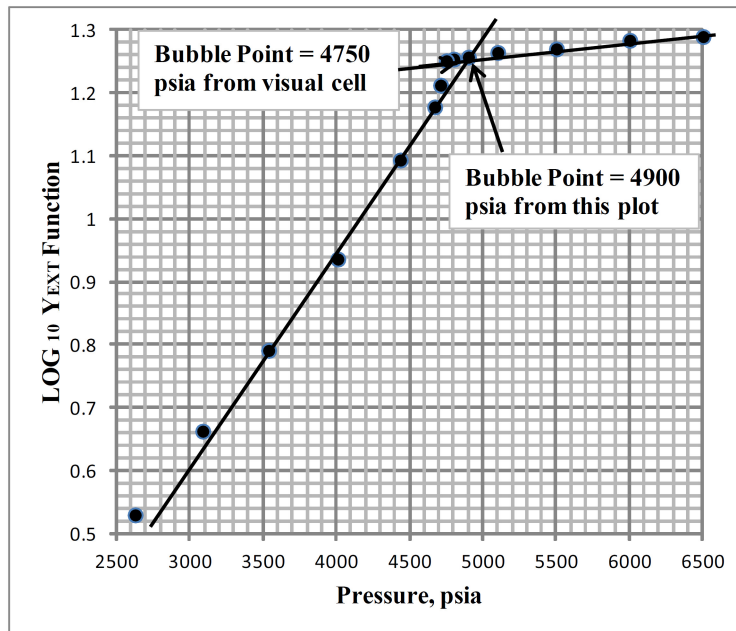| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
7000 (Pi)	**0.982 (Vi)**		
6500	0.986	19.490	1.290
6000	0.990	19.223	1.284
5500	0.994	18.628	1.270
5100	0.997	18.388	1.265
4900	0.999	18.079	1.257
4800	1.000	17.949	1.254
4750 (Pb)	**1.000**	17.838	1.251
4710	1.002	16.312	1.213
4670	1.004	15.068	1.178
4436	1.011	12.407	1.094
4009	1.031	8.636	0.936
3537	1.061	6.183	0.791
3088	1.1016	4.602	0.663
2627	1.1634	3.388	0.530

(Source: PVT Report).

Figure A7—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Worldwide Sample RS3 (Black Oil).

Table A8—CCE Data and Calculated Y_{EXT} Data for Literature Sample LS6 (Volatile Oil)

Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
4500 (Pi)	**0.947 (Vi)**		
4000	0.955	12.374	1.093
3500	0.964	11.818	1.073
3000	0.975	11.033	1.043
2500	0.988	10.236	1.010
2400	0.991	10.017	1.001
2300	0.994	9.826	0.992
2200	0.997	9.600	0.982
2115 (Pb)	**1.000**	9.395	0.973
2092	1.004	8.794	0.944
2068	1.009	8.212	0.914
2043	1.015	7.578	0.880
1990	1.028	6.494	0.813
1927	1.049	5.301	0.724
1834	1.087	3.992	0.601
1669	1.186	2.485	0.395

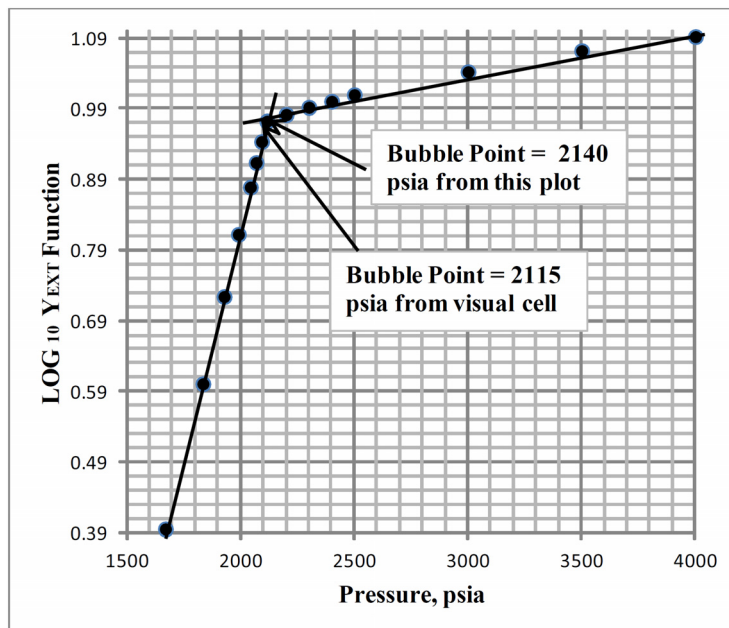(Source: Coats and Smart, 1986).

Figure A8—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Literature Sample LS6 (Volatile Oil).

Table A9—CCE Data and Calculated Y_{EXT} Data for Literature Sample LS7 (Volatile Oil),

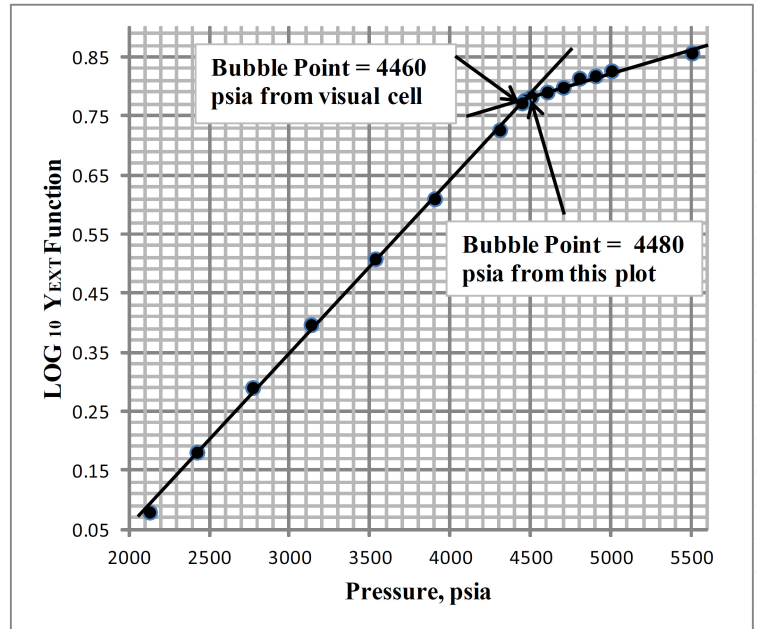| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
6000 (Pi)	**0.959(Vi)**		
5500	0.970	7.199	0.857
5000	0.983	6.715	0.827
4800	0.988	6.523	0.814
4700	0.992	6.296	0.799
4600	0.995	6.181	0.791
4500	0.998	6.069	0.783
4460 (Pb)	**1.000**	**5.988**	**0.777**
4443	1.001	5.925	0.773
4305	1.010	5.332	0.727
3900	1.041	4.078	0.610
3531	1.081	3.226	0.509
3132	1.143	2.496	0.397
2769	1.223	1.954	0.291
2422	1.336	1.518	0.181
2128	1.474	1.202	0.080

(Source: Coats and Smart, 1986).

Figure A9—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Literature Sample LS7 (Volatile Oil).

Table A10—CCE Data and Calculated Y_{EXT} Data for Worldwide Sample RS4 (Volatile Oil),

| Pressure psia	Relative Volume (1)	Y_{EXT} Function	Log Y_{EXT} Function
10000 (Pi)	**0.952(Vi)**		
9500	0.960	5.878	0.769
9000	0.969	5.668	0.753
8500	0.978	5.494	0.740
8000	0.988	5.320	0.726
7800	0.992	5.251	0.720
7700	0.994	5.215	0.717
7600	0.996	5.183	0.715
7500	0.999	5.142	0.711
7437 (Pb)	**1.000**	**5.117**	**0.709**
7419	1.001	5.099	0.708
7394	1.001	5.065	0.705
7370	1.002	5.049	0.703
7345	1.003	5.027	0.701
7322	1.003	5.010	0.700
7203	1.006	4.942	0.694

(Source: PVT Report).
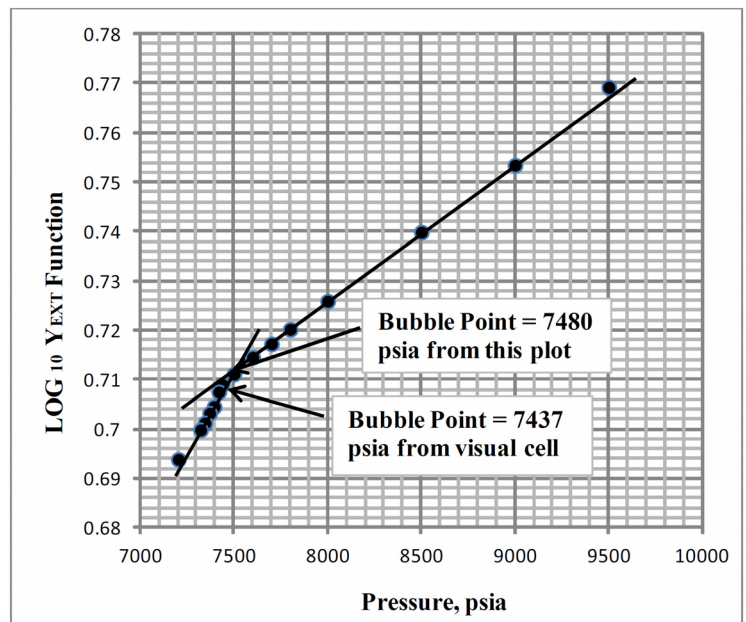
Figure A10—Graphical Plot to Determine BPP by the Y_{EXT} Function Method for Worldwide Sample RS4 (Volatile Oil).