Shrinkage Loses Resulting from Liquid Hydrocarbon Blending

by Harry James

Background

Pipeline integrity balance and custody transfer accuracy have been the focus of measurement specialists since the industry began trading and transporting liquid hydrocarbons. Even with the best volumetric measurement equipment, unaccounted for discrepancies still were occurring. Temperature, pressure and meter factor corrections were not enough to explain these discrepancies.

Mathematicians have been telling us for centuries that one plus one equals two. In an ideal world of Newtonian physics this is the case but in the world of volumetric hydrocarbon measurement one plus one is usually less than two. However it can, in rare circumstances be greater than two. As stated in the Dec. 1967 edition of API Publication 2509C regarding the result of blending two different hydrocarbons, "If the nature of the molecules of the components differ appreciably, then deviation from ideal behavior may be expected. This deviation may either be positive or negative; that is, the total volume may increase or decrease when components are blended. ….. Inasmuch as petroleum components contain molecules of various sizes and weights, solutions of two separate components are seldom ideal. Consequently it is to be expected there may be a change in volume associated with the mixing or blending of petroleum components of varying gravities and molecular structure."

In liquid petroleum blending however, the result has always been shrinkage. In this paper, only the negative deviations or losses will be addressed.

How Does Shrinkage Occur?

If you want to have fun with your friends when you are out at a sports bar, ask for some beer and tomato juice. Make a wager that you can put three ounces of beer and five ounces of tomato juice in an eight ounce glass and it will not be full to the eight ounce line. They will usually take the bait.

First pour the five ounces of tomato juice into the eight ounce glass. Now slowly pour the three ounces of beer into the tomato juice. Voila, you win.

Blending of hydrocarbons of differing densities is similar in concept to mixing beer and tomato juice.

This shrinkage behavior can be visually illustrated by mixing marbles and sand. If one takes a litre of marbles and a litre of sand and pour them both into a two litre container, the sand will fill the voids left by the geometry of the marbles resulting in less than two litres of mixture in the two litre container.

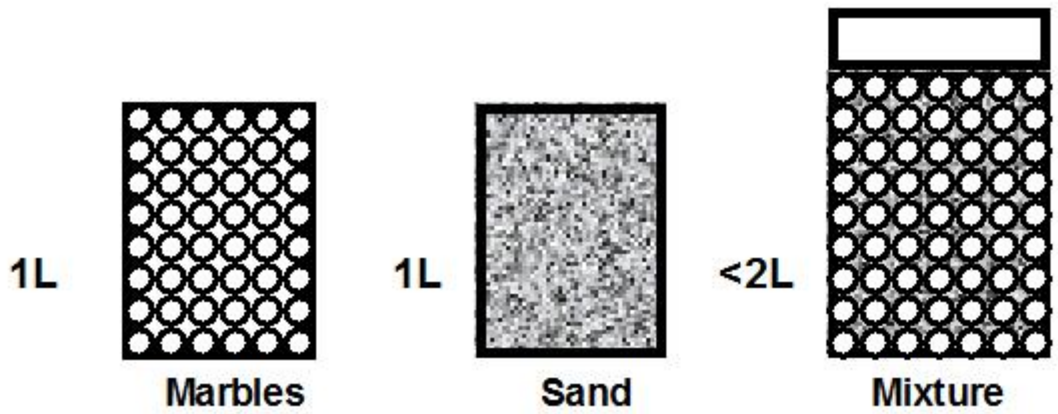

Figure 1

Now, if there were just two molecule sizes it would be easy to determine geometrically the amount of shrinkage that would occur. However, there are numerous molecule sizes and an infinite number of mixtures possible in hydrocarbon blending. Solving the problem using geometry becomes virtually impossible. Consequently, another method of quantifying losses caused by blending shrinkage had to be found.

Empirical Testing

Empirical testing by a number of major oil companies has produced vast amounts of blending data. Evaluation of this data has allowed development of formulas and tables which can be used to predict, within a reasonable degree of accuracy, the amount of shrinkage that will occur when crude oils are blended with lighter diluents.

An API Measurement Committee correlated blending and shrinkage data collected in the 1950's. In 1962, API released publication 2509C containing the following formula and tables which served as the accepted industry standard for over thirty years.

$$S = 0.0000214C^{-0.0704}G^{1.76}$$

Where:

S = shrinkage factor as a decimal fraction of the lighter component (Diluent).

C = concentration, in liquid volume % of the lighter component in the mixture.

G = gravity difference, in degrees API.

Through the 1980's increased blending of crude oils with diluent concentrations outside the range of the 2509C data revealed losses that 2509C did not adequately account for. This created a strong incentive to improve the accuracy of shrinkage equations and tables. Through the determined efforts of the API Committee on Petroleum Measurement, additional data was evaluated from studies conducted by D.R. Booker, K. Schuchardt, H.M. Childress and P.R. Scott. The result of numerous reviews and a lot of cooperation resulted in the equations published in the Manual of Petroleum Measurement Standards, Chapter 12 section 3 released in 1996.

Customary Units: (Bbls, °F, °API etc.

$$S = 4.86 \times 10^{-8}C(100 - C)^{0.819}G^{2.28}$$

Where:

S = volumetric shrinkage, as a percentage of the total mixture ideal volume.

C = concentration, in liquid volume % of the lighter component in the mixture.

G = gravity difference, in degrees API.

SI Units: (m^3, °C, kg/m^3 etc.)

$$S = 2.69 \times 10^{4}C(100 - C)^{0.819}\left(\frac{1}{dL} - \frac{1}{dH}\right)^{2.28}$$

Where:

S = volumetric shrinkage, as a % of the total mixture ideal volume.

C = concentration, in liquid volume % of the lighter component in the mixture.

(1/dL – 1/dH) = inverse density difference of light (dL) and heavy (dH) components in m3 /kg.

Tables have been produced from these equations as MPMS Chapter 12.3 Table 3 for Customary Units and MPMS Chapter 12.3 Table 5 for SI Units.

USING THE EQUATION (API 12.3)

There are three basic applications for the shrinkage equations.

1. **Determining the volumetric shrinkage in a blend of known component volumes.**

This is a direct application of the shrinkage formula.

Assume a blend of 10,000 m^3 of 845 kg/m^3 crude oil with 1,500 m^3 of 645 kg/m^3 diluent:

% Concentration of diluent C:

= (Volume of diluent / (Volume of diluent + Volume of crude) x 100

= (1500 / (10000 + 1500) X 100 = 13.04%

The inverse density factor (1/dl – 1/dh)

= (1/645 – 1/845) = 0.00036696

Using:

$S = 2.69 \times 10^4 C (100 – C)^{0.819} (1/dL – 1/dH)^{2.28}$

$S = 2.69 \times 10^4 (13.04) (86.96)^{0.819} (1.47 \times 10^{-8})$

= 0.199873 %

Volumetric shrinkage = 22.985 m^3 of blend

Resulting blend volume = 11,500 – 22.985 *= 11,477.015m*^{3}

Unaccounted for, this shrinkage represents a volumetric loss. Knowing that mass is conserved, the resulting mass of the blend must be the arithmetic sum of the crude and diluent masses. Now, if the volume of the blend is less than the sum of the component volumes and the mass remains constant, the density must be greater than the weighted average density of the components. This leads to the next application of the shrinkage formulas.

2. Determining the density of the blend (mass balance)

Using the blend determined above and knowing that mass is conserved:

Original mass = mass of crude + mass of diluent

= 10,000 X 845 + 1500 X 645 = 9,417,500 kg.

Theoretical density dT of ideal blend is:

dT = (Original masses)/(Original volumes)

= 9,417,500 kg/ (11,500.01m^3

= 818.913 kg/m^3

Actual Blend density dA (mass balance):

dA = Original mass / Blend volume

= 9,417,500 / 11,477.02 = 820.552 kg/m^3

This brings us to the third application of the shrinkage formulas. Blending to a specific target density with known components.

3. Determining the amount of diluent required to blend crude oil to a specific density:

Using the values from our case study where we determined that the resulting blend density would be 820.552 kg/m^3 the objective now is to determine how much diluent (m3) of density 645 kg/m^3 would be required to blend 10,000 m^3 of crude of density 845 kg/m3 to the target density of 820.552 kg/m^3.

The first step is to determine the theoretical diluent requirements.

VD = VC ((dC – dB)/(dB – dD))

Where (dC – dB)/(dB – dD) is the concentration fraction of the diluent and:

VD = Volume of diluent required
VC = Volume of crude being blended
dC = density of Crude
dB = density of Blend
dD = density of Diluent

VD = 10,000 X (845 – 820.552) / (820.552 – 645) = 1,392.61 m^3

Using the API 12.3 shrinkage equation we find that the blending 10,000 m^3 of 845 kg/m^3 crude with 1392.61 m^3 of 645 kg/m^3 diluent actually results in:

11,371.26 m^3 of blend (B1) at 822.10 kg/m^3 . (See Table 1, Iteration 1.)

Now to reach the desired density, the blend B1 must be further blended with the 645 kg/m^3 diluent to the original target density of 820.55 kg/m^3. Again, the resultant density is higher than the target. (See Table 1, Iteration 2.)

This process is repeated (called iterating) until the resulting density from the shrinkage formula equals the target density. This usually requires three to four iterations to achieve. Table 1 shows the results of the above blending at each iteration. The resultant total volume of diluent required is 1500.00 m^3, which is identical to the case study value.

		Iteration 1	Iteration 2	Iteration 3	Iteration 4
Diluent Density	kg/m^3	645.000	645.000	645.000	645.000
Raw Crude Density	kg/m^3	845.000	822.104	820.645	820.552
Target Density	kg/m^3	820.552	820.552	820.552	820.552
Raw Crude Volume	m^3	10,000.00	11,371.11	11,470.24	11,476.61
Raw Crude Mass	kg	8,450,000.00	9,348,250.09	9,413,082.71	9,417,253.77
Required Diluent Volume	m^3	1,392.61	100.51	6.47	0.41
Diluent Mass	kg	898,250.09	64,832.62	4,171.06	266.21
Total Blend Mass	kg	9,348,250.09	9,413,082.71	9,417,253.77	9,417,519.98
Volume % Diluent in Blend	%	12.224	0.876	0.056	0.004
% Volume Shrinkage, API 12.3		0.189	0.012	0.001	0.000
Total Calculated Blend Volume	m^3	11,392.64	11,471.65	11,476.73	11,477.05
Shrinkage Volume	m^3	21.50	1.38	0.09	0.01
Total Actual Blend Volume	m^3	11,371.13	11,470.26	11,476.64	11,477.05
Actual Blend Density	kg/m^3	822.104	820.651	820.558	820.552

Table 1 (Using API 12.3 SI Units)

TWO STAGE BLENDING

The question arises: If we blend in two stages, is the calculated two stage shrinkage equivalent to the calculated single stage shrinkage? To check this, let's blend 10,000 m^3 of 845 kg/m^3 crude to 830 kg/m^3 and then dilute the blend to 820.55 kg/m^3

Blend order		Blend A – B	Blend AB – C	Blend A – C	Blend AC – B
Diluent Density	kg/m^3	645.000	700.000	700.000	645.000
Raw Crude Density	kg/m^3	845.000	820.552	845.000	832.297
Raw Crude Volume	m^3	10000.00	11,477.02	10,000.00	10,993.63
Diluent Volume	m^3	1500.00	1,000.00	1,000.00	1,500.00
Volume % Diluent in Blend	%	13.180	8.035	9.123	12.099
% Volume Shrinkage, API 12.3		0.202	0.036	0.059	0.169
Shrinkage Volume	m^3	22.98	4.49	6.33	20.68
Total Actual Blend Volume	m^3	11477.02	12,472.53	10,993.68	12,473.03
Actual Blend Density	kg/m^3	820.552	811.182	832.297	811.152

Table 2.(Using API 12.3 SI Units)

Stage 1.	Crude	10,000 m^3 at 845 kg/m^3
(4 iterations)	Diluent	(X) m^3 at 645 kg/m^3
	Target density	830 kg/m^3

Using the shrinkage equation with the above criteria results in a requirement of 873.68 m^3 of diluent to give a resulting volume of 10,859.66 m^3 at 830 kg/m^3 and a total shrinkage of 14.02 m^3.

Stage 2.	Crude	10,859.66 m^3 at 830 kg/m^3
(4 iterations)	Diluent	(X) m^3 at 645 kg/m^3
	Target density	820.55 kg/m^3

The resulting volume is 11,477.17 m^3 at a density of 820.55 requiring 1500.17 m^3 of diluent, which again is within 0.0113% of the original case. This shows that using the equation for staged blending is effectively equivalent to one step blending.

BLENDING ORDER

The next concern is to determine if the equation holds regardless of the order in which blending occurs.

To verify this let's use our test blend and dilute it with 1000 m^3 of 700 kg/m^3 diluent and then calculate the blending results in the reverse order. That is, blend the 845 kg/m^3 crude first with the 1000 m^3 of 700 kg/m^3 diluent, then with the 1500m^3 of 645 kg/m^3 diluent.

The resulting shrinkage shown in Table 2 indicates that there is difference in the calculated shrinkage (.007m^3 or 0.03%), calculated volume (0.50m^3 or 0.004%) and calculated density (0.03kg/m^3 or 0.0037%) resulting from the order of blending. While this does not compute quite as well as the staged blending, it is well within the accuracy to which density and volumes can be measured. The number of decimals to which the values are rounded can affect the shrinkage calculations.

SENSITIVITY TO DENSITY

The accuracy of the density determination is critical to the precision of blending. For example, a change of 1 kg/m^3 from 845 to 846 kg/m3 in our example results in a difference in diluent requirement from 1500 m^3 to 1561.9 m^3 or an additional 61.9 m^3

A change of 1 kg/m^3 in the diluent from 645 to 646 kg/m^3 results in a change of diluent required from 1500 to 1507.5 m^3. While not as large as the effect of the same error in the accuracy of the density of the crude, it is still a significant difference.

What this shows is density errors have a significant effect on blending calculations, which can result in large dollar losses.

It is therefore imperative that precision and accuracy of density measurement be given high priority.

Using the API 12.3 Tables

In API MPMS 12.3.5 Recommended Standard it states that the printed tables are the Standard. The equations used to derive the tables are those described in the section on Empirical Testing.

A description of how to use the API 12.3 tables, in both Customary and SI units has been included in the publication under sub-sections 5.4.1 and 5.4.2. The procedures presented are easy to follow.

Precautions on Using the API MPMS Chapter 12.3 Equations and Tables

Section 6 of Publication 12.3 identifies a number of items that users of these shrinkage factors need be aware of.

1. These tables and equations were developed under lab conditions where the temperatures were near 15oC (60oF) and between 100 – 700 kPa. (15-115 psi). Use of these tables outside these conditions is not recommended. The accuracy may be questionable.
2. Shrinkage calculations may differ between customary units and SI units. This is partially due to the reference temperature difference (60oF and 15oC). Other minor differences may occur. Therefore, it is essential buyers and sellers agree on which tables are to be used.
3. Experimental data suggests that factors other than density affect volumetric behavior. For extenuating circumstances, it is recommended that specific testing be performed with the same methodology and precision used for the data in the API publication.
4. The equations and tables developed in API 12.3 were determined from the following range of oils and diluents.

Heavy Components	Light Components
644 – 979 kg/m3	581 – 889 kg/m3

Alternative Equations / Tables

The API 12.3 equations or tables have not proven totally adequate in predicting the shrinkage experienced when blending certain eastern Alberta heavy crude oils with various condensates. As a result, Nova Chemicals & Research Technology performed a series of accurate blending scenarios. A "best fit" equation was developed which can be applied to a limited range of specific heavy crude oils.

The equation developed is:

$$S = (0.0266Fc) + (-0.0004Fc^2) + (0.000001339Fc^3)$$

Where Fc is the % concentration of the diluent in the total ideal blend volume, and

S is the shrinkage factor as a % of total ideal blend

Results of independent shrinkage tests on similar blends of eastern Alberta heavy crude oils and condensates confirmed that this alternative equation is more accurate than API 12.3 or 2509C but only for the range of blends tested. This supports the API recommendation that buyers and sellers should agree on the method of shrinkage determination that will be used for transactions between them.

Conclusions

The equations and tables in API MPMS Chapter 12 Section 3 are a valuable tool in quantifying shrinkage that occurs as a result of blending hydrocarbons of different densities. It has been illustrated that using the API equation from MPMS Chapter 12 Section 3 to calculate shrinkage resulting from blending is not dependent on the order of blending nor the stages in which the blend is achieved.

The accuracy of volumetric and density measurement has a significant effect on the accuracy of the calculations. For the equations and the tables to be effective, accurate and precise measurement of volumes and density is a must.

The API equations and tables were developed using data within a specific range of crude oils and diluents. Blending outside the limits of the data can affect the accuracy of calculated shrinkage.