

A Practical Approach to Continuous Liquid Allocation Measurement



Overview

Electronic flow measurement (EFM) methodologies have been applied to natural gas measurement for decades. Today, EFM methods are also being used to account for stabilized liquid product transfers that occur between pipelines, tanks and transportation vessels in midstream and downstream applications. Oil allocation measurement performed near production wellheads requires different calculations than those needed for stabilized products. This paper describes a system and methodology for liquid hydrocarbon accounting based on continuous allocation measurements. This methodology conforms to the relevant API standard and incorporates traditional EFM techniques to maintain audit trails.

Background

Oil operators often co-mingle production from multiple wells into common processing and storage facilities. The products derived from the processing facility are sold (i.e., crude oil, natural gas, NGL) or disposed of (i.e., water) in aggregate. For commercial reasons, it is necessary to allocate the revenue and cost from these financial transactions to the individual wells. Regulatory requirements and operational considerations dictate that hydrocarbon and water volumes also be allocated to individual wells. To support this allocation, it is necessary to estimate the flow from each well. Estimates are commonly derived using one of two methods:

- **Continuous Allocation Measurement** — each well flows through a dedicated three-phase measurement system prior to co-mingling.
- **Bulk and Test** — each well's flow is periodically routed through a three-phase test measurement system.

This paper focuses on accounting methods for liquid quantities derived from continuous allocation measurement processes.

Although multi-phase flow meters are used in some applications, most operators still rely on three-phase separators and single-phase meters to obtain allocation measurements.

A three-phase separator is intended to divide the full well stream mixture into free gas, free water and oil. In most cases, the separator's outlets convey wet gas, oily water and a saturated hydrocarbon liquid phase which includes residual water, respectively. If a dump valve sticks and remains open, the oil outlet stream can also include free gas, or the water outlet stream could contain oil and/or gas. If the well is slugging and instantaneous inflow exceeds the designed separator capacity, oil may also flow through the gas outlet.

Under normal operation, the oil outlet of the separator will contain a saturated hydrocarbon mixture confined under elevated pressure and subjected to elevated temperature. This mixture is at its bubble point. As the confinement pressure and temperature change, mass will convert from the liquid phase to the vapor phase. The oil outlet stream will also contain some amount of residual water. One of the major challenges in allocation measurement is to predict how much of this emulsion stream will eventually end up in the stock tank as stabilized oil.

Figure 1 depicts the relationship between the separator emulsion mass and the final mass of the stabilized products. During processing and weathering, the live emulsion stream will produce four products: crude oil, NGL, natural gas and free water. The ratio of each product will vary with the molecular composition of the produced fluids and with the processing methods and processing conditions.

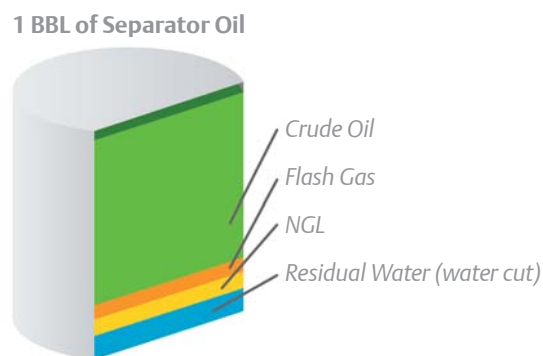


Figure 1. Finished products derived from a barrel of separator oil.

The process depicted in Figure 1 will follow the principal of mass conservation. The final weathered mass will equal the mass exiting the separator, but the industry accounts for hydrocarbon by volume. Since the density of each finished product changes with temperature and pressure (Figure 2), it is difficult to reconcile the separator volume to the standard volume of each finished product.

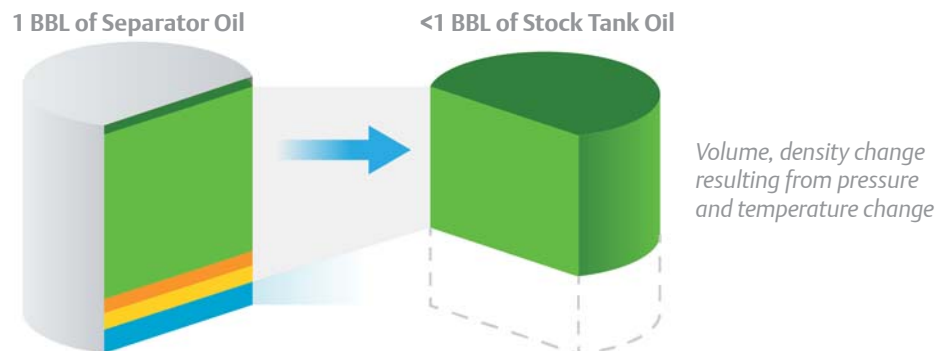


Figure 2. One barrel of separator oil results in less volume of stock tank oil due to mass loss and density change.

The current industry standard for continuous liquid allocation measurement is described in API MPMS 20.1.

API MPMS 20.1 defines the term shrinkage factor as the relationship between the measured volume of stock tank oil and measured volume of the oil exiting the separator (emulsion minus water). Figure 3 indicates the effect of the shrinkage factor.

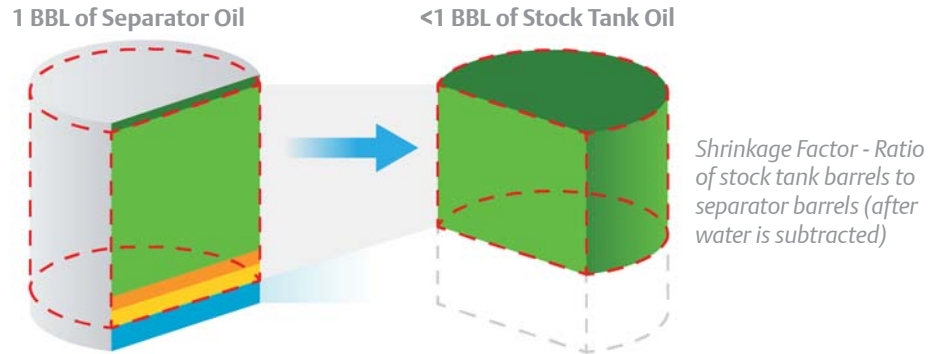


Figure 3. Shrinkage factor.

Hydrocarbon Liquid Allocation Measurement in a Field Flow Computer

If the shrinkage factor is known or can be closely estimated, one can use Equation 1 to estimate the volume of stabilized stock tank oil that would result from a measured volume of separator emulsion.

$$\text{Theoretical volume} = \text{Measured emulsion volume} * (1 - X_w) * SF \quad (\text{eqn 1})$$

Where:

- *Theoretical volume* is the estimated volume of stabilized stock tank oil
- *Measured emulsion volume* is the meter indicated volume / K-factor * meter factor
- X_w is water cut (corrected for live flowing conditions if necessary)
- *SF* is an “all-inclusive” shrinkage factor

Careful inspection of Equation 1 reveals that the shrinkage factor must account for:

- Mass lost to natural gas flashing
- Mass lost due to NGL flashing
- Density change of the remaining hydrocarbon mixture due to temperature change ($CTL_{o,m}$)
- Density change of the remaining hydrocarbon mixture due to pressure change ($CPL_{o,m}$).

API MPMS Section 20.1.9.5 explains the procedure for calculating theoretical stabilized oil production from allocation meter readings and other inputs. Appendix A of this paper provides a detailed review of those methods and supports the use of Equation 1 for the general case.

API MPMS Section 20.1.7.4 outlines methods for deriving the shrinkage factor from fluid samples and by other means.

API MPMS Section 20.1.7.4.5 recognizes that an equation of state (EOS) model can be used to derive the shrinkage factor for a specific hydrocarbon mixture and specific process conditions. EOS models rely on compositional analysis of the produced hydrocarbon mixture. The EOS must also be configured to model the flash conditions encountered by the fluid stream as it passes through the production and processing equipment. Using an EOS model and a prescribed set of separation stages and conditions,

a process engineer can derive the shrinkage factor and other properties of the hydrocarbon mixture at various points in the process. Process engineers who are familiar with EOS models understand that the shrinkage factor and other downstream fluid properties are significantly dependent on the temperature and pressure of the first-stage separation process. In other words, it is commonly understood that the shrinkage factor varies with the pressure and temperature of the allocation separator. Figure 4 is a tabular presentation of the EOS-derived shrinkage factors vs. pressure and temperature for an unconventional oil.

		Separator Temperature						
		80	90	100	110	120	130	140
Pressure	250	0.915	0.922	0.928	0.934	0.940	0.945	0.949
	350	0.895	0.903	0.910	0.917	0.923	0.929	0.934
	450	0.880	0.887	0.895	0.902	0.909	0.915	0.921
	550	0.866	0.874	0.882	0.889	0.896	0.903	0.909
	650	0.854	0.863	0.870	0.878	0.885	0.892	0.898

Figure 4. Shrinkage Factor Table of an Unconventional Oil.

The variation in shrinkage factor vs. pressure and temperature should be included in the allocation measurement calculation. Since EOS models are computationally-intensive and require tuning by a skilled engineer, it is impractical to embed the EOS model in a field flow computer. An alternative method is to use an EOS model to develop shrinkage factors in a tabular form, as in Figure 4. This table of fluid properties can be configured into the field flow computer. Consequently, the field flow computer calculations will follow the logic in Figure 5.

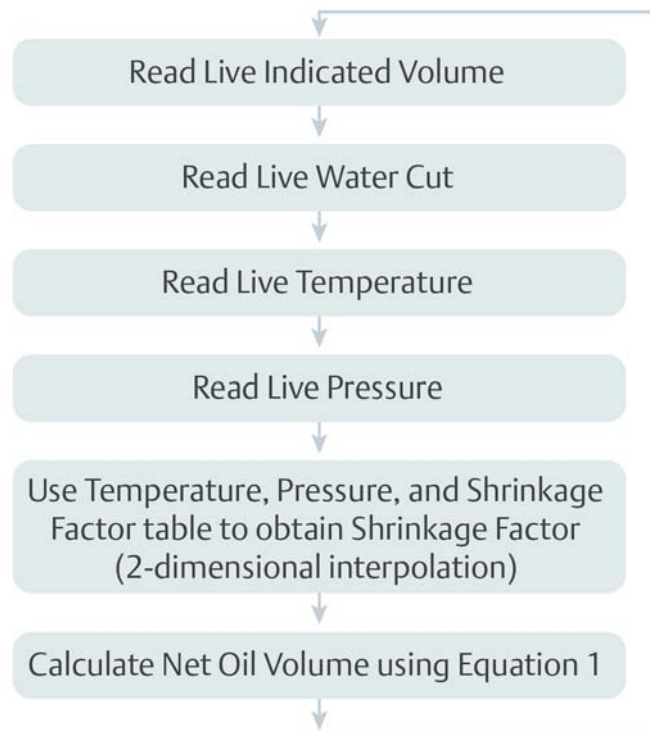


Figure 5. Flow computer calculation process for continuous allocation measurement.

The algorithm described in Figure 5 can be embedded in a field flow computer to produce real-time estimates of the stabilized oil flow rate from allocation oil meters. The flow computer can accumulate estimates of stabilized oil for various time periods, including hourly, daily and monthly totals. These accumulations are consistent with the latest API standards for allocation measurement (API MPMS 20.1).

It should be noted that the shrinkage factors derived from an EOS model are “all-inclusive” and account for:

- Mass lost to natural gas flashing
- Mass lost due to NGL flashing
- Density change of the remaining hydrocarbon mixture due to temperature change ($CTL_{o,m}$)
- Density change of the remaining hydrocarbon mixture due to pressure change ($CPL_{o,m}$).

Therefore, it is not necessary to include $CTL_{o,m}$ in the allocation calculation when the shrinkage factor is derived using an EOS model.

If the shrinkage factors used by the flow computer are derived from the volumetric techniques described in API MPMS 20.1.7.4.4, it follows that the $CTL_{o,m}$ term is required to be in conformance with the API MPMS 20.1 standard.

Systematic Oil Allocation Accounting

The field flow computer is part of a larger system which facilitates hydrocarbon accounting. Using methods outlined in API MPMS 21.1, field flow computers commonly accumulate flow quantities, along with supporting flow calculation input values, in hourly and daily records. This data can be extracted from the field flow computer up to 35 days after the flow occurs. These records, along with associated events and meter configuration information, are transferred to a hydrocarbon accounting system. This system provides a repository with an audit trail to maintain the integrity of the original data. Corrections to prior period values are performed using the original source variables for the flow correction. To support these corrections, it is critical that all parameters relevant to the calculations be transferred from the flow computer to the accounting system.

Binary file formats, such as CFX, are commonly used to transfer EFM data from flow computers to back-office accounting systems as shown in Figure 6. These binary file formats have evolved from their early emphasis on natural gas flow accounting to include attributes for stabilized oil accounting. Since the calculations associated with allocation measurement (API MPMS 20.1) are different than those used for stabilized products (API MPMS 12), current versions of these binary file formats do not always contain the attributes necessary to transmit source variable values and computed volumes associated with allocation measurement.



Figure 6. Synchronizing the accounting system with the flow computer database.

The creators of the CFX format had the forethought to provide ‘User Defined’ data elements in each section of the binary file. Utilizing some of these ‘User Defined’ fields in a consistent manner allows all the necessary allocation measurement data to be transferred from the flow computer to the hydrocarbon accounting system.

The parameters needed to support allocation measurement calculations are fewer in number than those needed to support accounting for stabilized products. Therefore, a smaller amount of flow computer 'periodic' memory is required to facilitate systematic oil allocation accounting than is required for accounting with stabilized liquid products. Appendix B provides details of the required data elements and recommendations for mapping each value to the CFX file.

Figure 7 outlines the preferred oil allocation methodology described in this document. Figure 8 provides an overview of an alternative method.

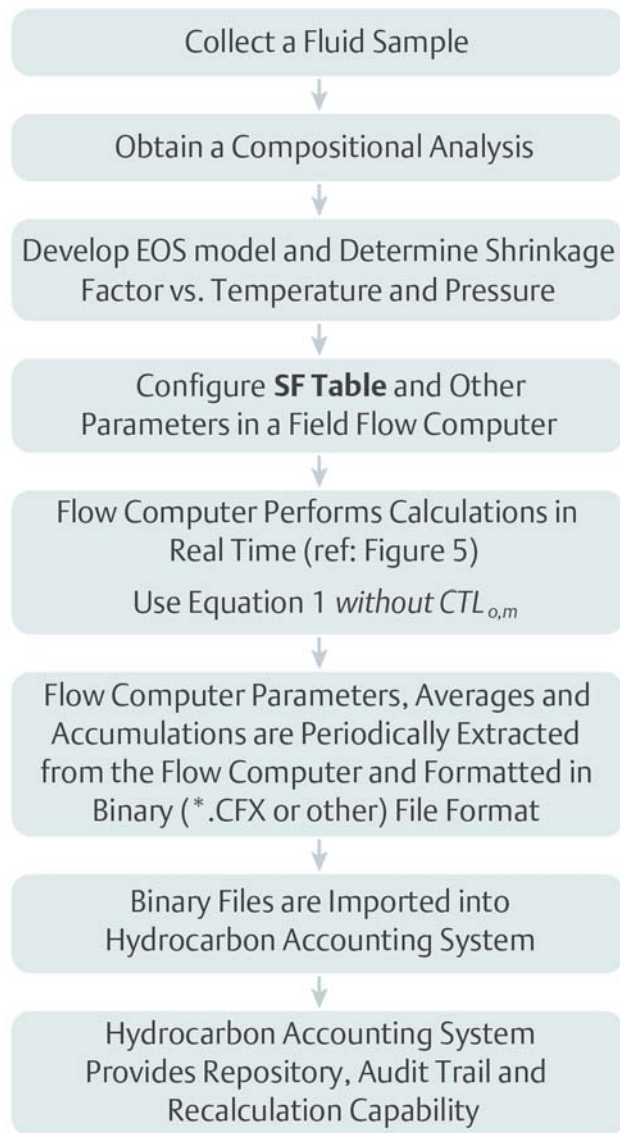


Figure 7. Overview of the preferred allocation accounting methodology.

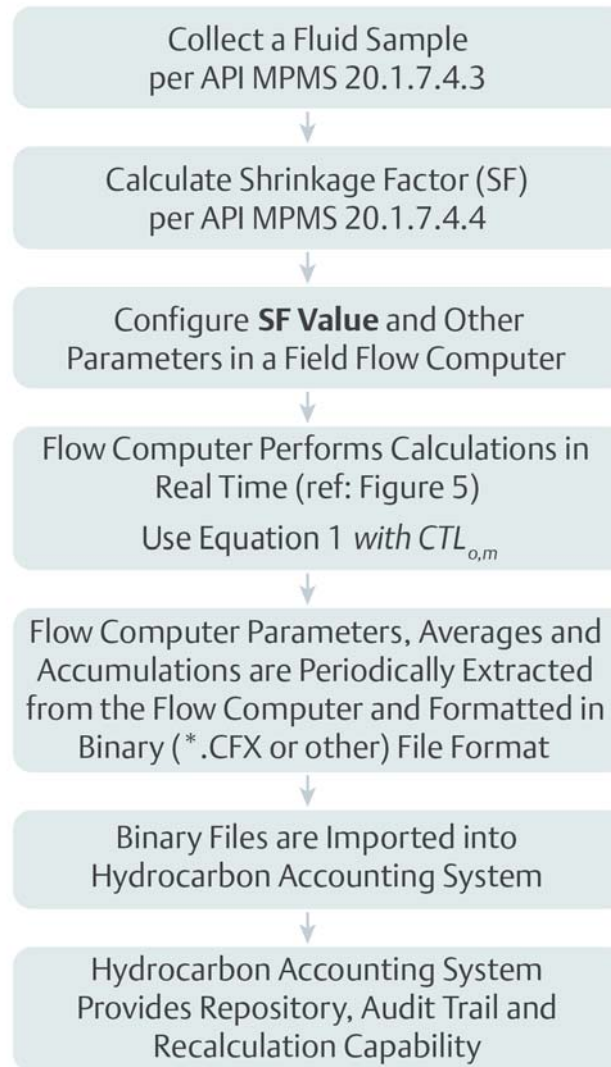


Figure 8. Overview of the alternative allocation accounting method.

Conclusions

A system for managing oil allocation measurement data more efficiently utilizes traditional EFM techniques to maintain audit trails and provides for corrections to the calculated flow volumes. This system includes calculations in the flow computer which are consistent with the current industry standard for continuous allocation measurement (API MPMS 20.1). The system also provides for transfer of all required data attributes to a hydrocarbon accounting system via CFX files. Within the hydrocarbon accounting system, an audit trail can be maintained for resolution of measurement problems and/or disputed volumes. The hydrocarbon accounting system will also possess all attributes necessary to reproduce the flow computer's calculations.

Appendix A: Allocation Calculations per API MPMS 20.1.9.5

This appendix is devoted to the study of calculation methods outlined in API MPMS 20.1.9.5 for the calculation of theoretical stock tank production from allocation meter measurements. Evidence will be presented to confirm the various methods outlined in API MPMS 20.1.9.5.1 are mathematically equivalent. Only the derivation of the water cut term varies between Procedures A, B and C.

API MPMS 20.1.9.5 provides three different methods for calculating theoretical production from allocation meter measurements. It describes the conditions under which each method is to be applied. The following table summarizes the three methods.

Water Cut [%]	Water Cut Sampling Techniques	Water Cut Sampling Type	Relevant Section
<~5%	Static	Proportional Sampling	20.9.5.2 "Procedure A"
>~5%	Static	Proportional Sampling or Grab Sampling	20.9.5.3 "Procedure B"
>~5%	Dynamic	"In-Line Analyzer"	20.9.5.4 "Procedure C"

The equation presented in API MPMS 20.1.9.5.2 is:

$$\textit{Theoretical Production} = \textit{Indicated Volume} * \textit{MF} * \textit{SF} * \textit{CSW} * \textit{CTL} \quad (\textit{eqn 20.1.9.5.2})$$

When the definition of the *CSW* term is applied, this equation takes the form:

$$TP = IV * MF * SF * (1-WC) * CTL \quad (\textit{eqn A.1})$$

Where *WC* is the water cut from a static sample – uncorrected for meter conditions.

There is no clear guidance on the *CTL* term. Since this section is applicable only to low water cut, a prudent interpretation is that $CTL_{o,m}$ is an appropriate substitution. Based on this substitution, eqn A.1 becomes:

$$TP = IV * MF * SF * (1-WC) * CTL_{o,m} \quad (\textit{eqn A.2})$$

The equation presented in API MPMS 20.1.9.5.3 is:

$$\textit{Theoretical Production} = \textit{Indicated Volume} * \textit{MF} * (1 - X_{w,m}) * CTL_{o,m} * \textit{SF} \quad (\textit{eqn 20.1.9.5.3})$$

This equation takes the form:

$$TP = IV * MF * SF * (1-X_w) * CTL_{o,m} \quad (\textit{eqn A.3})$$

The equation presented in API MPMS 20.1.9.5.4 is:

$$\textit{Theoretical Production} = \textit{Indicated Volume} * \textit{MF} * (1 - X_{w,m}) * CTL_{o,m} * \textit{SF} \quad (\textit{eqn 20.1.9.5.4})$$

Which is also of the form of equation A.3.

Careful inspection of equations A.2 and A.3 reveals that these equations are identical, except for the source from which the water cut has been derived.

From the perspective of a flow computer, water cut is simply an input to the calculation equation. API MPMS 20.1.7.2 provides limited guidance for the selection and application of different methods and different equipment for deriving the water cut. As this document focuses on flow computer and hydrocarbon accounting aspects of oil allocation measurement, no further discussion of the water cut parameter will be included in this section.

The need for the $CTL_{o,m}$ term in equations A.2 and A.3 is arguable. For reasons described in the main body of this paper, $CTL_{o,m}$ is not necessary when the shrinkage factor has been derived from an equation of state model.

The preceding data provides support and justification for the use of equations presented in Appendix B of this document.

The key conclusion from this appendix is that the flow computer only needs to support a single calculation, regardless of the 'Field of Application' discussion in API MPMS 20.1.9.5.1. For the sake of completeness, this document proposes support for two calculations: one which includes $CTL_{o,m}$ and one which considers $CTL_{o,m}$ to be included in the shrinkage factor term.

Appendix B: Hydrocarbon Liquid Allocation Measurement Calculations and CFX Data Element Mapping

This appendix provides details of the recommended oil allocation measurement calculation and provides recommendations for mapping data elements to the CFX file. These data elements allow the hydrocarbon accounting system to be synchronized with the flow computer database.

The flow computer will apply different calculations based on whether the shrinkage factors were derived from an equation of state (EOS) or from volumetric sample analysis (API MPMS 20.1.7.4.4). This differentiator will be signified in the flow computer through a configuration parameter. For purposes of this document, the configuration parameter will be called SF_source and will be signified by a Boolean value (1 = SF includes CTL, 0 = SF does not include CTL).

Calculations, data retention and data transfer (via CFX) are described for the two cases below. For simplicity, the flow computer should implement the periodic history logging schema and CFX mapping as described for the second case, 'Using a constant empirically-derived (API MPMS 20.1.7.4.4) shrinkage factor,' which is the most general form.

Using an Eos-Derived Shrinkage Factor Table

If an EOS is used to develop a tabulation of shrinkage factor vs. temperature and pressure, the allocation calculation takes the form of:

- $IV = \text{Indicated Volume}$
 $= \text{Raw Meter Reading} * KF \quad (\text{eqn B.1})$

Where:

- $KF = \text{Meter K-Factor}$

$$GV = IV * MF \quad (\text{eqn B.2})$$

Where:

- $GV = \text{Gross Volume}$
- $MF = \text{Meter Factor}$

$$NUV = GV * (1 - X_w) \quad (\text{eqn B.3})$$

Where:

- $NUV = \text{Net Unshrunk Volume}$
- $X_w = \text{Water Cut at (or corrected to) live conditions}$

$$TP = NUV * SF \quad (\text{eqn B.4})$$

Where:

- $TP = \text{Theoretical Production}$
- $SF = \text{Shrinkage Factor (a function of temperature, pressure and shrinkage factor table)}$

Required Flow Computer Periodic History Logging

Value	Type of Aggregation
Temperature	Flow-weighted average based on gross volume
Pressure	Flow-weighted average based on gross volume
Indicated Volume	Accumulation during the period
Shrinkage Factor	Flow-weighted average based on gross volume
Water Cut	Flow-weighted average based on gross volume
Gross Volume	Accumulation during the period
Net Unshrunk Volume	Accumulation during the period
Theoretical Production	Accumulation during the period

Mapping to CFX File

Value	Input/Output	Static/Dynamic	CFX File Location
Meter K-Factor	Input	Static	Meter Configuration. K-Factor (offset 192)
Meter K-Factor	Input	Static	Meter Configuration. Meter Factor (offset 188)
Shrinkage Factor (SF) Table	Input	Static	User Defined Characteristics.02 (offset 21) through User Defined Characteristics.27 (offset 546)
SF_source	Input	Static	User Defined Characteristics.01 (offset 0)
Temperature	Input	Dynamic	Flow-weighted average > periodic history.meter temperature (offset 32)
Pressure	Input	Dynamic	Flow-weighted average > periodic history.meter pressure (offset 36)
Indicated Volume	Input	Dynamic	Accumulated value > periodic history.indicated volume (offset 40)
Shrinkage Factor	Input	Dynamic	Accumulated value > periodic history.user defined 01
Water Cut	Input	Dynamic	Accumulated value > periodic history.S&W percent (offset 438)
Gross Volume	Output	Dynamic	Accumulated value > periodic history.gross volume (offset 64)
Net Unshrunk Oil	Output	Dynamic	Accumulated value > periodic history.user defined 02
Theoretical Production	Output	Dynamic	Accumulated value > periodic history.user defined 03

Note that Net Unshrunk Oil and Theoretical Production are double-precision floating point numbers in the flow computer but are only single-precision floating point numbers in the CFX User Defined fields. A minor (but tolerable) loss of precision will occur during conversion.

Using a Constant Empirically-Derived (API MPMS 20.1.7.4.4) Shrinkage Factor

If a single shrinkage factor is derived using methods outlined in API MPMS 20.1.7.4.4, the allocation calculation takes the form of:

- $IV = \text{Indicated Volume}$
 $= \text{Raw Meter Reading} * KF \quad (\text{eqn B.5})$

Where:

- $KF = \text{Meter K-Factor}$

$$GV = IV * MF \quad (\text{eqn B.6})$$

Where:

- $GV = \text{Gross Volume}$
- $MF = \text{Meter Factor}$

$$NUV = GV * (1 - X_w) \quad (\text{eqn B.7})$$

Where:

- $NUV = \text{Net Unshrunk Volume}$
- $X_w = \text{Water Cut at (or Corrected to) Live Conditions}$

$$TP = NUV * SF * CTL_{o,m} \quad (\text{eqn B.8})$$

Where:

- $TP = \text{Theoretical Production}$
- $SF = \text{Shrinkage Factor (a function of temperature, pressure and shrinkage factor table)}$
- $CTL_{o,m} = \text{CTL of Oil at the Meter (based on base oil density and temperature)}$

Required Flow Computer Periodic History Logging

Value	Type of Aggregation
Temperature	Flow-weighted average based on gross volume
Pressure	Flow-weighted average based on gross volume
Indicated Volume	Accumulation during the period
Shrinkage Factor	Flow-weighted average based on gross volume
Water Cut	Flow-weighted average based on gross volume
Gross Volume	Accumulation during the period
Net Unshrunk Volume	Accumulation during the period
Theoretical Production	Accumulation during the period
$CTL_{o,m}$	Flow-weighted average based on gross volume

Mapping to CFX File

Value	Input/Output	Static/Dynamic	CFX File Location
Meter K-Factor	Input	Static	Meter Configuration. K-Factor (offset 192)
Meter K-Factor	Input	Static	Meter Configuration. Meter Factor (offset 188)
Shrinkage Factor (SF) table	Input	Static	User Defined Characteristics.02 (offset 21) through User Defined Characteristics.27 (offset 546)
SF_source	Input	Static	User Defined Characteristics.01 (offset 0)
Oil Base Density	Input	Static	configuration. Liq: Stock tank density
Temperature	Input	Dynamic	Flow-weighted average > periodic history.meter temperature (offset 32)
Pressure	Input	Dynamic	Flow-weighted average > periodic history.meter pressure (offset 36)
Indicated Volume	Input	Dynamic	Accumulated value > periodic history.indicated volume (offset 40)
Shrinkage Factor	Input	Dynamic	Accumulated value > periodic history.user defined 01
Water Cut	Input	Dynamic	Accumulated value > periodic history.S&W percent (offset 438)
Gross Volume	Output	Dynamic	Accumulated value > periodic history.gross volume (offset 64)
Net Unshrunk Oil	Output	Dynamic	Accumulated value > periodic history.user defined 02
Theoretical Production	Output	Dynamic	Accumulated value > periodic history.userdefined 03
CTL _{o,m}	Output	Dynamic	Flow-weighted average > periodic history.meter pressure (offset 494)

Note that Net Unshrunk Oil, Theoretical Production and CTL_{o,m} are double-precision floating point numbers in the flow computer but are only single-precision floating point numbers in the CFX User Defined fields. A minor (but tolerable) loss of precision will occur during conversion.

Mapping of Shrinkage Factor Table to a CFX File

If an EOS-derived shrinkage factor table is used, it can be mapped to the CFX ‘User Defined Characteristics’ fields.

The shrinkage factors will be developed as a function of temperature and pressure using an EOS model. The flow computer will support up to a 4 x 4 table as shown below. In addition to the elements noted in the table, there will be a ‘number of columns used’ attribute and a ‘number of rows used’ attribute.

		Temperatures			
		100	115	130	145
Pressure	75	SF1	SF5	SF9	SF13
	150	SF2	SF6	SF10	SF14
	225	SF3	SF7	SF11	SF15
	300	SF4	SF8	SF12	SF16

Columns in the table will represent temperature values. Rows in the table will represent pressure values.

For example, SF7 will be the shrinkage factor appropriate where separator pressure is +225 psi and separator temperature is +115°F.

The flow computer will read the live pressure and temperature and perform 2D linear interpolation within the table. If live values fall outside the table, the flow computer will ‘clamp’ values at the nearest edge of the table.

Mapping of Table Values to CFX ‘User Defined Characteristics’ Fields

When creating a CFX file from the flow computer, mapping will occur as illustrated below (UDC = User Defined Characteristics).

		Temperatures			
		UDC18	UDC19	UDC20	UDC21
Pressure	UDC22	UDC02	UDC06	UDC10	UDC14
	UDC23	UDC03	UDC07	UDC11	UDC15
	UDC24	UDC04	UDC08	UDC12	UDC16
	UDC25	UDC05	UDC09	UDC13	UDC17

The number of columns used will be mapped to UDC26. The number of rows used will be mapped to UDC27.

Note that ‘User Defined Characteristics’ are alpha-numeric fields in the CFX file. In the flow computer, these values are single-precision floating point numbers. When copying from the flow computer database to the CFX file, the values should be converted to alpha-numeric using masks as follows:

Values	Mask
UDC2 through UDC17	#.####
UDC8 through UDC25	####.#
UDC26 through UDC27	#



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