

Improve yield accounting by including density measurements explicitly

Reconcile both mass and volume simultaneously

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The growing standard in oil refining yield accounting is to use statistical data reconciliation to assist in detecting and diagnosing malfunctioning flow and inventory meters and possible mis-specified oil movements. However, as we demonstrate in this article, potentially harmful and undetectable gross errors can occur that may distort the yield accounting results and overall health of the production balance. The solution is to reconcile both mass and volume simultaneously instead of reconciling mass or volume separately, as is currently done. It is made possible by explicitly including density measurements into the reconciliation process and solving a bilinear data reconciliation problem using off-the-shelf commercial software.

Reconciling mass and volume with densities. Historically, yield accounting was primarily concerned with closing the volume balance around an entire oil refinery every month to satisfy only the financial month-end reporting requirements and to calculate overall yields of final products based on crude oil receipts. Rarely would process units inside the refinery boundary be included in the monthly volume balance given that many of the units do not conserve volume (i.e., volume flow in minus volume flow out plus any change in inventory does not equal zero).

More adventurous refiners realized this limitation of volume balancing around process units. They remedied it by multiplying the volume amounts by a known and representative material density and then performing a mass balance with some process units included where appropriate. This also allowed them to monitor and steward each month the overall refinery weight gain/loss metric for them to better assess refinery health.

Later, refiners realized that, by including inventory, there was some measurement redundancy in the system and that statistical mass reconciliation could be performed on the monthly numbers. With the advent of automated and accessible data collection systems, refiners realized that they could also run these mass reconciliation programs daily as opposed to just monthly, given the advances in refinery-wide information systems. This dramatically increased the diagnostic capability in terms of detecting and identifying plausible measurement and logging faults the day after, instead of potentially as much as a month later.

This article highlights the added diagnostic power of simultaneous mass and volume reconciliation when density measure-

ments are included explicitly. Densities now become variables in the reconciliation whereby it is volume times density that represents mass used in the conservation of matter equations or balances. Of course, mass must be conserved for all nodes used in the network. However, because volume variables are now available (instead of premultiplying or aggregating volume times density beforehand), volume balances can also be included where appropriate.

The benefit of including volume balances is that errors in flow measurements can be isolated from errors in the density. The diagnostic capabilities become much *sharper*, thus improving the chances of detecting and identifying a gross error that previously would have been overlooked, as we illustrate in our example to follow. In the simultaneous approach, the measurements are *cross-checked* not only with the mass balances but also simultaneously with the volume balances. If a gross error does exist, then being consistent with other realistic constraints will force the reconciliation to push some of the measurement adjustments away from what is expected or normal variation, hence providing a symptom of the problem.

Historically, when a site mass balance problem was detected, a refinery would resample the largest tanks for density and attempt to validate the instrument vs. actual level in hopes of finding the cause. With this technique, determining which tanks may have gauge problems and which ones may have density errors is more likely.

Small oil refinery example. This example represents a small hypothetical oil refinery with crude oil and vacuum distillation (CRD and VAC) units, a reforming (REF) unit and a fluidized catalytic cracking (FCC) unit. There are 24 tanks and 5 pipeline receipt and shipment points (Fig. 1). None of the processes are included in the volume balance, only the mass balance. All tanks are included in both the mass and volume balances—the circles labeled with the prefix “J” are junction nodes that also conserve both mass and volume, except for JFGD, which represents the refinery fuel gas drum and only conserves mass. Junctions also exhibit zero flow accumulation.

For clarity, we have deliberately omitted showing the 44 stream connections, active for the day reconciliation period in question, between the objects. Table 1 details the stream flow volumes and densities. Note that the 3 flows to JFGD from CRD, FCC and

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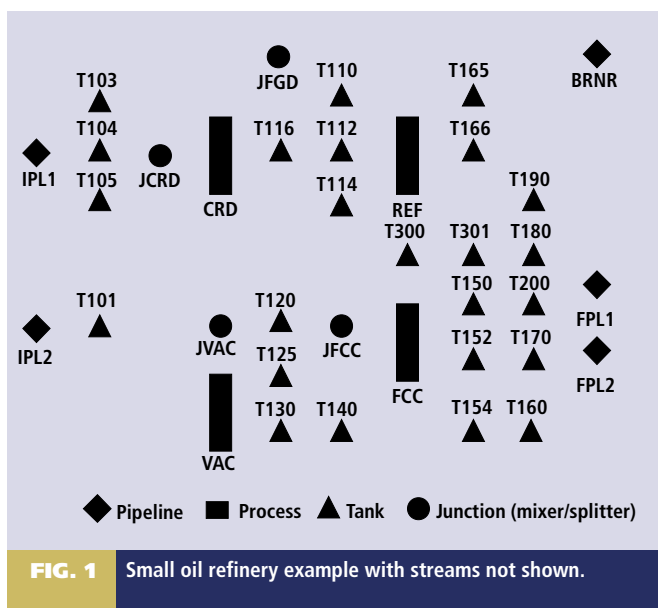


TABLE 1. Stream flows with densities (nodes CRD, VAC, FCC, REF and JFGD mass balance only).

	Source	Destination	Volume, bbl	Density, SG
1	CRD	JFGD	290,000 lb	–
2	CRD	JVAC	48,983.10	0.931
3	CRD	T110	52,465.19	0.751
4	CRD	T112	18,827.92	0.837
5	CRD	T114	55,451.73	0.844
6	CRD	T116	8,457.65	0.915
7	FCC	T300	5,772.16	0.600
8	FCC	JFGD	1,407,000 lb	–
9	FCC	T150	43,615.44	0.782
10	FCC	T154	29,352.47	0.900
11	FCC	T152	26,674.08	0.830
12	FCC	T160	8,996.46	1.037
13	JFGD	BRNR	(Unmeasured, lb)	–
14	IPL2	T101	62,362.64	0.956
15	IPL1	T103	324,327.23	0.844
16	IPL1	T104	162,164.29	0.844
17	IPL1	T105	0 (Fixed)	0.844
18	JVAC	T120	0 (Fixed)	0.931
19	JVAC	VAC	50,037.68	0.931
20	JCRD	CRD	185,019.64	0.844
21	JFCC	FCC	101,037.96	0.935
22	REF	JFGD	730,000 lb	–
23	REF	T165	26,986.35	0.811
24	REF	T166	10,556.58	0.830
25	REF	T300	9,121.32	0.600
26	T101	JFCC	65,281.09	0.956
27	T103	JCRD	5,494.19	0.844
28	T104	JCRD	179,059.72	0.844
29	T105	JCRD	465.73	0.844
30	T110	REF	56,770.15	0.751
31	T116	FCC	8,694.34	0.915
32	T120	JFCC	5,754.48	0.931
33	T125	JFCC	16,035.00	0.935
34	T130	JFCC	9,121.45	0.956
35	T140	JFCC	3,072.47	0.979
36	T170	FPL2	6,751.99	0.977
37	T180	FPL1	0 (Fixed)	0.753
38	T180	FPL2	27,197.73	0.753
39	T190	FPL2	74,344.06	0.735
40	T200	FPL2	25,353.68	0.809
41	T301	FPL2	255.95	0.600
42	VAC	T125	16,290.30	0.935
43	VAC	T130	8,923.28	0.956
44	VAC	T140	23,302.91	0.979

REF are mass flows where the mass flow from JFGD to BRNR is unmeasured.

Table 2 details the opening and closing inventories with densities for the tanks. The bold-faced closing density for T300 is the injected gross error that is to be illustrated.

Considering the model and measurements presented, we describe the workflow of solving the example refinery yield accounting problem without and with the density measurements included as reconciliation variables explicitly. First, we solve a linear mass reconciliation whereby the aggregated product of volume times density is used collectively in the solver. We apply a tolerance or uncertainty of 10% on all the mass variables. For example, for stream flow #1 in Table 1, we expect the true value to lie somewhere between 261 and 319 lb.

The overall objective function value for the sum of squared adjustments to the mass flow measurements is 28.954, with a statistical threshold value of 44.985 at 95% confidence. This means that because 28.954 is less than the threshold value, no gross errors in the mass network are statistically detectable above what is known as background noise or common-cause variation. When a linear volume reconciliation is performed, neglecting nodes CRD, VAC, FCC, REF and JFGD, we arrive at an objective function value of 22.035, with a threshold value of 38.885. This too does not indicate any perceptible gross errors or defects in the system, which is not surprising given that the injected density gross error is not seen at all in the volume balance. Thus, performing separate mass and volume reconciliations does not detect that a true gross error has been injected.

Will simultaneous mass and volume reconciliation do any better? When the bilinear reconciliation solver is run, the objective function is 369.487, with a threshold value of 77.931 requiring five iterations. Tolerances on volumes are 10% and those on density are 0.005 absolute in specific gravity units of measure. This indicates that at least one gross error is present. The individual measurement statistics are then interrogated with the top 10 largest density outliers shown in Table 3.

The bold-faced values are greater than a 95% confidence threshold statistic of 3.281. Clearly, tank T300 is singled out, having the top three density outlier statistics. This is precisely where

TABLE 2. Tank opening and closing inventories with densities.

Tank	Material	Opening volume, bbl	Opening density, SG	Closing volume, bbl	Closing density, SG
1 T101	Heavy vacuum gas oil	79,531.45	0.956	76,604.33	0.956
2 T103	Crude oil	440,201.93	0.844	759,297.52	0.844
3 T104	Crude oil	537,188.56	0.844	520,555.70	0.844
4 T105	Crude oil	227,012.13	0.844	226,808.96	0.844
5 T110	Naphtha	164,500.27	0.751	160,045.16	0.751
6 T112	Kerosene	148,469.14	0.837	169,596.48	0.837
7 T114	Diesel	128,372.97	0.850	181,491.44	0.850
8 T116	Atmospheric gas oil	199,228.23	0.915	198,924.09	0.915
9 T120	Atmospheric tower bottoms	66,487.61	0.931	59,886.82	0.931
10 T125	Light vacuum gas oil	91,315.37	0.935	91,430.28	0.935
11 T130	Heavy vacuum gas oil	35,459.96	0.956	35,192.67	0.956
12 T140	Vacuum tower bottoms	122,246.27	0.979	141,478.12	0.979
13 T150	Light cracked naphtha	162,374.54	0.782	205,713.75	0.782
14 T152	Heavy cracked naphtha	108,352.19	0.830	134,405.86	0.830
15 T154	Light cracked cycle oil	162,116.70	0.900	191,726.94	0.900
16 T160	Slurry oil	82,456.20	1.037	92,702.86	1.037
17 T165	Light reformate	110,141.98	0.812	136,515.29	0.812
18 T166	Heavy reformate	107,338.04	0.830	117,641.26	0.830
19 T170	Asphalt	61,538.17	0.977	54,216.45	0.977
20 T180	Premium gasoline	151,755.67	0.754	125,241.84	0.754
21 T190	Regular gasoline	366,595.02	0.735	292,717.00	0.735
22 T200	Heavy fuel oil	46,950.53	0.809	22,198.59	0.809
23 T300	LPG	3,923.36	0.600	18,754.99	0.650
24 T301	LPG	2,479.02	0.600	2,230.12	0.600

the gross error was injected. If we make the density measurement for the closing inventory unmeasured or calculated and run the bilinear reconciliation, we get an objective function of 70.175 and a threshold value of 76.778. This indicates that statistically there are no more gross errors in the network when the closing density error is removed.

A further benefit of the simultaneous approach is to study the effect on the LPG yield, which is the material in tank T300 being received from the rundowns of the FCC and REF processes. When only mass reconciliation is run and we back out the volume flows assuming a fixed density, the results are shown in Table 4 for the rows labeled "Mass only." When the simultaneous mass and volume reconciliation is run with T300 closing inventory set to unmeasured, the results are labeled "Mass and volume."

Table 4 illustrates that when the mass reconciliation alone is run with the injected density gross error, the common practice of backing out the volume amounts shows that production of LPG from FCC and REF is over-inflated. This translates to a high yield by volume of LPG produced. This over-inflation is well within the expected or normal variation as indicated by the percent difference column (i.e., all are less than 10%). No indication of a fault is flagged.

Running the mass and volume reconciliation simultaneously and removing the density gross error, Table 4 shows a much closer

TABLE 3. Top ten individual measurement outlier statistics for densities.

	Source	Destination	Density outlier statistic
1	REF	T300	17.426
2	FCC	T300	17.328
3	T300	Closing inventory	17.300
4	JFCC	FCC2	5.658
5	T140	JFCC	4.582
6	T125	JFCC	3.679
7	T101	JFCC	3.424
8	REF	FGAS	3.420
9	T120	JFCC	2.745
10	T130	JFCC	1.744

TABLE 4. Tank T300 volume balance results with mass and mass and volume reconciliation.

Reconciliation	Rundown	Reconciled volume, bbl	Difference from measurement, bbl	Percent difference
Mass only	FCC	6,002.28	230.12	3.9%
Mass only	REF	9,832.18	710.86	7.8%
Mass only	T300 Closing	18,592.11	-162.88	-0.9%
Mass & volume	FCC	5,706.18	-65.98	-1.1%
Mass & volume	REF	9,197.87	76.55	0.8%
Mass & volume	T300 Closing	18,827.42	72.43	0.4%

agreement to the measured volume flow and inventory values. It should also be mentioned that a side benefit of including density measurements explicitly is that we can invoke the constraint that volume conserves explicitly. For example, if we perform a volume balance around the tank using the backed-out volumes, we get an imbalance of $6,002.28 + 9,832.18 + 3,923.36 - 18,592.11 = 1,165.71$ bbl. However, using the results from the simultaneous mass and volume reconciliation, we get $5,706.18 + 9,197.87 + 3,923.36 - 18,827.24 = 0.17$ bbl (the nonzero 0.17 bbl is due to round-off). This clearly demonstrates the volume conservation on the tank. **HP**



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