TWO-PHASE FLOW METERING USING A LARGE CORIOLIS MASS FLOW METER APPLIED TO SHIP FUEL BUNKERING

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Abstract

With rising oil prices, there is growing interest in more accurate measurement during transfers of marine fuel oil, whether for the purposes of environmental monitoring or for validating custody transfer. Air entrainment is a common problem in marine fuel transfer (bunkering) operations, which can induce measurement errors in many metering technologies. The latest generation of Coriolis mass flow meters is able to operate in both single- and two-phase (oil-air) flow conditions. Witnessed trials have taken place at the National Engineering Laboratory in the UK using a large (200mm diameter) Coriolis flowmeter. The accuracies of the mass flow and density measurements were assessed for steady single-phase and two-phase flow on high and low viscosity oils. Meter accuracy was further assessed over a series of simulated bunkering operations, in which the meter started and finished empty of oil, with periods of both single and two-phase operation. Further trials of a metering skid are currently being carried on a bunkering vessel in Singapore.

Figure 1. A bunker barge alongside a container ship in Singapore. The hose boom lifts the fuel supply line to the height of the container ship.

1. Introduction

In 2006, approximately 350 million tonnes of marine fuel were supplied from bunker vessels (Figure 1), fixed shore side installations, and road tankers worldwide. At current prices, this equates to approximately $200 billion of transactions annually. There is a growing economic and environmental focus on the measurements taken during the bunkering process (i.e. the physical transfer of ship fuel)[1], in terms of both quantity (usually measured in volume but sold by mass), and of fuel quality (such as viscosity, density and sulphur content). For example, the International Marine Organisation (IMO) is introducing a series of measures to impose significant cuts in the permitted levels of sulphur in marine fuel[2], in order to reduce harmful emissions. For the efficient enforcement of such measures, reliable methods are needed for monitoring both the sulphur content and the quantity of fuel at the point of supply.

There are two distinct classes of marine fuels: distillate grades, often described as gas oils, and the residual fuel grades. “Residual” refers to the crude oil content remaining after the lighter and more valuable components have been removed by the oil refining process. Currently about 90% of marine fuel is residual, however many ships use at least some gas oil to drive auxiliary power systems. There is a significant price differential between the two classes, with gas oil selling at about $1100 per tonne, while residual fuel is only about $650 per tonne (priced in July 2008). There are thus strong economic incentives for refineries to develop increasingly effective techniques for extracting more light components – especially through the use of catalytic cracking – and this is leading to greater variability in the composition and quality of unblended residual fuels. At the same time environmental concerns about emissions, and a diminished appetite by ship-operators for marine engine problems caused by undesirable components in marine fuels, has lead to a call for tighter regulation. Conventionally, residual fuels have been simply specified by viscosity; current standards (e.g. ISO 8217:2005[3]) provide more thorough specifications for the defined fuels grades (including density, flash point, pour point and limits on components such as sulphur), but the grades are still labelled according to their nominal viscosities, so that for example the fuel grades RMF-180 and RMG-380 specify maximum kinematic viscosities of 180cSt and 380cSt respectively, measured at the standard temperature of 50ºC.

Marine engines which burn residual fuel require ancillary equipment to pre-process the fuel. Centrifuges and filters are fitted as standard equipment to remove water and undesirable solids and sediments such as catalytic fines. It is also usually necessary to heat the fuel to enable it to flow easily to the engine. Some of the practical problems associated with metering residual fuel in the bunker transfer process can be appreciated by noting that at ambient temperature in high latitude ports, some fuel grades are effectively solid. It is thus necessary to ensure that the fuel supply pipework is kept entirely clear between transfers (usually achieved by “blowing down” with high pressure air at the end of each transfer), to prevent solid fuel blockages. Even at an elevated pumping temperature, the viscosity of the fuel is high, and so air entrainment is a significant challenge to any metering system that might be used for fuel bunkering. To complete a delivery and avoid oil spills, drips and fuel run back, bunker delivery points often purge the line with slugs of high pressure compressed air. This may exacerbate air entrainment at the beginning and end of the delivery or in some cases at each bunker barge tank changeover.

Another regular feature of bunkering operations is “tank stripping”, whereby the last dregs of fuel (together with increasing amounts of air) are pumped out of one storage tank on the bunker barge before the supply is switched to another. A typical modern bunker vessel of perhaps 4,000 tonnes capacity may have 6-10 such fuel storage tanks operating in port/starboard pairs: a high proportion of bunker transfers will thus include a period of tank stripping. The situation is now improving with the advent of double hull tankers. In these newer design vessels the space between the inner skin (the tank) and the outer skin can be utilised to include a “hat box” and sloping tank bottoms enabling all the oil to run to a small sump where the final pumping dry of the tank can be conducted very effectively.

Currently, the most widely used means of measuring the fuel transfer from bunker barge to receiving ship is by tank dipping. In this procedure, the level of the fuel in each of the bunker barge tanks is recorded, along with temperature information, prior to the transfer of fuel to the receiving ship. This exercise is repeated at the end of the transfer[1]. Ship-specific calibration tables are used to map the recorded dip levels into corresponding volumes, and the difference in volume between the beginning and end of the bunkering operation gives the transferred quantity. The tank calibration tables are normally derived from calculated data and the tank is not calibrated by measurement and filling. Further calculations, based on the density of the fuel (as certified by the supplier) yield the delivered mass. One difficulty of current practice is that regular recalibration of the measurement system, as practiced in most custody transfer applications, is rarely possible. A further difficulty is the measurement error that may be introduced by entrained air.

Given the developing two-phase capabilities of Coriolis mass flow meters, BP Marine commissioned work to identify a flow meter solution for bunker vessels that is capable of providing an ‘irrefutable quantity measurement’. In addition MARPOL Annex VI[4] requires that all deliveries of marine fuel are accompanied by a bunker delivery note which records the sulphur content and the density of the fuel as delivered. The advantages of such a scheme include the continuous provision of flow and other data throughout the bunkering procedure, including the detection and monitoring of two-phase flow. The system utilises a universal approach to bunker metering by incorporating all deck measurement equipment in a standard half-container size skid which can be easily swapped on and off the ship to enable regular calibration checks and maintenance (Figure 2). The skid also supports a sulphur monitoring system and in the future other on-line or at-line monitoring parameters. This aspect of skid operation is not discussed further in this paper.

Figure 2. Half-container size skid can be swapped off the bunker barge for calibration or maintenance.

2. Laboratory Trials

After discussions with various suppliers, BP carried out qualifying trials at the UK's National Flow Facility, the National Engineering Laboratory in East Kilbride near Glasgow (NEL). The Oxford/Invensys team used a 200mm diameter Coriolis flowtube based on typical flowrates of up to 140kg/s (504 tonnes/hour). As shown in Figure 3, the flowmeter was suspended in the "flag" position, and was not supported within a skid, but mounted directly onto the flow lab pipework. The two-phase flow modelling and measurement techniques used were substantially similar to those described in Henry et al.[5], which discusses trials on a smaller meter at the same facility for an application with Venezuelan heavy (i.e. high viscosity) crude oil.

The meter was tested with a light gas-oil (7cSt) and a viscous oil (“Primol” - 200cSt at 15ºC), representing distillate and residual fuel grades respectively. In the single phase flow tests, the mass flow reading showed errors within ± 0.15% across the flow range 40kg/s to 140kg/s (144T/hr to 504 T/hr). This turndown ratio is typical for marine bunkering operations where fuel pumping rates are reduced at the beginning and at the end of the delivery. Similarly, the density reading was within 0.1% for single phase flow. The meter was further tested in two phase flow with gas volume fractions between 1% and 30%. The meter continued to operate under all test conditions. Errors never exceeded -6% and were generally within ± 3%. Repeatability for any one test varied between 0.2% and 3%. These results will be reported in more detail in a future paper.

Note that the errors observed in steady two-phase flow are likely to be of larger magnitude than during a normal bunker operation, for two reasons. Firstly, it is expected that for the majority of the bunker the flow will be in single phase, and secondly when two-phase does occur, the flow rate and gas void fraction are both likely to vary, which will lead to cancellation between positive and negative flow errors[4].

This principle was demonstrated in a a further series of simulated bunker loading tests where the experiment began with an empty pipe and a low gas flow followed by single phase oil interrupted by short bursts of gas (simulating tank stripping), finishing with an empty pipe. Figure 4 presents the time profile of one such bunker simulation experiment. The top graph shows the mass flow rate from the test meter (solid line), and from a reference meter (dot-dashed line), which was kept full throughout the experiment. After the onset of flow, steady, single-phase flow is established at about 120s. However, between 240-300s, bursts of air are injected into the flow stream to simulate tank stripping or other process disturbance. After a further period of single phase flow, the flow is reduced, a valve between the reference and test meter is closed to keep the reference meter full of liquid, and a blast of high pressure air (at about 520s) is used to clear the lines and return the test meter to its empty starting condition. Note that this final slug of liquid seen by the test meter but not the reference meter, is balanced at the start of the batch (at about 30s) by the delay in the onset of flow as seen by the test meter. Overall, therefore, the test and reference meters should report the same totalised flow.

The second graphs show the density of the air/oil mixture observed by the test meter, while the third graph shows the corresponding gas void fraction or percentage of air by volume in the two-phase mixture. The correlation with the mass flow behaviour is clear. In the initial period of flow, between 50s and 120s, the GVF slowly decreases from 50% down towards zero. During the tank stripping simulation, peak GVF is approximately 25%, and it is only after the blow through (at 520s) that the meter returns to the empty condition. Finally, the lowest graph shows a simple Boolean flag indicating the presence of two-phase flow, which occurs for about 40% of the batch duration – a higher proportion than might be expected in an actual bunker. It is intended that detection of two phase flow will be recorded and transmitted to both delivery and receiving operators as a warning of potential flow upset conditions and obviously the poorer measurement precision if two phase flow is allowed to persist for extended periods.

Table 1 shows the results of five such bunker simulation trials. The average error is less than 0.5%, and the repeatability is also about 0.5%. With a greater proportion of time spent in single-phase flow rather than two-phase flow in the batch, it can be expected that the errors would be smaller.

Overall, the trial was deemed to be a success, and a field trial in Singapore was arranged.

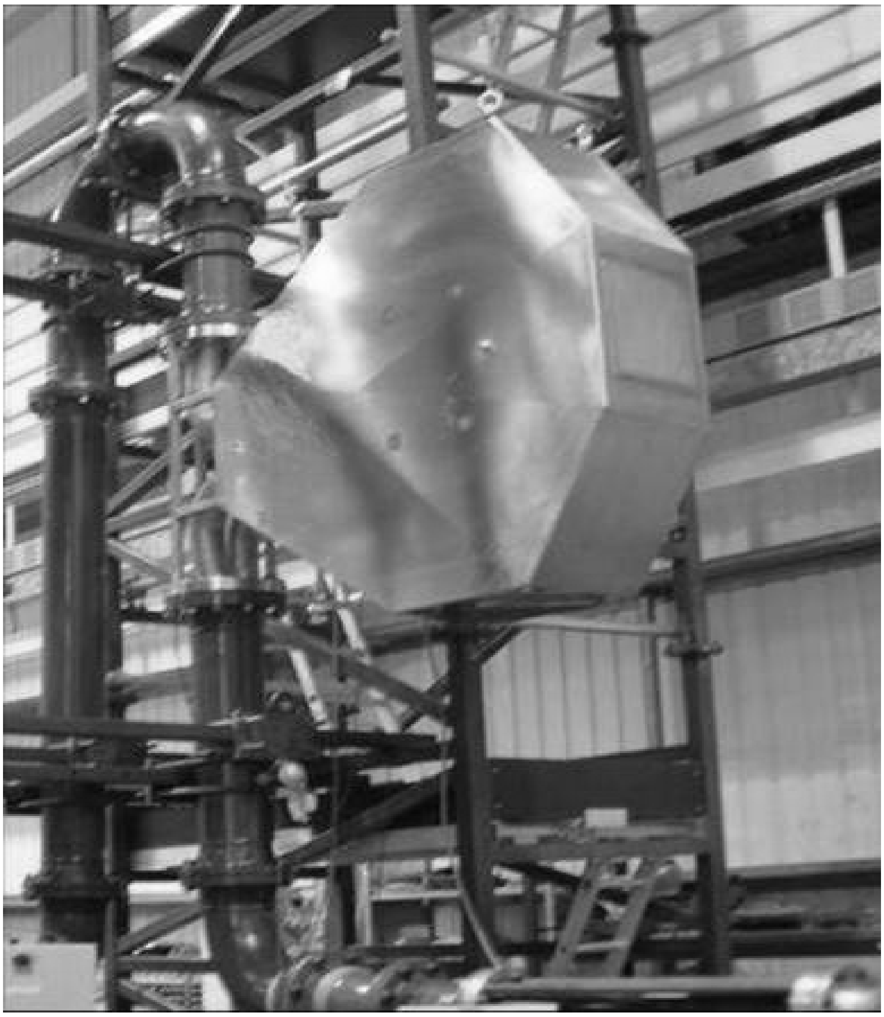

Figure 3. 200mm flowtube during two-phase flow trials at NEL

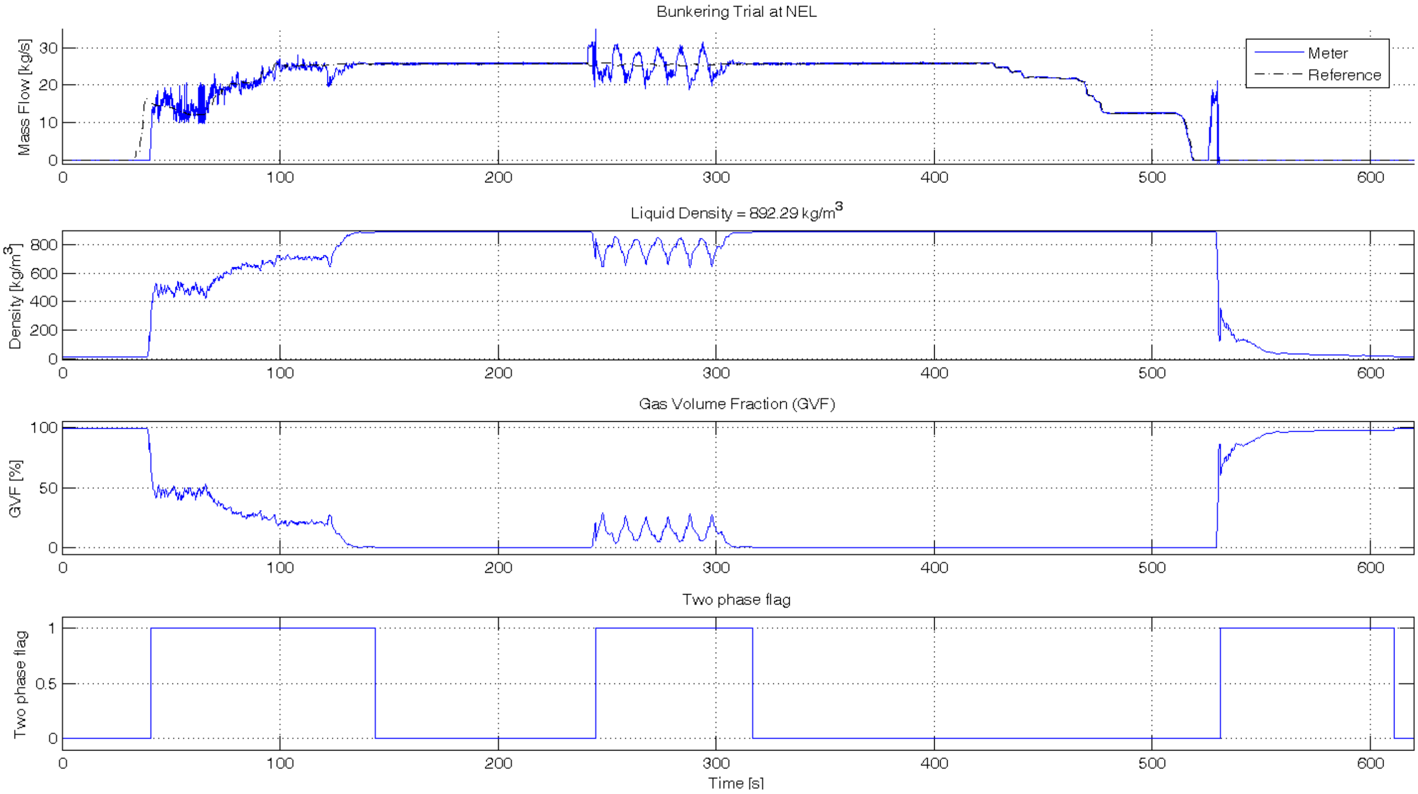

Figure 4. Batch trial simulating bunker transfer, including tank stripping.

Run Index	Reference Total (kg)	Meter Total (kg)	Meter error (kg)	(%)
1	13679.86	13651.15	-28.71	-0.21
2	14300.85	14273.60	-27.25	-0.19
3	12444.67	12419.29	-25.38	-0.20
4	13092.49	13017.37	-75.12	-0.57
5	13356.90	13255.77	-101.13	-0.76
		Mean Error	-51.52	-0.39
		Spread (max - min)	75.75	0.57

Table 1. Results from NEL trials simulating bunkering batch

3. Singapore Trials

The next stage of the testing has been the construction of a half-size container skid (Figure 5), further calibration trials on water at the Mogas test lab in Singapore, and installation onto the bunker barge “Pride”, chartered for bunkering service by BP. Figure 6 illustrates the location and function of the skid on board the vessel. The Pride has four main pairs of tanks, each served by two outlet valves – a 200mm main suction valve, and a100mm tank stripping valve. The latter is positioned lower in the tank body to access the last few inches of liquid. Fuel from the tanks is sent via the cargo pump room and the flowmeter skid to the hose boom and then onto the customer vessel. The monitoring equipment for the skid is located in the cargo control room, with a direct communications link to Oxford.

As part of the site acceptance testing for the skid, a set of trials were carried out in which residual fuel (RMG-380) was pumped from one set of tanks (Tanks 3, port and starboard) to another (Tanks 4) via the metering skid. This was achieved by attaching the end of the hose to the manifold for loading fuel, so that the path followed by the fuel is from Tanks 3, through the cargo pump room and metering skid, out of the delivery hose, back through the loading manifold of the bunker barge (not shown in Figure 6) and finally into Tanks 4.

This is of course not a conventional operation for the barge, and illustrates one of the difficulties of field trials of this nature – the absence of high quality reference measurements. Dip readings for Tanks 3 and 4 were taken at each step of the trial, and in order to minimise the amount of air transferred a valve at the manifold was used to keep much of the pipework full when flow was stopped to take readings. Nevertheless, it was not possible to ensure that the same mass of liquid was held in the intervening pipework after each batch. The calculation from dip reading through to volume and finally to mass also introduces a number of uncertainties, and as will be seen there was strong evidence of low levels of air in the fuel oil, which will entail additional errors. The project partners have agreed that laboratory trials are the most certain way of gauging meter performance accurately, where good reference measurements are available. Field trials have poorer reference measurements, but demonstrate the robustness of the equipment in real bunkering applications and yield new and detailed information on the bunkering process itself.

The 900 tonnes of fuel in Tanks 4 were entirely transferred to the initially empty Tanks 3 in a series of batches as follows. The first batch was of 100 tonnes, which also filled the pipework. There followed three batches of approximately 200 tonnes, followed by a final 200 tonne batch which finished with tank stripping.

The results are shown in Table 2. At each step, the dip readings for Tanks 3 and 4 yield mass readings. The difference in mass at each stage can be compared with the totalised mass flow through the meter skid. Note the agreement between the two tank readings themselves is only within ± 2.5%. Overall, the Coriolis meter readings are consistent with those based on tank dipping. The first batch is a special case, as the ship pipework between Tank 3 and the metering skid needs to be filled before the Coriolis meter begins to register flow – hence the Coriolis meter reaches a smaller total for this batch. A further comparison can be made between the totalised flow over all of the batches: Tanks 3 began with a calculated 908.8 tonnes, Tank 4 ended with 913.0 tonnes, while the Coriolis meter observed 903.4 tonnes. While this shows overall agreement within 1%, the most likely explanation for the difference is the presence of air. The meter showed clear indications of low levels of entrained air throughout the trial, and as the volumetric dipping process is unable to distinguish between entrained air and fuel, this will result in elevated estimates of mass from the dip readings.

For example, Figure 7 shows the time series from the Coriolis meter for the last batch, including the period of tank stripping. The low density readings, particularly at the start of the batch before flow starts, strongly suggest entrained air, a diagnosis reinforced by other Coriolis meter parameters not discussed here. The period of two-phase flow during tank stripping at the end of the batch is extensive, and it is encouraging that the Coriolis meter maintained operation and generated good measurement data during these challenging conditions.

4. Next Steps

At the time of writing, the Singapore trial is continuing (Figure 8). Much will be learned from observing, over a two-month period, commercial bunker transfers of a range of fuel types to a variety of customer vessels. It is already clear, for example, that the level of air entrainment observed in the tank to tank trial is only present in some consignments of fuel. After the successful completion of the first stage of the trial, bunker receipt issuing equipment (BRIE) will be added to the system to demonstrate the generation of commercial receipts from the metering data. Overall, the provision of a robust, two-phase capable metering system offers the potential to replace manual dipping readings with continuous, accurate, multi-parameter monitoring which, when coupled with seaboard communication systems such as Singapore's WISEPORT[6] wireless broadband, can integrate seamlessly into the digital economy, and enhance the integrity, quality assurance and economic and environmental efficiency of the bunkering industry and achieve "irrefutable quantity measurement".

Figure 5. Metering skid installed on bunker barge in Singapore

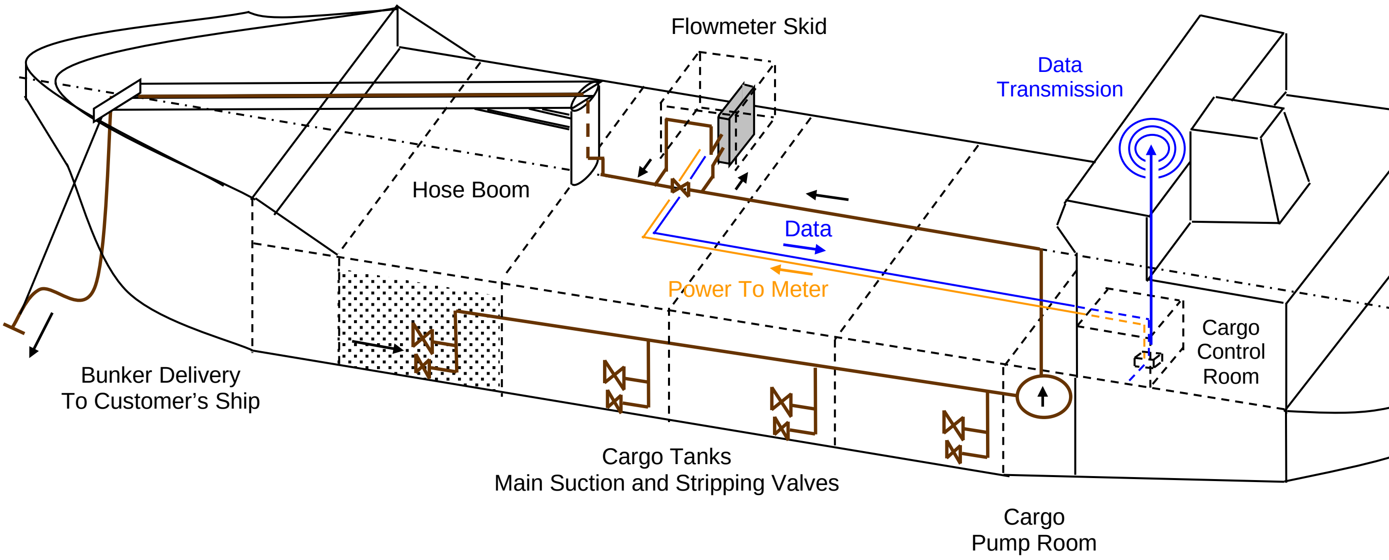

Figure 6. Flowmeter skid is installed immediately prior to the hose boom.

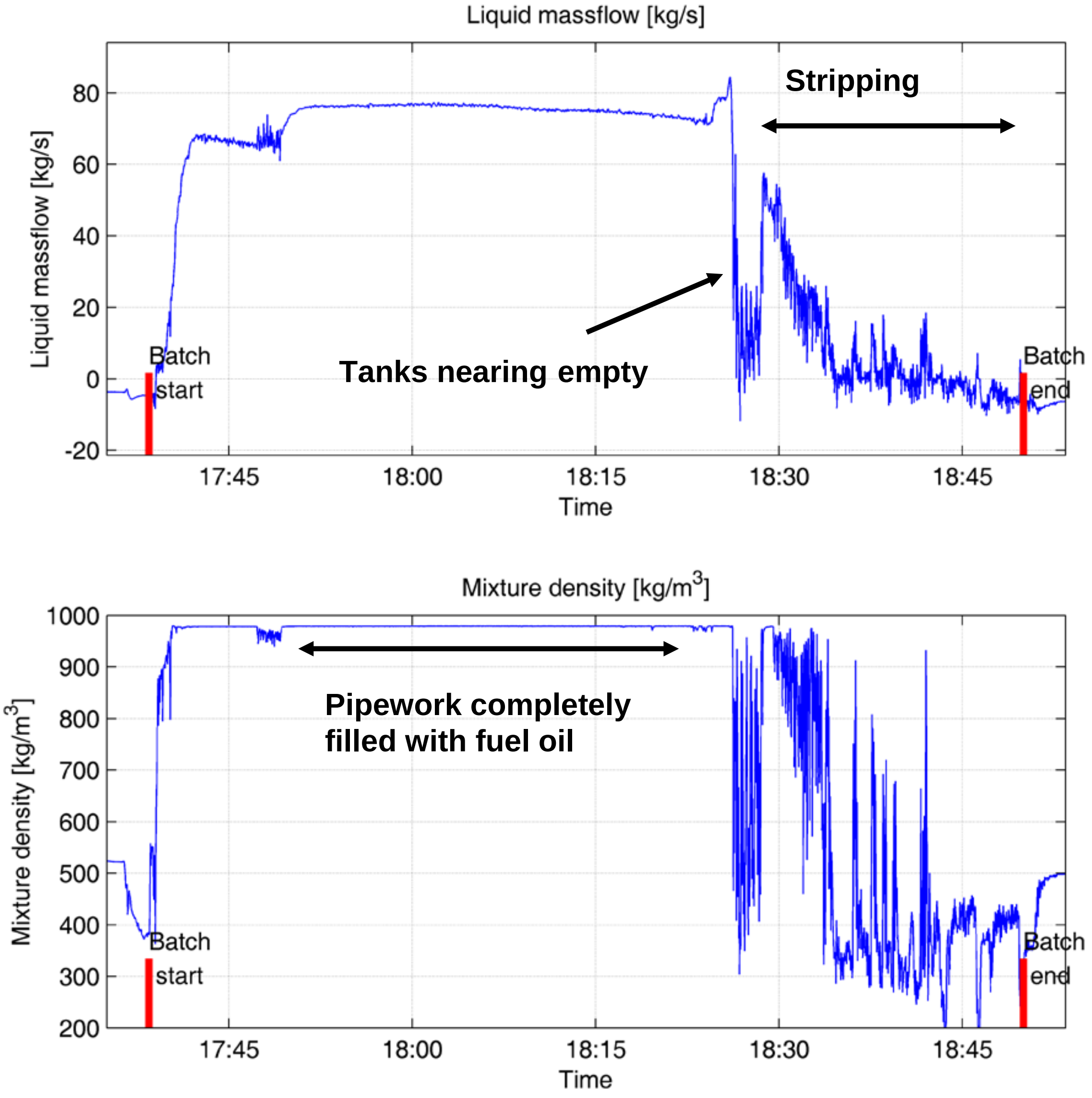

Figure 7. Time series of mass flow and density during batch 5, including tank stripping.

Event	Mass in Tank (t) (via dipping)		Change in Mass (t) since last dip reading			Change in Mass Error (%) based on Tank 3 result		Comments
	Tank 3	Tank 4	Tank 3	Coriolis	Tank 4	Coriolis	Tank 4	
Initial reading	908.822	0.000	N/A	N/A	N/A	N/A	N/A	No transfer
Batch 1 100t + fill pipes	810.671	100.378	98.151	95.034	100.378	-3.175	2.219	2t (estimate) needed to fill pipework
Batch 2 200t	613.665	302.204	197.006	199.254	201.826	1.141	2.388	Coriolis between tank estimates
Batch 3 200t	411.012	500.394	202.654	199.519	198.189	-1.547	-2.253	Coriolis between tank estimates
Batch 4 200t	216.126	695.762	194.886	195.961	195.368	0.552	0.247	Coriolis above tank estimates
Batch 5 200t + tank strip	0.000	912.996	216.126	213.582	217.234	-1.177	0.510	Coriolis below tank estimates

Table 2. Results of tank-to-tank testing with Singapore barge

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Figure 8. In the continuing trial, the metering skid is monitoring commercial transfers of bunker fuel.