Fuel Flow Metering for Fishing Vessels

Phase II Report: Fuel meter tests under laboratory conditions

The Sea Fish Industry Authority

with support from:

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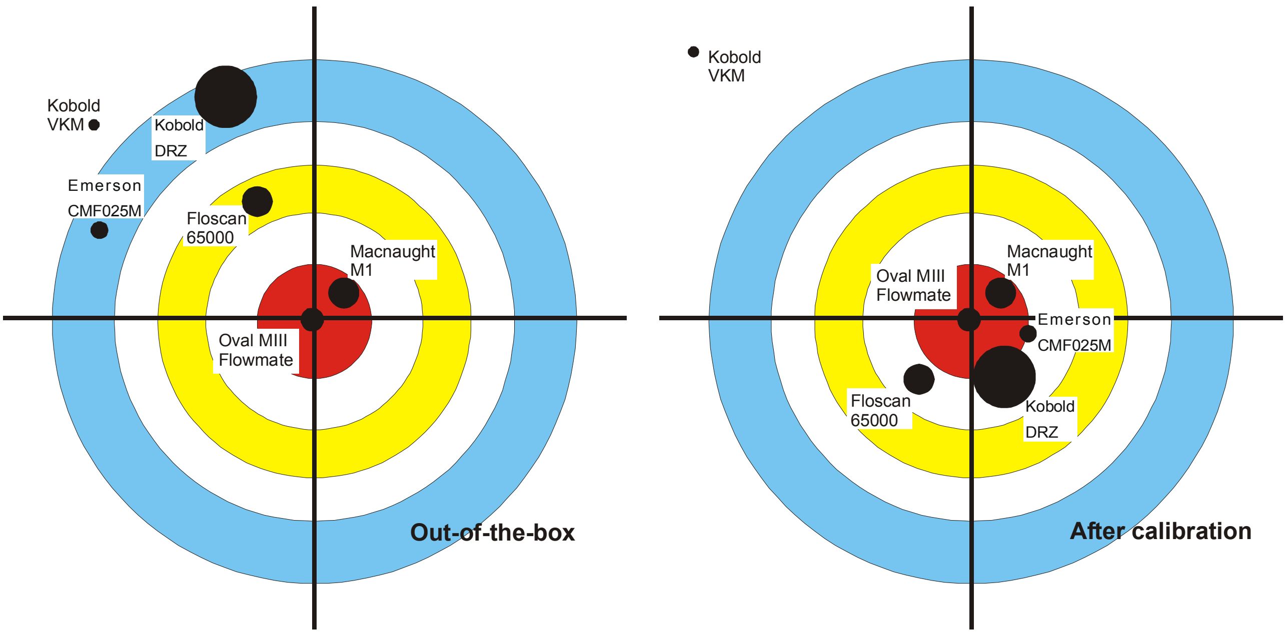
Executive Summary

The Phase II testing of fuel flow measurement systems for fishing vessels investigated the performance of six flow metering devices. These were: i) the Macnaught M1 gear meter (£263 ex. VAT), ii) the Oval MIII oval gear meter (£185 ex. VAT), iii) the Kobold DRZ oscillating piston meter (£258 ex. VAT), iv) the Kobold VKM variable aperture meter (£562 ex. VAT), v) the Floscan 65000 turbine inferential meter (£583 ex. VAT) and vi) the Emerson CMF025M coriollis meter (£3000-£4000 ex. VAT). The prices indicated for flow meters i) to iv) do not include signal processing, sensor energisation and display equipment, which will add another £330 + VAT to the total equipment cost if a DataTrack 284, dual-channel, panel mount indicator is used, as was done in this study.

The diagram below illustrates the relative performance of the measurement systems incorporating the various flow metering sensors. The position of the circle relative to the centre of the target represents the accuracy of the observations, with close to the target centre being better. The diameter of each circle represents the repeatability, or precision, of the observations, with smaller being better.



Some of the meters will require calibration on board a fishing vessel in order to produce valid observations. The notable exceptions to this are the Macnaught M1 and the Oval MIII Flowmate gear meters which produced valid observations "out-of-the-box", and for this reason top our ranking.

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Introduction

During Phase I of the research, reviews were undertaken of diesel engine fuel delivery systems and fluid flow metering theory in the context of the research objective of finding the best fuel flow meter to indicate diesel engine fuel consumption for fishing vessels. Specific characteristics of flow transducers that made them suitable for measurement of fuel consumption on board a fishing vessel were identified. These were used to guide a search for fuel flow transducers available on the market. Several different types of meter that may be suitable were identified.

In Phase II of the research, devices were procured such that each type of transducer identified in the Phase I work were represented. In general, and where possible, the devices were specified such that they were suited to metering the fuel consumption rates for the CSM Dynamometer Diesel Engine Test Cell, which would be the main topic of the Phase III component of the research. For the Phase II component, further equipment was procured that enabled the provision of constant rates of fuel flow with high precision and repeatability. This was done so that the fuel meters selected could firstly be tested for their accuracy and precision without being installed on the test engine (where meter performance could be influenced by engine operational factors such as vibration and pulsating flows). Overall, the purpose of Phase II testing is to assess the performance of the meters under controlled conditions. Flow metering tests were performed across the full-scale range of each device, with a view to assessing their performance in terms of accuracy and precision.

The range of devices covers gear and piston positive displacement meters, variable aperture meters, turbine meters and Coriolis mass flow meters.

Final Phase II device selections

Table 1: Final fuel metering devices selected for Phase II testing.

Manufacturer & Model	Meter type	Minimum Flowrate (l/hr*)	Maximum Flowrate (l/hr*)	Quoted Accuracy (% FSD*)	Quoted Repeatability	Cost (ex-VAT)
Macnaught M1	Oval gear	2	100	0.5%	0.03%	£263
Oval MIII Flowmate	Oval gear	2	100	0.5%	Not specified	£185
Kobold DRZ	Oscillating piston (+ve displacement)	6	420	1.0% of observation	0.2% of observation	£258
Kobold VKM	Variable aperture	12	66	3.00%	Not specified	£562
Flowscan 65000 Cruisemaster	Turbine meter (2 meters + instrument + pulse dampeners)	1	180	Not reported	Not reported	£583
Emerson CMF025M	Coriolis meter	0 (kg/h)	2180 (kg/h)	0.05% of observation over upper 90% of FSD	0.025% of observation over upper 90% of FSD	£3000-£4000

* Unless otherwise specified

In comparison to the device selections indicated in the Phase 1 report:

- The project procured a Coriollis mass flow meter from, Emerson Process Management. Emerson's Micromotion CMF025M, priced between £3000-£4000 which substituted for both the Bronkhurst Cori-flow meter and the Siemens Mass 2100 Coriollis meters in the original selection line up.
- The delivery lead time of the Bronkhurst Liqui-flow was too long for it to feature within the testing programme.
- There were no correctly scaled versions of the Parket DataFlow Compact meter for the test engine trials of Phase III so this device was not procured.
- The Magnaught M2 meter was substituted by the Magnaught M1 meter as the latter was of a more suitable FSD range for the test engine and adopted the same metering principle.

Two meters that did not make the original shortlist were subsequently added to the Phase II trial list. These were the Kobold DRZ meter, an oscillating piston metering device, and the Kobold VKM which is a variable aperture fuel metering device.

- The Kobold DRZ was selected because it appeared to be of more robust construction than the other positive displacement units tested (the Magnaught M1 and the Oval MIII Flowmate) and should it jam, in principle it would still allow fuel to flow through it. This would obviate the need for a by-pass leg, potentially simplifying installation on board a fishing vessel.
- The Kobold VKM was selected because the device is relatively insensitive to fuel cleaniless, had only one, slow moving, moving part (potentially meaning minimal maintenance) and has an inbuilt by-pass arrangement.

The results of the Phase-II testing programme serve as a reference point, against which the meter performance in the Phase-III trials are compared. In Phase III trials, the meters were installed within the fuel line leading to the test engine. Comparison of results from Phase II and Phase III trials permitted identification of whether the performance of a meter degrades in the operational environment for which it is intended.

The accuracy and repeatability of the Emerson CMF025M is obtained by calculation. The device was operated at a turndown ratio of between 1000:1 and 50:1 which, through this calculation, degrades quoted accuracy and repeatability. The quoted accuracy is only for the display on the device, the analogue output potentially introduces another 0.2% error in accuracy.

The project team were not able to obtain a quote of the accuracy and repeatability from Floscan for the 65000 Cruisemaster.

Accuracy and Repeatability

Accuracy, in science, engineering, industry and statistics, is the degree of conformity of a measured/calculated quantity to its actual (true) value. Bias is the term for the magnitude of the disparity between a measured or calculated quantity from its actual (true) value. Precision (also called reproducibility or repeatability) is the degree to which repeated measurements or calculations will show the same or similar results. The results of a measurement or calculations can be accurate but not precise, precise but not accurate, neither, or both. If a result is both accurate and precise, it is called valid.

A useful way to graphically visualise the distinct meanings of accuracy and precision is via the so-called 'target analogy' (Figure 1). The centre of the target represents the actual (true) value of a quantity and the crosses represent observations of the quantity using a measurement system. The four targets shown illustrate the performance of four distinct measurement systems, each with their own characteristics of accuracy and precision. A measurement system producing valid observations is illustrated in the top RHS. Measurement systems on the LHS exhibit bias, meaning that they produce inaccurate observations. The bias in these systems can be eliminated through the process of calibration. Measurement systems on the bottom row exhibit low repeatability or low precision. Measurement systems of this type can still be useful if a large number of observations are taken and the observations are averaged; this corresponds to determining the centroid of the cluster of observations. Any bias apparent in this average can again be removed through calibration.

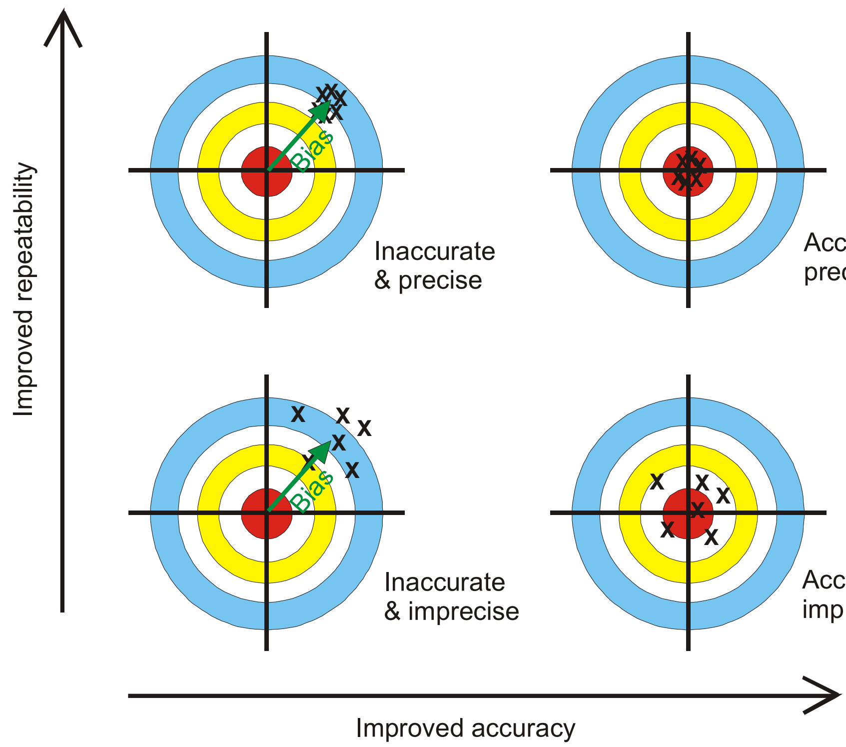


Figure 1: The 'target analogy' illustrating the concepts of accuracy and precision

The Flow Meter Test Facility

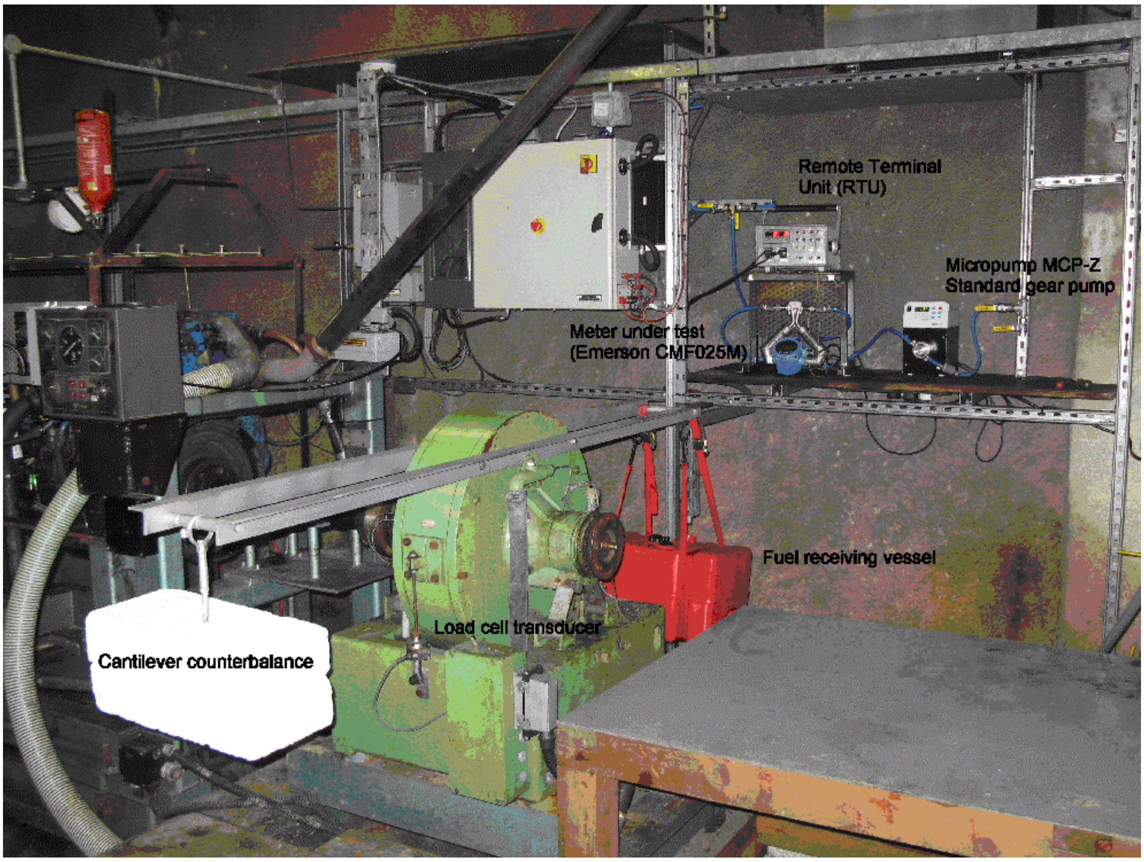


Figure 2: Photograph of the flow meter test arrangements.

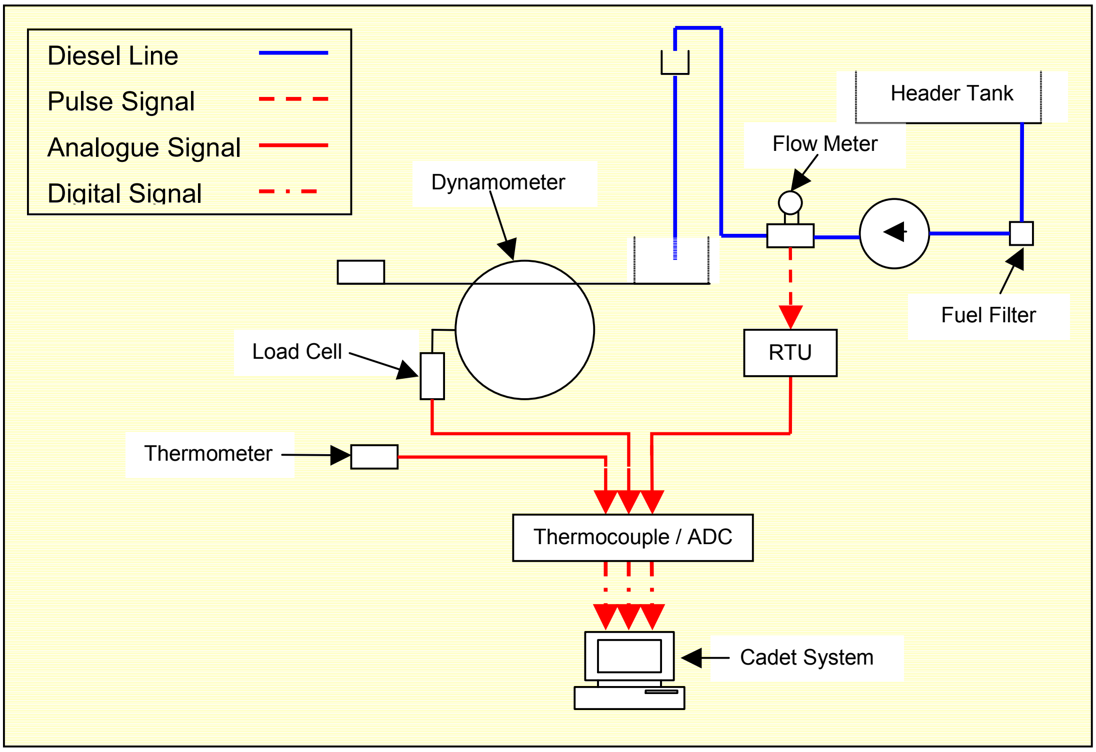


Figure 3: Flow meter test facility schematic

Constant flow rate dispensing pump

In order to evaluate the performance of the flow-rate transducer under test, a volumetrically constant fluid flow was passed through the transducer, which was then discharged into a fuel receiving vessel suspended on a balance system.

Figure 4: Constant flow rate dispensing pump, Ismatec pump drive unit & Micropump pump head

A digital gear-drive dispensing pump was selected so that a steady volumetric flow can be easily ‘dialled in’, and the drive unit programmed to operate for a specified time period. The pump drive was supplied by Ismatec (£1702+VAT) and the pump head (L20S6Z) was supplied by Micropump (£408+VAT). Ismatec were consulted on the accuracy and precision of this set up, and reported that accuracy and repeatability of better than 1% should be returned in steady conditions of temperature, viscosity and back pressure. The pump conditions were rendered stable in the test cell chamber, and a pump calibration exercise with an accurate balance and timing revealed that the constancy of flow was an order of magnitude greater than any of the indicated repeatability figures for the meters under test. The constancy (repeatability) of flow was better than 0.003%, and the project team were confident that when Phase II trials were underway, the flows experienced by the meters were constant to this level of precision.

While the constancy of the dispensing pump was high, in order to achieve a similar level of accuracy in known flows, the pump would have had to be calibrated with each of the meters in turn to take account of, for example, varying pressure drops across the meters. It was considered that this would introduce unnecessary additional complications. So, rather than do this, a separate mass balance was used to determine the magnitude of the constant flow provided by the dispensing pump.

Figure 5: a) Swan-Neck b) Receptacle Tank

When the pump was powered down, it became evident that its gears had low resistance to back rotation. This meant that, unmodified, the pump head was incapable of restricting flow in the 'off' condition. Consequently, the fuel was routed through a swan-neck arrangement in order to maintain a positive pressure-differential between the header tank and the point of discharge and thus undesirable siphoning or spill effects were avoided. The swan-neck was placed after the meter under test so that the fuel was not aerated prior to being passed through it (see Figure 3).

A bracket was also constructed so that the fuel could be discharged into the balance system without the pipe loading the balance.

The mass balance

For Phase II testing, the mass balance assembled had a requirement to accurately measure up to around 20 kg of fuel passed to the fuel receiving tank. The dynamometer/load-cell of the engine test rig was reconfigured as a mass balance, utilising its calibration beam to support the fuel receiving tank, counterbalanced with a concrete block. The advantage of this arrangement was that a channel from the load cell to the CP Engineering logging system was already established so that reliable time stamps would be returned with mass values; reliable mass flow rates would then be recovered.

As the load cell was already calibrated for its use on the dynamometer, these values were left unchanged in the logging system. However an auxiliary calibration exercise was undertaken to provide corrections to the logged values. This was done using masses that are traceable to the DKD standard via a mass set CBP5000, serial number 50325 provided by Calibration Dynamics Ltd. For two separate cases, covering low mass range tests and high mass range tests, logged values of mass recorded by the CP Engineering data acquisition system were compared with known masses placed on the fuel receiving tank. Least squares adjustments were undertaken in both cases for the parameters of a linear correction function, to ensure that the mass values measured by this system were free from bias, that is, they are thus assumed to have low error. The time stamps of mass values recorded by the logging system are based on the computer clock (operating at least in the MHz range) and were thus also assumed to be free of error.

The precision of logged values of the mass on/in the fuel receiving tank ultimately depended on the resolution of the analogue to digital converter in the CP Engineering data acquisition system. This was 16 bits over the 500 kg range of the dynamometer load cell, or around 2g when the moment arms of the load cell and fuel receiving tank are considered. By repeated logging of mass over 20 second measurement periods at 10 Hz, this was improved upon to around 1g (Table 2) for low mass ranges and around 4g for high mass ranges (Table 3).

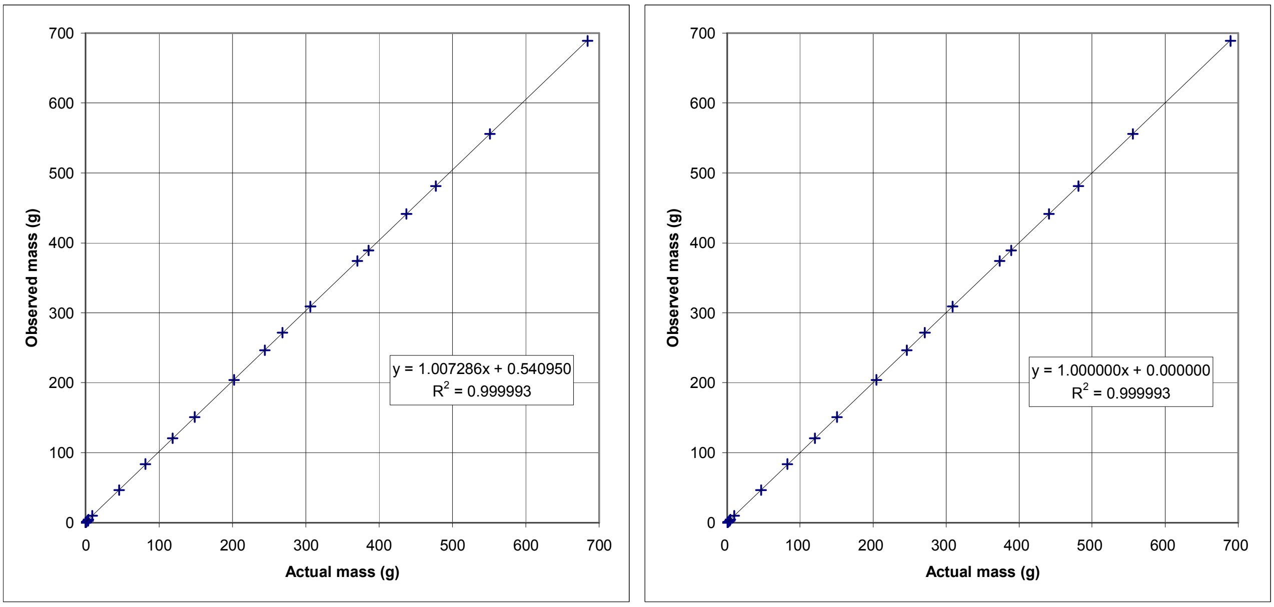


Figure 6: Comparison of logged mass versus actual mass before and after calibration correction for low mass range.

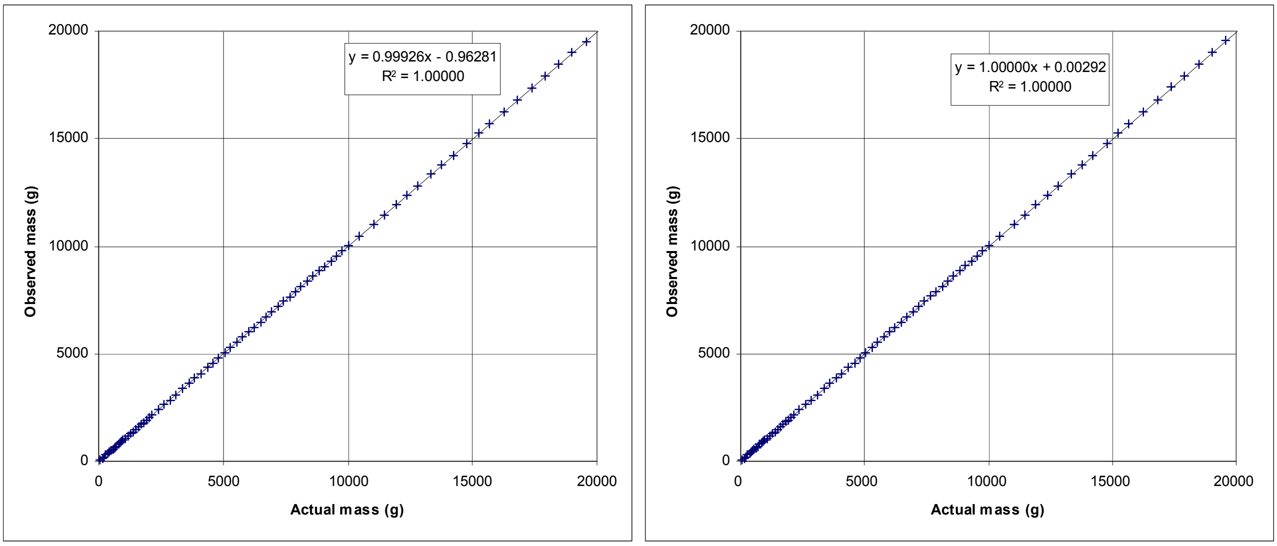


Figure 7: Comparison of logged mass versus actual mass before and after calibration correction for high mass range.

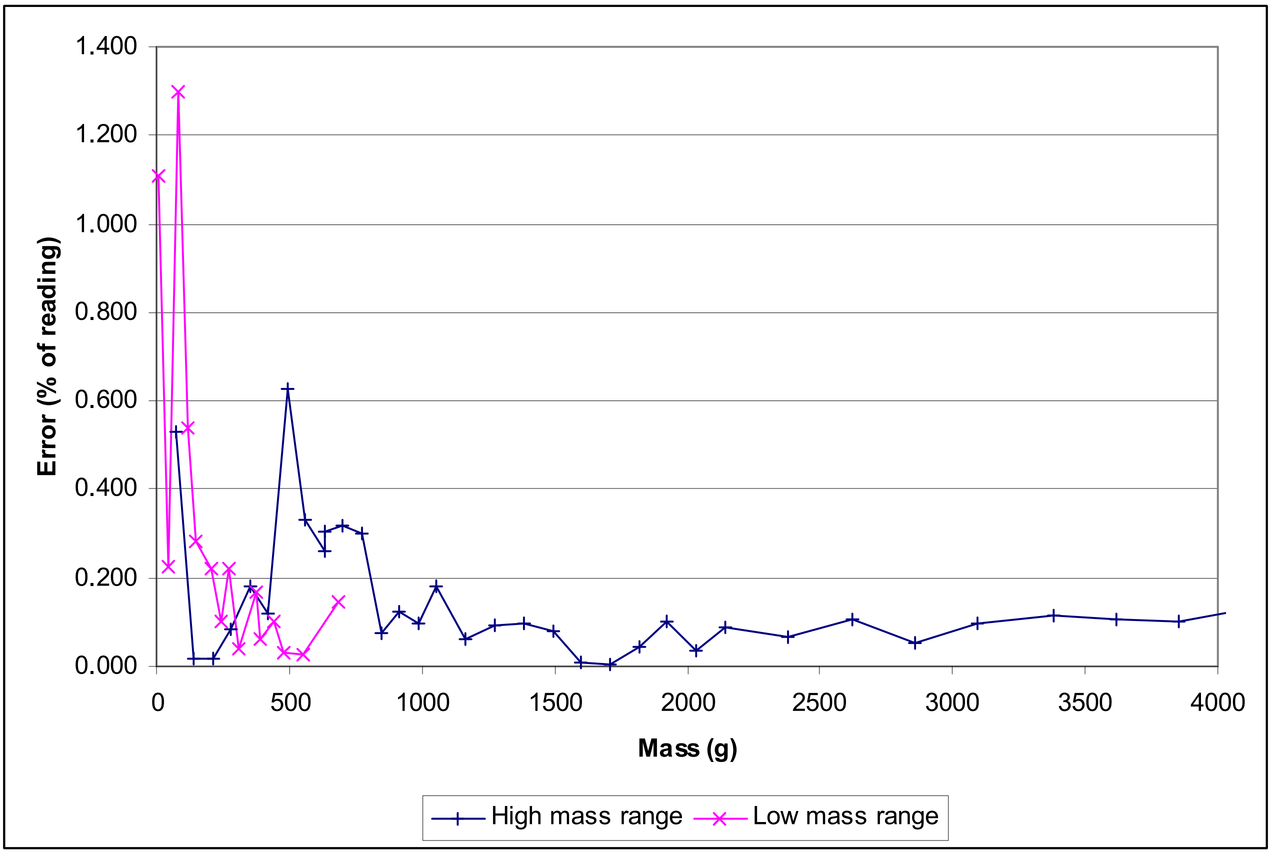


Figure 8: Error (% of reading) versus mass, after the load cell calibration.

Table 2: Dynamometer load cell calibration correction for low mass ranges.

Actual	Observed Mass - before calibration correction				Observed Mass - after calibration correction			
Mass (g)	Average (g)	Variance (g2)	Std Dev (g)	Error (g)	Average (g)	Variance (g2)	Std Dev (g)	Error (g)
0.00	0.04	0.09	0.30	0.04	0.58	0.09	0.30	0.58
0.71	0.49	0.20	0.45	-0.22	1.03	0.20	0.45	0.32
1.44	1.22	0.10	0.31	-0.22	1.77	0.10	0.32	0.33
2.70	3.14	0.05	0.23	-0.22	3.71	0.05	0.23	1.01
4.13	3.77	0.43	0.66	-0.36	4.34	0.44	0.66	0.21
9.78	9.28	0.41	0.64	-0.50	9.89	0.42	0.65	0.11
46.47	45.49	0.21	0.44	-0.98	46.36	0.21	0.44	-0.11
83.66	81.44	0.36	0.60	-2.22	82.58	0.36	0.60	-1.08
120.81	118.75	0.11	0.33	-2.06	120.16	0.11	0.34	-0.65
150.95	148.89	0.19	0.43	-2.06	150.52	0.19	0.44	-0.43
203.96	202.40	0.19	0.43	-1.56	204.41	0.19	0.44	0.45
246.60	244.03	0.07	0.27	-2.57	246.35	0.07	0.27	-0.25
271.53	268.43	0.14	0.38	-3.10	270.93	0.14	0.38	-0.60
308.93	306.28	0.13	0.35	-2.65	309.05	0.13	0.36	0.12
374.11	370.24	0.14	0.38	-3.87	373.48	0.14	0.38	-0.63
389.30	385.72	0.18	0.43	-3.58	389.07	0.19	0.43	-0.23
441.45	437.28	0.24	0.49	-4.17	441.01	0.24	0.49	-0.44
481.00	477.13	0.16	0.39	-3.87	481.15	0.16	0.40	0.15
555.76	551.34	0.16	0.40	-4.42	555.90	0.16	0.40	0.14
688.68	684.16	0.38	0.67	-4.52	689.69	0.39	0.68	1.01

Table 3 Dynamometer load cell calibration correction for high mass ranges

Actual Mass (g)	Observed Mass - before calibration correction				Observed Mass - after calibration correction			
	Average (g)	Variance (g2)	Std Dev (g)	Error (g)	Average (g)	Variance (g2)	Std Dev (g)	Error (g)
70.15	68.76	0.3046	0.55	-1.39	69.78	0.3050	0.55	-0.37
140.44	139.39	0.2845	0.53	-1.05	140.46	0.2849	0.53	0.02
210.76	209.67	0.4647	0.68	-1.09	210.79	0.4654	0.68	0.03
281.33	279.92	0.4265	0.65	-1.41	281.10	0.4271	0.65	-0.23
351.61	349.74	0.2157	0.46	-1.87	350.97	0.2161	0.46	-0.64
421.5	419.72	0.3301	0.57	-1.78	421.00	0.3306	0.57	-0.50
492.3	487.90	1.4733	1.21	-4.40	489.23	1.4755	1.21	-3.07
562.25	559.01	0.2998	0.55	-3.24	560.40	0.3003	0.55	-1.85
632.69	629.60	0.1881	0.43	-3.09	631.04	0.1884	0.43	-1.65
632.69	629.33	0.3563	0.60	-3.36	630.76	0.3568	0.60	-1.93
702.96	699.24	0.4006	0.63	-3.72	700.73	0.4012	0.63	-2.23
773.35	769.50	0.3812	0.62	-3.85	771.04	0.3818	0.62	-2.31
843.82	841.58	0.3227	0.57	-2.24	843.17	0.3232	0.57	-0.65
914.52	911.74	0.5104	0.71	-2.78	913.39	0.5112	0.71	-1.13
985.21	982.53	0.4076	0.64	-2.68	984.23	0.4082	0.64	-0.98
1055.89	1052.23	0.5528	0.74	-3.66	1053.98	0.5536	0.74	-1.91
1164.84	1162.29	0.2304	0.48	-2.55	1164.12	0.2308	0.48	-0.72
1273.55	1270.48	0.2609	0.51	-3.07	1272.39	0.2613	0.51	-1.16
1382.56	1379.23	0.2079	0.46	-3.33	1381.22	0.2082	0.46	-1.34
1491.92	1488.69	0.2478	0.50	-3.23	1490.76	0.2482	0.50	-1.16
1600.63	1598.33	0.2615	0.51	-2.30	1600.49	0.2619	0.51	-0.14
1709.06	1706.78	0.2450	0.49	-2.28	1709.02	0.2454	0.50	-0.04
1817.23	1814.09	1.3843	1.18	-3.14	1816.41	1.3863	1.18	-0.82
1925.26	1920.88	0.2755	0.52	-4.38	1923.28	0.2759	0.53	-1.98
2034.5	2031.28	1.2209	1.10	-3.22	2033.76	1.2227	1.11	-0.74
2144.25	2139.84	0.3010	0.55	-4.41	2142.40	0.3014	0.55	-1.85
2382.43	2378.14	0.4774	0.69	-4.29	2380.88	0.4781	0.69	-1.55
2622.56	2616.85	0.3974	0.63	-5.71	2619.77	0.3979	0.63	-2.79
2859.14	2854.58	0.4103	0.64	-4.56	2857.67	0.4109	0.64	-1.47
3094.86	3088.63	0.9354	0.97	-6.23	3091.89	0.9368	0.97	-2.97
3380.42	3373.01	0.2403	0.49	-7.41	3376.49	0.2407	0.49	-3.93
3618.08	3610.57	7.9935	2.83	-7.51	3614.23	8.0054	2.83	-3.85
3854.73	3846.94	0.1646	0.41	-7.79	3850.77	0.1649	0.41	-3.96
4092.95	4083.62	0.5267	0.73	-9.33	4087.63	0.5275	0.73	-5.32
4349.18	4340.69	3.6741	1.92	-8.49	4344.89	3.6795	1.92	-4.29
4586.05	4577.16	0.8332	0.91	-8.89	4581.53	0.8344	0.91	-4.52

Data acquisition system

The engine and dynamometer test facility is built around a Cadet 3099 Supervisory Control and Data Acquisition (SCADA) system, provided by CP Engineering. This provides a minimum update frequency of 10Hz on each channel, and provides a corresponding timestamp resolved to 0.1s when the channel is logged.

The SCADA system was extended to meet the requirements of flow meter testing by the addition of two analogue signal inputs for the flow-rate transducers. The channels are recorded at up to 16 bit resolution, over user-selectable voltage ranges. Generally, a voltage range of –0.25V to 10.25V was selected for logging the indicated flow rates from the meters under test.

As various transducer types produce different kinds of output signal (i.e. voltage output, current output, pulse count output or frequency output) a Remote Terminal Unit (RTU) was constructed that converted all of the possible transducer outputs types into 0-10V analogue voltage signals.

The RTU is built around a DataTrack 284, dual-channel, panel mount indicator that can accept pulse, time to live, relay contact and encoder signals (~ cost: £330 + VAT). It also provides one analogue output, which was routed into the CP SCADA system. In the case that the output signal of the meter under test was a pulse output, the DataTrack 284 was used to convert this to an analogue voltage output, corresponding to pulse frequency. In the case that the output signal of the meter under test was a current in the range 4-20mA, this was passed through a 500 Ω precision resistor. In the case that the output signal of the meter under test was a voltage output in the range 0-10V, this was patched straight through the RTU to the latter's analogue output channel.

Both the pump and RTU can be fully programmed via RS-485 communication.

The meters under test also had varying power requirements. Consequently, the RTU was additionally constructed to provide local connection points for regulated transducer excitation voltages of 10V, 12V and 24V, for convenience in testing.

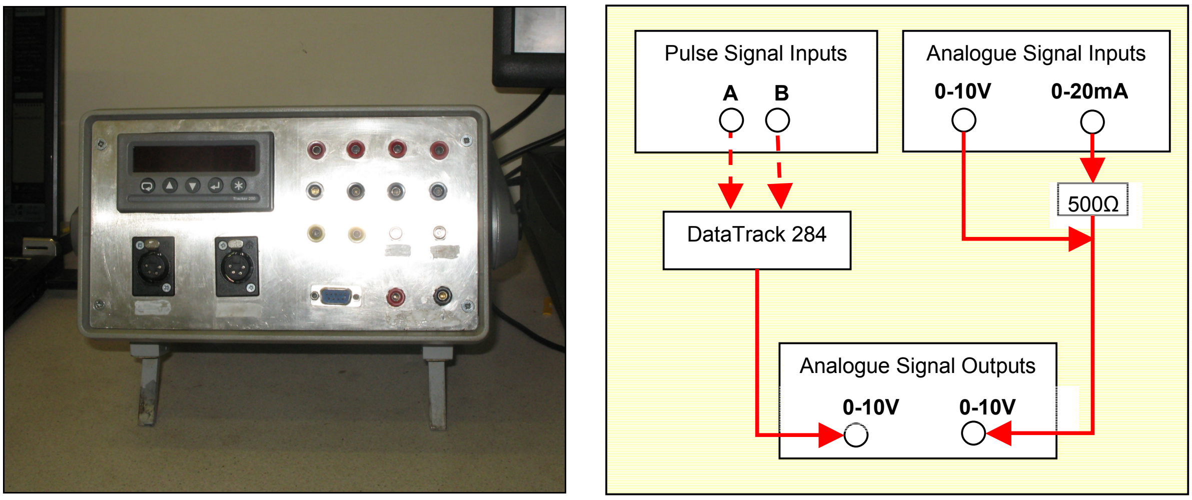


Figure 9: LHS, Remote Terminal Unit; RHS, Remote Terminal Unit Schematic Diagram

DataTrack 284 to CP SCADA system interface

Pulse signals from flow meters are routed through the DataTrack 284 signal-processor and converted into an analogue voltage output. For most of the meters, the DataTrack 284 was set to produce a voltage in the range 0-10 V when the frequency of sensed pulses was between 0 and 100Hz. The accuracy of information relayed by the DataTrack 284 thus relies on reliable timing of pulses from the transducers at the input side. For the DataTrack 284 the timebase error is < 100ppm which would account for an error of 0.01Hz over the 0 to 100 Hz range that the analogue output channel was set to. Errors attributable to the DataTrack 284 in processing pulse signals also occur at the output side. According to the manufacturer's specifications, the digital to analogue conversion of the pulse signals (equivalently the pulse frequency signals) occurs with a worst case error of 0.2% of span (0.2Hz) and 0.1% typically (0.1Hz). The conversion also suffers minor drift due to temperature changes quoted at <100ppm, equivalent to 0.01Hz for the settings used. The resolution of the digital to analogue conversion is 0.05% corresponding to 0.05Hz.

The implication of these specifications is that care must be taken when setting the range of the analogue channel for pulse signal flow meter outputs, such that any inaccuracy of the flow meter itself is not swamped by the inaccuracies arising from the processing of the raw signal by its signal processor – the DataTrack 284 in this case.

After conversion of a pulse signal in the DataTrack 284, an analogue voltage signal in the range 0-10V is produced, that in turn is passed to the analogue to digital converter of the CP SCADA system where the digital value is displayed or logged. The range of the analogue to digital converter was set at –0.25V to 10.25V (to ensure that maximum and minimum analogue signal values could be properly sensed).

Pulse signal interface calibration

Calibration of the DataTrack 284/CP SCADA interface proceeded as follows. The DataTrack 284 was set to "count" mode, and instructed to provide a linear output of 0 to 10 V over a count range of 0 to 100. Five data points of equal spacing were then recorded using the CP SCADA system's software calibration, providing a new calibration gain and offset (New gain: 0.0016155, New offset: -2.6034700) which were stored in the logging system

Table 4: Pulse signal interface calibration results

RTU count defined	CP SCADA system A to D Count	RTU count value sensed after calibration.
0	01653	0.07
25	17061	24.96
50	32524	49.94
75	48021	74.98
100	63547	100.06

In testing, the DataTrack instrument was set to output a range of 0 to 10V over a frequency range of 0 to 100Hz for most frequency output instruments. The exception to this was the Floscan 65000 which used the same analogue output range to represent 0 to 200Hz. Thus, in most cases, the recorded "RTU count" value is identical to the frequency in Hz, except in the case of the Floscan, where the value needs to be doubled.

Analogue voltage or current signal interface calibration

For the analogue current inputs to the RTU, the DataTrack instrument's analogue output was connected to the 4 – 20 mA input of the RTU, and the DataTrack was instructed to provide a 4 – 20mA output in count mode, with 4mA representing 0 and 20mA representing 100. The current was measured prior to logging with a digital multimeter, and this value was given to the Cadet Calibration software, so that the values recorded on the logs were equivalent to the current signal. The gain and offset values found were: New gain: 0.0003223, New offset: -0.4818885.

Table 5: Analogue signal interface calibration results

Measured Current	CP SCADA system A to D count	Displayed / logged value after calibration
3.99mA	13896	4.00
7.98mA	26247	7.98
11.97mA	38629	11.97
15.97mA	51034	15.97
19.96mA	63457	19.97

Here, the greatest inaccuracy was 0.01mA, considerably less that 0.1% of full scale.

The decision was made to record the input of all transducers using these values directly, and any further calculation required to compute the flow rate being indicated by the transducer at the time of logging would be made as part of further analysis. This would allow for the rapid switching-out of transducers as testing got underway, and possible adjustment of transducer calibration constants, if so desired.

Diesel density temperature correction

The density, and therefore specific volume, of a fluid is a function of temperature and pressure. However pressure only has a slight effect upon the density of an incompressible fluid, and any variation in atmospheric pressure throughout the test would be insignificant. While the thermal expansion coefficient of diesel is still very small, temperature was a factor considered relevant to testing. The thermal expansion characteristic of our diesel fuel was empirically derived by circulating a sample of diesel around a small circuit, consisting of a pump, an inline density meter and a thermometer. Around 60 data points were collected as the temperature of the diesel increased from 15 °C to 17.5 °C, which resulted in a clearly linear relationship between temperature and density, regressed ($R^2 = 0.9947$) to:

$$\rho(T) = -0.74T + 875.74$$

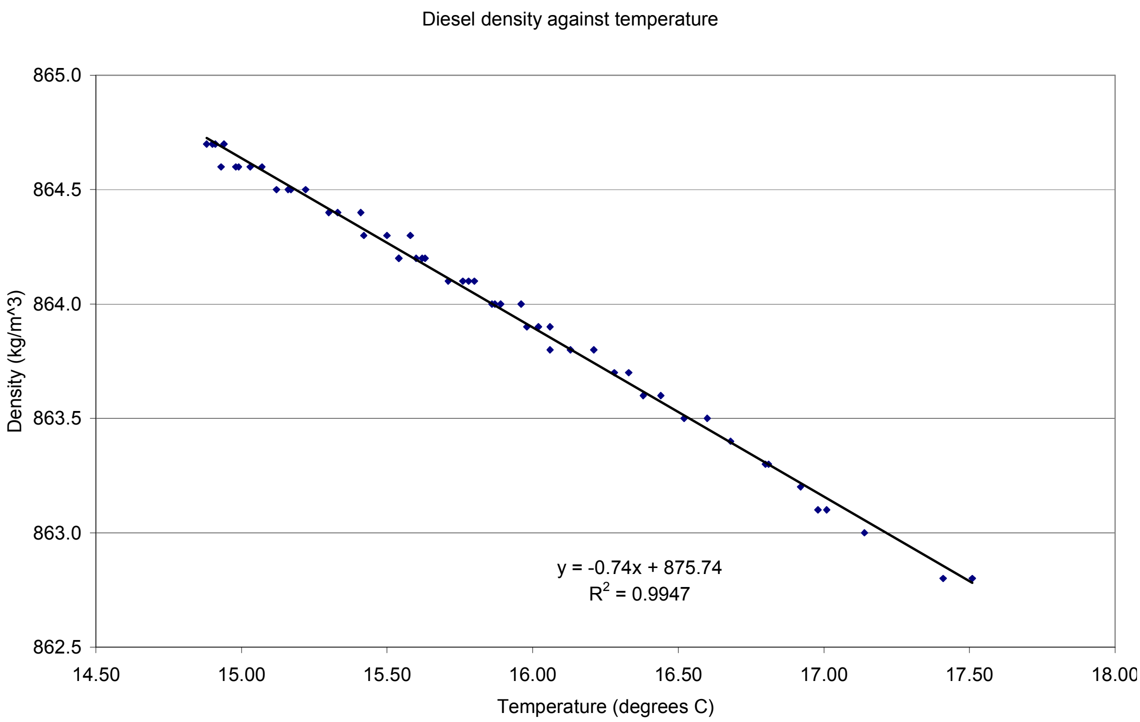


Figure 10: Relationship between temperature and density of test fuel

This density function was used in all subsequent calculations involving volumetric / mass conversion.

Phase II Test Procedures

Experimental Procedure

The meter is installed in the test rig and any air trapped in the line expelled.

Once the test run has been setup on the SCADA system, the pump is activated and programmed to operate at the correct speed to produce the desired, nominal, flow-rate for a period one minute greater than the length of the test run.

The test procedure involves the simultaneous acquisition of:

- the timestamp from the SCADA system
- the output signal of the flow meter, mapped to the range 0-10V by the RTU
- the torque exerted on the dynamometer by the mass of fuel in the receptacle tank, and;
- ambient temperature, (to permit a fuel density correction to be applied)

at 5-second intervals throughout each each test run. Each time-stamped datum is a 5 second average value of instantaneous values sampled at 10Hz. The first 60 seconds of 5 second averages were discarded from the analysis to eliminate any settling effects.

Two types of test run were undertaken in Phase II testing for each meter tested:

- FSD test runs where the set points were at 20%, 40%, 60%, 80% and 100% of the meters' full scale flow rate, where the duration of each set point was 6 minutes in total.
- Engine flow rate runs where the set points were at 3.6 l/hr, 4.98 l/hr and 8.0 l/hr, flow-rates that coincided with part of the Phase III engine test plan. The duration of these set points were 16 minutes to further reduce the variance of the mass balance observations.

Data Analysis Procedure

The 5 second averages of torque measured by the dynamometer load cell were firstly converted to fuel mass using the geometry of the calibration jig and then subsequently converted to fuel volumes using a temperature corrected diesel density. The actual volume flow rate for the test run was then established by least squares regression of a linear fit to the volume time series, and recording the value of the gradient parameter of this line.

The SCADA system also logs 5 second average values of the output signal of the meter under test (in the range 0-10V), relayed to the SCADA system by the RTU. These are firstly converted back to units of the native output signal (i.e., either Hz, mA or V, as appropriate) and then a meter manufacturer supplied conversion factor is used to return this to units of flow rate. The flow rate values are accumulated to form a fuel volume time series. The indicated flow rate reported for the test run is established by least squares regression of a linear fit to the volume time series, and recording the value of the gradient parameter of this line.

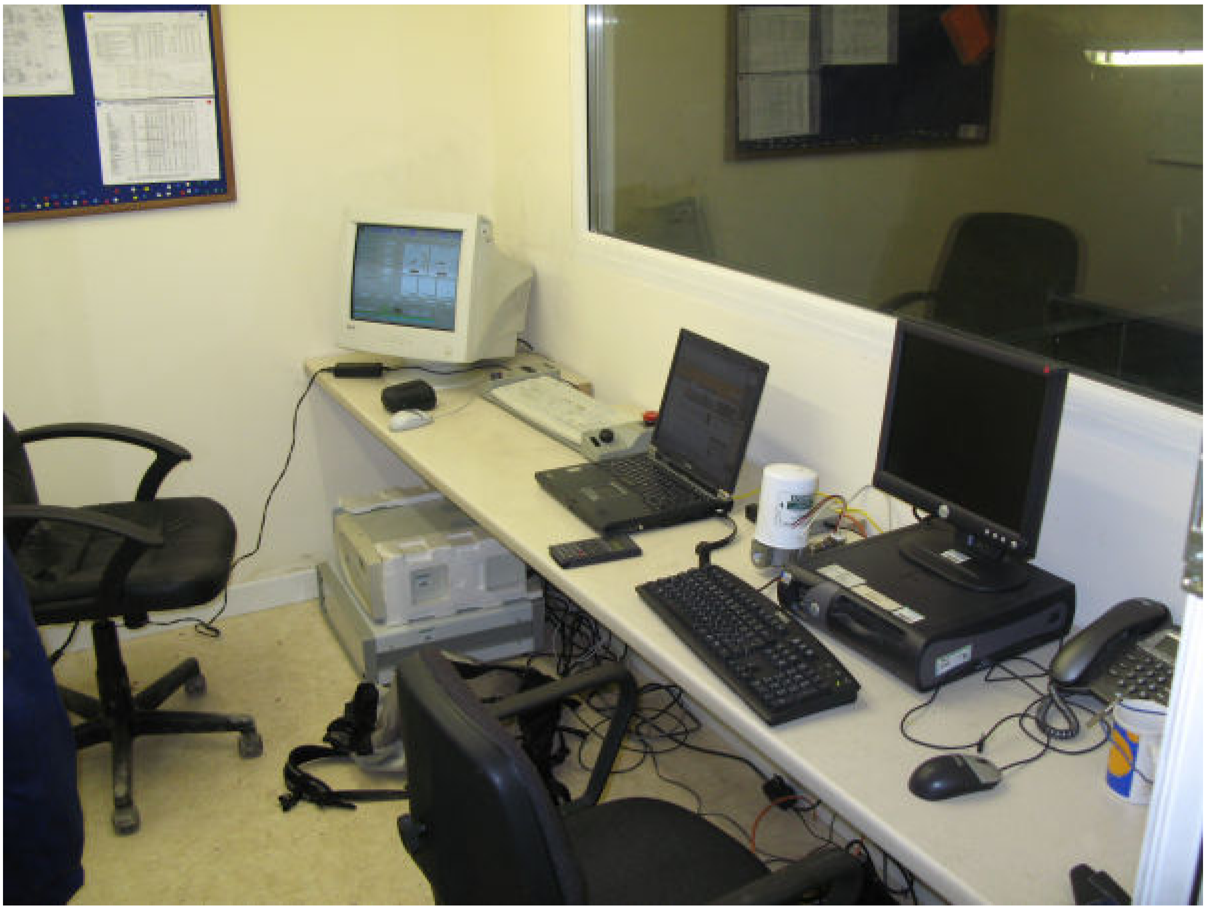


Figure 11: Control room showing CP Engineering instrument rack on floor beneath computer screen

Practically, the data analysis is undertaken using the LINEST least squares regression function within Microsoft Excel. This has the further advantage of returning the standard error for the estimated parameter (the gradient, or more specifically, the average flow rate for the test run). The standard error is defined as the standard deviation of the parameter divided by the number of observations. As the number of observations is known, this provided a convenient method for simultaneous determination of the least squares error standard deviation of the flow rate as well as the least squares error average flow rate for the test run – for both the actual (or known) and indicated (by the meter under test) flow rates.

Calibration procedure

Some devices tested did not come with strict calibration coefficients. Notably, the Floscan 65000 unit requires user calibration, and it was only loosely suggested by the manufacturer that 12600 pulses per litre would be read, partly since they informed the research team that the output is non-linear.

Therefore, it was decided that all units should undergo the most appropriate form of re-calibration to the output of that device, so that they may be fairly compared with each other. Initially, however, manufacturer's calibration coefficients, no matter how arbitrary, were used.

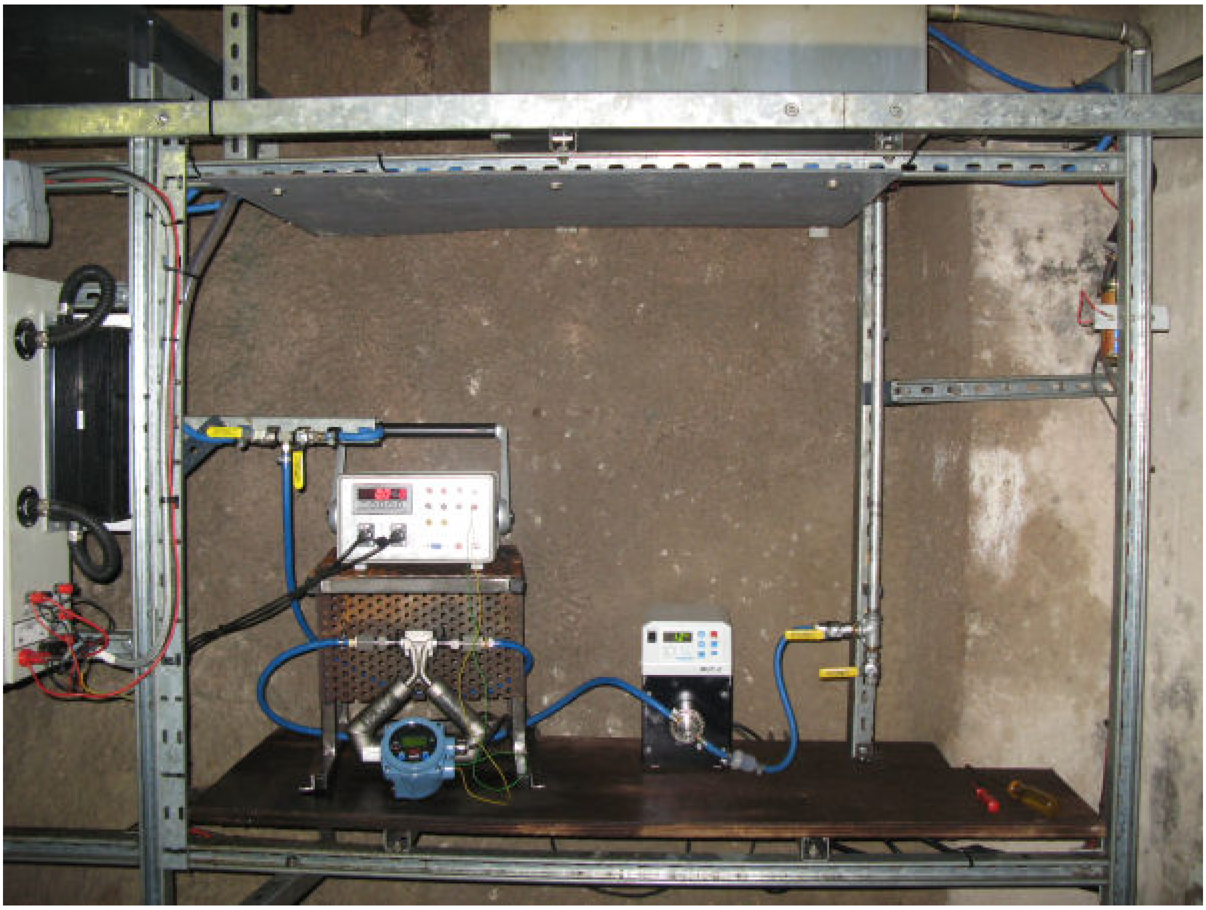


Figure 12: A meter (Emerson CMF025M – Micromotion Elite) under test

Since there is some uncertainty as to what the true value of the constants used in the calibration of the Floscan system are, it was decided that all of the "Full Scale" frequency or signal level results should be linearly regressed against the instantaneous estimated flow rate derived from the mass balance measurements at identical time signatures, thus providing a new gain and offset to apply to the raw data. Since all devices (bar the VKM) responded somewhat linearly, this should improve the accuracy of the devices over the full scale.

This process indicates how accurate each of the devices 'could' be, given accurate calibration constants, and obviously does not reflect an "out-of-the-box" accuracy – which is suspected to be of equal or greater importance to skippers.

For these reasons, in the results sections that follow, the results are firstly reported for an "out-of-the-box" condition and then reported after the flow meter calibration indicated above.

Description of test result sheets

The cumulative volumes are the final values of the datasets plotted against time to calculate flow rate for the dynamometer arm and transducer respectively.

The inaccuracy in indicated flow rate as a percentage of the measured flow rate is calculated by the following:

$$= \frac{Q_{indicated} - Q_{measured}}{Q_{measured}} \cdot 100\%$$

The inaccuracy in indicated flow rate as a percentage of the full scale flow rate is calculated by the following:

$$= \frac{Q_{indicated} - Q_{measured}}{Q_{\max}} \cdot 100\%$$

The inaccuracy in cumulative volume as a percentage of the measured volume is calculated by the following:

$$= \frac{V_{indicated} - V_{measured}}{V_{measured}} \cdot 100\%$$

The inaccuracy in cumulative volume as a percentage of the full scale flow rate is calculated by the following:

$$= \frac{V_{indicated} - V_{measured}}{Q_{\max} * \Delta T_{total}} \cdot 100\%$$

The variance of the indicated and measured flow is given by:

$$\sigma^2 = (\sqrt{N} S_E)^2$$

where N is the number of observations and S_E is the standard error of the data against the regression analysis for the indicated and measured data respectively.

The graphs following these tables indicate the accuracy of the flow meter, and the linearity of its response.

The graph on the left describes the indicated flow versus the measured flow rate, and in the ideal case should form a straight, 45 – degree line from the origin, displaying a perfect 1:1 ratio between indicated and measured values. Any deviation in gradient indicates imperfect calibration, and any deviation from the linear fit line indicates a non-linear response of the transducer, which is to say that a certain number of pulses at one flow rate may not indicate the same amount of passed fuel as at another flow rate, or similarly for the analog outputs.

The graph on the right describes the inaccuracies of indicated flow rate against measured flow rate. If a meter describes itself as having a constant error of, say, 0.5% of its full scale, then this manifests itself as a series of values between two straight, horizontal lines at ±0.5% for the inaccuracy versus full scale graph, and a curved (1/x) graph for the inaccuracy versus measured flow, with inaccuracy increasing at lower flow rates.

If a meter describes itself as having a constant error as a percentage of measured flow rate, then we would expect the inaccuracy versus measured flow to be within two horizontal lines, and the inaccuracy versus full scale to increase with increasing flow rate.

For a turbine-type meter, the typical response curve is to heavily under-read, followed by a short section of over-reading where, with sufficient electronic calibration, it is acceptable to take readings, followed by a linear section where inaccuracy versus measured flow is constant. This is the most accurate range of flow-rates for the transducer, and is where most turbine-type flow meters operate.

Macnaught M1

Figure 13: Macnaught M1

Device Description

The Macnaught M1 is an oval gear positive displacement meter, one of a range of devices that should provide a suitable meter size for almost any large diesel engine. The principle of operation is outlined in the Phase 1 report. One of the gears contains a permanent magnet, which in the case of our meter, closes a reed switch every time the gear revolves once. Other devices in the series use Hall Effect Sensor pickups, which would require a permanent excitation voltage to be provided. The reed switch system is marginally simpler, requiring just two wires and virtually any DC power supply, but due to use of moving parts in the switch, shall eventually wear, and there is a risk of taking multiple counts if debounce precautions are not taken.

By the nature of their design, positive displacement meters are highly linear over their operating range, and are generally accurate. In a working environment, entrained gases must be considered, since they produce large over-read errors, and any particulates in the fluid must be removed, to reduce wear on the moving parts and reduce risk of blockage. If the device does become jammed, there is no alternative fuel flow route, so a bypass must be installed. For the M1 model, one pulse represents 1.00ml of fluid passing through the meter, and so, at its maximum flow rate of 100 l/hr, a frequency of 27.8Hz would be expected, and at its minimum flow rate of 2 l/hr, the frequency would be 0.556 Hz.

Test Set-up

The device was connected to the CSM Flow-Meter test facility with connections as follows:

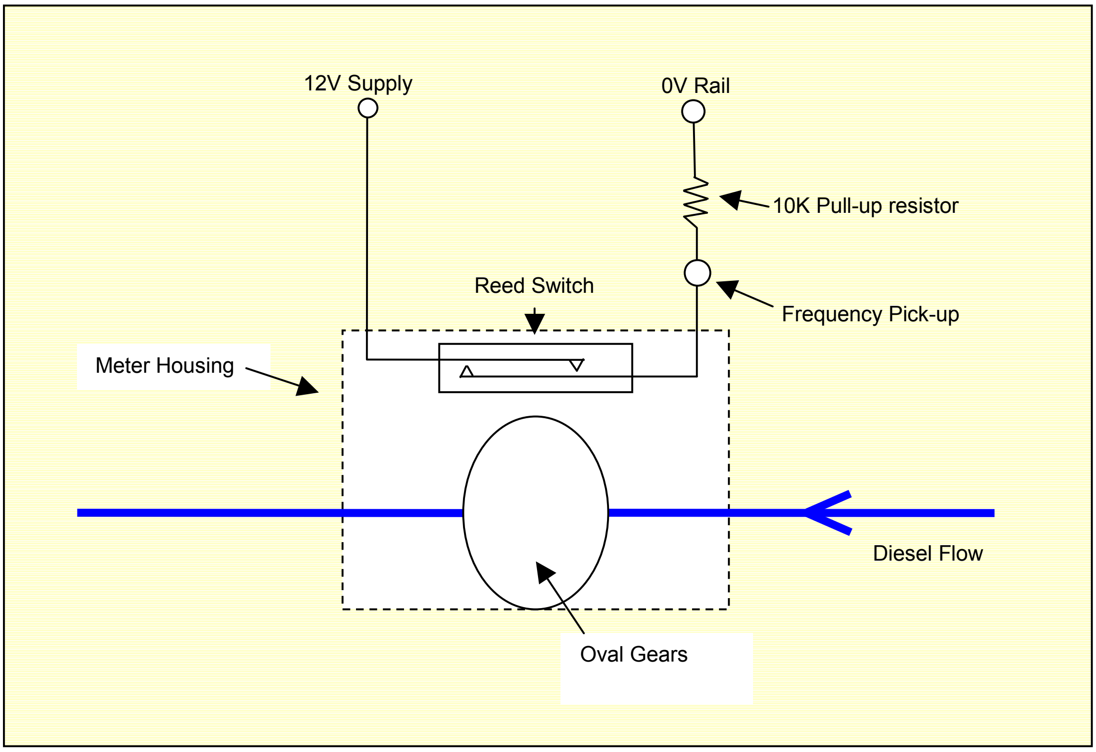


Figure 14: Test set-up for Macnaught M1

The frequency pick-up of the DataTrack 284 was ranged so that 0Hz was represented by a 0V signal, and 100Hz by a 10V signal. As described previously, this entails a maximum error of 0.07Hz, or 0.252 l/hr, in logging the indicated value, plus a further 0.05 Hz due to the resolution of the instrument, incurring a maximum possible error of 0.432 l/hr.

The following test points were chosen for five minute, “full scale” runs. The purpose of these runs was to establish how closely the model followed its specifications.

Pump Speed	Expected Flow Rate
RPM	l/hr
285	20.0
570	40.0
855	60.0
1140	80.0
1425	100.0
427	30.0

The final test point was not initially required, but was run due to a miscommunication in setting up a test run, and the data was retained as giving us a clearer picture of the device's behaviour.

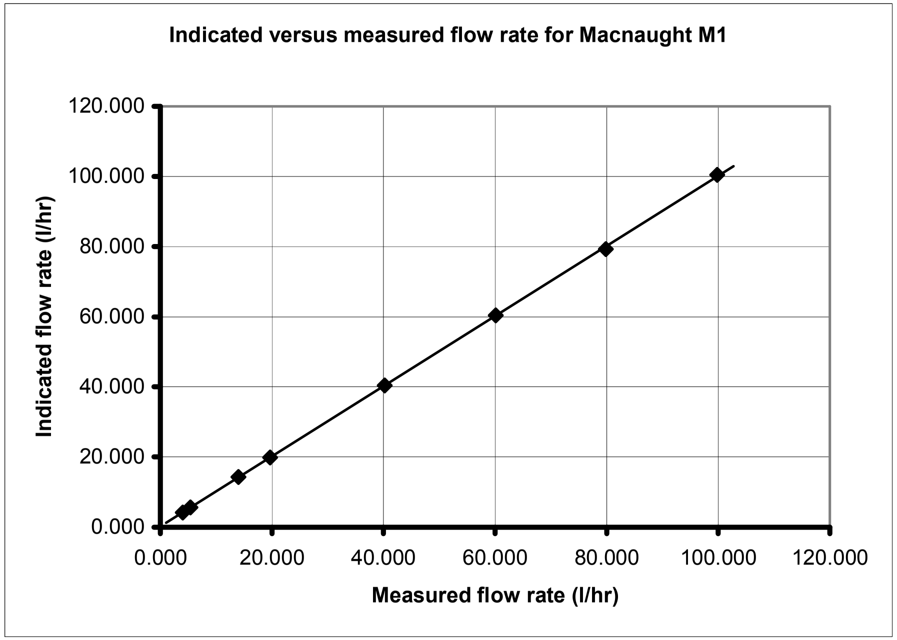
Three "Engine Speed", fifteen-minute long test runs were also chosen, corresponding as neatly as possible with flow rates that would be produced in Phase III, so that direct comparison could be attempted. Respectively, they represent the lowest flow rate possible with our pump – similar to our engine's "cruise and shoot" fuel consumption; our engine's "Steaming" condition; and our engine's "Trawling" condition.

Pump Speed	Expected Flow Rate
RPM	l/hr
60	4.2
83	5.8
198	13.9

Table 6: “Out-of-the-box” performance of the Macnaught M1 fuel flow meter – first set

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.031	4.205	1.006	1.051
83	5.8	5.363	5.612	1.342	1.403
198	13.9	14.040	14.315	3.510	3.578
285	20.0	19.654	19.878	1.639	1.657
570	40.0	40.200	40.427	3.294	3.308
855	60.0	60.132	60.402	5.012	5.033
1140	80.0	79.872	79.286	6.657	6.616
1425	100.0	99.784	100.398	8.316	8.359

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
4.31	0.17	4.46	0.18	0.00460	0.02694
4.66	0.25	4.57	0.25	0.00284	0.01059
1.96	0.27	1.93	0.27	0.00651	0.02020
1.14	0.22	1.07	0.21	0.02894	0.06414
0.56	0.23	0.42	0.17	0.02749	0.10542
0.45	0.27	0.43	0.26	0.04609	0.16395
-0.73	-0.59	-0.61	-0.49	0.43874	0.20992
0.61	0.61	0.53	0.52	0.17708	0.26174



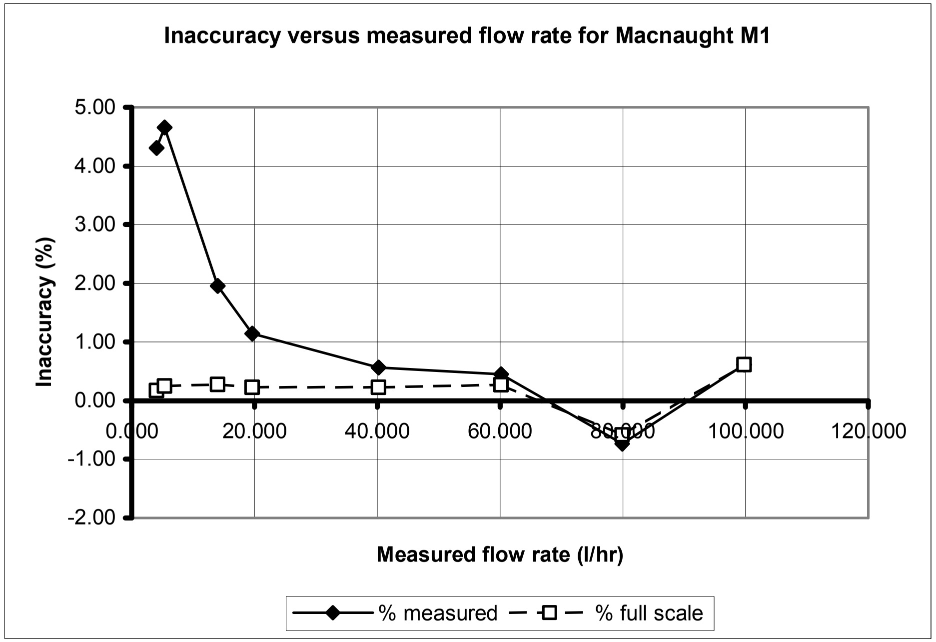


Table 7: Performance of the Macnaught M1 fuel flow meter after device calibration – first set

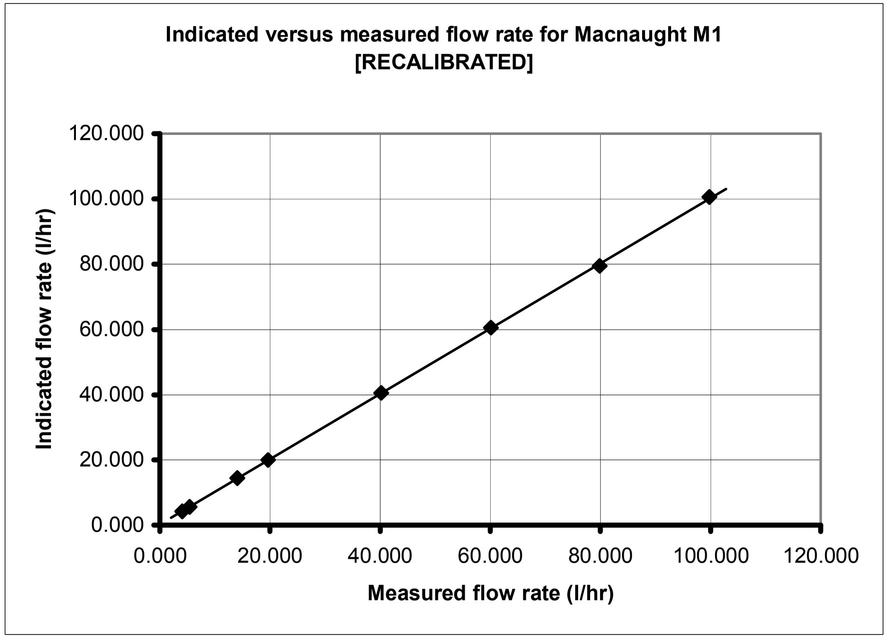
RECALIBRATED

Phase 2 Summary

Macnaught M1

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.031	4.257	1.006	1.064
83	5.8	5.363	5.666	1.342	1.417
198	13.9	14.040	14.380	3.510	3.594
285	20.0	19.654	19.951	1.639	1.663
570	40.0	40.200	40.526	3.294	3.316
855	60.0	60.132	60.529	5.012	5.044
1140	80.0	79.883	79.433	6.658	6.632
1425	100.0	99.784	100.577	8.316	8.374

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
5.60	0.23	5.75	0.23	0.00461	0.02694
5.66	0.30	5.58	0.30	0.00284	0.01059
2.42	0.34	2.40	0.34	0.00652	0.02020
1.51	0.30	1.44	0.28	0.02898	0.06414
0.81	0.33	0.67	0.27	0.02753	0.10542
0.66	0.40	0.64	0.39	0.04615	0.16395
-0.56	-0.45	-0.40	-0.32	0.43668	0.20956
0.79	0.79	0.70	0.70	0.17732	0.26174



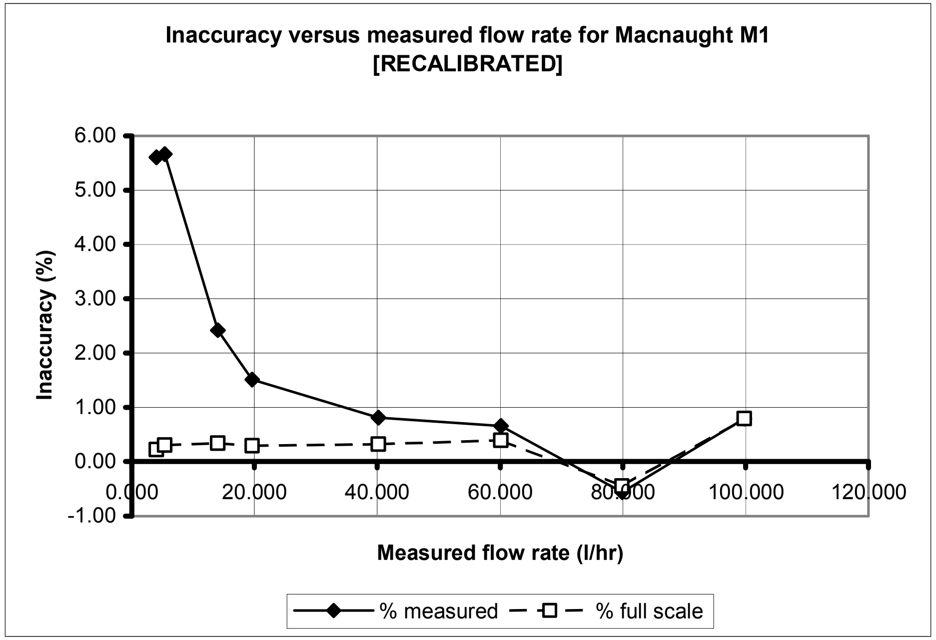


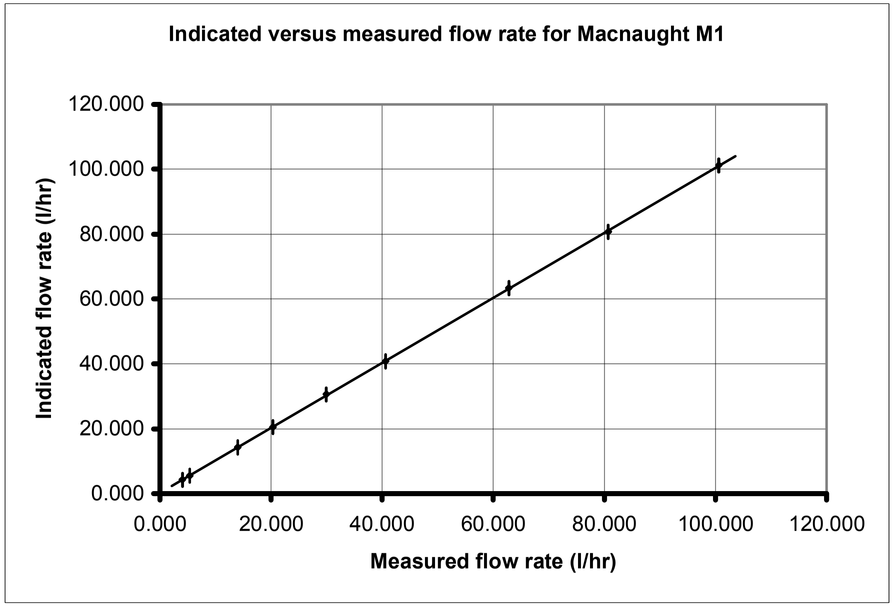
Table 8: “Out-of-the-box” performance of the Macnaught M1 fuel flow meter – second set

Phase 2 Summary

Macnaught M1

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.088	4.316	1.018	1.076
83	5.8	5.363	5.612	1.342	1.403
198	13.9	14.040	14.315	3.510	3.578
285	20.0	20.363	20.578	1.697	1.715
427	30.0	29.947	30.658	2.457	2.513
570	40.0	40.610	40.857	3.381	3.403
855	60.0	62.808	63.386	5.214	5.267
1140	80.0	80.687	80.754	6.721	6.726
1425	100.0	100.612	101.180	8.362	8.404

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
5.58	0.23	5.67	0.23	0.00796	0.02320
4.66	0.25	4.57	0.25	0.00284	0.01059
1.96	0.27	1.93	0.27	0.00651	0.02020
1.06	0.22	1.05	0.21	0.01199	0.05756
2.37	0.71	2.28	0.68	0.01523	0.11564
0.61	0.25	0.67	0.27	0.04856	0.12890
0.92	0.58	1.02	0.64	0.19283	0.18850
0.08	0.07	0.07	0.06	0.08601	0.21321
0.56	0.57	0.51	0.51	0.18721	0.27414



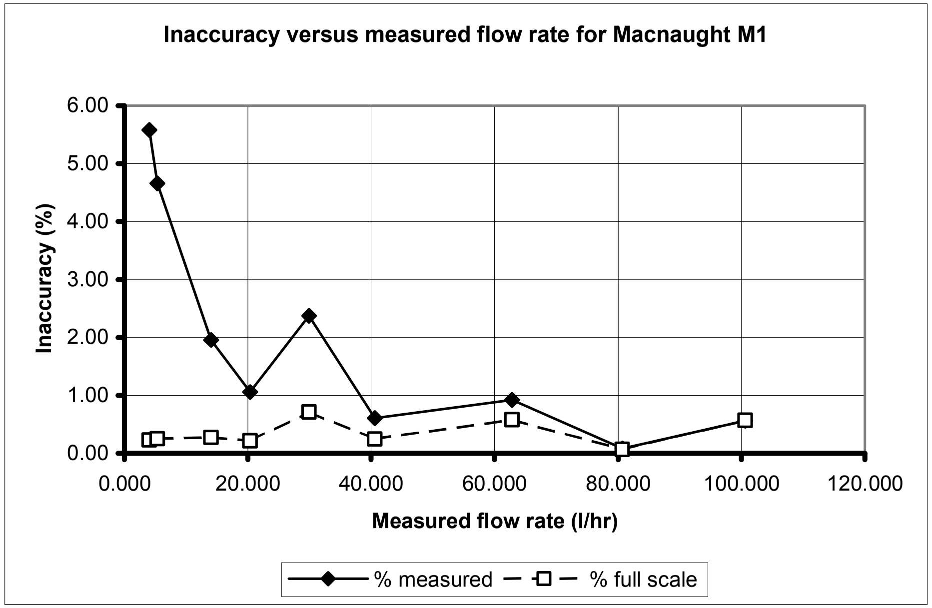


Table 9: Performance of the Macnaught M1 fuel flow meter after device calibration – second set

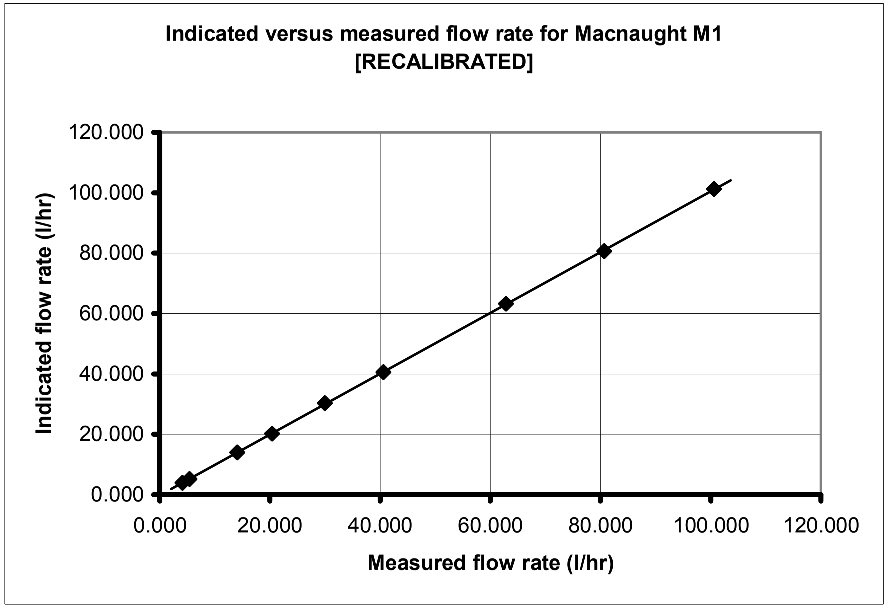
RECALIBRATED

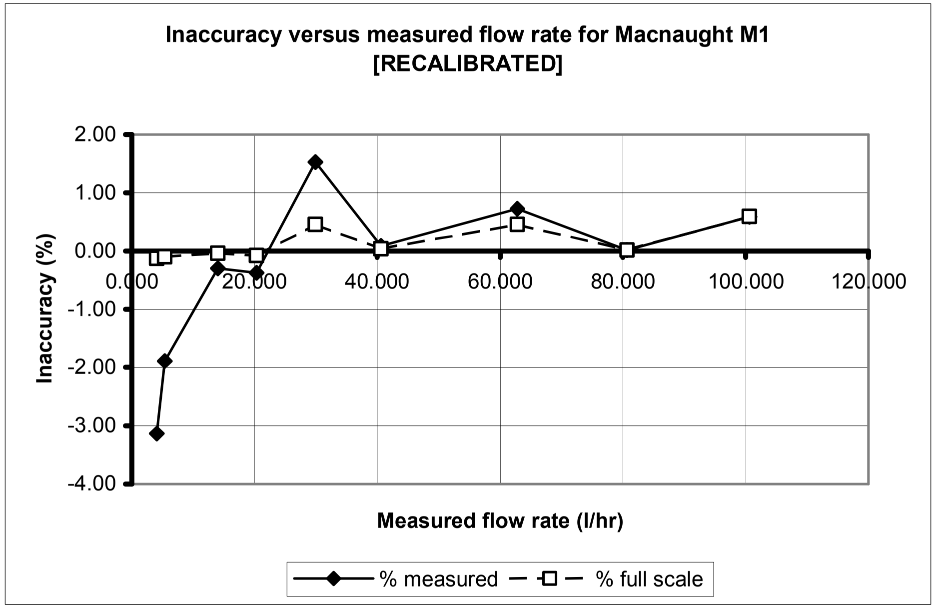
Phase 2 Summary

Macnaught M1

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.088	3.960	1.018	0.987
83	5.8	5.363	5.261	1.342	1.316
198	13.9	14.040	13.998	3.510	3.499
285	20.0	20.363	20.286	1.697	1.690
427	30.0	29.947	30.405	2.457	2.492
570	40.0	40.610	40.645	3.381	3.386
855	60.0	62.808	63.263	5.214	5.257
1140	80.0	80.687	80.700	6.721	6.722
1425	100.0	100.612	101.206	8.362	8.406

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
-3.13	-0.13	-3.07	-0.13	0.00799	0.02320
-1.89	-0.10	-1.97	-0.11	0.00285	0.01059
-0.30	-0.04	-0.33	-0.05	0.00653	0.02020
-0.38	-0.08	-0.39	-0.08	0.01204	0.05756
1.53	0.46	1.44	0.43	0.01529	0.11564
0.09	0.04	0.15	0.06	0.04875	0.12890
0.73	0.46	0.83	0.52	0.19360	0.18850
0.02	0.01	0.01	0.01	0.08635	0.21321
0.59	0.59	0.53	0.53	0.18795	0.27414





Discussion

The results clearly show that the Macnaught M1 behaves in a highly linear manner, and performs almost entirely within specification, which is to say that it is accurate to within 0.5% of its full scale deflection. Very notably, there is no inaccuracy that could not be accounted for by the error within our logging system. Variance is generally low, but there are a couple of outliers that are entirely unexpected.

OVAL MIII Flowmate

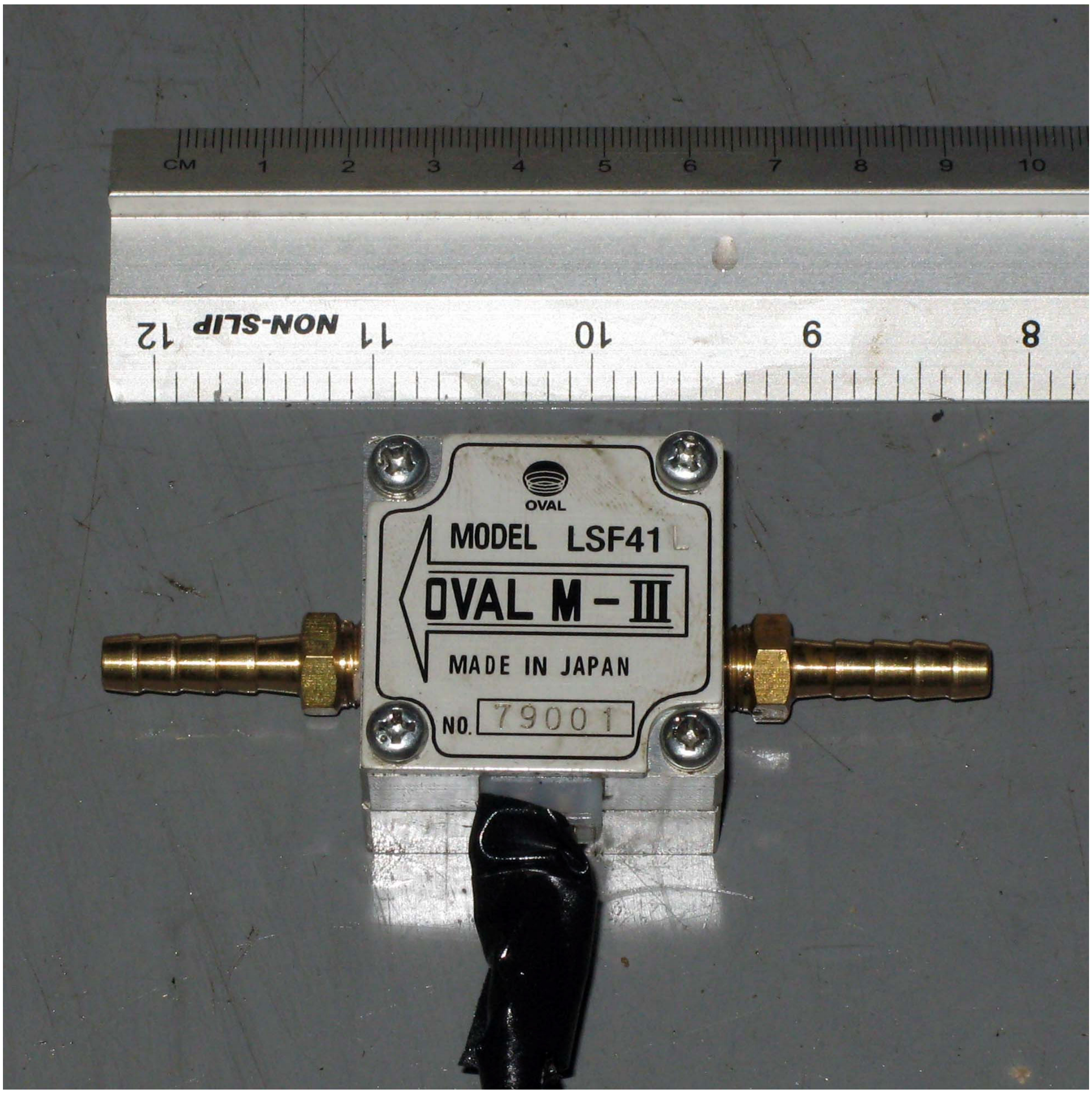


Figure 15: Oval MIII Flowmate

Device Description

The Oval M-III LSF41 Flowmate is, in working principle and construction, virtually identical to the Macnaught M1, and similar in price. It was chosen to reflect the prevalence of these types of flow transducers in the fuel flow measurement market. Again, this range contains models suitable for most engine sizes. Physically, it is the smallest of the tested meters, and installation is as simple as the Macnaught.

Test Set-Up

As Macnaught M1

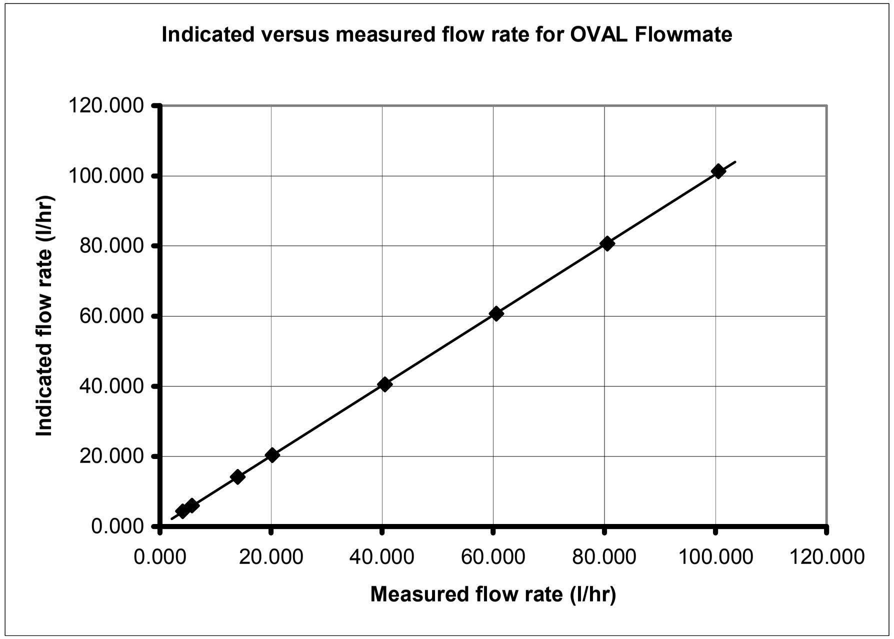
Table 10: “Out-of-the-box” performance of the Oval MIII Flowmate fuel flow meter

Phase 2 Summary

OVAL Flowmate

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.119	4.307	1.030	1.076
83	5.8	5.795	5.969	1.450	1.492
198	13.9	13.987	14.094	3.498	3.522
285	20.0	20.221	20.365	1.686	1.697
570	40.0	40.513	40.504	3.374	3.376
855	60.0	60.579	60.705	5.049	5.053
1140	80.0	80.543	80.634	6.713	6.723
1425	100.0	100.529	101.296	8.378	8.438

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
4.57	0.19	4.47	0.18	0.00540	0.01258
3.00	0.17	2.85	0.17	0.00255	0.01306
0.76	0.11	0.71	0.10	0.00676	0.02070
0.71	0.14	0.65	0.13	0.01160	0.08130
-0.02	-0.01	0.07	0.03	0.02236	0.10888
0.21	0.13	0.07	0.04	0.07016	0.16526
0.11	0.09	0.16	0.13	0.09418	0.21669
0.76	0.77	0.72	0.73	0.16689	0.26232



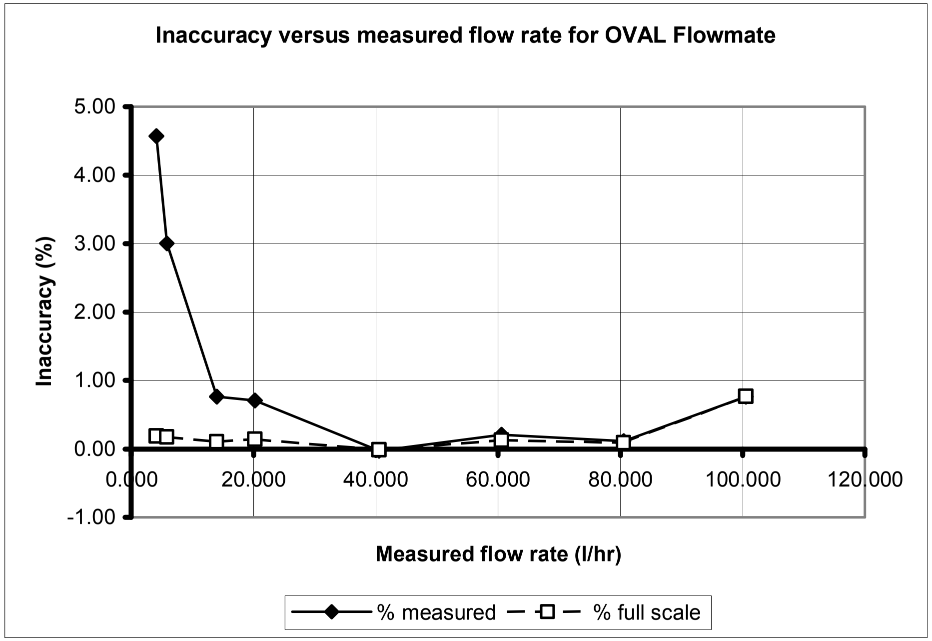


Table 11: Performance of the Oval Flowmate fuel flow meter after device calibration

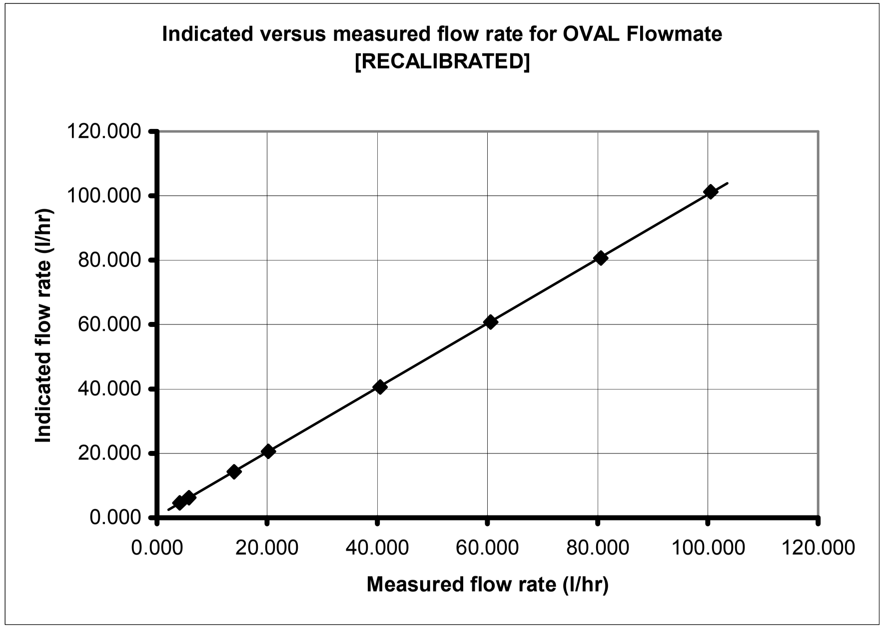
RECALIBRATED

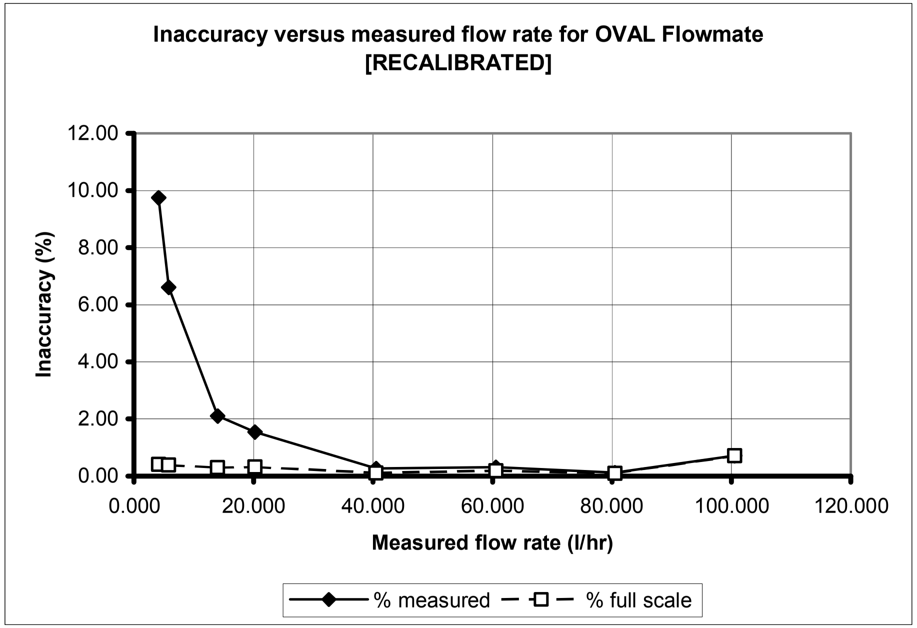
Phase 2 Summary

OVAL Flowmate

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.119	4.520	1.030	1.130
83	5.8	5.795	6.177	1.450	1.544
198	13.9	13.987	14.281	3.498	3.569
285	20.0	20.221	20.534	1.686	1.711
570	40.0	40.513	40.617	3.374	3.386
855	60.0	60.579	60.764	5.049	5.058
1140	80.0	80.543	80.638	6.713	6.724
1425	100.0	100.529	101.243	8.378	8.434

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
9.75	0.40	9.64	0.40	0.00538	0.01258
6.60	0.38	6.44	0.37	0.00255	0.01306
2.10	0.29	2.04	0.29	0.00674	0.02070
1.55	0.31	1.48	0.30	0.01157	0.08130
0.26	0.10	0.35	0.14	0.02230	0.10888
0.31	0.19	0.17	0.10	0.06997	0.16526
0.12	0.09	0.16	0.13	0.09392	0.21669
0.71	0.71	0.67	0.67	0.16643	0.26232





Discussion

The results are similar to the Macnaught meter, and numerically superior, though it should be noted that the accuracy of our logging system is insufficient to comment definitively on the relative accuracy of these two transducers. The Oval Flowmate generally shows slightly higher variance, but has no real outliers. The variance of the two devices is of the same order, and, in general, there is little to distinguish between them at this stage. The Flowmate performed better than the manufacturer's specification of an inaccuracy less than 0.5% of full scale, with the exception of the final test point, where it slightly underperformed, possibly due to overspeed issues. It is interesting to note that both of these devices record high at low flow rates, which would not be expected of positive displacement meters and lends weight to the possibility that the logging system's uncertainty contributed a large amount to the inaccuracy of these readings.

Kobold DRZ

Figure 16: Kobold DRZ

Device Description

The Kobold DRZ is an oscillating piston positive displacement meter, built on the same principle as many water meters. Since it does not have geared teeth, and has fewer moving parts than the oval geared meters, it promises to be more robust, and provides an exceptional turn-down ratio, measuring flows between 6 and 420 l/hr. This is the only model in its range, but this scale should be sufficient for engines up to 2000hp, depending on the return ratio. The promised accuracy is 1% of measured flow. The piston drives a shaft with two magnets on it, which pass a Hall-Effect sensor that is driven by a 12-24V DC excitation voltage. The output is then amplified by a PNP transistor, and appears as a pulse at a rate of 468 pulses per litre, or 2.315 ml per pulse.

It should be noted that most of the engine scale tests are below the lowest quoted range for this device. Therefore, whilst the focus is on accuracy over its full scale in Phase II, in Phase III the main concern will be with change in behaviour than true accuracy.

An additional benefit that an oscillating piston meter promises over an oval gear meter is that, despite being positive displacement, according to the manufacturer, if the piston is stopped, there is still an open path for diesel to pass through. This shall be verified once the meters can be fully examined. However, as with all positive displacement meters, precautions must be made to avoid entrained gases and particulates in the flow, for the same reasons as dictated by the Macnaught M1.

Test Set-up

The device was connected to the CSM Fuel Flow testing rig with connections as follows:

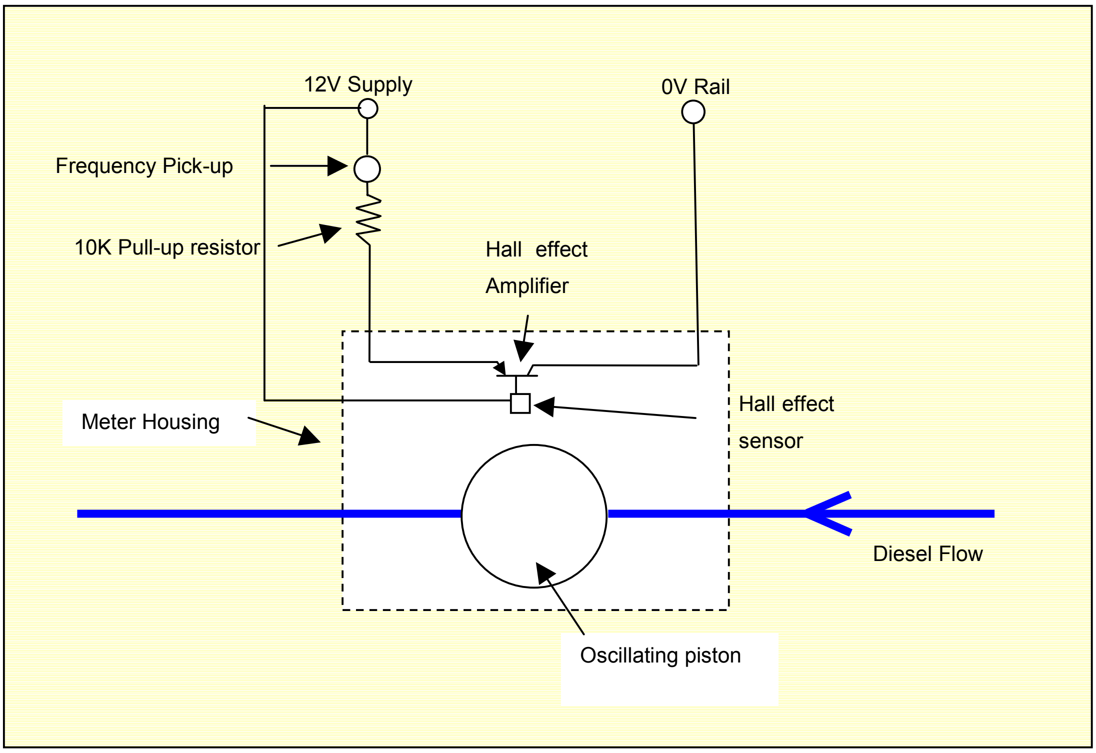


Figure 17: Test set-up for Kobold DRZ

The frequency pick-up of the DataTrack 284 was ranged so that 0Hz was represented by a 0V signal, and 100Hz by a 10V signal. As described previously, this entails a maximum error of 0.07Hz, or 0.583 l/hr, in logging the indicated value, plus a further 0.05 Hz due to the resolution of the instrument, incurring a maximum possible error of 1.00 l/hr.

The following test points were chosen for five minute, “full scale” runs. The purpose of these runs was to establish how closely the model followed its specifications.

Pump Speed	Expected Flow Rate
RPM	l/hr
1197	84.0
2393	168.0
3590	252.0
4786	336.0
5983	420.0

However, on running, it was discovered that the pump could not drive diesel through the meter at speeds greater than 4185 rpm (approximately 294 l/hr) without opening the pump's internal bypass valve. This will be discussed with more detail below. It suffices to say here that the test runs were curtailed at this value.

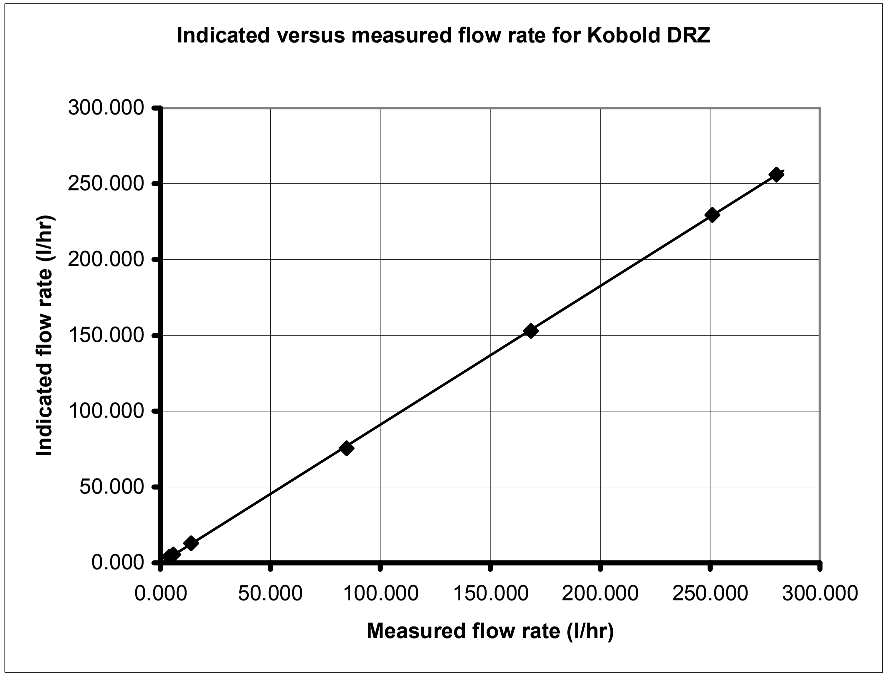
The "Engine Speed" runs were performed as for all other meters.

Table 12: “Out-of-the-box” performance of the Kobold DRZ fuel flow meter

Phase 2 Summary

KOBOLD DRZ

Test Point	RPM Estimated Flow rate	Balance Arm Measured Flow Rate	Meter Indicated Flow Rate	Balance Arm Measured Cumulative Volume	Meter Indicated Cumulative Volume	Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
rpm	l/hr	l/hr	l/hr	l	l	% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
60	4.2	4.139	4.075	1.033	1.019	-1.55	-0.02	-1.34	-0.01	0.00162	0.01413
83	5.8	5.802	5.550	1.449	1.387	-4.34	-0.06	-4.23	-0.06	0.00184	0.01799
198	13.9	14.001	12.765	3.504	3.189	-8.83	-0.29	-8.99	-0.30	0.00381	0.02584
1197	84.0	84.765	75.479	7.064	6.287	-10.96	-2.21	-11.00	-2.22	0.05174	0.22255
2393	168.0	168.484	152.994	13.806	12.531	-9.19	-3.69	-9.23	-3.70	0.52073	0.43578
3590	252.0	250.987	229.454	20.897	19.121	-8.58	-5.13	-8.50	-5.07	0.77051	0.63934
4134	290.2	280.225	256.033	23.314	21.332	-8.63	-5.76	-8.50	-5.66	1.03404	1.26564



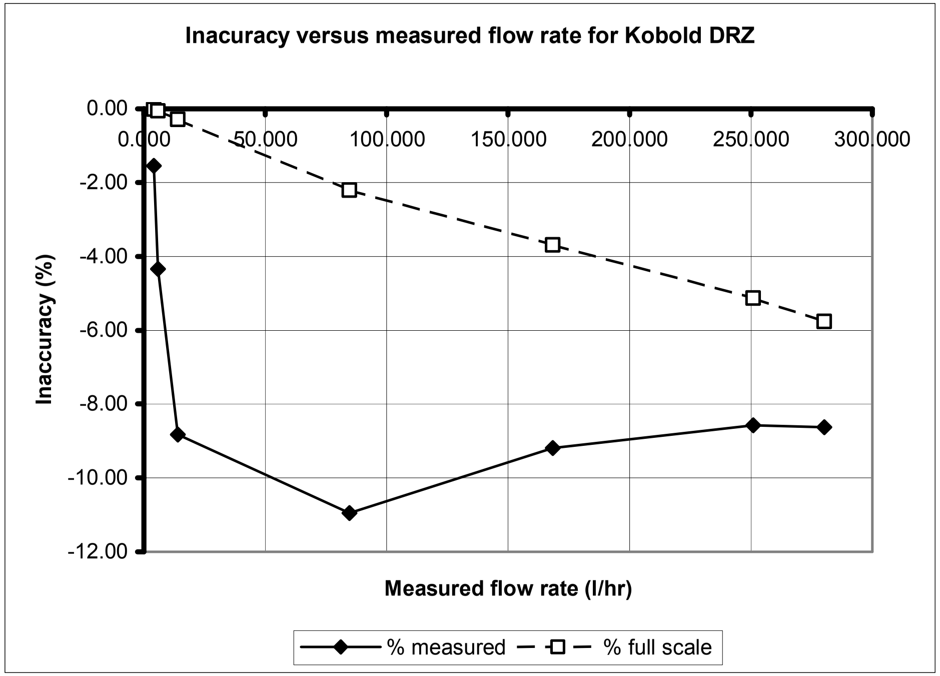


Table 13: Performance of the Kobold DRZ fuel flow meter after device calibration

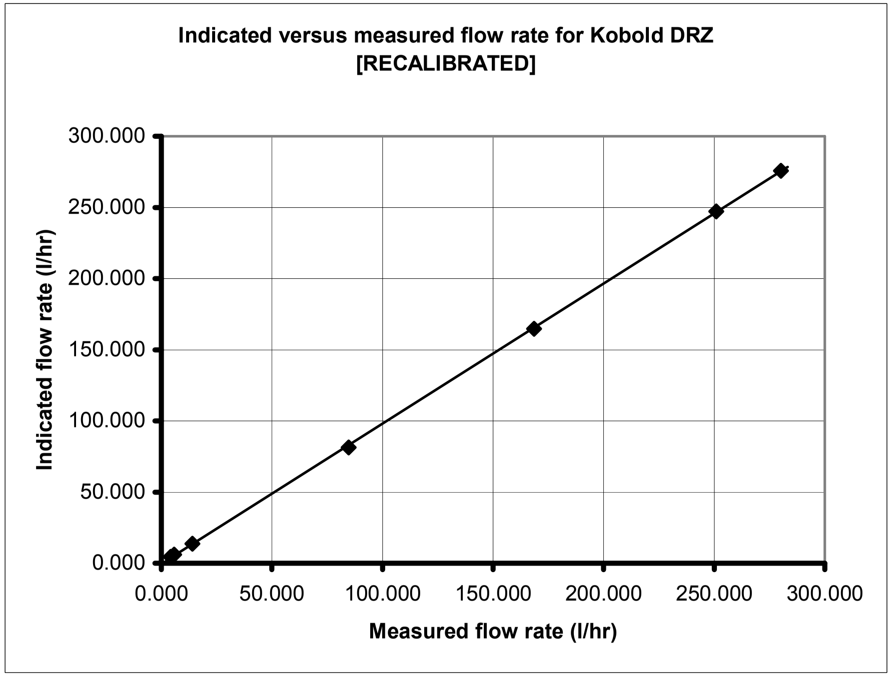
CALIBRATED

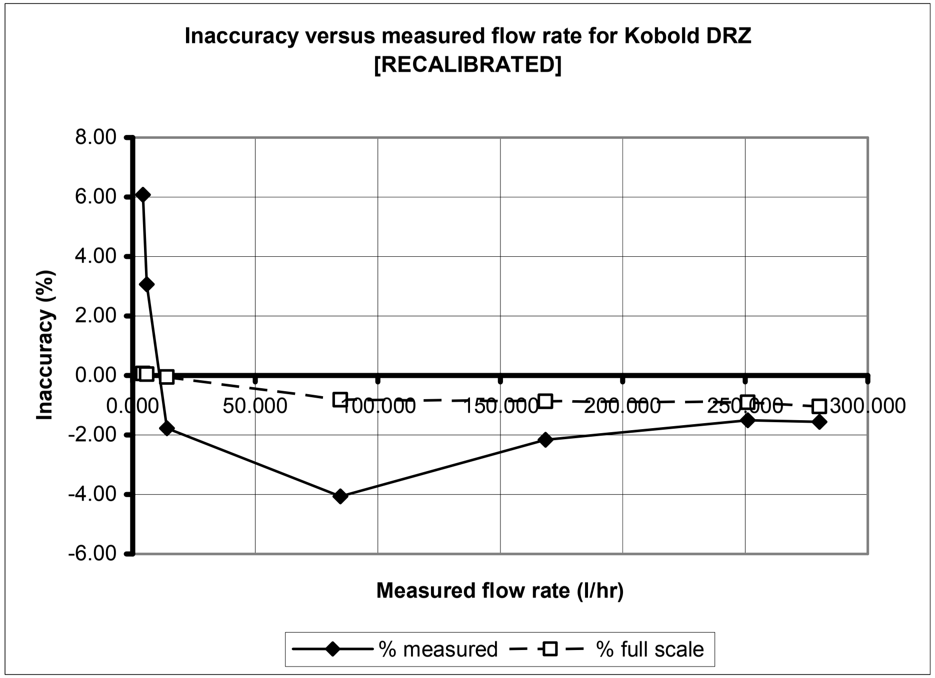
Phase 2 Summary

KOBOLD DRZ

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.139	4.391	1.033	1.098
83	5.8	5.802	5.980	1.449	1.495
198	13.9	14.001	13.753	3.504	3.435
1197	84.0	84.765	81.319	7.064	6.773
2393	168.0	168.470	164.831	13.806	13.501
3590	252.0	250.987	247.207	20.897	20.601
4134	290.2	280.225	275.842	23.314	22.982

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
6.07	0.06	6.29	0.06	0.00175	0.01413
3.06	0.04	3.18	0.04	0.00198	0.01799
-1.77	-0.06	-1.95	-0.07	0.00411	0.02584
-4.07	-0.82	-4.11	-0.83	0.05574	0.22255
-2.16	-0.87	-2.21	-0.89	0.56102	0.43578
-1.51	-0.90	-1.42	-0.85	0.83012	0.63934
-1.56	-1.04	-1.42	-0.95	1.11404	1.26564





Discussion

The Kobold DRZ, in general, provided a linear response to flow rate. However, it did not perform to specification – the average error was almost 9% of reading, rather than 1%, with the error increasing with increasing flow rate. The manufacturers, on consultation, were puzzled by this behaviour, and suggested that it might be caused by the low duty cycle of the waveform generated by the Hall Effect sensor, where at high frequencies the frequency-to-voltage conversion unit in the RTU might not be counting every pulse. However, on observing the waveform on an oscilloscope, it was revealed that the duty cycle is almost 50%. The manufacturer insisted that their calibration coefficient was correct in current installations, so this was unlikely to be the cause of the errors. Investigations into the underperformance of this device continue.

Also of note is the fact that at high flow rates, the back-pressure generated by the device was high enough to open the bypass valve in the pump head and prevent any further pumping. This valve was set to open at approximately 3 bar, and due to the swan-neck arrangement, there is very little initial reverse pressure in the system. For obvious reasons, a suction pump cannot overcome a pressure of more than 1 bar, and the loading that this device might put on a lifting pump at high flow rates on a larger engine might impair the engine’s operation. It did not noticeably affect our engine’s performance in Phase III due to the relatively low flow rates used, but this is something to consider for practical deployment.

Kobold VKM

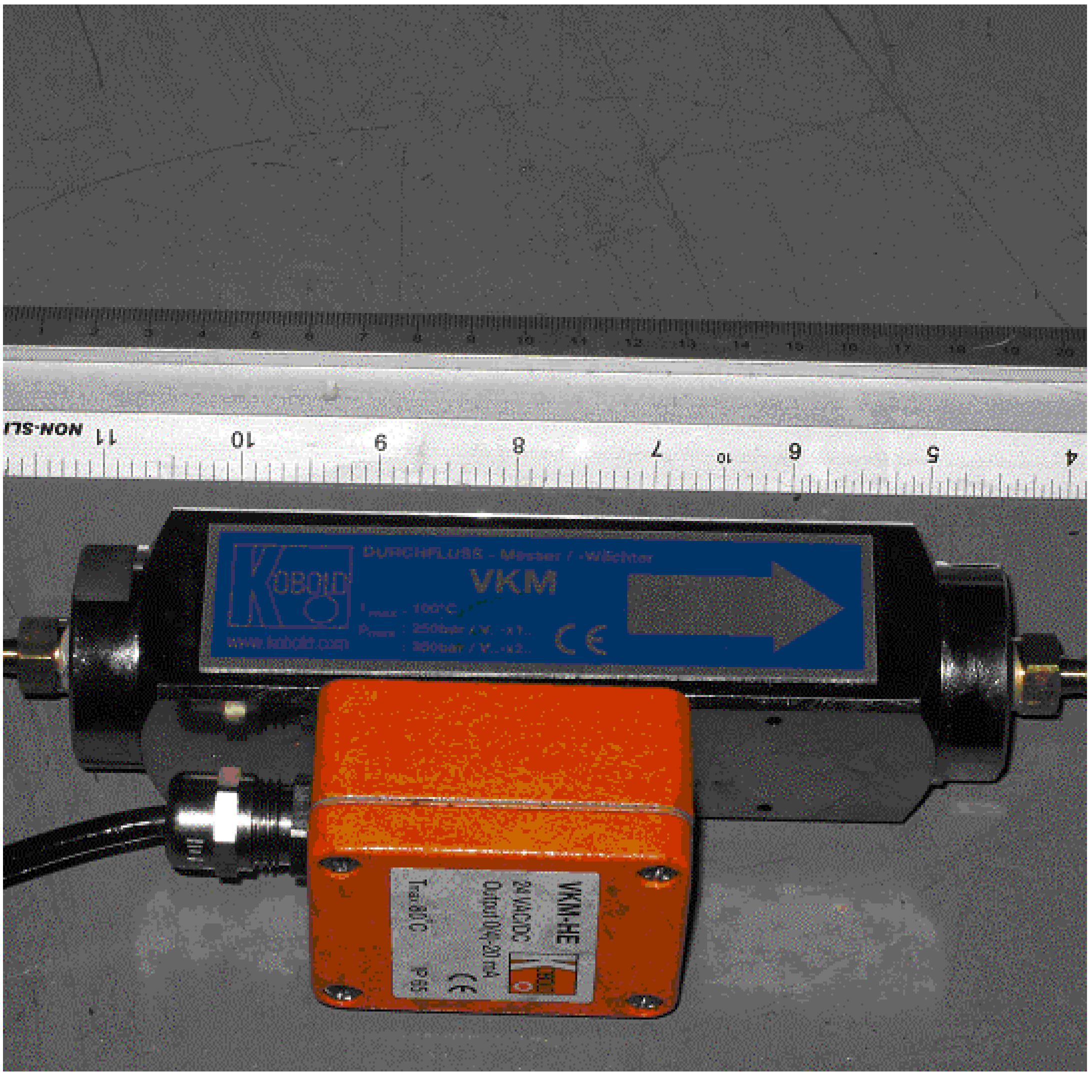


Figure 18: Kobold VKM

Device Description

The Kobold VKM is a variable aperture meter, as defined in the Phase I report. Its "float" is spring driven, so the device does not have to be maintained in an upright condition. The float consists of an orifice plate attached to a magnet, and so even when the device is fully closed there is still a pathway for fluid to pass. The magnet drives a Hall Effect Sensor, which is then amplified such that it provides a 4 – 20mA signal over the flow range of the device. The device tested was quoted as responding over the range 12 – 66 l/hr, which is fairly small, and, like the DRZ, doesn't include most of the our engine test points. Change in behaviour was more important to observe on engine test points, whilst the accuracy could be assessed over the "full scale" test points.

The variable aperture meter was chosen to test due to its simplicity and reliability, providing a clear flow path even when damaged, unaffected by small particulates, and not responsive to entrained gases. The quoted accuracy of 3% would be unacceptable for fuel totalisation, but for indication, might be sufficient.

The VKM required a power supply of 24V AC or DC ±10%, and so was connected to the engine battery. Physically, it is a heavy and solid device, one of the largest and most massive tested. Unlike the oval gear meters, which could sit easily in-line, this would require mounting somewhere in the engine room.

Test set-up

The device was connected to the CSM Fuel Flow test rig with connections as follows:

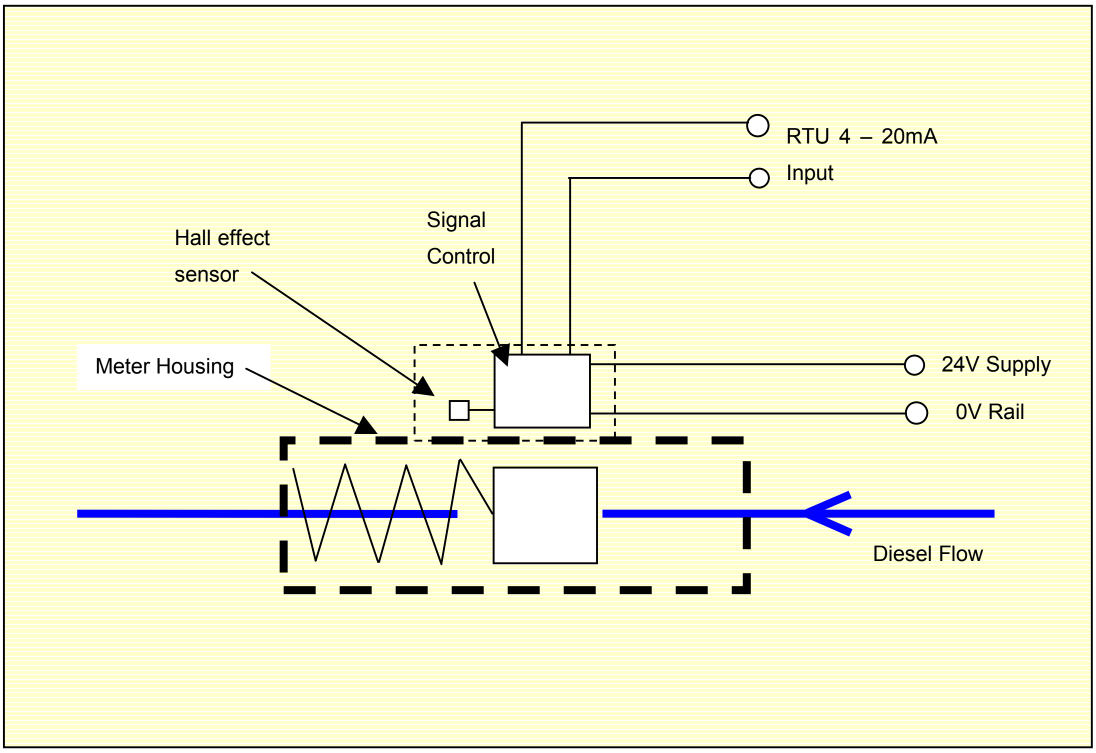


Figure 19: Test set-up for Kobold VKM

The CP SCADA system was calibrated as detailed above, and it was taken that the 4 – 20mA range would be distributed linearly across the flow rate range, thus 4mA = 12 l/hr, 20mA = 66 l/hr. The error incurred in logging therefore would not exceed 2.96 ml/hr.

The following test points were chosen for five minute, “full scale” runs. The purpose of these runs was to establish how closely the model followed its specifications.

Pump Speed	Expected Flow Rate
RPM	l/hr
214	15.0
427	30.0
641	45.0
940	66.0

The same “Engine Scale” tests were run as for all other meters.

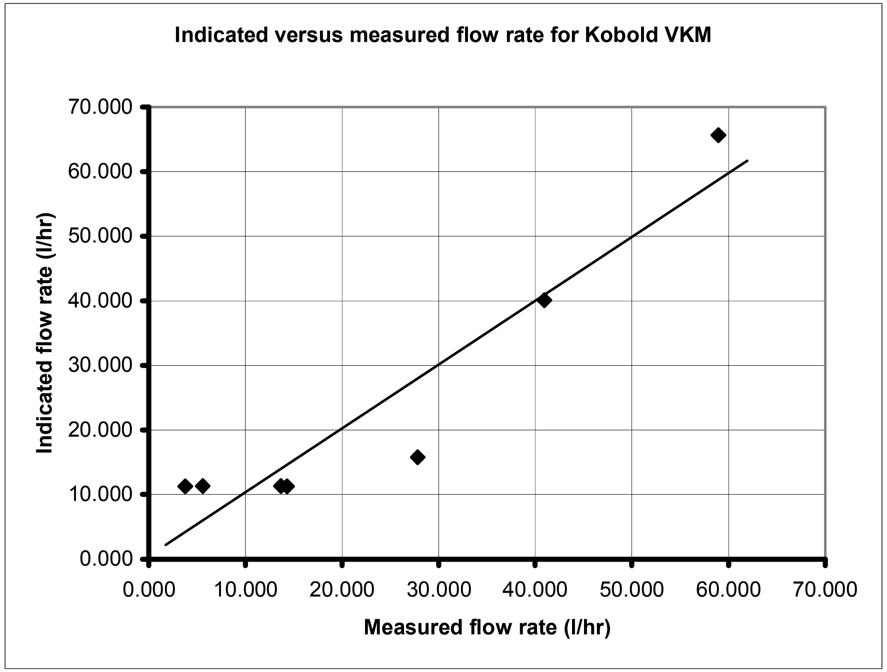
Table 14: "Out-of-the-box" performance of the Kobold VKM fuel flow meter

Phase 2 Summary

KOBOLD VKM

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	3.764	11.276	0.942	2.819
83	5.8	5.580	11.287	1.242	2.508
198	13.9	13.670	11.291	3.417	2.823
214	15.0	14.314	11.262	1.196	0.938
427	30.0	27.824	15.786	2.280	1.288
641	45.0	40.936	40.083	3.410	3.337
940	66.0	58.940	65.647	4.916	5.470

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
199.61	11.38	199.07	11.37	0.00201	0.01114
102.28	8.65	101.97	8.64	0.01084	0.02636
-17.40	-3.60	-17.39	-3.60	0.00968	0.02828
-21.32	-4.62	-21.51	-4.68	0.00698	0.03638
-43.27	-18.24	-43.52	-18.37	0.11615	0.07142
-2.08	-1.29	-2.12	-1.32	0.03718	0.10562
11.38	10.16	11.27	10.08	0.00491	0.15566



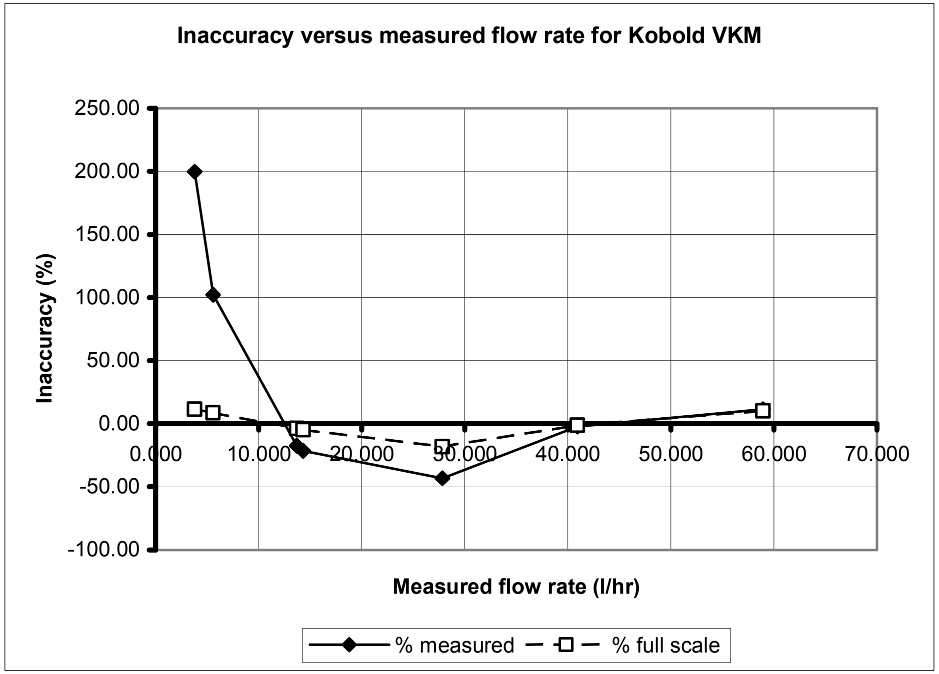


Table 15: Performance of the Kobold VKM fuel flow meter after device calibration

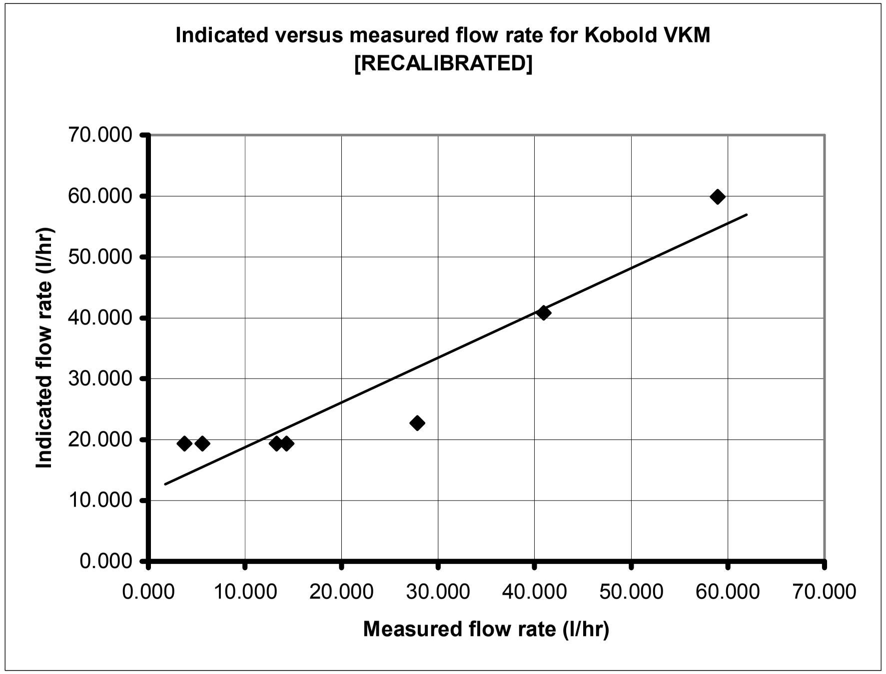
RECALIBRATED

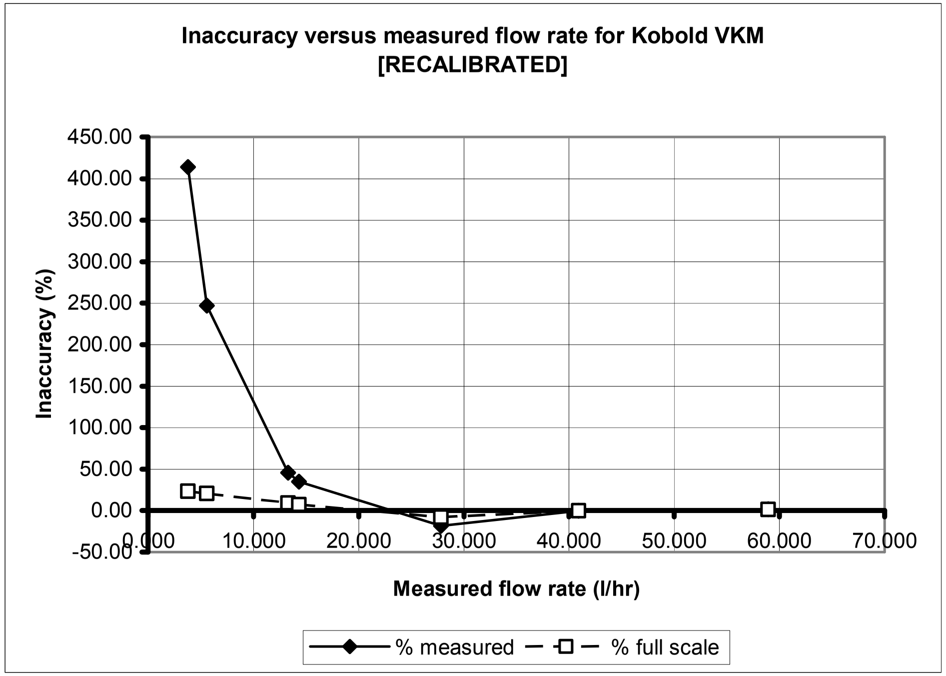
Phase 2 Summary

KOBOLD VKM

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	3.764	19.351	0.942	4.837
83	5.8	5.580	19.359	1.242	4.302
198	13.9	13.292	19.362	3.323	4.841
214	15.0	14.314	19.340	1.196	1.612
427	30.0	27.826	22.710	2.280	1.855
641	45.0	40.936	40.810	3.410	3.399
940	66.0	58.940	59.853	4.916	4.988

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
414.12	23.62	413.27	23.61	0.00150	0.01114
246.91	20.88	246.40	20.88	0.01851	0.02636
45.66	9.20	45.67	9.20	0.01652	0.02533
35.12	7.62	34.80	7.56	0.00520	0.03638
-18.39	-7.75	-18.62	-7.86	0.08652	0.07142
-0.31	-0.19	-0.33	-0.20	0.02770	0.10562
1.55	1.38	1.45	1.30	0.00366	0.15566





Discussion

Clearly, the VKM's response is highly nonlinear. This was expected at the low flow rates – however, at the flow rate that the device was supposed to begin operation (12 l/hr), there is no indication of flow. On correspondence with the manufacturer, it was revealed that the device has a large amount of "stiction" inherent. The accuracy, therefore, is compromised, but it is noted that the variance of the device is low, and it is claimed by the manufacturer that the repeatability of the observations is good, though their linearity is poor.

Due to the unresponsiveness of this device at the engine flow rates, and its poor accuracy, it shall not be taken through to Phase III testing.

Floscan Cruisemaster 65000

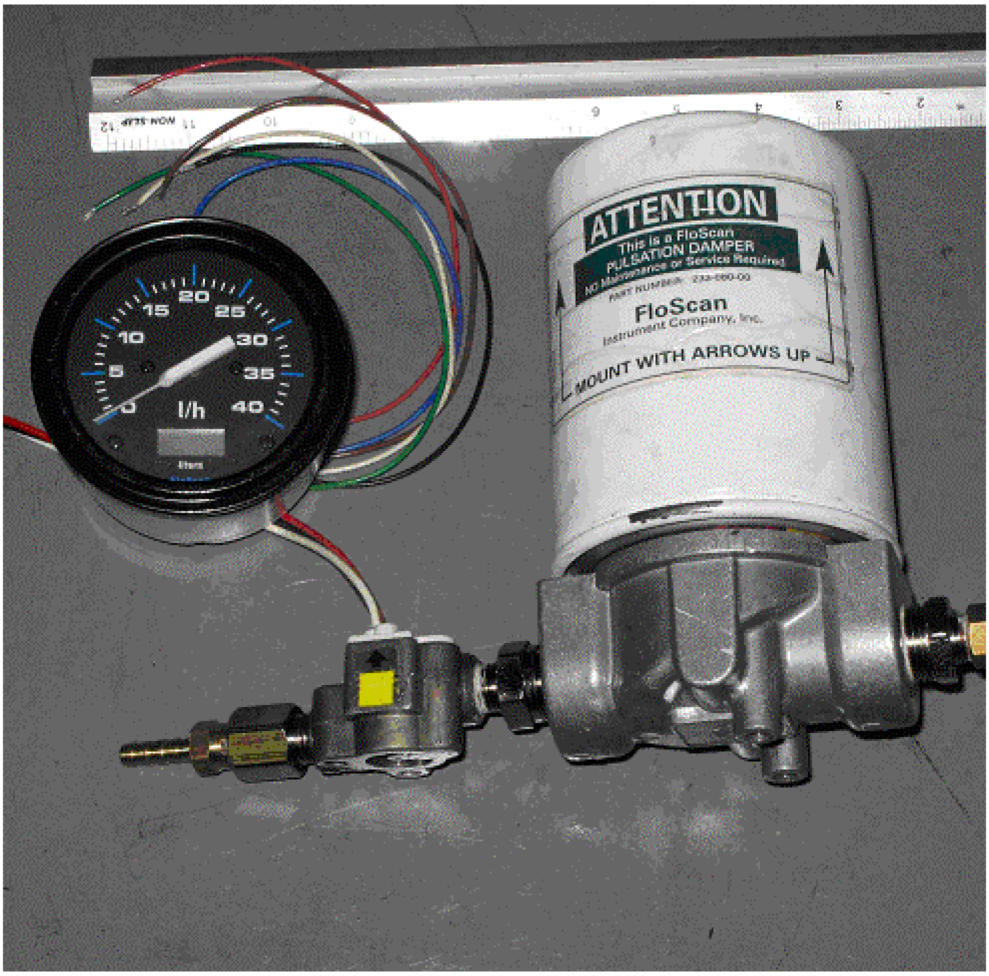


Figure 20 Floscan 65000

Device Description

The transducer of the Floscan 65000 system is part of the only "complete solution" obtained for this study. Whilst for all other flow meters, it would be necessary to purchase at least instrumentation and fittings, the Floscan system comes with everything except cabling.

The Floscan transducer is a turbine-type inferential flow meter, with an integrated flow straightener. The large, white pot it is attached to is a pulsation dampener, sold with the device. This is necessary to prevent any transient errors occurring as the turbine spins up and down in a pulsating flow regime. Obviously, this should not be an issue in Phase II testing; the dispensing pump provides a constant, near pulseless flow, but the dampener was fitted anyway, for consistency.

The output is of pulse form, from an "opto-electronic" signal generating system. As the turbine spins, blades interrupt a light signal from an LED to a phototransistor. On consultation with the manufacturer, it was quoted that this happens approximately "12600" times for every litre passing, but is "non-linear". The user is required to calibrate the device fully, adjusting the totaliser values. The instantaneous values would be unaffected by this.

Several things can be drawn from this. Firstly, that the rate indicator is inherently inaccurate. Secondly, that the behaviour of the engine affects the response of the device. Thirdly, that the transducer is operating out of its ideal range. By their principle, turbine-type transducers are very nearly linear over their normal range [Baker, RC, An introductory guide to flow measurement, 1988, pp88 MEC]. However, so long as the transducer produces repeatable readings, modern electronics should be able to correct this problem. We were also warned not to overspeed the device, since that might cause the turbine to "disintegrate," so that begs the question "where *is* the normal range of this transducer?"

The advantage of using an inferential type flow meter is that they do not block off the flow if they fail. However, they are still affected by entrained gases and pulsating flows, and are damaged by particulates. Having moving parts, they do require maintenance, as do positive displacement meters.

The device works off 12V DC, and the output is a pulse amplified by an NPN transistor.

Test set-up

The device was connected to the CSM Fuel Flow test rig with connections as follows:

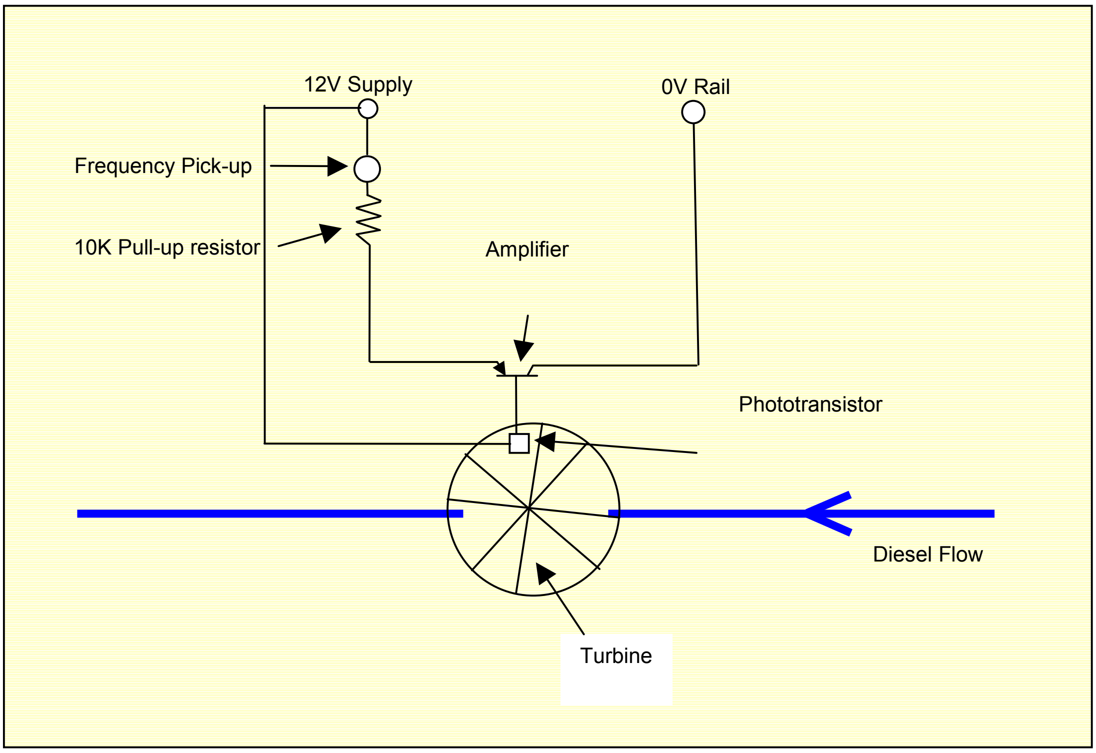


Figure 21: Test set-up for Floscan 65000

The frequency pick-up of the DataTrack 284 was ranged so that 0Hz was represented by a 0V signal, and 200Hz by a 10V signal. This doubles the uncertainty of the frequency values compared with the previous three frequency-type transducers, but due to the larger number of pulses per litre, ultimately gives a lower uncertainty of flow rate than any of the previous. The CP SCADA logging entails a maximum error of 0.14Hz, or 0.040 l/hr, in logging the indicated value, plus a further 0.10Hz due to the resolution of the instrument, incurring a maximum possible error of 0.067 l/hr.

The following test points were chosen for five minute, "full scale" runs. The purpose of these runs was to establish how closely the model followed its specifications.

Pump Speed	Expected Flow Rate
RPM	l/hr
142	10.0
285	20.0
427	30.0
570	40.0

The same "Engine Scale" tests were run as for all other meters.

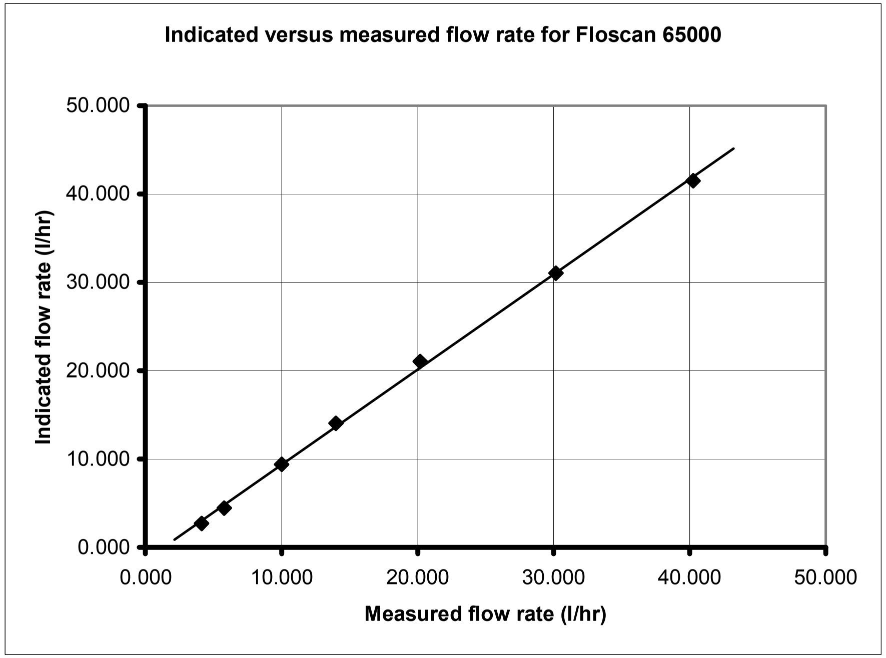
Table 16: "Out-of-the-box" performance of the Floscan 65000 fuel flow meter – first set

Phase 2 Summary

Floscan 65000

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.124	2.714	1.034	0.676
83	5.8	5.789	4.436	1.448	1.107
142	10.0	10.009	9.386	0.833	0.773
198	13.9	13.998	14.068	3.501	3.502
285	20.0	20.186	21.029	1.655	1.724
427	30.0	30.182	31.021	2.507	2.560
570	40.0	40.239	41.501	3.344	3.432

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-34.20	-3.53	-34.62	-3.58	0.02478	0.01418
-23.37	-3.38	-23.52	-3.41	0.00605	0.01215
-6.23	-1.56	-7.20	-1.80	0.05169	0.03606
0.50	0.18	0.03	0.01	0.01780	0.02979
4.18	2.11	4.19	2.11	0.01907	0.06609
2.78	2.10	2.11	1.58	0.15231	0.09195
3.14	3.15	2.61	2.61	0.17069	0.12314



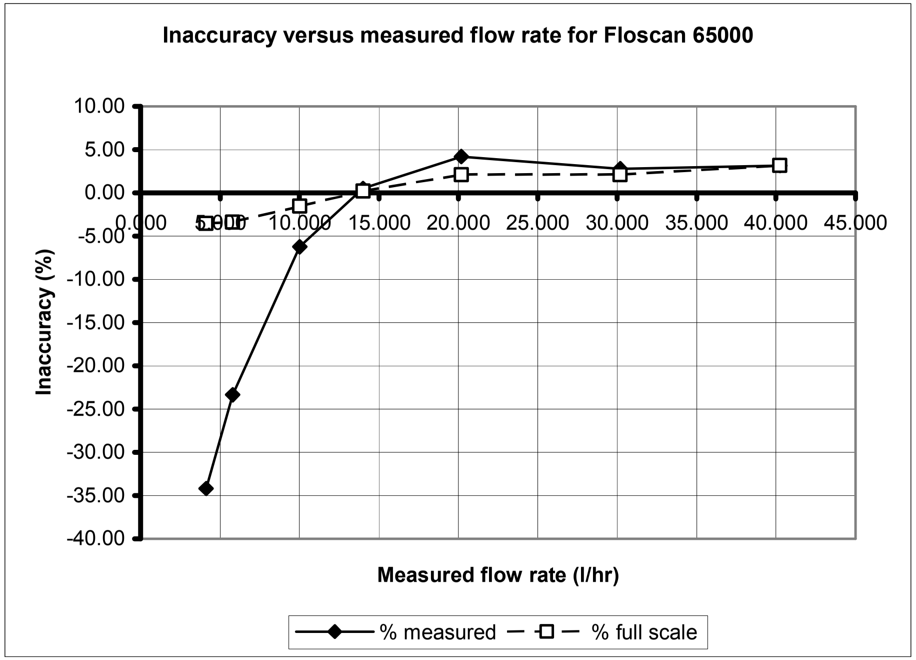


Table 17: Performance of the Floscan 65000 fuel flow meter after device calibration – first set

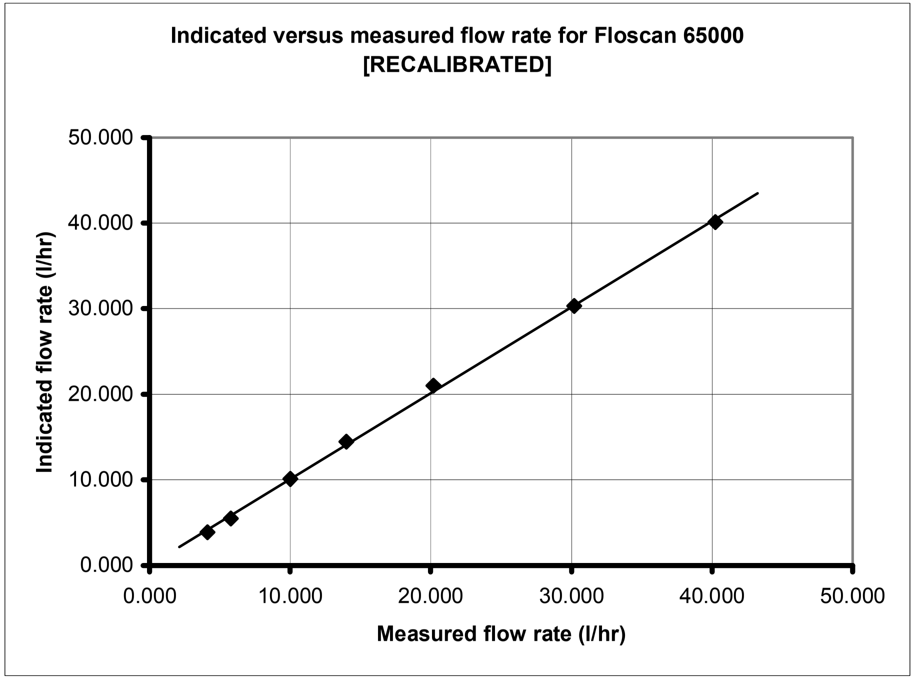
RECALIBRATED

Phase 2 Summary

Floscan 65000

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.124	3.866	1.034	0.964
83	5.8	5.789	5.476	1.448	1.367
142	10.0	10.009	10.103	0.833	0.834
198	13.9	13.998	14.480	3.501	3.606
285	20.0	20.186	20.988	1.655	1.721
427	30.0	30.182	30.328	2.507	2.504
570	40.0	40.239	40.126	3.344	3.319

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-6.28	-0.65	-6.74	-0.70	0.02316	0.01418
-5.41	-0.78	-5.57	-0.81	0.00566	0.01215
0.93	0.23	0.04	0.01	0.04832	0.03606
3.45	1.21	3.00	1.05	0.01664	0.02979
3.97	2.00	3.98	2.01	0.01783	0.06609
0.49	0.37	-0.13	-0.10	0.14239	0.09195
-0.28	-0.28	-0.77	-0.77	0.15957	0.12314



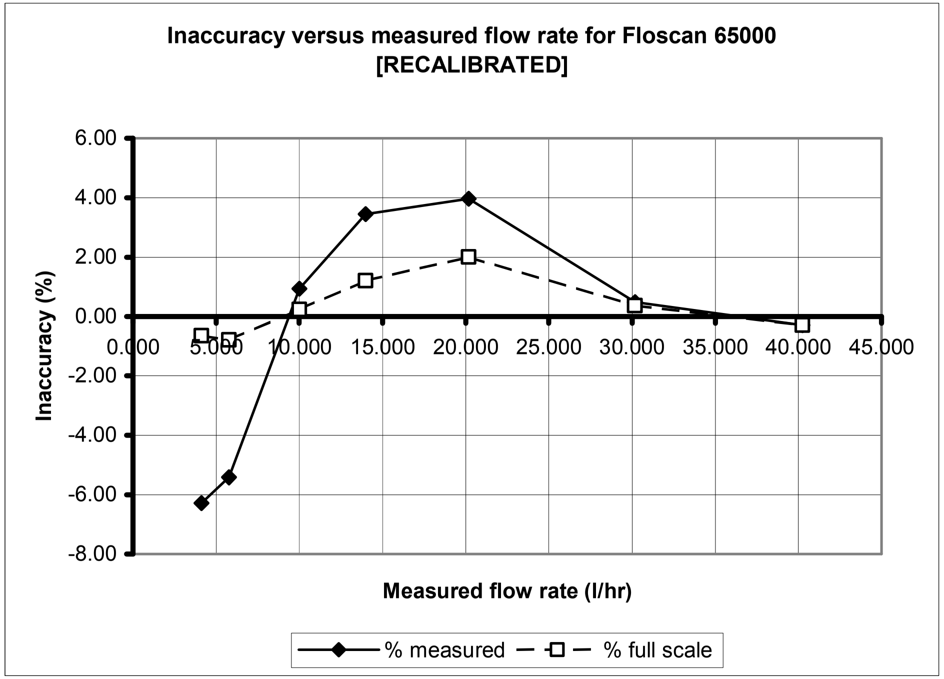


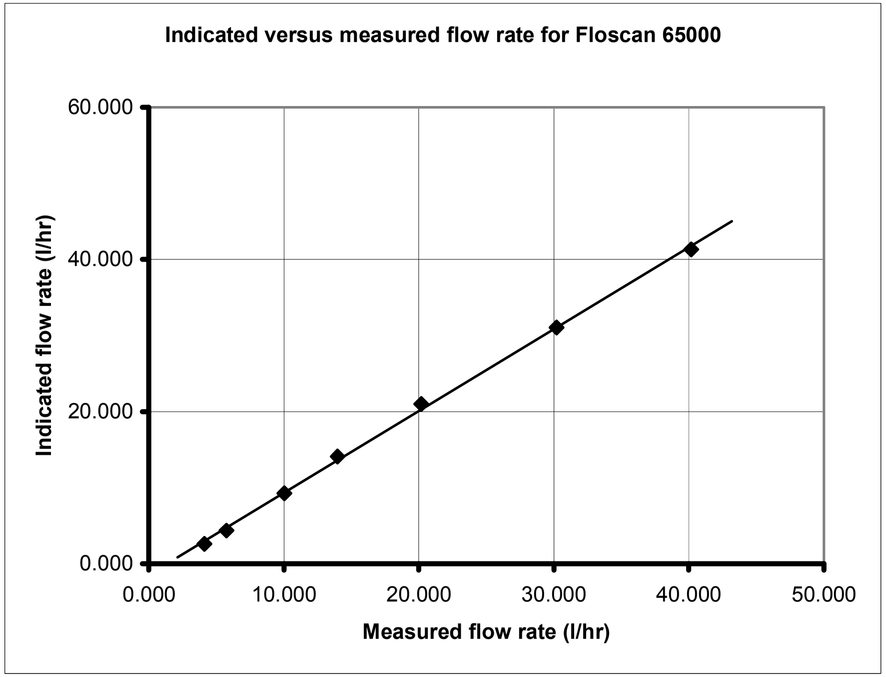
Table 18: "Out-of-the-box" performance of the Floscan 65000 fuel flow meter – second set

Phase 2 Summary

Floscan 65000

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.127	2.604	1.032	0.646
83	5.8	5.757	4.359	1.439	1.088
142	10.0	10.026	9.285	0.836	0.771
198	13.9	13.984	14.111	3.494	3.518
285	20.0	20.175	20.989	1.656	1.720
427	30.0	30.182	31.079	2.510	2.549
570	40.0	40.178	41.329	3.341	3.394

Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
-36.91	-3.81	-37.42	-3.86	0.02054	0.00967
-24.29	-3.50	-24.37	-3.51	0.00670	0.02052
-7.39	-1.85	-7.79	-1.95	0.01423	0.03646
0.91	0.32	0.69	0.24	0.01319	0.02291
4.03	2.03	3.84	1.94	0.01270	0.06437
2.97	2.24	1.55	1.17	0.25303	0.09326
2.87	2.88	1.58	1.58	0.32209	0.11928



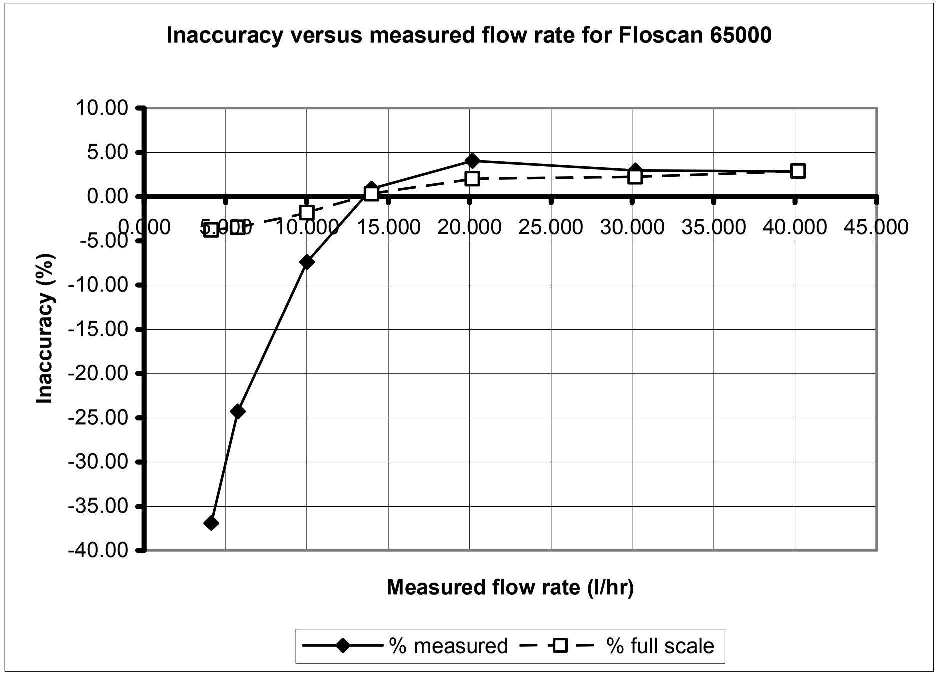


Table 19: Performance of the Floscan 65000 fuel flow meter after device calibration – second set

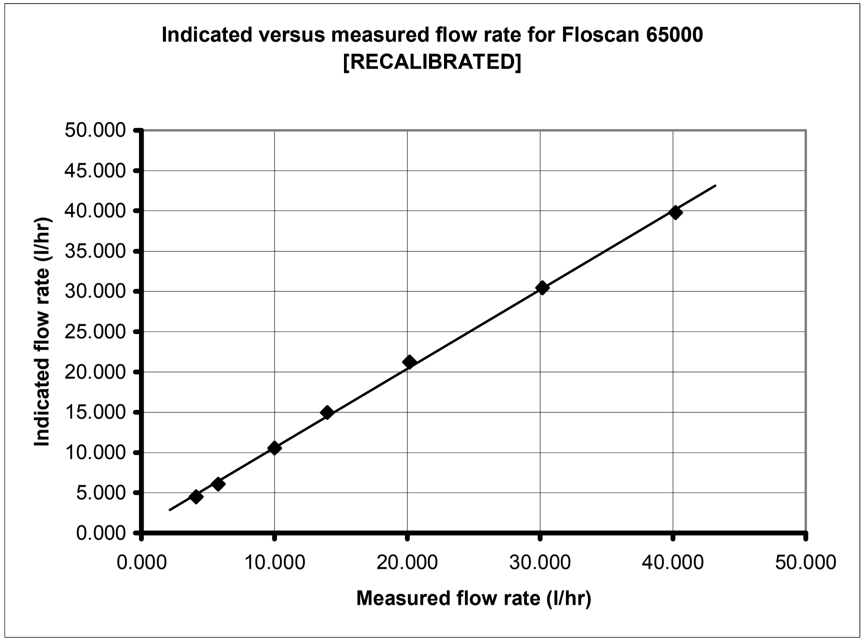
RECALIBRATED

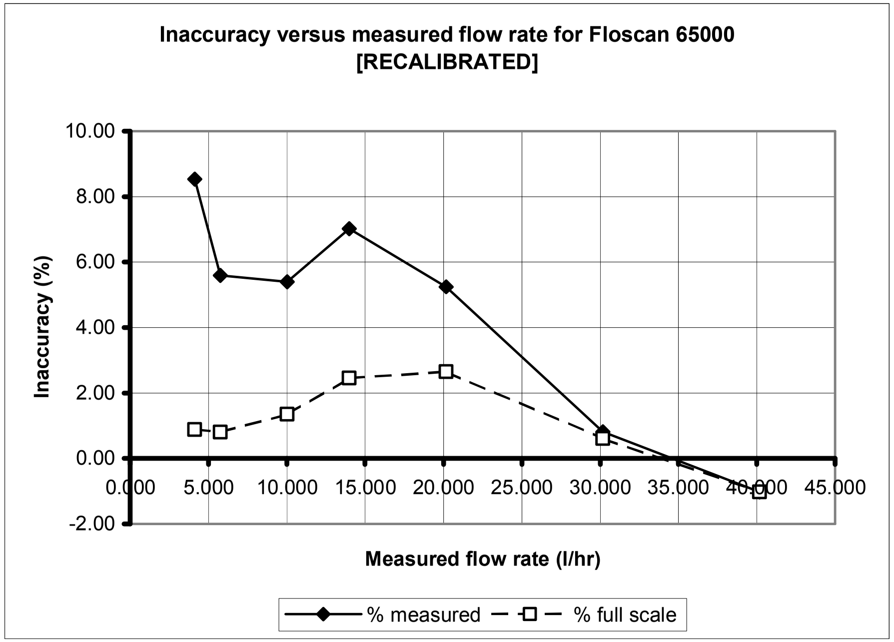
Total Summary

Floscan 65000

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l
60	4.2	4.127	4.479	1.032	1.115
83	5.8	5.757	6.078	1.439	1.518
142	10.0	10.027	10.567	0.836	0.878
198	13.9	13.984	14.965	3.494	3.733
285	20.0	20.175	21.232	1.656	1.740
427	30.0	30.183	30.426	2.510	2.498
570	40.0	40.178	39.767	3.341	3.268

Inaccuracy in Indicated Flow Rate		Inacuracy in indicated Cumulative Volume		Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
% measured	% full scale	% measured	% full scale		
8.54	0.88	8.03	0.83	0.01872	0.00967
5.58	0.80	5.51	0.79	0.00611	0.02052
5.39	1.35	5.01	1.26	0.01297	0.03646
7.02	2.45	6.83	2.38	0.01202	0.02291
5.24	2.64	5.05	2.55	0.01157	0.06437
0.81	0.61	-0.47	-0.35	0.23057	0.09326
-1.02	-1.03	-2.18	-2.19	0.29350	0.11928





Discussion

At first glance, it is easy to see that the manufacturer's claim that the transducer's response is nonlinear is false. There is simply no other fit that can match the data accurately. It is also interesting that the graph of inaccuracy versus flow rate exactly mimics the expected graph for this type of transducer. In general, the transducer, whilst not being quite as accurate as an oval gear meter, displays variances of the same order of magnitude.

Considering that the transducer was specifically sized for the small test engine, however, its performance at the lower flow rates is disappointing. It is also worth noting that the research team were advised to use a return line transducer by the manufacturer, even though there is virtually no return on the test engine. Judging by the inaccuracy displayed by this meter, any identical transducer on the return line would prove useless.

Emerson CMF025M Micromotion Elite

Figure 22 Emerson Micromotion Elite CMF025

Device Description

The Micromotion Elite, produced by Emerson process management, is a high-precision coriolis mass flow meter. The basic principle of these devices is outlined in the Phase 1 report, but this particular model has integral temperature sensing, density calculation, mass-to-volumetric flow rate conversion, and a proprietary system to remove errors due to entrained air. It is, however, designed to work at a maximum flow rate of 2180kg/hr. This model was calibrated by the manufacturer to reach full scale over 40kg/hr, but this is a turndown ratio of approximately 50:1. At low engine speeds, the turndown ratio would increase to 1000:1. These facts, unfortunately, prove to make analysis of this device difficult. However, according to the device's specifications, even at 2 kg/hr, the inaccuracy should not exceed 1.35% of rate.

A coriolis mass flow meter was chosen because they allow for direct calculation of mass passing, without having to rely on temperature, pressure and other variables remaining constant. They do not obstruct flow when malfunctioning, have very few moving parts, and are not highly vulnerable to particulates. Entrained gases can be a problem, but this is accounted for in this model.

There were a number of signal outputs, but the 4 – 20mA was chosen for logging. Over a full scale of 40kg/hr, this gave a maximum uncertainty of 4g/hr, or approximately 4.7ml/hr on logging.

Power for this device was provided by 230V mains AC, but a number of options are available. However, since this is an active device, its power consumption will be considerably higher than the other transducers; up to 7 Watts. This will be negligible on most craft, but it does mean that it will require shut-down and restarting with the engine.

Test set up

The device was connected to the 4-20mA input of the RTU as for the Kobold VKM.

The following test points were chosen for five minute, "full scale" runs. The purpose of these runs was to establish how closely the model followed its specifications.

Pump Speed	Expected Flow Rate
RPM	l/hr
142	10.0
198	13.9
285	20.0
427	30.0
570	40.0
641	45.0

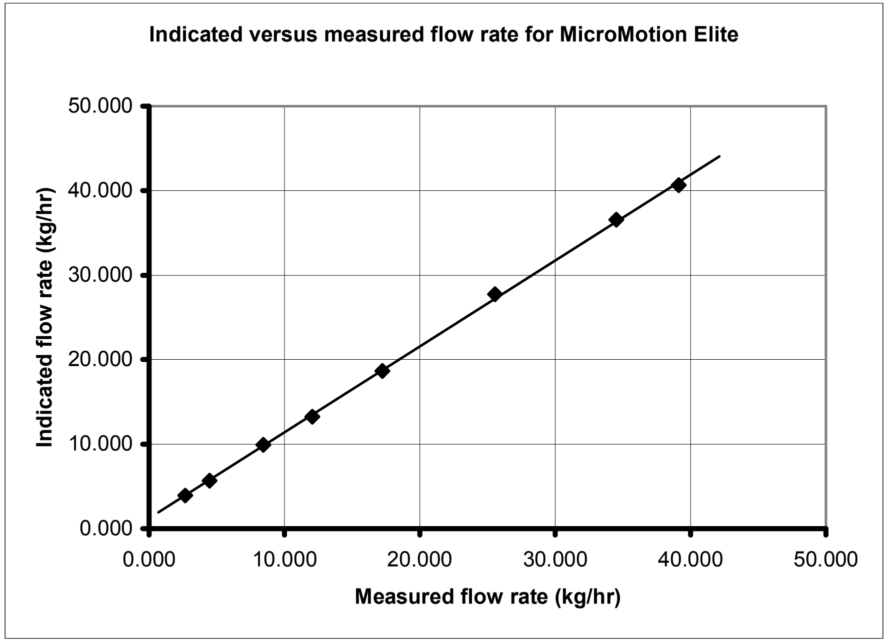
The same "Engine Scale" tests were run as for all other meters.

Table 20: "Out-of-the-box" performance of the Micromotion Elite fuel flow meter

Phase 2 Summary

EMERSON MICROMOTION ELITE

Test Point	RPM Estimated Flow rate	Balance Arm Measured Flow Rate	Meter Indicated Flow Rate	Balance Arm Measured Cumulative Volume	Meter Indicated Cumulative Volume	Inaccuracy in Indicated Flow Rate		Inaccuracy in indicated Cumulative Volume		Variance of Indicated Flow	Variance of Measured Flow
rpm	l/hr	l/hr	l/hr	l	l	% measured	% full scale	% measured	% full scale	$(l/hr)^2$	$(l/hr)^2$
60	4.2	2.699	3.943	0.676	0.986	46.07	3.11	45.74	3.09	0.00263	0.01009
83	5.8	4.470	5.699	0.993	1.265	27.50	3.07	27.39	3.06	0.00103	0.01308
142	10.0	8.453	9.914	0.705	0.827	17.28	3.65	17.28	3.65	0.02842	0.03506
198	13.9	12.087	13.269	3.023	3.318	9.78	2.96	9.76	2.95	0.00506	0.01974
285	20.0	17.249	18.657	1.415	1.527	8.16	3.52	7.90	3.42	0.00391	0.06268
427	30.0	25.565	27.746	2.135	2.314	8.53	5.45	8.40	5.38	0.05439	0.12830
570	40.0	34.527	36.554	2.878	3.048	5.87	5.07	5.92	5.11	0.01633	0.09963
641	45.0	39.118	40.629	3.260	3.386	3.86	3.78	3.87	3.79	0.00647	0.12783



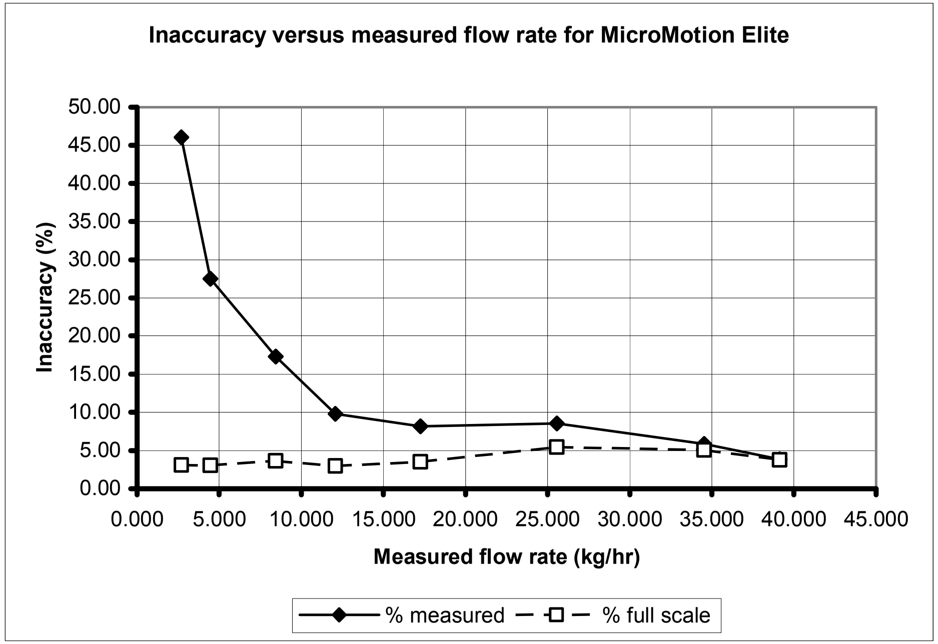


Table 21: Performance of the Micromotion Elite fuel flow meter after device calibration

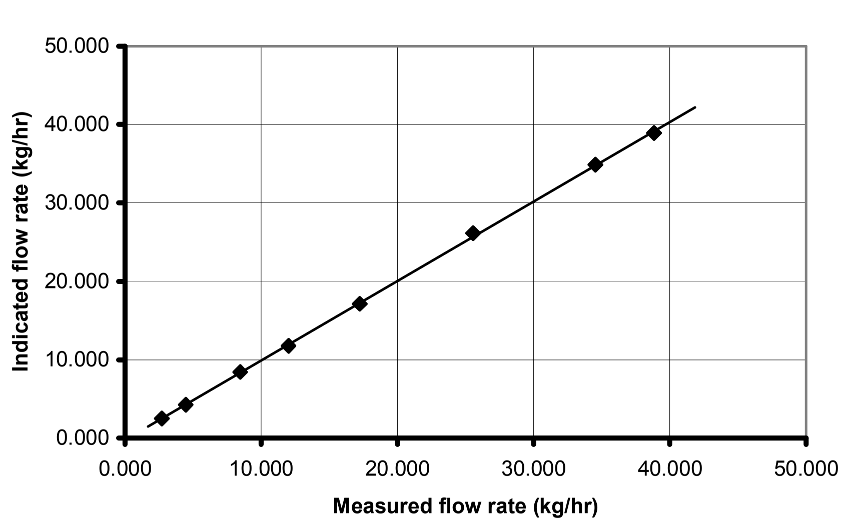
RECALIBRATED

Phase 2 Summary

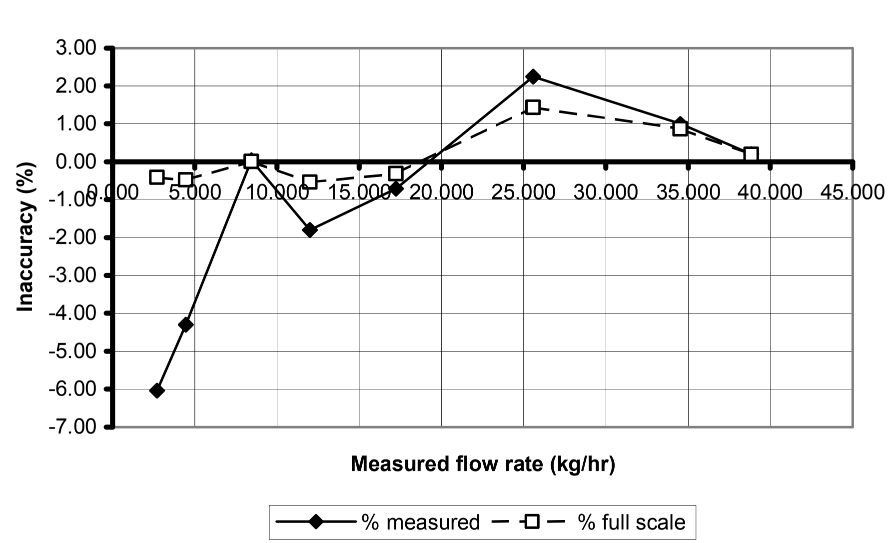
EMERSON MICROMOTION ELITE

Test Point rpm	RPM Estimated Flow rate l/hr	Balance Arm Measured Flow Rate l/hr	Meter Indicated Flow Rate l/hr	Balance Arm Measured Cumulative Volume l	Meter Indicated Cumulative Volume l	Inaccuracy in Indicated Flow Rate % measured	Inaccuracy in Indicated Flow Rate % full scale	Inaccuracy in indicated Cumulative Volume % measured	Inaccuracy in indicated Cumulative Volume % full scale	Variance of Indicated Flow $(l/hr)^2$	Variance of Measured Flow $(l/hr)^2$
60	4.2	2.699	2.536	0.676	0.634	-6.04	-0.41	-6.26	-0.42	0.00263	0.01009
83	5.8	4.470	4.278	0.993	0.950	-4.31	-0.48	-4.39	-0.49	0.00103	0.01308
142	10.0	8.453	8.456	0.705	0.705	0.04	0.01	0.06	0.01	0.02842	0.03506
198	13.9	11.999	11.784	3.001	2.947	-1.80	-0.54	-1.82	-0.54	0.00506	0.01974
285	20.0	17.249	17.126	1.415	1.402	-0.71	-0.31	-0.95	-0.41	0.00391	0.06268
427	30.0	25.565	26.138	2.135	2.180	2.24	1.43	2.12	1.36	0.05439	0.12830
570	40.0	34.527	34.873	2.878	2.908	1.00	0.86	1.05	0.91	0.01633	0.09963
641	45.0	38.835	38.913	3.236	3.243	0.20	0.19	0.21	0.20	0.00647	0.12783

Indicated versus measured flow rate for MicroMotion Elite [RECALIBRATED]



Inaccuracy versus measured flow rate for MicroMotion Elite [RECALIBRATED]



Discussion

Whilst the precision of this device is good, its accuracy is some way off the manufacturer's specifications. Neither is the output as linear as the positive displacement meters. We have attempted to contact the manufacturer to resolve this issue, but investigations are still underway.

Comparisons between flow meters and ranking

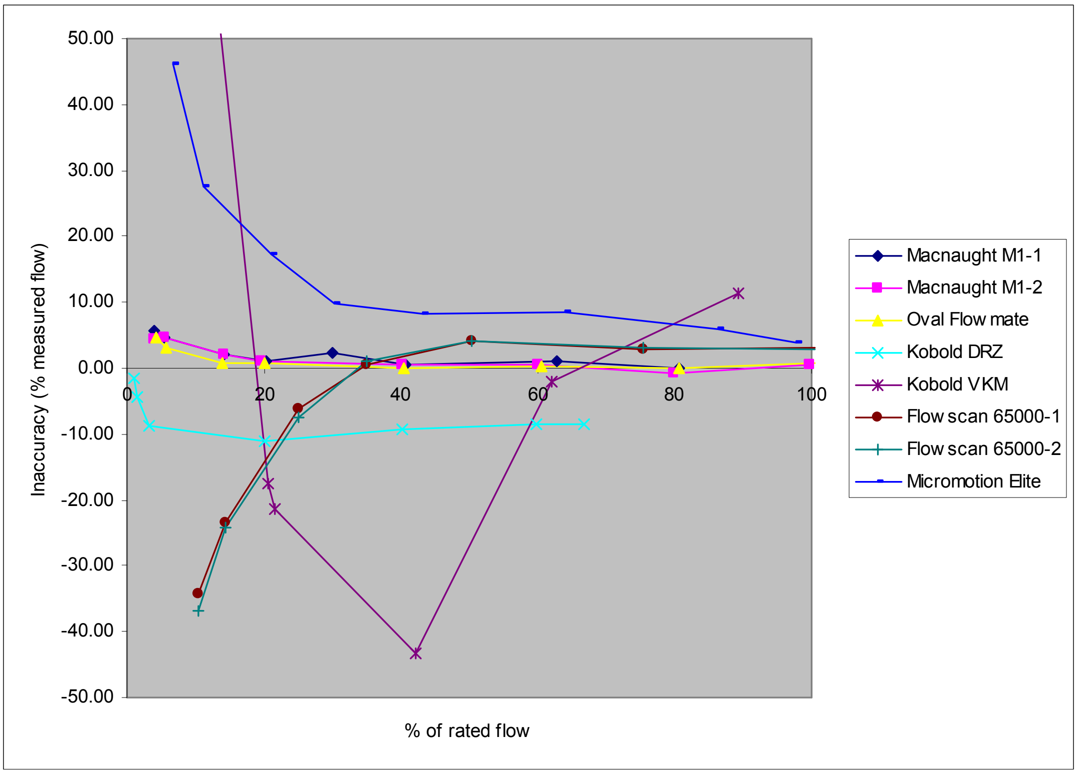


Figure 23: Accuracy of transducers as a proportion of the measured flow – "out-of-the-box"

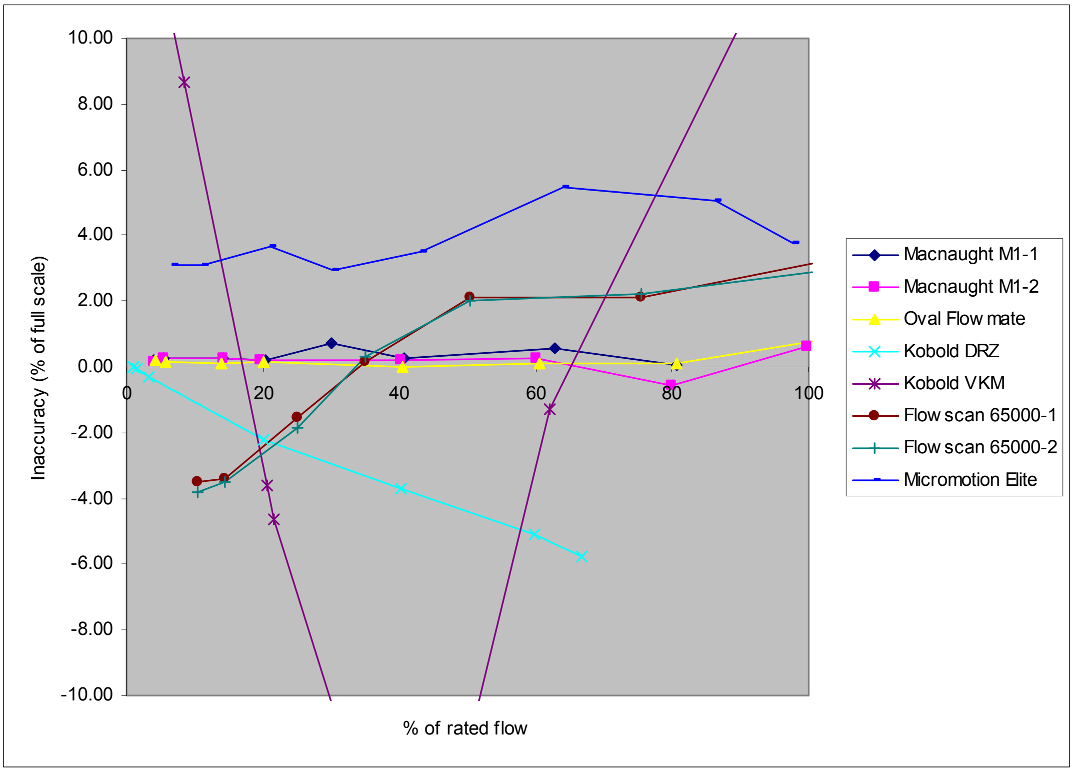


Figure 24: Accuracy of transducers as a proportion of full scale (rated) flow – "out-of-the-box"

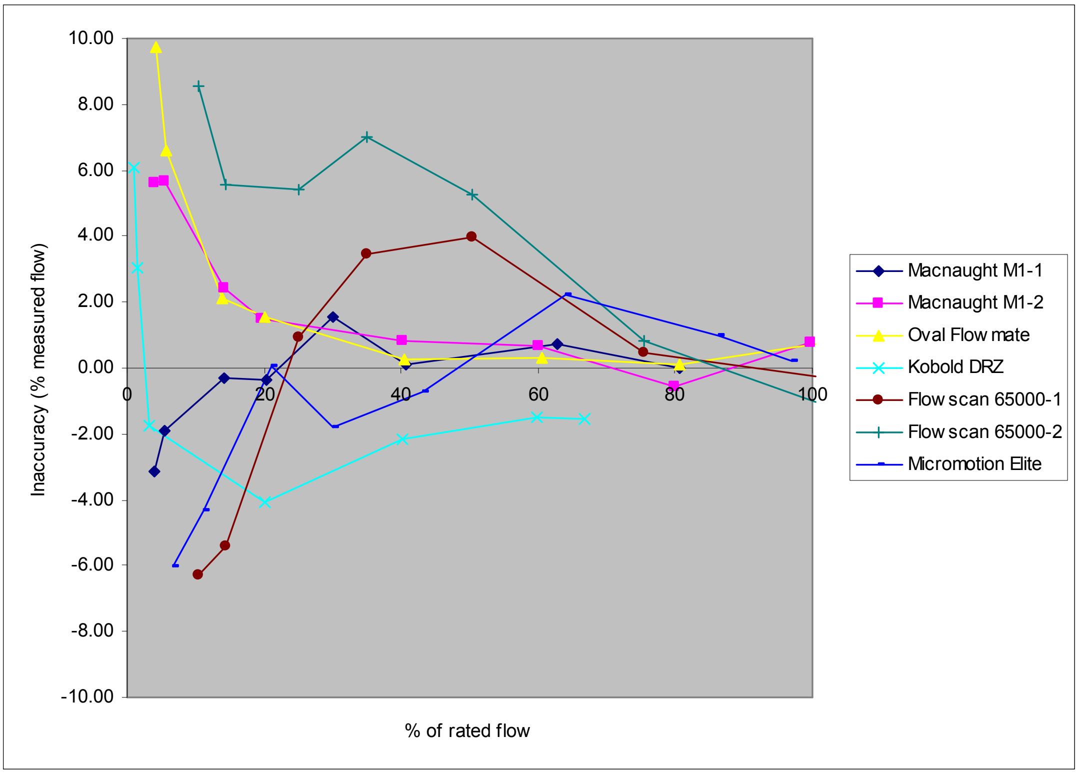


Figure 25: Accuracy of transducers as a proportion of the measured flow – after calibration

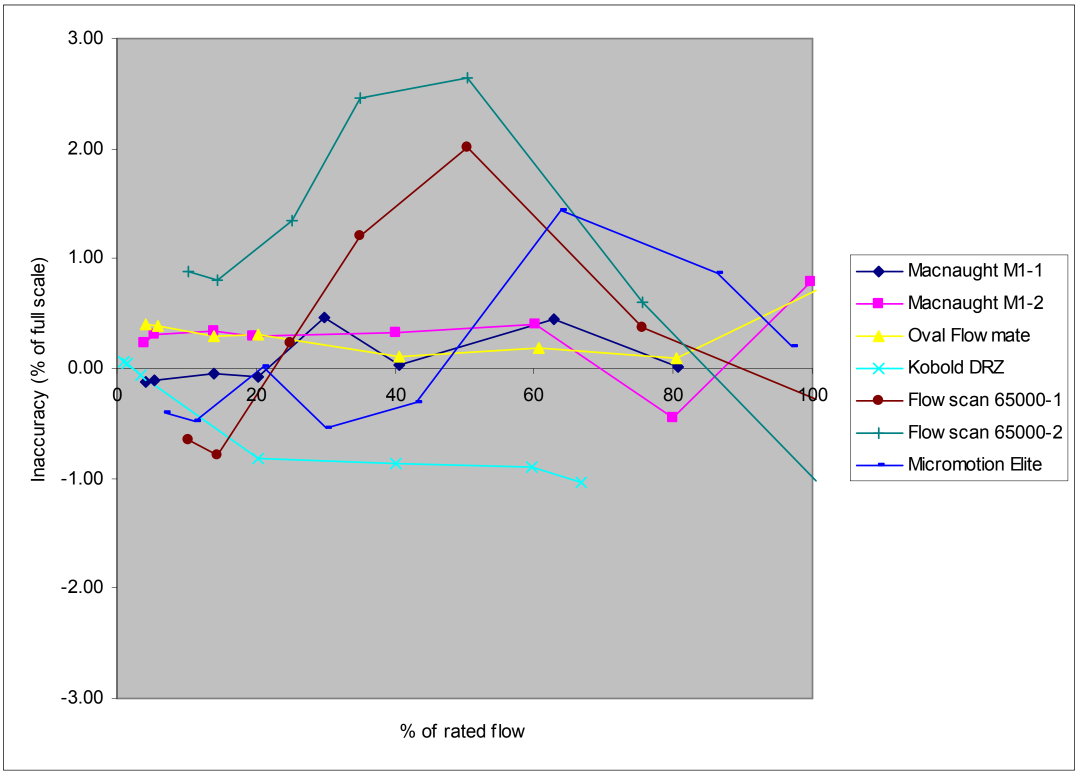


Figure 26: Accuracy of transducers as a proportion of full scale (rated) flow – after calibration

Observations on flow meter accuracy

The two oval gear positive displacement meters (the Macnaught M1 and the Oval Flowmate) have proved the most accurate, both outright and over the greatest turndown ratio.

The Micromotion Elite presents a fairly standard error curve, but larger than that shown in its specification. This may be due to the ELITE’s full scale being is far greater than the “calibrated” full scale used here.

The Kobold VKM is generally the least accurate meter tested. It is possible that the specific unit tested has suffered a malfunction; this issue has been taken up with the manufacturer.

Out-of-the-box, the Kobold DRZ flow meter returns observations that are of consistent accuracy when the flow is between 5% and 65% of rated flow.

Out-of-the-box, the Floscan 65000 returns observations that are of consistent accuracy when the flow exceeds ~45% of rated flow. The Floscan transducer accuracy curve has a form that is typical of turbine type transducers operating at flow rates below rated.

Calibration of the transducers led to improved accuracy in all cases, with the exception of the Kobold VKM.

Repeatability of transducers

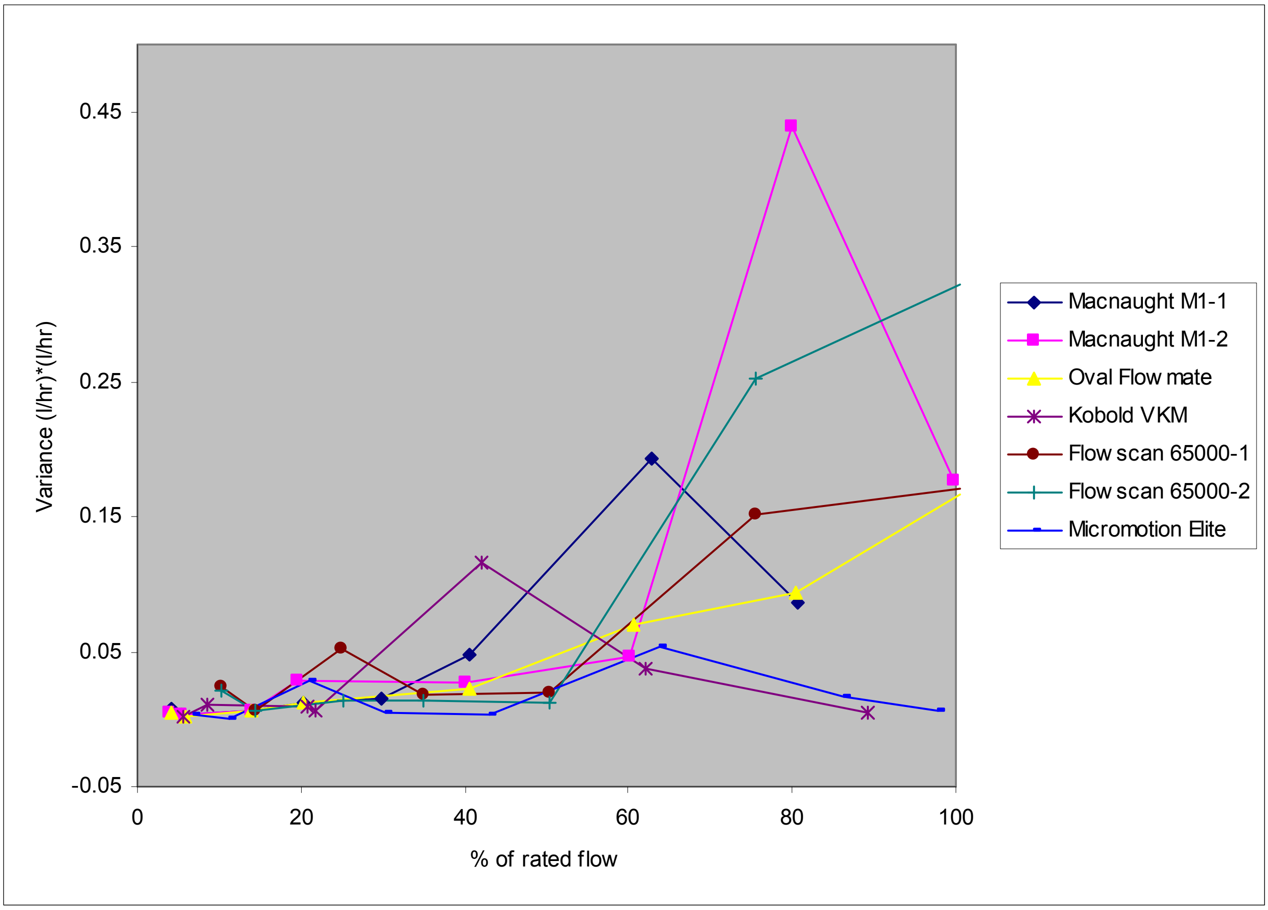


Figure 27: Plot of variance versus flow rate for meters under test.

The variance of indicated flow at each test run provides a measure of the precision of flow observations taken within the flow measurement system while a specific flow meter is being used. The repeatability curves thus also include variance due to operations undertaken within the signal processor, the signal channel configuration and logging system.

Repeatability is not affected by calibration. Calibration aims to eliminate bias in observation making such that observations become more accurate.

The variance of the Micromotion Elite coriolis meter remains consistently low over its full scale range.

The variance of the Kobold VKM variable aperture meter broadly remains low over its full scale range, but does exhibit a small peak in variance at around 40% of rated flow.

The variance of the Oval MIII Flowmate oval gear meter is generally low over its full scale range of flow, but does exhibit an approximately linear increasing trend.

While the variance of observations from the Macnaught M1 is low at the lower end of its full scale range, variance increases significantly and non-linearly, toward the upper end of its full scale range, from approximately 40-60% of full scale upwards.

While the variance of observations from the Flowscan 65000 is low at the lower end of its full scale range, variance increases significantly toward the upper end of its full scale range, from approximately 50% of full scale upwards.

Due to the suspected malfunction of the flow meter and its very poor accuracy, the variance curves for the Kobold DRZ are not presented.

Ranking of flow meter performance

As some devices are provided without full details of conversion factors for sensed physical quantities to flow rates, the primary means of ranking the metering devices was their accuracy after the calibration process.

Table 22: Flow measurement system performance using flow metering devices under test

Manufacturer & Model	Meter type	Quoted Accuracy (% FSD*)	Observed Accuracy# "out-of-the-box" (% FSD)	Observed Accuracy# after calibration (% FSD)	Observed Repeatability (Standard deviation @ ~25% of rated flow) (l/hr)	Observed Repeatability (Standard deviation @ ~75% of rated flow) (l/hr)
Rank: 1 Oval MIII Flowmate	Oval gear	0.5%	0.30%	0.36%	0.12	0.30
Rank: 2 Macnaught M1	Oval gear	0.5%	0.37% 0.38%	0.24% 0.43%	0.11 0.17	0.30 0.65
Rank: 3 Emerson CMF025M	Coriolis meter	0.05% of observation over upper 90% of FSD	3.93%	0.67%	0.12	0.15
Rank: 4 Kobold DRZ	Oscillating piston (+ve displacement)	1.0% of observation	3.34%	0.69%	0.25	1.06
Rank: 5 Floscan 65000 Cruisemaster	Turbine meter (2 meters + instrument + pulse dampeners)	Not reported	2.54% 2.61%	0.98% 1.58%	0.22 0.11	0.38 0.48
Rank: 6 Kobold VKM	Variable aperture	3.00%	9.82%	13.08%	0.08	0.08

* Unless otherwise specified

Determined as the root mean square of inaccuracy in indicated flow rate, across all test runs.

The Oval MIII and the Macnaught M1, perform to specification "out-of-the-box" and after calibration. Within our testing system, these devices provide the standard against which the others are compared.

Due to a possible out-lying value at high flow rate, the OVAL MIII Flowmate has been adversely affected by recalibration. Despite this, the Oval MIII Flowmate positive displacement meter appears to have the best combination of accuracy and precision.

The Kobold DRZ performs to specification after calibration. This confirms the possibility that the DRZ has an incorrect manufacturer provided conversion factor.

The Kobold VKM did not perform to specification. The response of this device is so nonlinear that calibration scarcely made any difference. The Kobold VKM variable aperture meter has been excluded from further testing (Phase III).

The Floscan 65000 performed reasonably well compared to the oval gear meters. The Floscan 65000 demonstrates a linear response to flow rate, contrary to discussions that have taken place with the manufacturer.

The Emerson CMF025M did not perform to specification either "out-of-the-box" or after calibration, but performed well compared to the oval gear meters after calibration, returning better repeatability at high flow rates. However, considering that this unit costs approximately £3500, whereas the rest of the meters cost approximately £250 each, it is surprising that it did not outperform the other meters.

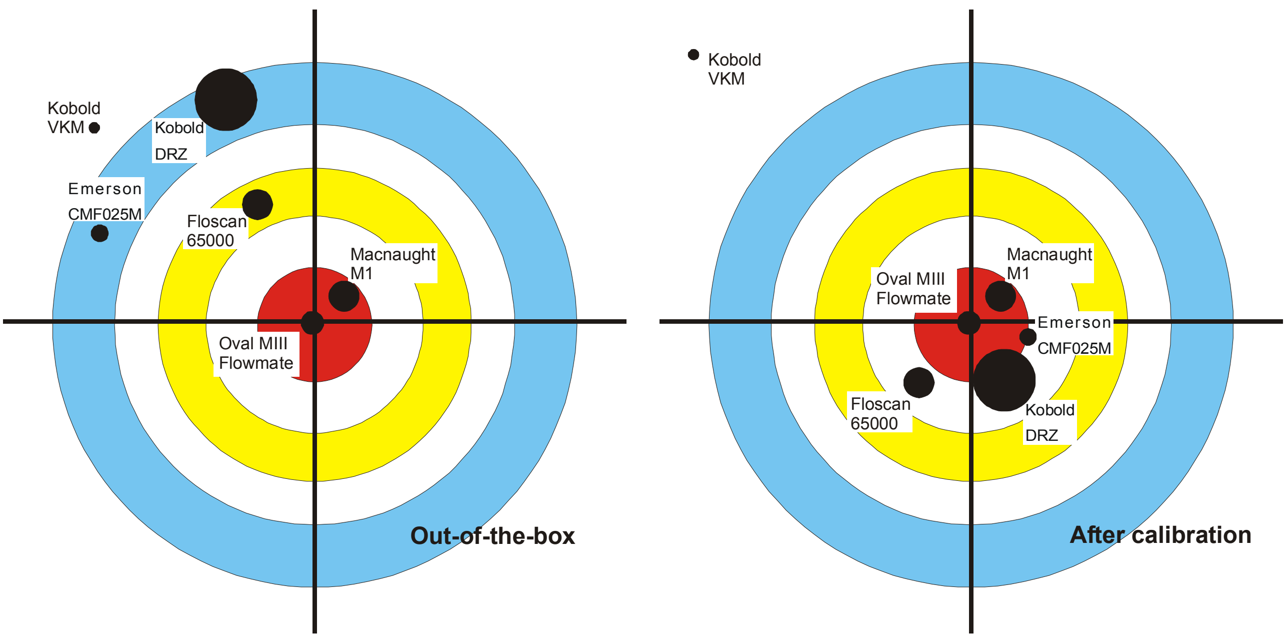


Figure 28: Relative performance of flow meters "out-of-the-box" and after calibration.

The ‘target analogy’ discussed earlier is revisited to graphically indicate the relative performance of the fuel flow measurement systems incorporating the flow meters under investigation. On the targets, the distance of the centre of the circle for a given meter represents the accuracy of the device, the size of the circle represents the repeatability of observations. The LHS target shows the relative situation before calibration of the devices, the RHS target shows the same, after calibration.

The diagram (Figure 29) illustrates that it is possible to use any of five of the six meters subjected to testing in an effective fuel metering role. As stated earlier, there are issues concerning a possible malfunction of the specific instance of the Kobold VKM that was procured, such that its performance as reported in Table 22 and in Figure 29 should not be over interpreted.

This issue aside, at the end of Phase II of the overall study, it becomes clear that the essential distinction between the fuel meters and their measurement systems will reduce to considerations of the ease of undertaking a calibration exercise on a working fishing vessel. According to the results, the gear meter devices (the Oval MIII Flowmate and the Macnaught M1) are likely to produce valid observations of fuel flow without requiring calibration *in situ*.

What remains to be investigated is whether the relative rank of any particular sensing device changes when the meter is installed on an engine and subjected to, for example, vibration and pulsating flows. This is the topic of the Phase III work.

Erratum

In the original release of this document, the Oval MIII fuel meter was referred to as the “Flowtech Oval MIII”. This was an error for which the authors apologise. The relevant entries and diagrams have been updated to reflect the correct text in this document which is “Oval MIII Flowmate”.