

The Impact of Mis-measurement on UK Oil Production

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1 INTRODUCTION

Density measurement is a key element of both mass and volume flow rate measurement in the oil industry and as such is fundamental to the commercial operation of facilities. The most widely implemented approach for mass flow measurement is to use a volumetric flow meter and a densitometer. All flow meters require periodic calibration; traceability within the UK is provided through the National Flow Measurement Standards Facilities at NEL, supported by the UK National Measurement Office UK under the Engineering and Flow Measurement Programme. All commercial densitometers also require periodic calibration and DECC identified a need for research into practical methods for in-situ calibration of densitometers, as well as a greater understanding of the effects on densitometer performance of variations in product density, pressure and temperature.

This is particularly important as more and High Temperature High Pressure (HTHP) fields come on stream, since more densitometers will be operating at temperatures and pressures significantly higher than those currently used as the reference conditions for calibration. In addition, as fields mature, quantities of produced water generally increase, resulting in higher process operating temperatures and the increased chance of slugs of water being carried through to the metering station.

NEL, custodians of a Primary Standard Facility for liquid density measurement, led a Joint Industry Project (JIP) aimed at providing the oil and gas industry with confidence in densitometer performance, by developing a calibration procedure which links traceably to National Standards [1]. Fourteen operators, a densitometer manufacturer, a densitometer calibration laboratory and DECC joined the project.

The key task of the JIP was the detailed characterisation of densitometers in well-controlled conditions, making use of accurately-characterised transfer standard fluids that covered the density and viscosity ranges which are encountered across the full temperature and pressure range of operation of UK offshore oil facilities. As a result of the project, DECC has issued revised guidance on calibration of densitometers for fiscal application in the UK sector of the North Sea.

2 BACKGROUND

As noted above, the most widely implemented approach for mass flow measurement is to use a volumetric flow meter and a densitometer. In this case, the uncertainty in mass flow measurement is dependent equally on the uncertainty in volumetric flow meter measurement and in densitometer measurement. The calculation of volume flow rate however also requires a knowledge of the density since it is necessary to reduce the measurements of volume throughput to standard conditions. It can therefore be seen that density measurement, volumetric and mass flow measurement are of equal importance.

DECC requires that all critical elements of fiscal measurement systems are traceable to national standards. In considering calibration frequencies, the cost of re-calibration is balanced against the financial exposure. Calibration should take place at the anticipated operating conditions unless it can be shown that additional measurement uncertainty is not thereby introduced.

All commercial densitometers, for use on gases or liquids, operate on an oscillatory principle and as such are not independent of other fluid properties. However, the theory of such methods is not rigorously established and even with careful design it is not possible to uncouple fully the effects of density from the other physical properties of the calibration fluids.

To maximise the accuracy attainable with such densitometers, it is necessary to calibrate them against reference fluids with similar physical characteristics (such as speed of sound and viscosity).

Conventionally, the calibration of most industrial densitometers is undertaken using fluids whose physical characteristics are significantly different to the actual working or operational fluids. Furthermore, the range of pressures and temperatures at which the instruments were normally calibrated was limited to near ambient conditions but many densitometers, particularly those used in offshore applications, operate under relatively high conditions of pressure and temperature. This can be a significant source of error in density measurement. Ideally, calibration should be undertaken at metering pressures and temperatures using fluids whose volumetric properties are known accurately across the full temperature and pressure range required for the calibration.

It has been accepted industry practice to quote a calibration at only a single reference temperature (generally 20 °C) and apply correction factors to account for the influence of temperature and pressure on both the calculated density and its uncertainty. However, recent work has raised a number of issues with regard to the whole calibration process, in particular when a densitometer is operated at temperatures and pressures different from the reference conditions. This has significant implications for fields operating in common transportation systems, where the mass allocations are based on densitometer readings.

3 OSCILLATORY DENSITOMETER THEORY

All commercial liquid density transducers operate on the same general principle. The manufacturers generally model the instruments as a simple spring mass oscillator system comprising the vibrating test section and the fluid contained in it, totally disregarding hydrodynamic effects. As the liquid density changes it in turn changes the total vibrating mass, which is then detected by a change in the resonant frequency. For a simple system, the resonant frequency f is given by:

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \quad (1)$$

where K is the stiffness and M is the mass of the element (M_1) plus the mass of the fluid (M_2).

If K , M and V_f (the volume of fluid in the test section) are constant then Equation 1 can be written in terms of density ρ as

$$\rho = K_0 + \frac{K_2}{f^2} \quad (2)$$

where $K_0 = -M_1/V_f$ and $K_2 = K/4\pi^2V_f$, or, in terms of oscillation period τ ,

$$\rho = K_0 + K_2\tau^2 \quad (3)$$

In recognition that Equation 1 is only a first approximation to the actual behaviour of an oscillating tube filled with liquid [2], Equation 3 is normally modified by the inclusion of a linear term K_1 , giving an empirical expression of the form

$$\rho = K_0 + K_1\tau + K_2\tau^2 \quad (4)$$

At any given temperature t and pressure p the three constants in Equation 4 can be determined by calibrating the device with three fluids of known density. To ensure the highest accuracy this should be undertaken across the full operational temperature and pressure range, thus requiring knowledge of the density of each calibration fluid at the corresponding conditions. Accepted practice however has been to calibrate at one reference temperature t_0 (normally 20 °C) at atmospheric pressure to determine the coefficients at those conditions and then apply correction terms to account for the effects of operation at other temperatures and elevated pressure. The correction terms are of the form

$$\rho_t = \rho_0 \{1 + K_{18}(t - t_0)\} + K_{19}(t - t_0) \quad (5)$$

where ρ_0 is the density at the reference calibration temperature t_0 and

$$\rho_{t,p} = \rho_t \left\{ 1 + K_{20A}(p - p_0) + K_{20B}(p - p_0)^2 \right\} + \left\{ K_{21A}(p - p_0) + K_{21B}(p - p_0)^2 \right\} \quad (6)$$

where the reference pressure p_0 is 1 bar absolute. The coefficients in Equations 4, 5 and 6 are determined for each instrument and these temperature and pressure coefficients are provided for use by the operator.

Initial determination of K_0 , K_1 and K_2 requires the use of three fluids of accurately known density. K_{18} and K_{19} are then determined at atmospheric pressure using one of these fluids and the pressure correction coefficients (K_{20A} , K_{20B} , K_{21A} and K_{21B}) are determined at t_0 . Current industrial calibration practice within the UK is to re-calibrate a densitometer annually but this is normally only undertaken at 20 °C and 1 bar absolute. Expanding Equation 6 by incorporating Equations 4 and 5 indicates that the coefficients are all cross-coupled and hence all calibrations should ideally be undertaken at the actual operating conditions of the device.

Taken in conjunction with a review carried out by the UK regulator for petroleum measurement and allocation in 2004 [3] which found a small but systematic 'offset error' when a densitometer is operated at a temperature different from the reference temperature, this raises a number of issues with regard to the whole calibration process and the calculation methodology. NEL has been aware for many years of the influence of other fluid properties (primarily viscosity and speed of sound) on the operation of oscillatory densitometers and sponsored work to investigate these effects [4, 5]. Accurate characterisation, and calibration, of oscillatory densitometers therefore requires knowledge of the effects of temperature and pressure on a number of fluid properties across the full operational range of the device.

4 TECHNICAL APPROACH

As part of previous Flow Programmes, the UK Department of Trade and Industry funded the establishment of density standard facilities at NEL [6]. These consist of two primary standard densitometers, one each for liquids and gases. In addition, a facility for the calibration of liquid densitometers (insertion and in-line devices) was also developed, based on the use of transfer standard fluids.

To be considered for use as true transfer standard fluids, fluids must either be single components or stable mixtures of known composition. Such fluids have the advantage that once their PVT behaviour has been established (using the NEL Primary Standard Densitometer) they can then be used in any other (transfer) facility without further characterisation, thus providing much closer traceability to primary standards.

As noted in Section 3, there is a coupling between fluid density and viscosity in an oscillatory densitometer and hence the chosen fluids must cover the density and viscosity ranges which are encountered across the full temperature and pressure range of operation of UK offshore oil facilities.

4.1 The NEL Primary Standard Liquid Densitometer

The NEL Primary Standard Liquid Densitometer is a hydrostatic balance densitometer used in conjunction with a magnetic suspension coupling [6-10]. Over the full operational range of the facility the total uncertainty in density is 0.015% at a 95% confidence level. However, over the limited temperature range investigated here ($20 \leq t \leq 100$ °C, $0.1 \leq p \leq 30$ MPa, $650 \leq \rho \leq 930$ kg m⁻³) the total uncertainty of measurement is within 0.010 % (at $k=2$).

4.1.1 Principle of Operation

Figure 1 shows the basic design of the magnetic suspension balance and the controlling principle of the magnetic suspension coupling. The coupling consists of an electromagnet and a permanent magnet. The electromagnet is attached to the under-pan weighing hook of a commercially available microbalance. Inside the coupling housing the permanent magnet is connected to the sample load by means of a coupling and decoupling mechanism. The coupling mechanism allows the weight of the permanent magnet to be tared out. The electronically controlled magnetic suspension coupling transmits the load through the wall of the pressure vessel to the microbalance at ambient conditions.

Control is effected by an electronic unit with position feedback obtained from the sensor coil and core. Using this technique the measuring or buoyancy force on the permanent magnet and its attachments, including the sample, are transmitted without contact and with negligible error through the walls of the test chamber to the microbalance.

The electronic control unit contains two separate PID controllers: the first, to raise and lower the permanent magnet and its attachments in a controlled way between its rest position and either the 'measuring' or 'tare' position; and the second, a fast response system, to effect stable position control at the required 'measuring' or 'tare' position. For density measurements the sample is replaced by a sinker immersed in the fluid under test, as shown in Figure 2. Compensating weights ensure that the balance is always operating near to its zero point, thus reducing linearity errors.

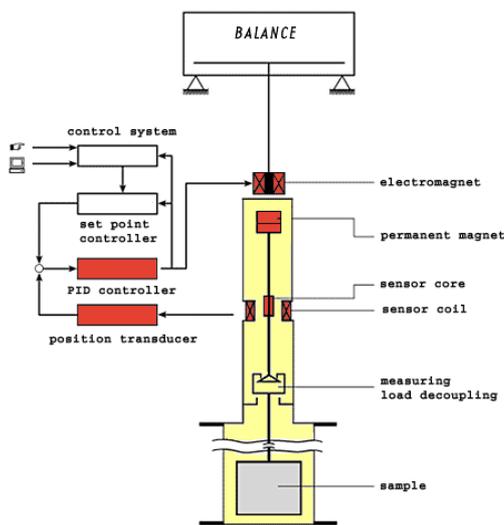


Fig. 1 - Magnetic suspension balance

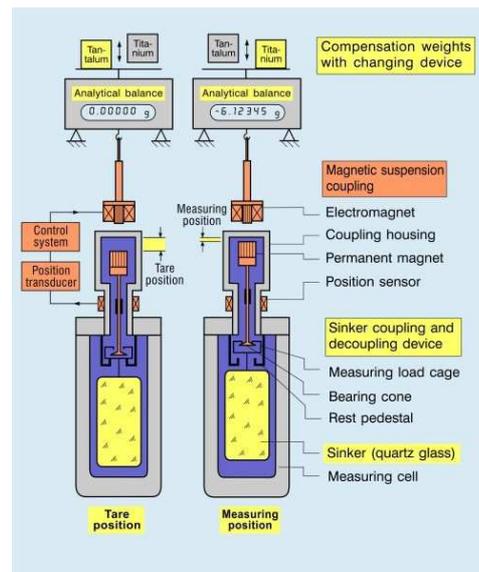


Fig. 2 - Magnetic-suspension coupling

In the 'measuring' condition, as indicated in Figure 2, the sinker is directly coupled to the permanent magnet and buoyancy forces act on all of the freely suspended components. In the 'tare' position, which is a few millimetres below the 'measuring' position, only the permanent magnet, the position sensor and part of the load decoupling device are freely suspended. Here the small carrier to which the sinker is attached is seated on an internal support. In this so-called 'zero-position' the balance can be tared and calibrated at all times even during a sequence of measurements. The difference in balance readings between the 'tare' and 'measuring' positions determines the buoyancy forces acting on the sinker and its carrier. The volume of the latter is less than 0.4 % of that of the sinker.

The NEL Primary Standard Liquid Densitometer utilises a single sinker: a solid cylinder of fused quartz with a volume of some 26 cm³. Only a single sinker need be used with liquid systems since the buoyancy forces are considerable, of the order of 25 to 45 % of the weight of the sinker, and the uncertainties in force measurement are negligibly small. Fluid density is calculated from

$$\rho = \frac{m_S - m_S^*}{V_S(t, p)} \quad (7)$$

where m_S is the true (vacuum) mass of the sinker, m_S^* is its apparent mass (weighed in a fluid-filled test cell) and $V_S(t, p)$ is the temperature and pressure-dependent volume of the sinker.

At each temperature and pressure a minimum of ten determinations of the apparent mass of the sinker are recorded and the mean value used in Equation 7. Figures 3 and 4 show examples of the stability of weighing the sinker at various conditions for measurements undertaken in 1999 and 2007 respectively, illustrating that the magnetic suspension coupling and weighing system is capable of determining the weight of the sinker in the fluid to within a few parts per million.

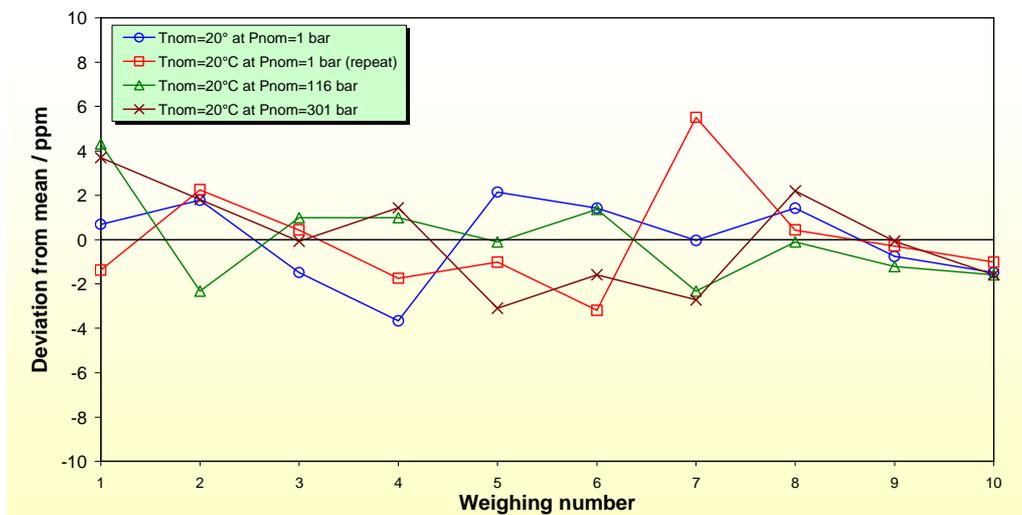


Fig. 3 - Example of weighing stability, toluene sample, 1999

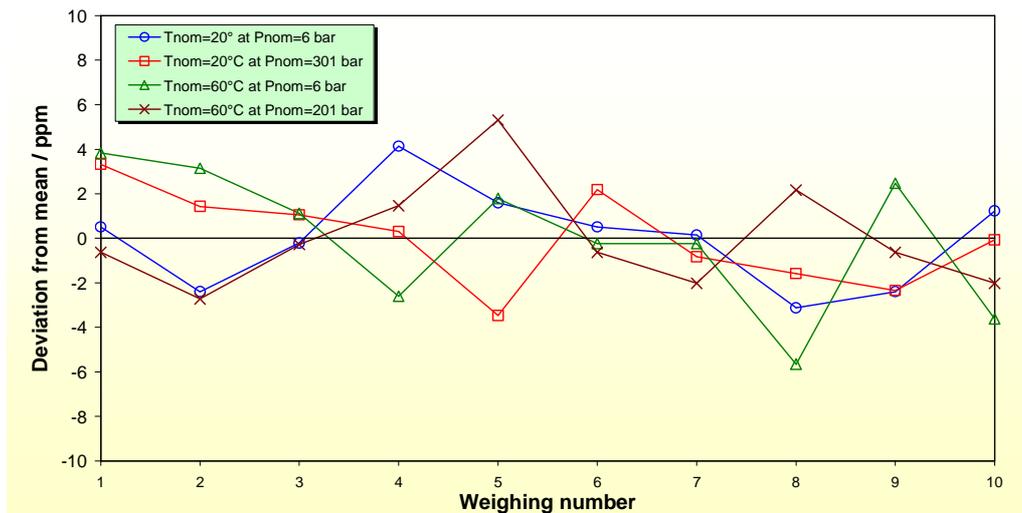


Fig. 4 Example of weighing stability, toluene sample, 2007

The major uncertainty associated with this method of measurement arises from the determination of the volume of the sinker and its dilation with temperature and pressure. The volume of the latter is established by careful weighing of the fused quartz sinker and its

associated stainless steel suspension in both air and pure water at near ambient conditions using a purpose-built apparatus. Using this apparatus the volume of the fused quartz cylinder has been established to within 30 ppm and the vacuum, or true, mass of the sinker has been established to within 3 ppm.

The volumes of the principal components of the densitometer are subject to dilation with both temperature and pressure; appropriate corrections are applied. The maximum total uncertainty in the dilation of the fused silica sinker due to the combined effects of temperature and pressure is estimated to be within 60 ppm over the operational range of the densitometer. The maximum contribution to the uncertainty in the calculation of liquid density arising from the dilation of the suspension cage and hook of the densitometer is around 1 ppm.

4.1.2 Supporting Systems

The densitometer is hung from a horizontally levelled platform mounted on robust aluminium alloy structures, as shown in Figure 5. The microbalance is mounted on the platform and the upper part of the suspension couplings is enclosed in a transparent housing. This can be fed from a dry-air source with a dew-point of -80 °C to prevent condensation of atmospheric moisture on the upper connecting rods and electromagnets when the densitometer is used at sub-ambient temperatures.



Fig. 5 - NEL Primary Standard
Liquid Densitometer

The magnetic-suspension couplings, the housing and the densitometer are contained in an oil-filled bath positioned beneath the platform. The bath consists of two Dewar vessels mounted concentrically and has provision, in the annular space between each Dewar, for both heating and cooling. Good circulation of the bath fluid is provided by magnetically-driven screw impellers mounted in the base of the outer Dewar vessels. The control temperature of the bath is monitored by a 25 Ω standard platinum-resistance thermometer positioned some distance above the screw-impeller. The thermometer is monitored through a data acquisition system and the power inputs to the heating/cooling circuits are adjusted using PID control software. The bath temperature is measured using four 25 Ω standard platinum-resistance thermometers attached around the periphery of the pressure vessel.

The temperature stability of the bath is within ± 1 mK over the entire operating range and the absolute temperature can be set to within a few millikelvins of the desired conditions. The total uncertainty in the temperature of the fluid in the densitometer is estimated to be 4 mK (at $k=2$).

The densitometer is provided with a sample loading system that enables test fluids to be introduced to the densitometer in a controlled manner. The pressure vessel and connecting pipework can be purged with nitrogen or methane, before being evacuated to very low pressure (~ 15 -20 Torr). This ensures that the system is then completely filled by the test fluid, with no vapour space.

A gas-operated pressure balance of the highest metrology class is used to provide reference gauge pressures accurate to within some 5 parts in 10^5 . Atmospheric pressure is measured by means of a calibrated digital barometer accurate to within 30 Pa. The pressure of the fluid under test in the densitometer is obtained with reference to the pressure of nitrogen in the gas-operated balance through a differential pressure indicator (DPI). The uncertainty in the

measurement of differential pressure is within 100 Pa. The absolute pressure of the fluid under test in the densitometer is obtained from the atmospheric pressure, gas-operated pressure balance and DPI readings, corrected for temperature effects and pressure heads in the connecting lines as necessary. The uncertainty in the calculated total pressure of the fluid in the densitometer is assessed as less than 0.03 % (at $k=2$).

4.1.3 Primary Standard Liquid Densitometer Performance

For each fluid studied in the NEL Primary Standard Liquid Densitometer, data from the measurements are fitted to an equation of the form

$$\rho_{t,p} = 1000 \sum_{i=1}^{13} a(i) \theta^{m(i)} \pi^{n(i)} \quad (8)$$

where θ is the reduced temperature, $\theta = t / 100$ for t in degrees Celsius on ITS90,
 π is the reduced pressure, $\pi = p / 30$ for p in MPa,
 $a(i)$ are coefficients and
 $m(i)$ and $n(i)$ are exponents.

This form of equation is capable to fitting the experimental data to within ± 10 parts per million. As the total uncertainty in the measured values of density is assessed as 0.01 % at a 95 % confidence level, values calculated from Equation 8 will have an uncertainty not exceeding 0.012 % across the temperature range from 0 to 100 °C at pressures up to 30 MPa.

As part of an international inter-comparison exercise carried out in 1999 [11], the NEL Primary Standard Liquid Densitometer was used to measure the density of a sample of ultra-pure toluene. One of the fluids chosen as a transfer standard for the JIP was toluene, allowing a comparison with the previous data and other literature data for toluene [10]. Figure 6 compares the NEL experimental data with values at corresponding pressures and temperatures calculated from an equation obtained by PTB (Physikalisch-Technische Bundesanstalt, Germany) from measurements undertaken using a similar magnetic suspension densitometer system.

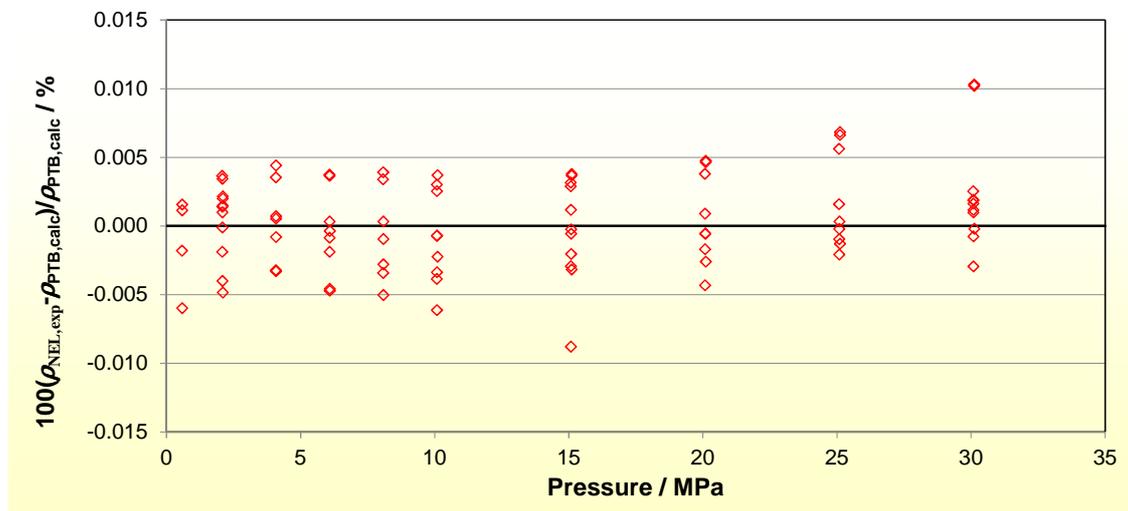


Fig. 6 - Comparison of PTB and NEL toluene density measurements

Across the full temperature and pressure range (20 to 100 °C and from atmospheric pressure up to 30 MPa) the two data sets have an average difference of 0.005% with all the data lying within ± 0.0075 % of the mean. PTB assessed the overall uncertainty of their experimental data as ± 0.0075 % (at $k=2$) and the uncertainty of values calculated from their fitting equation as ± 0.009 %. The overall uncertainty of the NEL experimental data from the 2007/2008 measurements has been assessed as ± 0.009 % (at $k=2$) and so the two sets of data agree to

well within their combined uncertainty, confirming the performance of the NEL Primary Standard Liquid Densitometer.

4.2 NEL Industrial Densitometer Calibration Facility

The NEL Industrial Densitometer Calibration Facility consists of an air thermostat in which an in-line or insertion type densitometer can be mounted. In conjunction with a pressurising system, this enables the temperature and pressure of the fluid in the densitometer to be set and maintained at any set-point across the range from 10 to 110 °C at pressures between 0.1 and 20 MPa and the period output signal from the densitometer to be measured.

From the measured temperature and pressure of the fluid in the densitometer the true density of the fluid at those conditions can be calculated from an equation of state for the fluid, derived from data obtained from measurements made on the fluid in the NEL Primary Standard Liquid Densitometer. The fluid density can then be compared with the value determined by the industrial densitometer.

4.2.1 Principle of Operation

In-line densitometers are mounted vertically within the air thermostat, as shown in Figure 7. To minimise torque-loading and mis-alignment effects, the densitometer is only clamped rigidly at the bottom flange and supported loosely at its mid-point and top. The fluid within the densitometer is circulated slowly, to ensure that it is at a uniform temperature throughout.



Fig. 7 - NEL Industrial Densitometer Calibration Facility

Temperature control is provided by an insulated enclosure plus heating and cooling circuits. A series of coils in the base of the enclosure are connected to an external circulation bath capable of maintaining the temperature of the coils between -80 and 20 °C. This provides a constant background temperature against which the heating circuit operates. The control temperature of the enclosure is monitored by a 25 Ω standard platinum-resistance thermometer positioned close to the mid-point of the enclosure. The thermometer is monitored by a control computer and the power inputs to the heating/cooling circuits are adjusted using PID control software.

The temperature of the air thermostat is stable to 5 mK over its operating range and the absolute temperature can be set to within a few millikelvins of the desired conditions. The temperature of the fluid within the industrial densitometer is measured by two 25 Ω standard platinum-resistance thermometers in the manifolds at the top and bottom of the fluid circulation loop. The total uncertainty in the temperature of the test fluid in the densitometer is assessed as 5 mK (at $k=2$).

The facility is provided with a sample loading and pressurising system that enables the densitometer under test to be filled with a transfer standard fluid and the pressure of that fluid to be set and maintained at pressures between 0.1 and 20 MPa. An external pressurising circuit generates and controls the pressure of the fluid in the densitometer under test. A computer-controlled pump supplies hydraulic fluid to a piston-in-cylinder interface to the transfer standard fluid. The feedback signal for the control system is provided by a

Quartzdyne pressure transducer on the transfer standard fluid side of the piston-in-cylinder interface.

During the tests undertaken as part of the JIP, the pressure of the transfer standard fluid in the densitometer under test was obtained with reference to the pressure of nitrogen in a gas-operated balance through a Yokogawa differential pressure transducer. The transducer was calibrated across a range of differential pressures from -5000 to 5000 Pa at static pressures from 2.5 to 15 MPa and a function derived to calculate differential pressure from the output voltage. The uncertainty in the measurement of differential pressure was within 50 Pa. The absolute pressure of the transfer standard fluid in the densitometer was obtained from the atmospheric pressure, gas-operated pressure balance and Yokogawa differential pressure transducer, corrected for temperature effects and pressure heads in the connecting lines as necessary. The uncertainty in the calculated total pressure was assessed as 0.03 % (at $k=2$).

Over the full operational range of the facility the total uncertainty in density of the transfer standard fluid (arising from uncertainties in its temperature, pressure and calculated value from the equation of state) is 0.02 % at a 95 % confidence level.

4.3 Transfer Standard Fluids

To be considered for use as true transfer standard fluids, fluids must either be single components or stable mixtures of known composition. Such fluids have the advantage that once their PVT behaviour has been established (using the NEL Primary Standard Liquid Densitometer) they can then be used in any other (transfer) facility without further characterisation, thus providing much closer traceability to primary standards. As part of the JIP initiation a survey was carried out to establish typical operating conditions of densitometers in North Sea applications. The data from the survey, summarised in Table 1, formed the basis of the test matrices for the densitometers and was also used to identify transfer standard fluids.

Table 1 - Densitometer Operating Conditions

Parameter	Full range	Most common range
Temperature / C	8 - 105	20 - 80
Pressure / bar	5 - 140	5 - 50
Density / kg m ⁻³	530 - 1180	700 - 850
Viscosity / mPa s	0.3 - 40	2 - 8

Whilst it would be ideal to cover the full operational range, in practice it would be very difficult to find suitable fluids. By agreement with the JIP sponsors, it was therefore decided to concentrate on the most common range, allowing, in principle, the use of four fluids.

Whilst there is still a degree of debate within academic circles about the relative merits of pure fluids or mixtures of accurately known composition as transfer standard fluids, for industrial calibration applications, pure fluids offer several advantages. All four of the selected transfer standard fluids are single components, thus ensuring that, within the limits of their stated purity, their composition will not change as a function of temperature, pressure or time, as could be the case for mixtures of hydrocarbons or other fluids. Furthermore, the four selected transfer standard fluids are all readily available in sufficient purity from normal laboratory chemical suppliers, thus requiring no further preparation (and hence eliminating potential contamination issues).

In addition to providing coverage of the key parameters, the fluids must be readily available in sufficiently high purity at reasonable cost. Iso-octane (2,2,4-trimethylpentane), toluene, and di-(2-ethylhexyl) sebacate meet these criteria, covering the low density / low viscosity, high density / low viscosity and high density / high viscosity conditions respectively. However, to a first approximation, fluid density and viscosity are correlated, making it difficult to find a low density / high viscosity fluid. Several potential low density / high viscosity fluids were identified but were discarded, either because they were too expensive or were unavailable in sufficient

purity. Iso-butanol (2-methyl propan-1-ol) was eventually selected as the fourth fluid; whilst neither particularly low density nor high viscosity, it does fall within the most common range and is readily available in high purity.

The fluids used in this work were obtained from Sigma-Aldrich; their key parameters are summarised in Table 2. All the fluids were used as received, with no additional purification or processing.

Table 2 - Transfer Standard Fluids

Fluid	Density at 20 °C kg m ⁻³	Viscosity at 20 °C mPas
Toluene	866.6	0.586
Iso-octane (2,2,4-trimethyl pentane)	692.9	0.502
Di (2-ethylhexyl) sebacate	915.6	21.3
Iso-butanol (2-methyl propan-1-ol)	801.8	4.03

5 INDUSTRIAL DENSITOMETER CHARACTERISATION

The survey of operating conditions for densitometers in North Sea applications also determined the most commonly used types. By far the most common was the Solartron Mobrey 7835 (now branded Micro Motion) from Emerson Process Management. The JIP sponsors therefore decided to characterise two of these instruments; one new device straight from the manufacturer (SN 354583) and one device which had been in service in a North Sea application (SN 355118).

5.1 Results

Both densitometers were installed in turn in the NEL Industrial Densitometer Calibration Facility. The period output signal from the densitometer was connected in accordance with the manufacturer's instructions to a traceably calibrated high resolution timer.

For each of the four transfer standard fluids a test matrix covering the temperature range from 20 to 100 °C at pressures up to 100 bar was used. At each nominal temperature and pressure the exact temperature, pressure and period output were recorded. The data were then processed by using the appropriate densitometer coefficients to convert the period to a density and this value compared to the value calculated at the corresponding conditions from the appropriate reference equation for the transfer standard fluid samples measured in the NEL Primary Standard Liquid Densitometer between 2007 and 2008.

Both densitometers were initially supplied with single-range pressure coefficients but three-range coefficients were supplied by Emerson Process Management in July 2007 for the new unit (SN 354583). In addition, as part of their contribution to the project, they also carried out a full re-calibration of the used unit (SN 355118) and provided both single- and three-range pressure coefficients, to allow full comparison of the two units.

Figure 8 shows the percentage differences between the densities calculated using the measured densitometer periods plus coefficients for the new densitometer (SN 354583) and values calculated from the reference equation for toluene at 20 and 100 °C.

At 20 °C it is clear that the change from the single- to three-range pressure coefficients significantly reduces the difference between the densitometer-determined value and the reference value for the fluid density for this particular densitometer. However, at 100 °C there is still a clear, and significant, pressure-dependent difference between the values.

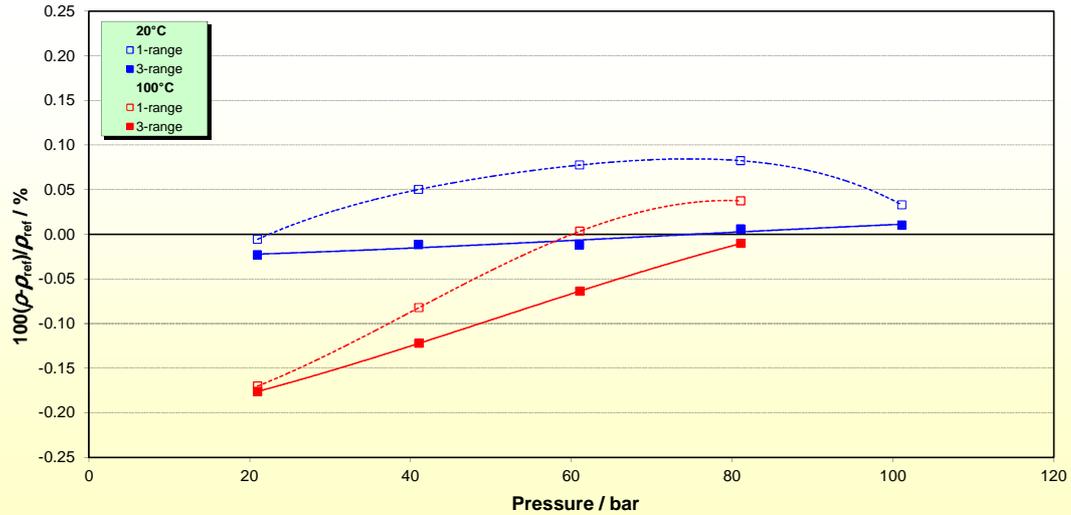


Fig. 8 - Deviations for Toluene for Densitometer SN 354583

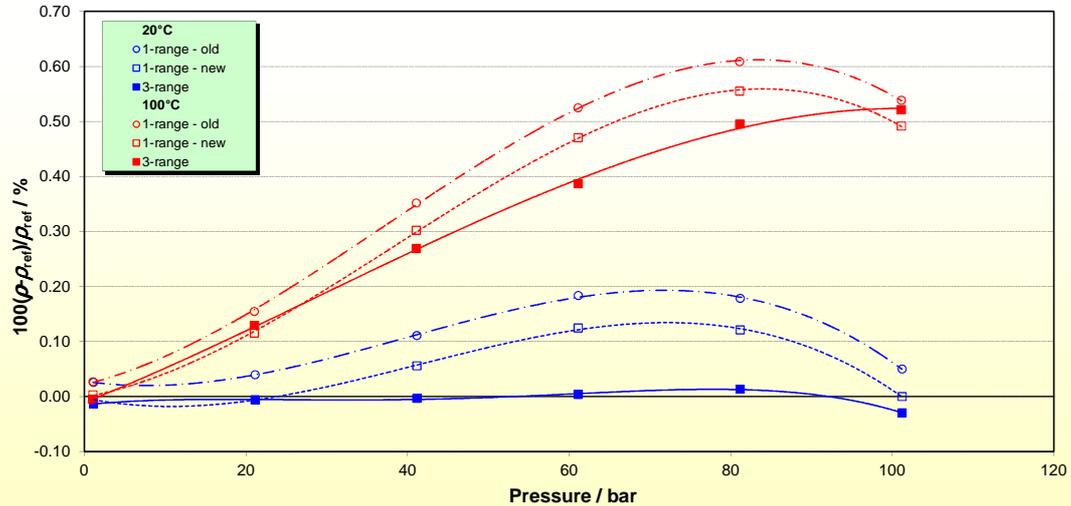


Fig. 9 Deviations for Toluene for Densitometer SN 355118

Figure 9 shows the corresponding deviations for the used densitometer (SN 355118). Once again, at 20 °C it is clear that the change from the single- to three-range pressure coefficients significantly reduces the difference between the densitometer-determined value and the reference value for the fluid density for this particular densitometer but at 100 °C the deviations are even more significant.

Similar patterns were obtained with the other three transfer standard fluids in each densitometer but there were significant differences between the fluids in a densitometer.

6 DISCUSSION

Whilst the forms of Equations 4 to 6 are superficially simple, substitution of Equation 4 in Equation 5 for ρ_0 and then substitution of the expanded expression in Equation 6 leads to an expression with seventeen coefficients and complex cross-terms in τ , $(t-t_0)$, $(p-p_0)$ and powers thereof. Due to the cross-coupling between the temperature and pressure coefficients, and depending on the fitting method used, small systematic errors in the fluid densities used to calculate the temperature corrections coefficients could lead to the effects shown in Figures 8 to 10.

In view of the previous practice of determining the temperature coefficients (K_{18} and K_{19}) for each densitometer only at atmospheric pressure and the pressure coefficients (K_{20A} , K_{20B} , K_{21A} and K_{21B}) only at the reference temperature (20 °C), it is not surprising that significant errors can occur.

On the basis of the deviations observed for the two densitometers characterised as part of this project plus data from densitometers calibrated by NEL directly for individual customers, it is possible to indicate the likely financial exposure to operators using densitometers calibrated with the previous procedures. A conservative estimate of the average error is of the order of 0.15 %. This will translate directly into an allocation error in a pipeline system. For a field with a production of 5,000 barrels per day, 0.15 % error in allocation due to a 0.15 % error in fluid density measurement will lead to an annual error of 2,738 barrels. Taking an average price of \$120 per barrel, this leads to a potential exposure of ~£212,000 per annum. It should be noted that this error could be positive or negative for an individual densitometer, but it should be noted that the financial exposure far exceeds the typical calibration costs.

In addition there are taxation implications. In 2011 government revenue from the UK's oil and gas resources was £11bn. However, the fiscal regime is not uniform across North Sea assets - some pre-1993 fields continue to pay Petroleum Revenue Tax (PRT). Allocation between PRT- and non-PRT-paying fields in shared pipelines depends, as noted above, on measurement of density.

On the basis of the work undertaken in the JIP, a number of recommendations were made, the most important of which was that densitometers should be calibrated at their anticipated operating conditions, i.e. simultaneously at temperature and pressure, using one or more transfer fluids, the density of which has been determined across the required temperature and pressure range with an uncertainty not exceeding 0.01 %, directly traceable to national standards.

On 1st March 2010, DECC issued a statement that, based on the JIP findings:

“It is therefore proposed that from July 2011, densitometers used in fiscal applications should be calibrated following the procedures set out the JIP report.”

and the recommendations have been incorporated in the current version of the Guidance Notes [12].

Emerson Process Management (as the maker of the most common type of densitometer used in the North Sea) has invested in a new calibration facility which will be capable of calibrating densitometers at elevated temperatures and pressures simultaneously. However, this facility is taking longer to come on-stream than originally anticipated, so NEL has modified its Industrial Densitometer Calibration Facility and is currently calibrating densitometers to the new procedure.

7 CONCLUSIONS

Accurate measurement of density is critical for the oil industry since oil flow in pipelines is largely measured by volume and conversions involving density are necessary for accurate financial reporting, fair trade and taxation. The discovery of an error in densitometer measurements led to a loss of confidence in the systems used to allocate production in shared transportation systems.

Building on the huge wealth of knowledge on instrumentation and physical properties of fluids plus a unique facility specifically for the accurate measurement of the density of fluids at high pressure and temperature, NEL provided the impetus for an industry solution. As a result, the UK oil industry and the regulator have regained confidence in the measurement of oil density and hence in oil production.

It is unlikely that a solution could have been found in a timely and cost-effective manner without the existence of the NMS facility at NEL. DECC was aware of the existence of the facility when the initial problem was identified and with the support of the NMS, through NEL, was therefore able to recommend the JIP as the best approach.

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9 NOTATION

$a(i)$	Coefficient of density fit		m_s	True (vacuum) mass of sinker	kg
$m(i)$	Exponent of density fit		m_s^*	Apparent mass of sinker	kg
$n(i)$	Exponent of density fit		p	Pressure	bar
f	Oscillation frequency	s^{-1}	t	Temperature	$^{\circ}C$
K	Spring constant	$kg\ s^{-2}$	V_s	Volume of sinker	m^3
K_0	Densitometer constant	$kg\ m^{-3}$	<u>Greek symbols</u>		
K_1	Densitometer constant	$kg\ m^{-3}\ s^{-1}$	θ	Reduced temperature	-
K_2	Densitometer constant	$kg\ m^{-3}\ s^{-2}$	π	Reduced pressure	-
K_{18}	Densitometer constant	K^{-1}	ρ	Fluid density	$kg\ m^{-3}$
K_{19}	Densitometer constant	$kg\ m^{-3}\ K^{-1}$	τ	Oscillation period	s
K_{20A}	Densitometer constant	bar^{-1}	<u>Subscripts</u>		
K_{20B}	Densitometer constant	bar^{-2}	0	Reference conditions	
K_{21A}	Densitometer constant	$kg\ m^{-3}\ bar^{-1}$			
K_{21B}	Densitometer constant	$kg\ m^{-3}\ bar^{-2}$			
M	Mass of fluid + tube	kg			

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