



Traceable Calibration of Liquid Densitometers

***Norman Glen
TUV NEL Ltd***

Traceable Calibration of Liquid Densitometers

Norman Glen, TUV NEL Ltd

1 INTRODUCTION

Density measurement is a key element of both mass and volume flowrate measurement in the oil industry. The most widely implemented approach for mass flow measurement is to use a volumetric flowmeter and a densitometer. In this case, the uncertainty in mass flow measurement is dependent equally on the uncertainty in volumetric flowmeter 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.

The essential requirements of a density measurement system are that:

- calibrations should only be carried out using instruments that form part of a calibration chain traceable to national standards and
- densitometers should be checked and calibrated regularly at actual operational conditions.

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).

However, the calibration of most industrial densitometers is undertaken using fluids whose physical characteristics are significantly different to the actual working or operational fluids. Additionally, the range of pressures and temperatures at which the instruments are normally calibrated is limited to near ambient conditions but many densitometers, particularly those used in offshore applications, operate under high pressure, high temperature conditions. 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.

Whilst the existence of these effects has been recognised, it was 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 a temperature different from the reference temperature. This has significant implications for fields operating in common transportation systems, where the mass allocations are based on densitometer readings. As a result, the Aberdeen-based Licensing and Consents Unit of DTI's Energy Group identified a need for research into practical methods for the 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. A Joint Industry Project involving oil companies, densitometer suppliers, DTI and NEL was therefore set up to address that requirement [1].

2 BACKGROUND

The aims of this project are:

- to give confidence in high temperature and pressure densitometer measurements by developing well characterized transfer standard fluids and
- to establish a calibration procedure that ensures traceability to National Standards, making use of the existing National Fluid Density Standard Facilities for high temperatures and pressures developed under previous Flow Programmes.

Using the National Density Standard Facilities, two densitometers of a commercial design will be calibrated across a range of temperatures and pressures using transfer-standard fluids characterized in the Primary Liquid Density Facility. Results from each densitometer will be assessed for accuracy and stability across the range chosen. The test programme will investigate the influence of fluid properties (density and viscosity), densitometer temperature and pressure on the calculated densities provided by the densitometers.

The calculated density values produced by the densitometers will be compared with the accurately known values for the transfer fluids and any differences noted. This will provide an assessment of the suitability of the current calculation procedure to convert measured oscillation periods to densities accurately across the full operational temperature and pressure range required for UK Continental Shelf use. In the event that significant differences are found, better calculation procedures will be developed.

As part of previous Flow Programmes, DTI funded the establishment of density standard facilities at NEL [2]. These consist of two primary standard densitometers, one each for liquids and gases. In addition, a transfer standard facility for the calibration of liquid densitometers (insertion and in-line devices) was also developed. The existence of the primary liquid densitometer and the transfer standard facility means that this project does not have to invest in costly and time-consuming facility development.

The National Fluid Density Standard Facilities were maintained in a mothballed state during the 2002-2005 Flow Programme. The task of bringing the facilities back up to full operational standard has been undertaken as a project within the 2005-2008 Flow Programme. The main part of the project, characterization of transfer standard fluids and characterization of reference densitometers, is being cash co-funded through a Joint Industry Project (JIP). To date, 13 operators (Talisman Energy (UK) Ltd, BP Exploration Operating Co Ltd, Paladin Resources Ltd, Kerr-Mcgee North Sea (UK) Ltd, BG International (CNS) Ltd, ChevronTexaco, Marathon Oil UK Ltd, Amerada Hess Ltd, Shell UK, Total E & P UK plc, ConocoPhillips, Exxonmobil and Nexen) and the densitometer manufacturer Solartron have joined the project. Discussions are also ongoing with other operators and densitometer suppliers. DTI Energy Group, Licensing and Consents Unit, Aberdeen, have also joined the project.

3 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 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_1 and V (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 $K_0 = -M_1/V$ and $K_2 = K/4\pi^2V$, 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 [3], 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 and pressure 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 a knowledge of the density of each calibration fluid at the corresponding conditions. Accepted practice however has been to calibrate at one reference temperature (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

$$\rho_T = \rho_0 \{1 + K_a(T - T_0)\} + K_b(T - T_0) \quad (5)$$

where ρ_0 is the density at the reference calibration temperature T_0 and

$$\rho_{T,P} = \rho_T \left\{ 1 + K_c(p - p_0) + K_d(p - p_0)^2 \right\} + \left\{ K_e(p - p_0) + K_f(p - p_0)^2 \right\} \quad (6)$$

Current industrial calibration practice is to calibrate each densitometer in a test rig using three fluids at atmospheric pressure and the reference pressure, the density of each test fluid being measured by two in-line transfer standard densitometers. The transfer standard densitometers are periodically calibrated using fluids of accurately known density. From at least 1986 accepted practice was to check the temperature coefficients (K_a and K_b in equation 5) of the transfer standard densitometers using air and then apply corrections for use with other calibration fluids and assume that no systematic bias was introduced. However, a note issued by the Licensing and Consents Unit of DTI's Energy Group [4] summarising a review carried out by industry, has found that there is a small but systematic 'offset error' when a densitometer is operated at a temperature different from the reference temperature.

Although the magnitude of the particular offset error identified by DTI seems small, $0.014\text{kg m}^{-3} \text{K}^{-1}$, a number of UK Continental Shelf fields operate with measuring stations at temperatures approaching 100°C. For a field producing 50,000 barrels per day the mis-measurement at the platform would be of the order of 25,000 barrels per annum. A similar effect will occur at the on-shore terminal. If the oil from a number of fields has been fed in to a common pipeline the allocation to each field is based on the 'measured' mass fed in by each. Clearly the actual mis-allocations will depend on the temperatures of each off-shore measuring station, the flow rates and the temperature of the on-shore measurements but could easily run to 10s of thousands of barrels per annum for each field. Assuming an average price of £12 per barrel, this amounts to £6 million over the 20 odd years this systematic error has been occurring. The mis-measurement on condensate fields will be greater than that for oilfields, as the relative error in density measurement is greater for lower-density product; in addition, condensate production tends to be at relatively high temperatures. Taken over the whole of the UK production, mis-allocation errors arising from this effect alone could run to several million pounds per annum and possibly hundreds of millions over a 20 year period.

In addition to this specific point, the review has raised a number of issues with regard to the whole calibration process and the calculation methodology. NEL have 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 [5-6]. For liquids, this clearly demonstrated the coupling between density and viscosity: it is possible to optimise a vibrating element to respond to either density or viscosity as a first-order effect but the other property is always present as a second-order effect. 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. Furthermore, a complete characterisation of a vibrating tube densitometer would also require to investigate additional effects including fluid velocity, torque loading, mounting misalignment etc.

4 TECHNICAL APPROACH

The NEL Primary Standard Densitometers are both based on the Archimedes buoyancy principle in which the density of a fluid is determined from measuring the apparent mass of a body immersed in the fluid:

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

where m_S is the 'true' mass of the sinker, m_S^* is the apparent mass of the sinker when surrounded by the fluid and V_S is the volume of the sinker. m_S can be determined by vacuum weighing and V_S by calibration with water. Because of the small differences between the true and apparent masses when working with gases the NEL Primary Standard Gas Densitometer uses a dual-sinker system. For the Primary Standard Liquid Densitometer that will be used for this work a single-sinker system is sufficient (Figure 1). A magnetic suspension coupling transmits the apparent mass of the sinker through the pressure vessel and thermostated bath to a precision microbalance.

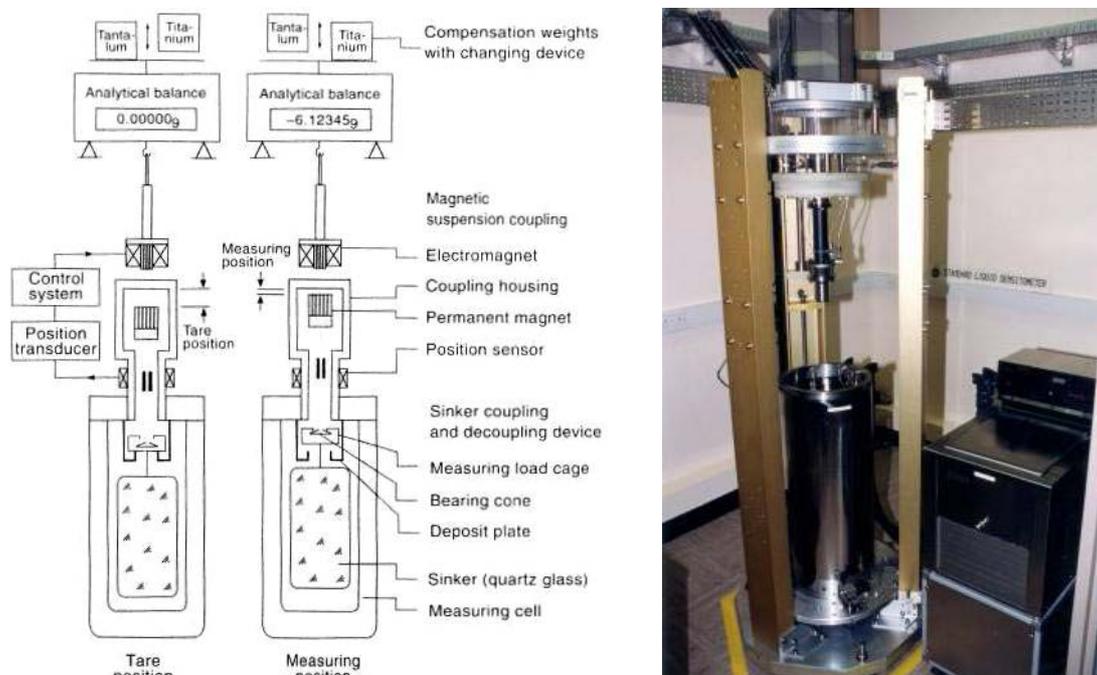


Fig. 1 – NEL Primary Standard Liquid Densitometer

The Primary Standard Liquid Densitometer is capable of determining the density of liquids across the temperature range from -40 to 150°C at pressures from 0.1 to 30 MPa with an expanded uncertainty of 0.015% (at 95% confidence).

The Transfer Standard Facility for the calibration of liquid densitometers consists of a thermostated enclosure with fluid pressurisation (Figure 2). The temperature of the enclosure can be controlled across the range from 10 to 125°C with an expanded uncertainty of 0.005K (at 95% confidence) and the fluid in the densitometer controlled between 0.1 and 20 MPa with an expanded uncertainty of 0.01% (at 95% confidence).

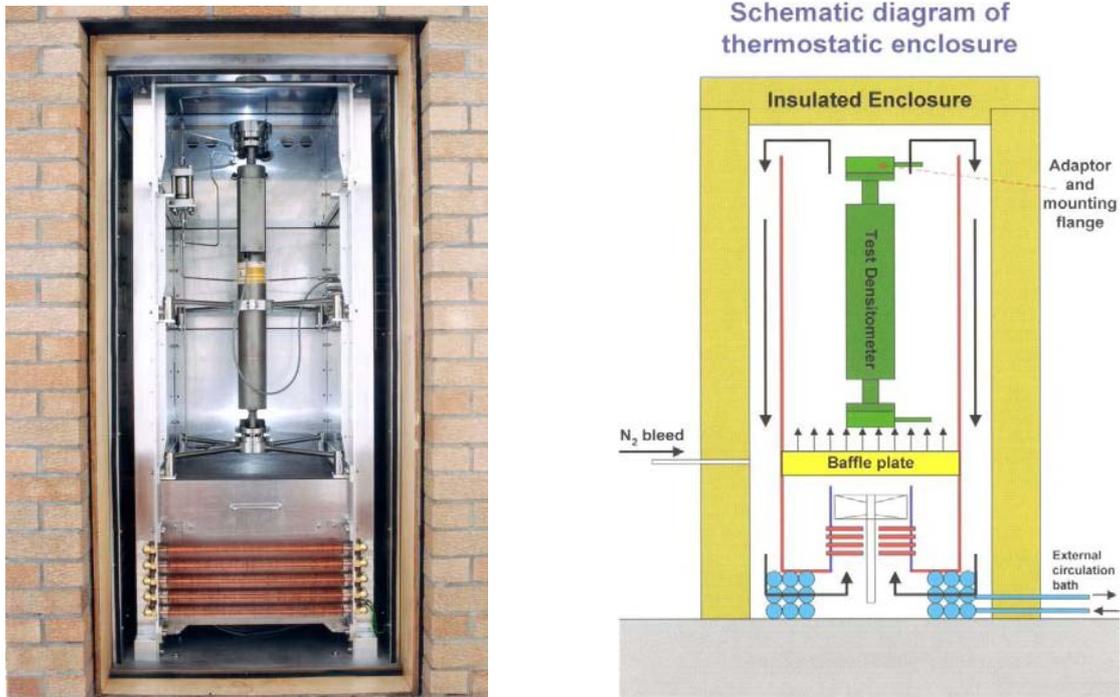


Fig. 2 – NEL densitometer transfer standard facility

The original concept for the Transfer Standard Facility envisaged that the facility would be directly linked to the NEL Primary Standard Liquid Densitometer. Whilst this has the merit that the fluid in the densitometer under calibration is the same as that in the Primary Standard Liquid Densitometer and at identical conditions, thus minimising the uncertainty in the fluid density, it has a number of practical drawbacks. In particular, the time required for the Primary Standard Liquid Densitometer to reach equilibrium and make a measurement is substantially longer than the time required in the Transfer Standard Facility. In addition, the task of cleaning the Primary Standard Liquid Densitometer is time-consuming, particularly if it has been filled with difficult fluids such as heavy oils.

In view of these considerations, a better approach is to use stable, accurately characterised transfer standard fluids. The first task is therefore the selection of a sufficient number of suitable fluids. As noted in Section 3, there is a coupling between fluid density and viscosity in an oscillatory densitometer and it is envisaged that a minimum of four fluids will be required to cover the density and viscosity ranges which are encountered across the full temperature and pressure range of operation of UK offshore oil facilities.

To be considered for use as true transfer standard fluids, the 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.

The Primary Standard Liquid Densitometer and the Transfer Standard Facility have now been fully re-commissioned. In addition to recalibration of all the instrumentation a number of minor modifications have been made to both facilities to simplify operation, particularly with high viscosity fluids. A survey of the JIP members provided information on current and future densitometer operating conditions. The temperatures, pressures and densities determined from the survey are all within the range of capabilities of both the primary standard densitometer and the transfer standard facility. Potential transfer standard fluids have also been identified and work is in progress on the first fluid.

4 CONCLUSIONS

Completion of the overall project (re-commissioning the facilities and undertaking the measurement programme) will provide the first stage in establishing a calibration procedure to provide traceability to National Standards for densitometers used in the UK sector of the North Sea and Continental Shelf. According to Douglas Griffin, DTI Oil & Gas Regulator,

“Errors in flow measurements using densitometers could run to several million pounds per annum and possibly amount to hundreds of millions over the last 20 years. This is the single biggest mis-measurement issue in the history of oil production and the Flow Programme has provided the impetus for the whole industry to address the issue”.

In addition to providing traceability for calibrations, the project is expected to lead to standards for the calibration of oscillatory densitometers for liquid service.

5 REFERENCES

- [1] Liquid Densitometer: Traceable calibration of liquid densitometers. A Joint Industry Project Proposal from NEL for the traceable calibration of liquid densitometers. Proposal FC03140, February 2005, NEL.
- [2] Watson, J. T. R., Ferguson, D. and Ryan, G. National standard facilities for the density of liquids and gases at elevated pressures. Paper presented at the Density Seminar held in the James Watt Conference Centre, NEL, on 24 October, 1994, in conjunction with the North Sea Flow Measurement Workshop, 1994.
- [3] Glen, N. F. Viscosity coefficient measurement at elevated pressure. PhD Thesis. University of Glasgow, Glasgow, 1985.
- [4] Griffin, D. Solartron Mobrey Densitometer Calibration Issue. DTI Energy Group, Licensing and Consents Unit, Aberdeen, 2004.
- [5] Retsina, T. Design of a vibrating rod densitometer for liquids at high pressure. PhD Thesis, Imperial College, London, 1987.
- [6] Padrel de Oliveira, C. M. B. Viscosity of liquid hydrocarbons at high pressure. PhD Thesis, Imperial College, London, 1991.