Coriolis flowmeter for commercial accounting of crude oil

M Yu Prakhova and A N Krasnov
Ufa State Petroleum Technological University, 1, Cosmonavtov ave., Ufa, 450062, Russia
E-mail: ufa-znanie@mail.ru

Abstract. Commercial accounting of oil and petroleum products is carried out using so-called CQCSs or crude quality control systems. The main measurement tool in the CQCS is a flowmeter: volumetric one for the indirect dynamic method and mass flowmeter for the direct dynamic method. The operation of any oil flowmeter varies depending on conditions of its verification in flow labs and depends on a large number of mutually affecting external factors. The total additional error from their action can significantly exceed the error declared in the measuring instrument type description. Therefore, studies of the influence of both experimental factors and through mathematical models are relevant.

The article simulates a change in the operation of a sensitive element of a Coriolis flowmeter - a flow tube - due to the deposition of paraffin on its inner surface, which is released under certain conditions from crude oil. The calculations performed on the model in the Aspen HYSYS software environment showed that deposits having accumulated within one year cause an error comparable with the requirements of regulatory documents for the accuracy of commercial accounting. Therefore, it is recommended to carry out additional monitoring of metrological characteristics in the verification interval in case of accounting of highly paraffinic oils.

1. Introduction
One of the main operations in the production and transportation of liquid and gaseous hydrocarbons is their operational and commercial accounting. These types of accounting differ from each other by accounting purposes and, as a consequence, requirements for accounting methods and instruments and the reliability of results [1]. Operational accounting is carried out within the enterprise for the purpose of operational control or evaluation of the results of production and economic activities of individual units. The requirements for the quality of operational accounting are established by the enterprise itself. Commercial accounting is carried out during transportation and acceptance of oil and petroleum products between suppliers and consumers: first, oil is transported from the producing companies to the trunk oil pipeline system (TP), and then the transporting company transports the oil to final consumers, for example, oil refineries. Commercial accounting is also carried out upon receipt and shipment of oil and petroleum products by rail and oil tank trucks. Another facility where accounting operations are carried out constantly is tank farms. In commercial accounting, the requirements for the used measurement methods, measuring instruments, measuring accuracy and organization of accounting are determined by standards, for example [2–5], and other regulatory documents and agreements of the parties adopted in the established manner.

The main accounting instruments at present are crude quality control systems (CQCSs). A CQCS (Fig. 1) includes a filter unit, a meter run unit (MRU), a crude quality measuring unit (CQMU), a verifier unit (stationary tube-piston unit (TPU) or compact prover), as well as the necessary shut-off and control...
valves and piping. All necessary calculations are performed by the information processing system (IPS) located in the CQCS control room.

Measurement of any oil quality process parameters or indicators is carried out in all CQCS components, which allows the CQCS to be considered as a measuring system designed for direct or indirect dynamic measurements of mass and quality indicators of oil corresponding to [6] and petroleum products. Therefore, each CQCS has a measuring instrument type approval certificate.

CQCSs implement a direct or indirect dynamic accounting method. According to [3], the direct method of dynamic measurements of the mass of oil and petroleum products is a method based on direct measurements of the mass of the product using mass meters in pipelines. The indirect method of dynamic measurements is a method based on measurements of the density and volume of a product in pipelines with the subsequent calculation of its mass.

If accounting and settlement operations between the supplier and the consumer are carried out in the fields, before the oil treatment station, then crude quality control systems (CQCS) are installed there; their feature is the measurement of the amount of associated petroleum gas along with the measurement of the quantity and quality of produced oil in compliance with the requirements of [7]. CQCSs operate in less favorable conditions due to the unstable composition of oil, the flow rate of which is measured. It contains a sufficiently large amount of impurities, including those able to form solid deposits on the internal surfaces of pipelines and measuring instruments, as well as liberated gas, which turns a single-phase medium into a two-phase one. Therefore, the existing experience in operating flow measuring instruments (MI), which are the basis of both accounting methods, is not always sufficient necessitating additional studies.

2. Relevance and Overview of the Existing Solutions

Regulatory documents concerning commercial accounting of oil impose rather stringent requirements on its accuracy (0.25% by gross mass and 0.35% by net mass for the direct and indirect dynamic method [3]), because even a small increase in the measurement error can lead to great financial losses [8]. The complexity of this task (providing high-precision measurements of oil mass) is associated with the dynamic measurement method adopted for accounting, which is based on the measurement of volumetric or mass flow rate.

The flow rate from the point of view of its measurement is the most complex technological parameter in comparison with the measurement of temperature, pressure or level. Any measurement instrument (MI), except for the basic error, also has additional ones arising from the influence of external conditions. Usually these are errors from ambient temperature, humidity, supply voltage, etc. In case of flow measurement, MI readings are affected not only by these external factors, but also by the physical
properties of the measured flow itself: density, viscosity, phase ratio in the flow, etc. And these physical properties, in turn, depend on the current process conditions, mainly thermobaric, and the nature of the flow (laminar or turbulent).

Thus, the flowmeter readings will depend on the following factors:

– properties of the measured medium, which is oil from various fields having a variety of properties (density, viscosity, content of paraffins, water, solids and dissolved gases);

– process parameters (temperature, pressure, measured medium flow rate and the nature of the flow) and local external measurement conditions (features of the natural landscape, location of the CQCS indoors or outdoors, etc.);

– state of process equipment and measuring instruments (state of the internal surface of pipelines, absence or presence of any deposits on the sensitive element of the flowmeter, etc.).

The study of flow MI behavior under the influence of these factors and their influence on the metrological characteristics (MC) of flowmeters is the subject of many surveys, for example, [9–15]. Surveys are carried out both on field samples and through mathematical modeling in various software environments. The object of research is mainly turbine flow transmitters as the most commonly used in CQCSs, as well as ultrasonic ones. Both types of flowmeters are volumetric flowmeters, i.e. implement an indirect method of mass flow measurement.

The direct measurement method is implemented by Coriolis flowmeters, which have recently become increasingly popular due to a great number of advantages compared to turbine and ultrasonic flow transmitters. If a few years ago their expansion was restrained by the high cost in comparison with the turbine flowmeters, the latest generation of multiviscous turbine flowmeters with a helicoidal rotor has already become comparable in price to the Coriolis ones. In case of commercial crude oil accounting, the use of Coriolis flowmeters is generally preferred. However, in the process of their operation, a number of problems arise that require additional study. This article discusses the results of one of these.

3. Problem Statement

The aim of the study is to quantify the error of the crude oil mass flow measurement by Coriolis flowmeters, resulting from the deposition of paraffin on the inner surface of the sensitive element of the flowmeter.

4. Theory

The principle of operation of Coriolis flowmeters is based on the Coriolis effect, i.e. the occurrence of additional force acting on the body, simultaneously participating in two movements - linear and rotational [16]. The linear movement is the movement of the fluid flow itself, and the rotational movement is simulated by the oscillation of the flow tubes created by a special drive (Fig. 2, a). Due to the change in the direction of linear movement when the fluid passes through the bend of the flow tube, the direction of the Coriolis force also changes (Fig. 2, b), which leads to deformation (twisting) of the tube (Fig. 2, c) and the appearance of a time lag (by phase) of oscillations of the inlet and outlet sections of the tube. This time lag is directly proportional to the Coriolis force, therefore, the mass flow rate.

![Figure 2. Coriolis flowmeter operating principle](image)
Structurally, Coriolis flowmeters consist of a sensor (one or two flow tubes placed in an external housing, an electromagnetic drive, detectors and a temperature transmitter) and a signal transducer from the sensor to the named mass flow value.

The oscillation frequency is always maintained resonant, because in this case the oscillations are created with the minimum energy consumption.

Thus, in the Coriolis flowmeter there are two parameters related to the flow nature and rate: these are the resonant frequency of tube oscillation and the phase shift between the oscillations of the inlet and outlet parts.

The resonant frequency of oscillation depends on the geometry of the tube, structural materials, and the mass of the entire structure (mass of the tubes and mass of the fluid inside the tubes). The mass of the tube is constant. Since the mass of the fluid is its density multiplied by the volume (which is also constant), the vibration frequency is determined by the density of the flowing liquid. Therefore, this density can be found by measuring the resonant frequency of oscillations of the tubes, and this can be done in the absence of a flow, if the tubes are filled with a fluid and oscillate.

Due to this, Coriolis flowmeters are usually positioned as mass-density meters. The phase shift is determined by the Coriolis force, i.e. depends on the fluid flow rate and, accordingly, the mass flow rate. It arises only in the presence of a flow. Coriolis flowmeters have high measurement accuracy, are independent of the flow direction and do not require the presence of straight sections of the pipeline before and after the flowmeter. Unlike turbine flowmeters, they do not require regular maintenance, have a long service life, and can be used to measure the flow rates of highly viscous fluids and fluids with gas inclusions. Their disadvantages are the relatively high cost, large dimensions, high pressure loss and the dependence of the readings on external vibrations.

However, when operating Coriolis flowmeters in real flows, characteristics of which are far from ideal conditions of test benches, various complications arise that significantly worsen the declared metrological characteristics of the flowmeter.

Leading companies - manufacturers of mass meters [17–22] utilize various design tricks allowing only to achieve a certain accuracy of measurements, further improvement is impossible for a number of reasons, independent of the manufacturers. So, when verifying flowmeters, water, the density of which cannot be an absolutely constant value, is used, and this leads to an additional error.

Another cause of the error may be a change in the state of the external pipeline, which also affects the accuracy of the readings. Moreover, external noise in some cases can lead to overestimation. It is very problematic to compensate for the influence of this factor, since it is unique for a specific installation site, installation quality and operating conditions. In addition, the detection of the influence of external factors on the flow transmitter is possible only for a gross and single distortion of the measurement results. If continuous interference of an oscillatory or vibrational nature is present, their identification is often impossible.

When mass meters are used for commercial accounting of crude oil, paraffins can be deposited on the inner surface of the flow tube causing an increase in its mass and, as a result, a decrease in the resonant frequency of oscillations at a constant density of the measured flow. However, in this case, not only the tube mass changes - deposition of paraffin will reduce its flow area leading to an increase in the flow rate proportional to the change in the phase shift and distortion of the measurement result.

[23] gives an example of calculating the increase in the paraffin layer thickness made according to the mathematical model of the CQCS meter run. In case of conditions considered in the study (temperature 15 °C, pressure 0.25 MPa, mass flow rate 8000 kg/h) for a year, its thickness increased from values close to zero at the end of the first month of measurements (0.007 mm) to almost one millimeter (0.92 mm). The mass meter verification interval is 4 years; therefore, it is advisable to quantify the error in flow measurement caused by internal deposits.

5. Materials and Methods
Aspen HYSYS software [24] was used to calculate and simulate the errors of the Coriolis flowmeter arising from paraffin deposits.
To describe the movement of the tube to calculate the influence of the Coriolis force and the natural frequency of the oscillation of the tube the following equations were used:

\[ m\dddot{x} + 2m_f\omega_0^2x - H \cdot x = F_0 \cdot \sin \omega_0 t, \]  

\[ H = E - m_f \omega_0^2 x > 0, \]  

where \( E \) is the modulus of elasticity under torsion shift, Pa; \( m \) is mass of the tube-fluid system, kg; \( m_f \) is mass of the fluid, kg; \( \omega_0 \) is the natural oscillation frequency of the tubes, Hz.

The mass of the tube-fluid system can be calculated by the formula

\[ m = m_t + m_f, \]  

where \( m_t \) is the mass of the tube, kg.

In the equation (1), the summand \( 2m_f\omega_0^2x \) takes into account the degree of influence of the Coriolis force, and \( m_f\omega_0^2x \) - the pressure of the fluid on the tube.

The resonant oscillation frequency of the tubes can be calculated based on the data containing the dimensions of the sensor element of the flowmeter. As an example, we took the parameters of the Micro Motion Coriolis flowmeter with an ELITE sensor of the CMFHC2 model (Fig. 3) [22]. The precisely resonant frequency of vibrations was chosen, since the value of the driving force (to maintain constant oscillations of the tube) is minimal.

The resonant frequency depends on the stiffness of the tube and its mass:

\[ \omega_0 = \sqrt{\frac{k}{m}}, \]  

where \( k \) is stiffness, kg/s².

![Figure 3. Design and overall dimensions of a flow tube](image-url)

Since the characteristic of the elastic element (tubes) is linear, its rigidity will be constant and determined by the formula

\[ k = E \cdot \frac{3\pi(d^4 - d_0^4)}{4L'}, \]  

where \( E \) is the elastic modulus of stainless steel; for AISI 316L stainless steel \( E = 198 \text{ kg/m}^2 \); \( L' \) is the tube length; \( L = l_1 + R = 0.17 + 0.14 = 0.31 \text{ m} \); \( d \) is the outer diameter of the tube; \( d = 0.01 \text{ m} \); \( d_0 \) is the inner diameter of the tube; \( d_0 = 0.007 \text{ m} \).

Tube mass

\[ m_t = \frac{(2l_1 + l_2) \cdot \pi \cdot (d^2 - d_0^2)}{4} \cdot \rho, \]  

where \( \rho \) is the steel density; \( \rho_t = 7700 \text{ kg/m}^3 \).
Fluid mass

\[ m_f = \frac{(2l_1 + l_2) \cdot \pi \cdot d_f^2 \cdot \rho_f}{4}, \]

(8)

where \( \rho_f \) is the fluid density; \( \rho_f = 870.7 \text{ kg/m}^3 \).

Knowing the value of the oil velocity \( \mathbf{u} \), we can calculate the phase difference of tube oscillations

\[ \delta \phi = \frac{2 \cdot \rho_v \cdot \mathbf{u} \cdot R}{E - \rho_v \cdot U^2}. \]

(9)

The relationship of the phase difference of oscillations \( \delta \phi \) with the mass flow rate \( Q_M \) is expressed by the formula

\[ \delta \phi = \frac{2 \cdot \omega \cdot L \cdot l}{k} \cdot Q_M. \]

(10)

where \( \delta \phi \) are phase differences of tube oscillations, rad; \( \omega \) is angular velocity of the fluid, rad/s; \( L \) is tube length, m; \( l \) is the distance between the branches, m; \( Q_M \) is mass flow rate, kg/s.

If we take into account that over time, there is an increase in paraffin deposits on the inner walls of the sensitive element of the Coriolis flowmeter, then formulas (3) and (8) will take a different look.

The mass of the entire system in this case can be found by the formula

\[ m = m_1 + m_f + m_p, \]

(11)

where \( m_p \) is the mass of paraffin deposits, kg.

The fluid mass is found by the formula

\[ m_f = \frac{(2l_1 + l_2) \cdot \pi \cdot (d_f^2 - 2x^2) \cdot \rho_f}{4}, \]

(12)

where \( x \) is the thickness of paraffin deposits, m.

The mass of paraffin deposits can be calculated by the formula

\[ m_p = \frac{(2l_1 + l_2) \cdot \pi \cdot (d_p^2 - (2x)^2) \cdot \rho_p}{4}, \]

(13)

where \( \rho_p \) is the density of paraffin deposits, kg/m\(^3\); \( \rho_p = 881 \text{ kg/m}^3 \).

The density of paraffin deposits is calculated based on the initial composition data by the Aspen HYSYS software.

6. Experimental Results and Practical Significance

The dependence of the phase difference of the tube oscillations on the thickness of the paraffin deposits on the inner walls of the Coriolis flowmeter tube is shown in Fig. 4, a.

The graph was obtained in Mathcad Professional using formula (9). As can be seen from the graph, at \( x = 0 \text{ mm} \) the phase difference of tube oscillations \( \delta \phi \) is \( 4,829 \cdot 10^{-4} \text{ rad} \), and at \( x = 0.92 \text{ mm} \) the phase difference of tube oscillations \( \delta \phi \) is \( 4,818 \cdot 10^{-4} \text{ rad} \).

Then, taking into account the relationship between the phase difference of oscillations and the mass flow rate represented by formula (10), we can conclude that with a thickness of paraffin deposits on the inner walls of the Coriolis flowmeter tube equal to 0.92 mm, the error in determining the flow rate will be 0.227%.

Thus, the graph of dependence of the relative error of the mass flow measurement on the thickness of paraffin deposits on the inner walls of the Coriolis flowmeter tube will take the form shown in Fig. 4, b.
7. Conclusion

The conducted studies allow us to draw the following conclusions.

Coriolis flowmeters are the most suitable instruments for commercial accounting of crude oil. However, in the process of measurement, it is necessary to take into account additional errors arising due to the fact that the oil may contain additional components, such as liberated gas, paraffins, etc. Paraffins can be deposited under certain conditions on the inner surfaces of the sensor element of the flowmeter changing its mass and causing an additional error.

Using the mathematical model built in the Aspen HYSYS software environment, we obtained the dependence of the phase difference of the tube oscillations and the mass flow measurement error on the thickness of paraffin deposits on the inner walls of the Coriolis flowmeter tubes.

The calculation results showed that for a Coriolis flowmeter with an outer tube diameter of 10 cm and a thickness of paraffin deposits on the inner walls of 0.92 mm, the relative error in determining the flow rate will be 0.227%. This measurement error is comparable with the maximum permissible error for direct and indirect methods of dynamic measurements established in regulatory documents and equal to ± 0.25% [4]. Such layer of paraffin is deposited in about a year, therefore, for highly paraffinic oils, it is necessary to control metrological characteristics in the verification interval to increase the accounting accuracy.

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