Measurement of Oil Consumption by Turbine Flow Meters in Conditions of Wax Deposition

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Abstract. Commercial metering of oil is performed at almost all stages of the life cycle, from well production control to the transfer of the produced oil to the end customer. In most cases, special systems for measuring the quantity and quality of commercial oil (SIQO) are used for this. If such a system implements an indirect dynamic measurement method, then a turbine flow meter is most often a means of measuring volumetric flow. Its accuracy depends on many external factors, including wax deposits on the inner surface of the measuring pipeline and on the elements of the flow meter itself. The article investigates the influence of the thickness of the paraffin layer on the error value of the turbine flow meter. It is shown that the decrease in metrological reliability occurs mainly due to the appearance of a paraffin layer in the measuring line itself. It is proposed to determine the timing of the metrological characteristics verification by indirect parameters, in particular, by the change in pressure in the measuring line.

1. Introduction
Any extracted and produced products must be accounted for by both the manufacturer and the consumer. Liquid hydrocarbons, i.e. oil and petroleum products, are no exception. Their accounting is carried out at all stages of the life cycle, during production, initial preparation, transport through main pipelines and transfer to oil depots or refineries. Depending on the purpose of accounting, it can be operational or commercial.

Custody transfer accounting is carried out by weight in accordance with a number of regulations. According to [1], the mass of oil can be determined by the direct static, direct dynamic, indirect volume-mass dynamic, indirect volume-weight static and indirect hydrostatic measurement techniques.

Among all the listed techniques, the dynamic ones are the most widespread in the fiscal metering of oil. The operation of systems for measuring the quantity and quality of commercial oil (SIQO) is based on these techniques [2].

The SIQO comprises a filter unit, a measuring line unit (MLU), the oil quality measuring unit (QMU), a verifier unit (fixed mechanical displacement prover (MDP) or compact prover), as well as the required shut-off and control valves and piping (figure 1). All the calculations required are performed by the data processing system (DPS) located in the SIQO’s control room [3].
CF is a coarse filter, MDP is a mechanical displacement prover, MLU is a measuring line unit, QMU is a oil quality measuring unit.

Figure 1. System for measuring the quantity and quality indicators of oil.

In the SIQO, the main measuring instrument is a positive displacement or mass flow meter. Turbine or ultrasonic flowmeters are used to measure volumetric flow, and Coriolis flowmeters are used for mass flow usually.

The accuracy of the metering is mainly determined by the accuracy of the flow meters themselves. In this case, the accuracy of volumetric flow meters should be higher than that of mass meters. This is because the total error will also include the error of the density meter and temperature transducer. Modern volumetric flow meters, in particular turbine ones, have good accuracy characteristics. For example, common turbine meters with helical rotor have an error of 0.15\%. However, under the influence of various external factors, this value can increase significantly. This article examines the impact on the operation and metrological characteristics of a turbine flowmeter of wax falling out of oil.

2. Materials and methods

Flow measurement is generally a more complex problem than measuring parameters such as temperature or pressure. In the case of measuring the oil flow rate, the flow meter is exposed to some basic external impacts that randomly affect each other [2].

Firstly, these are the properties of the medium being measured, which is crude oils from various fields having different properties (density, viscosity, the content of paraffins, water, mechanical impurities, and dissolved gases).

Secondly, these are random external disturbing factors generated by the conditions of the process equipment and measuring instruments (the conditions of the inner pipeline surface, e.g., paraffin deposits both in the pipes and on the sensitive elements of flow meters such as turbine blades or a Coriolis spool, etc.).

The interconnections between individual factors are difficult to quantify, despite the understandable physics of the occurring phenomena. Thus, e.g., a decrease in the pumped oil temperature entails an increase in density and viscosity, which, in turn, changes the rheological flow characteristics up to a change in the flow pattern (turbulent, transient, laminar). But even if the calculation dependencies are available, estimating the impact of this change on the flow rate is not possible since due to a decrease in temperature, e.g., an intensive paraffin deposition starts simultaneously in the measuring section, which also leads to a local flow narrowing and, again, a change in its rheological characteristics.
The listed problems are the subject of many scientific and scientific-practical studies [4 – 7]. Herewith, when speaking about the fiscal metering of crude oil, research is mainly focused on the impact of gas bubbles, which are released from oil under certain conditions and transform the measured medium from single-phase into two-phase one [8], thereby increasing the measurement error.

However, a major problem of the crude oil pipeline transportation is also paraffin deposition, which occurs under the effect of many factors [9 – 18]. This phenomenon is quite dangerous because at the very least reduced pipe diameter and increased surface roughness creates a larger pressure drop and reduced throughput. But at the worst, wax deposits can be so severe that the pipe is blocked and production ceases completely [10].

Wax deposition is conceptually similar to other deposition mechanisms encountered in the engineering and medical fields, such as crystallisation fouling, frost formation and atherosclerosis. A number of mechanisms have been proposed to describe the formation of wax deposits on pipe walls. These mechanisms include molecular diffusion, shear dispersion, Brownian diffusion and gravity settling [19 – 25].

It is very important to note that in fact, these deposits are uncontrollable since that their thickness cannot be measured directly in the deposition place. This leads to unpredictable changes in the operating conditions of both equipment and measuring instruments, and, as a consequence, affects the efficiency of their maintenance and metrological service.

Turbine flowmeters are a special case of velocity ones, whose principle of operation is based on the flow rate dependence of the speed of a body installed in the pipeline [26]. In oil metering systems, including crude oil, turbine flowmeters with an axial impeller are used, the rotation axis of which coincides with the flow axis (figure 2).

The fluid rotates the rotor at a speed proportional to the fluid speed and therefore, the total volumetric flow rate. An AC voltage pulse is generated in an inductive coil located outside the meter each time the blade crosses the magnetic field of the coil. The frequency of these pulses is proportional to the measured flow rate, and the number of pulses for a certain period corresponds to the amount of fluid passed.

The number of electrical impulses generated by the magnetic coil of a turbine converter during the passage of one cubic meter of liquid through it is called the conversion factor, or K-factor of the turbine flow meter. The K-factor is determined during verification and then periodically checked by comparison, i.e. the current value of the K-factor of the working flow meter is determined by the working standard. The error is found as the deviation (in percent) of the K-factor value of the flow meter, determined by in comparison, from the K-factor obtained during verification.

![Figure 2. Axial Impeller Flowmeter.](image-url)
Turbine meters implement the velocity-area measurement method, which is a type of indirect flow measurement based on the instantaneous flow rate and the cross-sectional area of the pipe in which it is measured [26]. Therefore, with wax deposits, the measurement error will increase both due to a decrease in the cross-sectional area (with deposits on the walls of the measuring section of the pipeline) and due to deposits directly on the elements of the flow meter itself.

The purpose of this study is to assess the significance of each of these factors in the commercial metering of oil.

3. Theoretical part

3.1. The Mathematical Model of a Turbine Flow Transducer

The turbine rotates due to the driving torque occurring when the fluid flow pushes (acts on) its blades [26]. Thereat, the driving torque is equivalent to the angular moment of the fluid mass equal to its flow rate. On the other hand, the driving torque is opposed by the moment of resistance consisting of the moments of viscous friction of the fluid against the blade surfaces, friction forces in the bearings, and the resistance forces of the tachometric converter.

The mathematical model of a turbine flow transducer (TFT) is a set of equations, logical conditions, constants, etc., linking the modal, design, and kinematic parameters describing the fluid flow in the turbine flow path [27]. The parameters defining the fluid flow pattern in the turbine (modal parameters) are its volumetric flow rate, pressure, kinematic viscosity, specific gravity, and temperature. The parameters characterizing the geometry of the turbine flow path (design parameters) are the nominal bore diameter, outer and sleeve diameters, radial clearance, number of blades, axial length, and the thickness and installation angle of the blade. Kinematic parameters are linear and angular flow velocities at design radii.

Let us consider the impeller rotation mechanism in more detail.

The axial impeller rotation speed can be expressed by the equation

\[ n = f(Q, v, \rho, M_R, D, d_{out}, d_{in}, Z, l, T), \]  

where \( n \) is the impeller revolution number per unit of time; \( Q \) is the volumetric fluid flow rate; \( v, \rho \) are the fluid kinematic viscosity and density, respectively; \( M_R \) is the moment of resistance from friction in the bearings and the tachometric converter reaction; \( D \) is the pipeline diameter; \( d_{out}, d_{in} \) are the outer and inner diameters of the impeller blades, respectively; \( Z \) is the number of impeller blades; \( l \) is the axial length of the blades; \( T \) is the impeller pitch.

The impeller motion equation has the form

\[ J \cdot \frac{d\omega}{dt} = \sum_{i=1}^{n} M_i, \]  

where \( J \) is the impeller inertia moment; \( \omega \) is the angular velocity of its rotation; \( \sum_{i=1}^{n} M_i \) is the sum of the torques of all forces applied to the impeller.

At a steady motion, the condition \( \frac{d\omega}{dt} = 0 \) is fulfilled, therefore, \( \sum_{i=1}^{n} M_i = 0 \). In expanded form, the sum of the torques acting on the impeller can be written as follows

\[ M_D - M_H - M_F - M_R = 0, \]  

where \( M_D \) is the driving torque; \( M_H \) is the hydraulic resistance moment; \( M_F \) is the moment of resistance from friction forces in bearings; \( M_R \) is the moment of the tachometric converter reaction.

Figure 3 shows a speed diagram at the axial impeller inlet and outlet [26].
C1, C2 are absolute fluid velocities at the impeller inlet and outlet; U is the impeller rotation velocity corresponding to the radius r at the blade to the plane perpendicular to the impeller axis inclination angle ϕ; v1 and v2 are the relative inlet and outlet fluid velocities; α1 and α2 are the angles between the inlet and outlet absolute and transient (rotational) velocities.

Figure 3. Speed Diagram at the Impeller Inlet and Outlet.

Had the impeller rotated without resistance, the vector of relative velocities at its inlet and outlet would coincide with the blade direction, i.e. the condition β1 = β2 = ϕ would be fulfilled, and the absolute velocity C10 would not change its direction when the fluid was passing through the impeller. For this ideal case, the angular impeller rotation velocity ωI can be found as follows

\[ ω_I = \frac{Q}{sr \tan ϕ}, \]  

(4)

where S is the area open to flow.

In fact, the impeller rotation faces resistance; therefore, the actual rotation velocity ω is somewhat less than the ideal velocity ωI due to the jet deflection at the outlet in the direction opposite to the impeller rotation and, as a consequence, the difference between the β2 and ϕ angles. This difference is estimated by the so-called impeller slip SK:

\[ S_K = \frac{ω_I - ω}{ω_I}. \]  

(5)

Then the actual velocity can be defined as follows

\[ ω = \frac{Q}{sr \tan ϕ} (1 - S_K). \]  

(6)

In practice, the slip value ranges from 2 to 5 % and is considered when verifying (calibrating) the TFT. In fact, this coefficient characterizes the relative error caused by the impeller load.

3.2. Assessment of the wax deposits influence on metrological characteristics

3.2.1 Wax Deposition on the inner surface of the measuring line. In this case, the paraffin deposition will affect the measurement result through a change in the flow area. Figure 4 shows the dependence of the relative error on the paraffin deposition based on the values obtained by simulating the deposition in the Ml during a month (a) and a year (b). The change in the thickness of the paraffin layer with time was obtained according to the model proposed by the authors in [2].
When implementing the indirect dynamic metering technique, the permissible relative error in measuring the $M_I$ flow rate should not exceed ± 0.15 % since otherwise, the SIQO will not be able to ensure the accuracy of ± 0.25 % prescribed by regulatory documents for metering the gross weight. As can be seen from the dependencies obtained, under unfavorable operating conditions, even for a rather short period of one to two weeks, paraffin deposition may cause an error placing the TFT on the border of metrological reliability.

3.2.2. Wax Deposition on the elements of the impeller. It should also be considered that paraffin is deposited on not only the inner measuring line surfaces but also the impeller blades and bearings, which may lead to a change in the moments in equation (3). To analyze the direct impact of paraffin deposits on the TFT operation, the issues included in (3) and considered in [26] should be analyzed in more detail.

According to the Euler equation, the elementary driving torque $dM_D$ applied by an elementary jet of fluid to the impeller is determined by the equation

$$dM_D = (rC_1 \cos \alpha_1 - rC_2 \cos \alpha_2) \rho \cdot dQ.$$ \hspace{1cm} (7)

When integrating it over section $S$, the total driving torque can be written as follows

$$M_D = A_1 \cdot Q^2 - A_2 \cdot \omega \cdot Q,$$ \hspace{1cm} (8)

$$A_1 = \frac{2\pi \rho}{S \xi} \int_0^S \frac{K^2}{\xi} \cdot r^2 dS,$$

$$A_2 = \frac{\rho}{S} \int_0^S Kr^2 dS.$$

where $K = C_4/C_{10}$ is the coefficient depending on the jet coordinates and the Reynolds number; $\xi$ is the coefficient depending on the jet coordinates.

$M_H$ consists of the torque of viscous friction of the fluid against the impeller flow path, which is proportional to the product $\rho Q^2$, and a small torque of the fluid friction against the end hub face, which is proportional to the angular impeller rotation velocity $\omega$:

$$M_H = A_3 \cdot Q^2 + A_4 \cdot \omega,$$ \hspace{1cm} (9)

where $A_3$ and $A_4$ are the coefficients depending on the impeller design, friction coefficients and fluid density.

The moment of resistance from the friction forces in bearings $M_F$ consists of the friction torque in
the thrust bearings (determined by the load, the friction coefficient, and the journal radius, and does not depend on $\omega$ and $Q$) and the friction torque in the thrust bearings (proportional to $Q^2$ since the axial force arises under the fluid friction against the impeller blades):

$$M_F = A_5 + A_6 \cdot Q^2.$$  

(10)

The tachometric converter reaction moment $M_R$ is proportional to the angular impeller velocity:

$$M_R = A_7 \cdot Q^2.$$  

(11)

Thus, the static TFT characteristic can be represented as follows

$$\omega = A \cdot Q - B - C,$$  

(12)

where $A = \frac{A_1 - A_2 - A_6}{A_2}$; $B = \frac{(A_1 - A_2 - A_6)(A_4 + A_7)}{A_2^2(1 + \frac{A_1 + A_7}{A_2}Q)}$; $C = \frac{A_5}{A_2^2Q + A_4 + A_7}$.

4. Results and discussion

The static characteristic equation (12) allows drawing the following conclusions on the impact of paraffin deposits.

All three parameters $A$, $B$, and $C$ in the above equation depend on the flow rate $Q$ expressly or impliedly. According to [26], the effect of parameters $B$ and $C$ is relatively small, and they affect mainly in different regions of the measurement range: the greatest effect of parameters $C$ and $B$ is at $Q = 0$ and the maximum $Q$ value, respectively. However, in the case of paraffin deposition on the impeller blades (occurring in the minimum velocity region) and thrust bearings, this statement requires additional research. It is only obvious that the effect of these parameters will change mainly due to a change in the friction torque in the thrust bearings, but it should be considered that paraffin itself acts as a lubricant. Also, its temperature in the thrust bearing will be higher than that of the main flow due to the high rotor speed. Therefore, a quantitative assessment of this factor influence requires additional research.

Thus, within the framework of this study, the error caused by the main affecting factor – the reduced useful area can be estimated: according to figure 4, it is rather significant. A change in the flow pattern, wall roughness, and flow area is critical for velocity meters, so, if the current thickness of the paraffin layer is known, this will allow the verification of metrological characteristics (VMC) in fact, and not according to the service regulations. In particular, for a turbine flowmeter, flushing and performing VMC with a 10-15-day interval can be recommended (for many SIQOs, this interval is currently one month).

5. Conclusions

As already mentioned, earlier the authors of this study proposed an algorithm for predictive diagnostics of of the measuring line state based on the pressure drop across it. Its use allows real-time estimation of the deposited paraffin layer thickness, which, in turn, makes it possible to quickly establish the approximation of the turbine flow meter readings to the limits of metrological reliability and to take appropriate measures, for example, VMC.

6. References

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