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doi:10.15199/48.2015.11.68

Automation of direct measurement and control of volumetric flow

***Abstract**. The paper presents a method for direct measurement of volumetric flow using a measuring cylinder with a free dividing piston. Original schemes of sensors and actuators connection have been provided as well as both input and output signal processing algorithms. Moreover, the influence of the key hardware parameters to the measurement accuracy has been considered.*

***Streszczenie.** Artykuł przedstawia metodę bezpośredniego pomiaru przepływu objętościowego z wykorzystaniem cylindra pomiarowego z wolnym tłokiem, Zaprezentowano oryginalne schematy połączeń czujników i aktuatorów, jak również algorytmy przetwarzania sygnałów wejściowych i wyjściowych. Przedyskutowano ponadto wpływ kluczowych parametrów sprzętowych na dokładność pomiaru. (**Automatyzacja bezpośredniego pomiaru i sterowania przepływem objętościowym**).*

Keywords: volumetric flow rate, flow rate control, volume and velocity measurements.
Słowa kluczowe: objętościowe natężenie przepływu, sterowanie natężeniem przepływu, pomiary prędkości i objętości.

Introduction

Accuracy improvement of volumetric flow measurement is very important issue, especially for high power engine maintenance, especially in case of vessels, trains, trucks, etc. Considering the worldwide volume of fuel consumption and fuel prices even a small improvement in accuracy of fuel flow control is equal to saving of hundreds of million dollars. The improvement of metering accuracy methods applied for different liquid components during the manufacture of strategic materials, medicine and the other products is also important. This is because accuracy is connected with the quality of the final product.

Methods for measurement of volumetric flow of fluids can conditionally be divided into direct and indirect or velocity methods. The method of a measuring tank and method of a measuring cylinder can be considered as direct.

Indirect method, or generally a method of velocity flow measurement is applied in connection with improvement of electric methods of measurement. The basic field of application is connected with the implementation of continuous automated flow metering of liquid and gaseous mediums. Orifice plate method, electromagnetic method, rotameter, calorimetric, ultrasonic, and tachometric and Coriolis methods can be considered as velocity volumetric flow measurement methods.

The common feature for all described methods is metering of flow passing through a tube with the known cross-section at a certain speed ϑ. The value of the speed ϑ is determined using parameters of a liquid medium, which is strongly correlated with the flow velocity.

The volumetric flow rate can be calculated using the following formula:

(1) $$V = S \cdot \vartheta \cdot \tau ,$$

where: V – fluid volume, S – cross-section of the tube, ϑ – flow speed, τ - metering time. Values of S and τ can be specified and determined with a high accuracy. The value of flow speed ϑ, on the contrary, can be determined using indirect methods mentioned above.

The detailed classification of the most widespread volumetric flow measurement methods is presented in Figure 1.

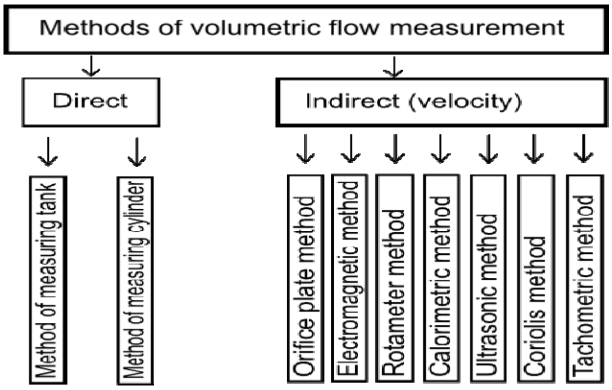

Fig.1. Classification of volumetric flow measurement methods

Volumetric flow methods overview

The volumetric flow measurement method cannot be widespread in control systems due to the absence of equipment providing the direct automated flow metering. Requirements for improvement in automation of control process stipulated alternative indirect measurement methods.

Orifice plate method is an indirect measurement method and is applied for fluid, gas and steam flow measurement.

In case of remote data transmission the differential pressure manometer is equipped with a transformer connected with a secondary device and other equipment [1].

This flow measurement method is the most widely used, orifice plates and differential pressure gauges are manufactured by majority of manufacturers.

Minimal value of electric conduction of a measured medium should be considered as a disadvantage of electromagnetic flow meters because this narrows a field of their application. Another disadvantage is a low level of information signal measured in microvolts. This fact stipulates for a higher protection of a transducer and connection lines from external interferences [2].

The main disadvantage of orifice plate based flow meters is the fact that its readings are affected by acute temperature and property changes of a measured medium. For example, there may be density or thermal conductivity properties of a medium. Information technologies are applied for controlling output signals. However, further improvement of thermal anemometers accuracy is restricted by existing faults depending on density and thermal conductivity characteristics of the measured medium [3].

Ultrasonic method of volumetric flow measurement is based on a propagation of ultrasonic waves in the fluid [4]. The basic disadvantage in application of the ultrasonic method is that velocity of ultrasonic waves depends on physical and chemical properties of a medium, such as temperature and pressure. And this dependence has a bigger effect compared to a medium velocity. As a result, the real ultrasonic propagation velocity in a flowing medium has a small difference compared to that in a stationary medium.

Coriolis flow meters have good measurement results for fluids with a constant chemical composition and do not need the pressure and temperature compensation. .Coriolis flow meters have no mechanical components and their output signals are processed with application of electronic circuits. However, these devices do not insure against errors caused by changes in a flow chemical composition, vibrations, density and viscosity of a fluid [5].

Tachometric flow meters provide a high accuracy in measurement at constant viscosity and density characteristics of a fluid. The measurement error for such flow meters is just 0,5 %, assuming that a measured fluid has no mechanical impurities [6].

Volumetric flow measure improvement

All the considered and omitted tachometric methods of volumetric flow measurement have complicated and multivariate correlations between an actual volume and indirectly determined flow velocity. As a rule, any analytic correlations of a measured parameter and actual volume of a fluid are true in a narrow range of influencing quantities. Any physical, chemical, electrical or composition characteristic changes in controlled fluid along with parameters of the primary transducers, as a rule result into increase in measurement error. Application of indirect methods for decrease of measurement errors needs measurement systems with multivariate sensors of influencing quantities and volumetric flow control according to ideal analytical relations.

A search for performance increase and volumetric flow control with a modification of a direct automated metering are actual tasks. Even a small improvement in measurement accuracy may result in a great improvement in quality and lead to multi-million economies in different industries and consumption of fuel and process liquids. There are several ways approaching to a solution to these tasks [7].

Method of direct volumetric fuel flow measurement with application of a measuring tank [7] and measuring hydraulic cylinder with a floating piston [8] becomes a more prospective method of volumetric flow measurement because it improves the accuracy. This method allows to designing precision measurement instrument with different ranges. But measurement accuracy in such devices depends on geometric properties of a measuring mechanism along with sensors errors and algorithms of control and processing of information. Current technologies enable precise implementation and maintenance of geometric characteristics of a measuring mechanism during the operation process. Methods of calculation and selection of geometric properties of a hydraulic cylinder are essential along with the detailed study of hardware and software effect on measurement accuracy. These methods are necessary for evaluation of obtainable accuracy boundary of precision measurement instrument.

Figures 2 and 3 illustrate a basic example of a volumetric flow measurement system structure of a large tractor, locomotive and marine engines consuming diesel gas oil with two stable conditions [8].

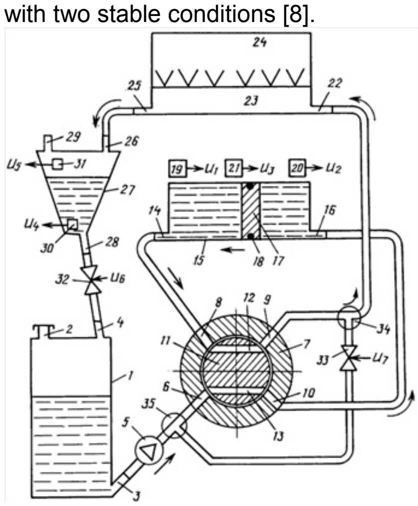

Fig.2. Volumetric flow measurement system of a diesel engine (stable condition 1)

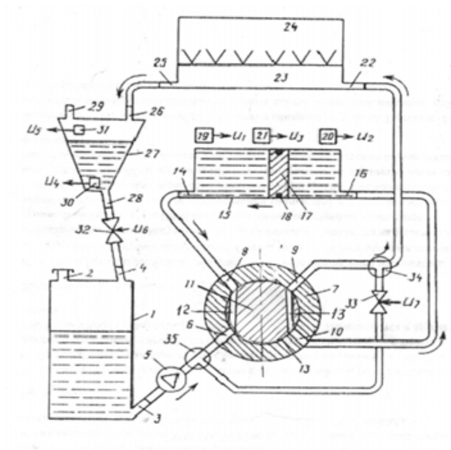

Fig.3. Volumetric flow measurement system of a diesel engine (stable condition 2)

In the Figures 2 and 3 1- denotes fuel tank; 2,3,4 – fuel tank tubes; 5 – fuel pump; 6,8,9,10 – stator tubes of a flow control device; 7 – housing of a flow control device; 11- rotor of a flow control device; 12,13 – rotor tubes; 14, 16 - adapters of a measuring hydraulic cylinder; 15 – measuring hydraulic cylinder; 17 – floating piston of the measuring hydraulic cylinder; 18 – piston O-ring; 19, 20 – end piston position alarms; 21 – extended frequency indicator of a piston position; 22,25 – engine inlet manifold tubes; 23 – engine inlet manifold; 24 – internal combustion engine; 26, 28, 29 – measuring tank tubes; 27 – measuring tank; 30 – low fuel level alarm of the measuring tank; 31 - top fuel level alarm of the measuring tank; 32,33 – electromagnetic valves, 34,35 – connectors.

Figure 2 shows the first stable condition. In this position of the rotor (11) the floating piston (12) under pressure of the fuel pump is moving to the left side and pushing the fuel out of the left side of the hydraulic cylinder (15) through elements (14), (8), (12), (9), (34) and (22) into the engine inlet manifold (23). When the floating piston (17) has reached its end left position it activates the alarm (19) and the signal U_1 makes the rotor (11) rotate by 90º and the system reaches the second stable condition (Figure 2). At this stable condition the piston (17) under pressure of the fuel pump (5) is moving to the right side and pushing the fluid out of the right side of the hydraulic cylinder (15) through elements (16), (10), (13), (9), (34) and (22) into the engine inlet manifold (23). This stable condition remains until the end piston positions alarm (20) is activated and its signal U2 the rotates the rotor (11) by 90º and the system returns to its first stable condition.

Details of this algorithm implementation may affect the accuracy of measurement because of the end time interval for the rotor (11) transition from one stable condition into another. The real time value of a flow control device transition from one stable condition into another is lying between 10^{-2} and 10^{-1} seconds. Specific features of the flow channel structure The indirect effect on control adequacy consists of breach of monotonous fuel supply into the inlet manifold (23). In other words, these transitions do not affect the accuracy of measurement owing to non-combustible properties of the fuel. But they affect the operation mode of the engine and the fuel consumption mode.

During operation all controlled volume of the fuel is continuously pumped through the measuring hydraulic cylinder (15). Figure 5 illustrates the diagram of the algorithm of volumetric flow storage control.

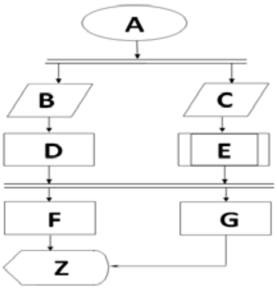

Fig.5. Diagram of the algorithm of volumetric flow storage control

In the diagram A denotes process beginning (power on); B – initial conditions settings (operation start with zero or specified non-zero values); C – control mode setting (metering within a certain period of time, certain number of cycles, fluid volume, metering before the fluid passage is complete and other); D – fluid flow storage control within a specified time interval; E – flow rate determination process; F – collection of information about a storage flow for a further presentation on a display H; G – collection of information about the flow rate for further presentation on a display Z that visualize information about the flow rate and storage flow.

The basic implementation of the algorithm of volumetric flow storage control is calculation of stable conditions of the measuring hydraulic cylinder and determination of the phase of the piston (17) intermediate condition at the beginning and the end of control period. This implementation is carried out with application of extended frequency indicator (21). With implementation of this algorithm it is also possible to implement the algorithm of flow rate determination in ON-LINE mode. The diagram of the algorithm of flow rate determination is illustrated in Figure 6.

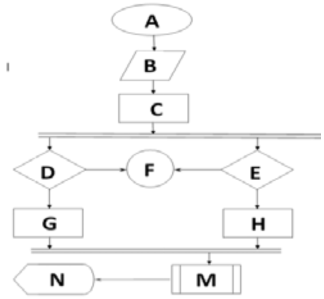

Fig.6. Diagram of the algorithm of volumetric flow storage control

In the diagram A denotes start of the process (power on); B – initial conditions settings (interval of a piston travel (hysteresis of output signals of extended piston position sensor (21)), metering frequency and so on); C – control for extended sensor (21) output signal values; D,E – comparison of sensor (21) output signals with set values; F – comparison result waiting; G,H - beginning and end of a metering interval; M – flow rate metering process; N – visualization of control results.

Flow rate is determined by travel of a piston inside the hydraulic cylinder within a certain period of time. It is also determined by a period of time within which a piston travels from one certain position to another. These positions are determined by a change of the output frequency of the sensor (21).

The specific feature of diesel engines is an incomplete consumption of fuel received from the inlet manifold (23). As a result, a certain amount of fuel is drained into the measuring tank (27) through tubes (25) and (26). Measuring tank (27) is equipped with low (30) and high (31) fuel level alarms. Filling the measuring tank activates the alarm (31). Alarm (31) signal U_5 generates signal U_6 for electromagnetic valve (32) opening and fuel from the measuring tank (27) is drained into the fuel tank until the alarm (30) is activated. As a result, volume of fuel drained from the measuring container (27) into the fuel tank (1) should be deducted from the results of volumetric flow storage control. Metering of fuel returned to the fuel tank (1) and control for operation of the electromagnetic valve (32) are subject to implementation using the algorithm of corrective control of a volumetric flow that is shown in Figure 7.

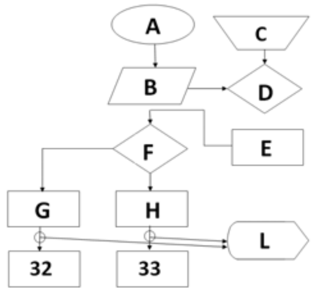

Fig.7. Algorithm of corrective control of a volumetric fuel flow

In the diagram A denotes process beginning (corrective control mode on); B - initial conditions settings (value of effective fluid volume containing in the measuring tank (27) with a level value changing from alarm (30) to alarm (31)); C – corrective control mode on and off; D – decision on activation or blocking of corrective control mode; E – control for activation of top fuel level (30) and low fuel level (31) alarms inside the measuring tank (27); F – decision on activation of valves (32) or (33); G, H – generation of electromagnetic valves (32) and (33) control signals; L – visual presentation of corrective control results.

During the detailed implementation of this algorithm there is uncontrolled drain of fuel from the manifold (23) into the measuring tank (27) at the time of U_6 signal action. That is why special important implementations of the measuring instrument can be equipped with an additional stopper electromagnetic valve installed between tubes (25) and (26). Closing this valve with signal U_6 eliminates uncontrolled drain from the manifold (23) into the tank (27) during fuel drain from the tank (27).

Interaction of measuring instrument operation algorithms and storage, formatting and presentation of information in digital and graphic formats are subject to implementation of the algorithm of operation control as shown in Figure 8.

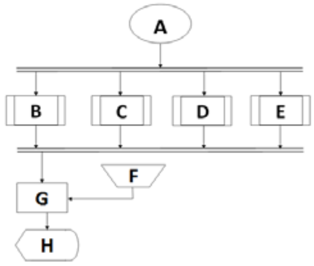

Fig.8. Algorithm of operation control

Figure 8 contains: A - process beginning (measuring instrument power on); B – control for rotor (11) (see the diagram on Figure 4); C – process of volumetric flow storage control (see the diagram on Figure 5); D – flow rate determination process in ON-LINE mode (see the diagram on Figure 6); E – process of corrective control of a volumetric flow (see the diagram on Figure 7). Operation control is important for measuring instruments of high power diesel engines. The process of measuring instrument control is concentrated in selection of a necessary combination of these algorithms. As a result, the measuring instrument has a high functionality and flexibility and can easily be adapted for different modes of operation.

Structure diagram of a hardware component of the volumetric fuel consumption measuring system applied for internal combustion engines is illustrated in Figure 9.

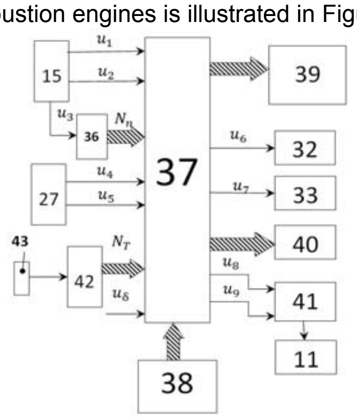

Fig.9. Structure of a hardware component of the volumetric fuel consumption measuring system.

This system includes a converter (36) of signals received from a sensor (21) and converting signals into code Nп of a piston (17) position inside the cylinder (15) or into the value of fuel volume inside one of cylinder (15) chambers, processor (37) with a control panel (38), display (39) and output connector (40) for connection of a user. Besides that, control output connectors of the processor (37) are connected to the electromagnetic valves (32) and (33), electric drive (41) of the flow control device (7). Measuring instrument may also have a digital thermometer (42) with output connectors of digital code N_T, temperature sensor (43) and signal input from a built-in or additional fuel level or volume sensor installed inside a fuel tank. Processor (37) carries out digital processing of signals u_1, u_2, u_4, u_5, u_6 codes N_K and N_T and generates controlling signals $u_6 ... u_9$, presents results of information processing and indications of basic blocks on a display (39) and output connector (40). With the use of a control panel (38) operator can change the data format of indicated information and, if necessary, switch operation modes of processor (37).

Contemporary construction materials and processing technologies eliminate errors caused by modification of geometric characteristics of a measuring hydraulic cylinder (15) and floating piston (17) owing to an insignificant extent of such modifications. Integration of a sensor and digital fuel thermometer into a hardware structure enables implementation of control for a temperature effect on the mode of fuel consumption and, if necessary, carry out the temperature offset using software components [8].

Conclusions

The method of a direct flow measurement with application of a measuring hydraulic cylinder containing a floating piston provides high accuracy of flow rate measurements owing to the application of special hardware and software solutions. It also enables control for fuel consumption at powerful diesel engines. Complete absence from vulnerable components and high level of output signals from sensors applied in this scheme opens the way for its application on boards of powerful transport facilities and provides a high accuracy of volumetric flow control. Application of measuring instruments with accuracy class 0.5 and equipped with measuring cylinders and floating piston has a potential within a range of the volumetric fluid flow from 10-2 l/min to 102 l/min.

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