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OPTIMIZATION AND RESEARCH OF TECHNOLOGICAL PARAMETERS OF SHUT-OFF DEVICE OF BIOMETHANE GAS-FILLING SYSTEM

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Abstract: The paper gives overview of working principles, modeling and testing results of new patented shut-off device. This invention is created by co-founder of *Hygen Ltd.* and relies to another invention of this company, which is used for a preparation of biomethane for its further transfer under pressure to a fuel tank of a vehicle. Research realized in close cooperation between all involved private and scientific institutions allowed to select most applicable parameters of the shut-off device and to create out most applicable construction of movable closing element. Tests of the shut-off device together with gas-filling device showed that system works immaculately and passes stability, hydraulic and temperature regime tests.

Key words: *shut-off device, bio-methane*

INTRODUCTION

The development of biogas production has been successful in recent years in Latvia. This is connected with governmental support, which guarantees that the electric power, produced in the result of burning of gas in CHP plants, have to be purchased by power company. Beside that, a number of companies are looking also for biogas cleaning and upgrading till natural gas standards, allowing get bio-methane, and utilize it in transport

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sector. As a result there was created special bio-methane filling system, which is more profitable in comparison with other analogues in the world.

Realized gas compression system relates to a preparation of gaseous fuel for its further transfer under pressure to fuel tank of vehicle. This object is achieved by a method for compressing gas by alternate transfer of gas into two vertically arranged compressing vessels, its compression and forcing into high-pressure vessels by filling the compressing vessels with working fluid under pressure by means of a hydraulic drive. A novelty of this method lies in that, each cycle of gas compressing and forcing out of the compressing vessels is performed until these vessels are fully filled with the working fluid contained in the compressing vessels and alternately forced out of one compressing vessel into the other in response to a signal sent by fluid-level sensor. To reduce the time for fueling a vehicle, the device may be provided with an additional accumulating vessel, to which the fuel tank of the vehicle is connected during the fuelling. Fuel tank may be filled with gas compressed up to 20 MPa (in the absence of a vehicle). The filling of the vehicle is connected to the accumulation vessel to fill the vehicle. In this case, the filling may be carried out within 5 minutes by hydraulic displacement of the gas from this vessel.

The objective of research is shut-off device that provides gas compression and secures from fluid inflow in a gas pipeline. Each of compression cylinders is equipped with shut-off device with built-in fluid-level sensor placed at the outer side of the body of the shut-off device. The shut-off device is equipped with moving closing element that has magnetic insert. There is a circular clearance between the outer wall of the tube and a body of the shut-off device that is made of non-magnetic material.

MATERIAL AND METHODS

The shut-off device construction is simple (Fig. 1). It has an inlet gas channel (1), an outlet gas channel (4), and a tube (11) connected by a T-shaped channel (5) with a high-pressure hydraulic line and low-pressure hydraulic line by electromagnetic valves. Between the outer wall of the tube (11) and a body (9) of the shut-off device made of non-magnetic material there is a circular clearance (10), which is common for the inlet and outlet gas channels (1) and (4). In the gas outlet channel (4) there is a valve comprising of a movable closing element (6) provided with a magnetic insert (7) and a seat (2) in a fitting (3). A fluid-level sensor (8) capable of detecting the full filling of a compressing vessel with working fluid placed at the outer side of the body (9) of the shut-off device and the magnetic insert (7) are located at the same level in the lower position of the movable closing element (6).

The gas filling and compression system works as follows. Gas is transferred to the fuel tank of vehicle through the circular clearance opening that is placed between an outlet gas channel (4) inner surface and movable closing element (6). At the same time compressing vessel is full filling with fluid. Once the working fluid has reached the lower edge of the movable closing element (6), said element moves upward from the lower position and closes by its tapered portion, the seat (2) of the shut-off device in the fitting (3). Simultaneously, the magnetic insert (7) leaves the area of the fluid-level sensor (4) of the compression vessel. The sensor sends a signal to the electronic control unit in order to change the hydraulic flow into a reverse mode, in which electromagnetic valves are closed [1, 2]. The working fluid from the completely filled compressing vessel begins to enter another compressing vessel.

Calculation, as also modeling in program *Autodesk Inventor*, was done before the producing of shut-off device. The calculation and modeling is obligatory to analyze the processes and factors that make impact on work of shut-off device and provides optimization of the work of shut-off device. Prototype and model was made to make sure about the shut-off device work in real life conditions.

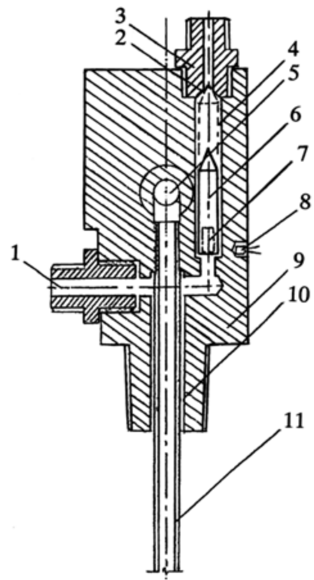

Figure 1. Shut-off device [1, 2]
1- inlet gas channel; 2 - seat; 3 - fitting; 4 - outlet gas channel; 5 - T-shaped channel; 6 - movable closing element; 7 - magnetic insert; 8 - fluid-level sensor; 9 - body of the shut-off device; 10 - circular clearance; 11 - tube

RESULTS AND DISCUSSION

In the process of calculation more attention was devoted to formation of hole range diameter of shut-off device (9–16 mm), diameter of movable closing element (7–14.5 mm), length of movable closing element (20–50 mm), cone angle (60–30º), movable closing element base surface shape (flat, bent inwards or curved). During the calculation of resistance more attention was developed to the material that was used (aluminum, brass, titanium and stainless steel). Variations were applied also to a cross-section of shut-off device (narrow hydrodynamic channel between inner cylindrical tubular and movable closing element outer surface).

Before calculations it was concluded that 2 main regimes are realized in gas passageway system – aerodynamic and hydrodynamic. Aerodynamic regime is realized when gas gets into cylindrical channel through valve that is located on the bottom of the shut-off device. At the same time gas flow affects pressure on the bottom of the shut-off device. Simultaneous gas is flooded around the surface of the movable closing element, moving through a narrow channel between the valve and the movable closing element outer surface. Hydrodynamic regime is implemented at the time when the system of shut-off device switches to spray out of fluid and movable closing element moves up till gas is displaced from the shut-off device.

Aerodynamic regime. The flow of the gas, affecting movable closing element, realize 2 processes. One of the processes is gas pressure on the movable closing element surface with force $F_1 = p_1 \cdot S_1$ (p_1 – gas flow pressure on surface S_1), and second process is symmetric gas flow around the surface of the movable closing element. In this case roughness may impact the procedure, considering the speed distribution of the gas.

For the process of calculation it is assumed that the gas flows with density ρ_2 and speed v_2 around the movable closing element with capacity V_1 and density ρ_1. It is assumed that the coefficient of the stretch of frontal resistance is equal to C=1.12 (as for a flat round plate) and cylindrical movable closing element base square is S_1. In this case the difference of pressure on the base of the movable closing element P_B and pressure on the top of the surface P_T is the following:

$$\Delta P = P_B - P_T \ll P_B,\ \Delta P = P_B - P_T \ll P_T \tag{1}$$

Within the framework of the shut-off device, it is obligatory to define such condition of the movable closing element when it is possible to realize Quasi-static conditions. To be more precise, it is not realized the movement of a movable closing element as a result of gas flow from the bottom to the top through a narrow aerodynamic channel (between inner cylindrical surface of shut-off device and outer surface of movable closing element).

The equation of the movable closing element balance condition can be put down as follows $A_1 + R + R_2 + P_1 = 0$, taking into consideration the fixed position of the movable closing element $v_1 = 0$ and plunger flooding with gas stream, where are used the following parameters (all units of measure are in SI system) [3, 5]:

- Archimedes' force:

$$A_1 = (\rho_2 - \rho_1) \cdot g \cdot V_1 \tag{2}$$

- The weight of the movable closing element:

$$P_1 = \rho_1 \cdot g \cdot V_1 \tag{3}$$

- Resistance force at the moment of movable closing element flooding:

$$R = C \cdot S_1 \cdot \frac{\rho_2 \cdot v_2^2}{2} \tag{4}$$

- Extra resistance force that is determined by the flow of the gas in a narrow aerodynamic channel, that is complicated function, consisting of several parameters: gas viscosity ν_2, cross section of a narrow aerodynamic channel d_ς, gas speed channel v_ζ and the length of the effective movable closing element l_c:

$$R_2 = \psi\{\nu_2, d_\varsigma, v_\varsigma, l_c\} \tag{5}$$

The last one allows define the speed of the gas flow inside the channel of shut-off device:

$$v_2 = \sqrt{\frac{2V_1 \cdot g}{C \cdot S_1}\left(\frac{\rho_1}{\rho_2 \cdot} - 1\right) - R_2} \cdot \tag{6}$$

It was concluded that the speed of gas flow inside the channel of shut-off device is 0.2 m·s^{-1}, but gas flow rate is ≈9.6 l·min^{-1}.

Hydrodynamic regime. In this case it is assumed that fluid flow with density ρ_2 and speed v_2 are moving towards the movable closing element with capacity V_1 and density ρ_1.

It is assumed that the coefficient of the stretch of frontal resistance is equal to C=1.12 (as for a flat round plate) and base square of cylindrical movable closing element is S_1. In this case the difference of pressure on the base of the movable closing element P_B and pressure on the top of the surface P_T is following:

$$\Delta P = P_B - P_T << P_B,\ \Delta P = P_B - P_T << P_T \tag{7}$$

Also it is assumed that the speed of the movable closing element v_1 in comparison to the speed of the fluid in channel v_2 is $(v_1 - v_2) > 0$.

Within the framework of the shut-off device, it is obligatory to define such condition of the movable closing element when it is possible to realize Quasi-static conditions. To be more precise, it is not realized the movement of the movable closing element as a result of gas flow from the bottom to the top through a narrow aerodynamic channel (between shut-off device inner cylindrical surface and movable closing element outer surface).

Taking into consideration the situation that the movable closing element flows constantly because of fluid impact and movable closing element moves from the bottom to the top with speed $v_1 = const$ the equation of the movable closing element movement can be put down as follows [4]:

$$K_1=\rho_1\cdot g\cdot V_1=\int_0^{\tau_1}(A_1+R+R_2)dt=(\rho_2-\rho_1)\cdot g\cdot V_1\cdot\tau_1+\int_0^{\tau_1}\frac{1}{2}C\cdot S_1\cdot\rho_2\cdot v_2^{\ 2}\cdot dt+\int_0^{\tau_1}R_2dt. \quad (8)$$

In this case the equation for the speed of movable closing element in time distance 0 till τ_1 is the following:

$$v_1=\left(\frac{\rho_2}{\rho_1}-1\right)\cdot\tau_1+\int_0^{\tau_1}\frac{1}{2}C\cdot\frac{S_1}{V_1}\cdot\frac{\rho_2}{\rho_1}\cdot v_2^{\ 2}\cdot dt+\int_0^{\tau_1}R_2dt \quad (9)$$

As a result of movable closing element movement at the Quasi-static conditions, provided amount of fluid flows from the bottom pipe at the base of shut-off device and movable closing element moves constantly through the channel (faster than speed of fluid) till the exit of the channel is opened.

As example, $\rho_1=8880\ kg\cdot m^{-3}$, $\rho_2=750\ kg\cdot m^{-3}$, $l_c=0.05\ m$, $C=1.12$, $R_2=4.68\ N$:

$$v_1=\left(\frac{\rho_2}{\rho_1}-1\right)\cdot\tau_1+\int_0^{\tau_1}\frac{1}{2}C\cdot\frac{S_1}{V_1}\cdot\frac{\rho_2}{\rho_1}\cdot v_2^{\ 2}\cdot dt+\int_0^{\tau_1}R_2dt\approx$$
$$\approx\left(\frac{\rho_2}{\rho_1}-1\right)\cdot\tau_1+\frac{1}{2}C\cdot\frac{S_1}{V_1}\cdot\frac{\rho_2}{\rho_1}\cdot v_2^{\ 2}\cdot\tau_1+R_2\cdot\tau_1=$$
$$=\left(\frac{0.75}{8.88}-1\right)\cdot 0.05+\frac{1}{2}\cdot 1.12\cdot\frac{1}{0.05}\cdot\frac{0.75}{8.88}\cdot 0.2^2\cdot 0.05+5.08\cdot 0.05\approx 0.22m\cdot s^{-1},$$

At the same time consumption of fluid was $v_2\cdot S_{channel}=0.2\cdot 0.8\cdot 10^{-6}=0.16\cdot 10^{-6}$, $m^3\cdot s^{-1}$ or $v_2\cdot S_{channel}=0.16\cdot 60\approx 9.6l\cdot\min^{-1}\leq 10l\cdot\min^{-1}$ during the time used for moving of closing element under the influence of fluid flow, $\tau_1=0.05\ s$.

It was concluded that the speed movement of the movable closing element is 0.2 $m\cdot s^{-1}$ faster than the speed of fluid (considering the fact $(v_1-v_2)>0$).

In the case when the optimal effective measurement proportion and the proportion of surface of shut-off device is exceeded, it is possible that the movement of the movable closing element is variable with the acceleration $a_1=dv_1/dt$, and the equation of the movable closing element movement can be put down as follows:

$$A_1+R+R_2=\rho_1\cdot g\cdot V_1\cdot a_1 \quad (10)$$

and it can be concluded that the speed of the movable closing element:

$$v_1=\left(\frac{\rho_2}{\rho_1}-1\right)\cdot\tau_1+\int_0^{\tau_1}\frac{1}{2}C\cdot\frac{S_1}{V_1}\cdot\frac{\rho_2}{\rho_1}\cdot v_2^{\ 2}\cdot dt+\int_0^{\tau_1}R_2dt \quad (11)$$

To the constant value of the speed $v_{1,0} = \left(\frac{\rho_2}{\rho_1} - 1 \right) \cdot \tau_1$ variable parts $v_{1,1} = \int_0^{\tau_1} \frac{1}{2} C \cdot \frac{S_1}{V_1} \cdot \frac{\rho_2}{\rho_1} \cdot v_2^{\,2} \cdot dt$ and $\int_0^{\tau_1} R_2 dt$ are connected. Variable parts define the speed of the movable closing element from the beginning till the end when gas is displaced from the shut-off device with a help of fluid. As a result movable closing element closes the channel that was used for gas flow out from the shut-off device.

According to the calculations the movable closing element functions as normal and carries out the assigned exercise. All attention was devoted to the movable closing element base surface influence on shut-off device operation accomplishing the development of the construction. Flat movable closing element base was selected to satisfy the conditions.

The spurt influence is the following, when the movable closing element has curved surface:

- Curved surface:

$$R_{convexity} = \rho_2 \cdot \frac{Q_0^{\,2}}{S_0} (\cos \varphi - 1) = C_{convexity}(\varphi, Q_0, S_0) \cdot S_1 \cdot \frac{\rho_2 \cdot v_2^{\,2}}{2} \tag{12}$$

ρ_2 – fluid density, Q_0 – fluid consumption at the entrance, S_0 – cross section of the channel at the entrance, φ – spurt declination angle;

- Bent inward surface:

$$R_{concave} = \rho_2 \cdot \frac{Q_0^{\,2}}{S_0} (\cos \varphi + 1) = C_{concave}(Q_0, S_0, \varphi) \cdot S_1 \cdot \frac{\rho_2 \cdot v_2^{\,2}}{2} \tag{13}$$

In those cases the movable closing element frontal resistance stretch coefficient $C(Q_0, S_0, \varphi)$ depends on 3 parameters: Q_0 – fluid consumption at the entrance, S_0 – cross section of the channel at the entrance and φ – spurt declination angle. These 3 parameters allow make concrete optimization in actions with shut-off device.

Modeling of shut-off device also was made using *Autodesk Inventor* program to predict the resistance of the movable closing element. The results of modeling showed that the shut-off device has high resistance and function ordinarily.

Prototype and model were made based on calculations. Shut-off device was tested on one step hydraulic gas fuel high-pressure compressor system prototype, and at the same time several tests were made:

1) Test on mechanical resistance (hydraulic test, 20 MPa);
2) Test on movable closing element action during the charge of a balloon;
3) Test on gas channel closing safety (if fluid do not get into the gas pipe);
4) Test on operation stability (every cycle time was measured);
5) Test on system on pressure changes (20 MPa), (as an example of gas – compressed nitrogen and as an example of fluid – motor mineral oil, hydraulic oil ATF);
6) Test on temperature regime.

As a result of tests it is concluded that shut-of device passed all tests and works correctly and constantly. Shut-off device closed gas channel and fluid did not get into the gas pipe. The movable closing element passed the test on regimes of temperature and pressure up to 65 MPa.

CONCLUSIONS

1. As a result of calculations appropriate shut-off device construction for bio-methane gas filling system was made.
2. Modeling showed that the shut-off device has high resistance and functions normal during short time period.
3. Therefore experiments are required to analyze the resistance of shut-off devices under repeated pressure during long term conditions.
4. Experimental results showed that using of unsuitable working fluid on shut-off device prototype can rise high-risk of corrosion.
5. As a result of tests it is concluded that shut-of device pass the hydraulic test and works correctly and constantly.
6. The movable closing element passed the tests on regimes of necessary temperatures and pressure up to 65 MPa.

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OPTIMIZACIJA I ISPITIVANJE TEHNOLOŠKIH PARAMETARA UREĐAJA ZA ISKLJUČENJE GASNOG SISTEMA ZA PUNJENJE BIOMETANA

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Ključne reči: *uređaj za isključenje, bio-metan*

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