Impulse mode of physical and technical gases parameters control based on the jet force action effect

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Abstract. This paper presents the results of research on the use of the jet force action effect for physical and technical gases parameters monitoring systems and devices. Authors considered and proposed the impulse mode of physical and technical gases parameters control based on the jet force action effect, which provides high accuracy and sensitivity measurements, and presented possible control devices based on the use the impulse mode of physical and technical gases parameters control: the density sensor used for single-component gases parameters control and the sealing capacity control sensor used for binary mixtures parameters control. For each device were determined static characteristics and the physical, technical and design parameters, which ensure a high level of sensors accuracy and sensitivity.

1. Introduction

A number of works are devoted to the physical and technical gases parameters control based on the use of the jet force action effect [1, 2, 3]. The jet force action effect is proposed for the use to obtain information on various physical and technical gases and liquid properties in some other sources [4, 5, 6, 7, 8].

The paper presents the research data on gas parameters when it flows out onto the limited dimensions plate, commensurate with the jet force action section dimensions acting on it. The air is ejected from the environment with a constant gas flow, which makes the task of the gases parameters impossible [9]. In this regard authors of this paper propose the use of the impulse injection of the analyzed gas dose into the reference gas flow, which "pushes" the dose of the analyzed gas through a certain inductive resistance. This appilment on the one hand prevents the mixing of the analyzed gas dose with the comparative one and on the other hand it makes it possible to reduce the wave processes influence caused by switching the doser when the analyzed gas is introduced.

For the physical and technical gases parameters control the jet force action \( F \) acting on the limited dimensions plate is calculated by the equation [10]:

\[
F = \rho S_e v_0^2,
\]

where \( \rho \) - the gas density, \( v_0 \) - the mean square gas molecules velocity, \( S_e = S_e \left( 1 + 0.35 \frac{h}{d_e} \right)^2 \).
the jet «trace» area on the plate, \( S_c = \frac{\pi d_c^2}{4} \) - the tube jet area, \( d_c \) - the tube jet diameter, \( h \) - the distance from the tube jet to the plate.

Taking into account the total effect of all forces by introducing the empirical coefficient \( k \) obtained during the research the jet force action \( F \) on a plate of limited dimensions will be:

\[
F = kPS_c \left( 1 + 0.35 \frac{h}{d_c} \right) \left( 0.3 + 0.14 \frac{h}{d_c} \right)^{-1} = kPS_c \left( 0.3 + 0.14 \frac{h}{d_c} \right)^{-2},
\]

where \( P \) - the pressure before it goes out from the tube jet, \( k \approx 0.85 - 0.95 \).

To include the effect from all forces acting on the jet force action \( F \) on the limited dimensions plate in equation (1) we introduce an empirical coefficient \( k \) from equation (2) since the both equations are identical:

\[
F = k\rho S_t v_0^2.
\]

The use of the jet force action effect allows to solve the problems of the physical and technical parameters control of single-component gases and binary mixtures. Blueprints and descriptions of the pneumatic gas density sensor used for single-component gases and the jet photocompensation sealing capacity control sensor used for binary mixtures are given as examples of the corresponding use in this paper.

2. The gas density control

The principle of the impulse density sensor operation is based on a comparison of the reference gas jet force action and a dose of the analyzed gas jet force action. The pneumatic gas density sensor [11] consists of the sensing element and the compensation measuring circuit (figure 1).

![Figure 1. The pneumatic gas density sensor.](image-url)

The sensing element is the plate 1 suspended on the gas support 2. The plate rotation is recorded by changing the distance between the tube jet 4 and the shutter 5 rigidly fixed on the plate 1. The measuring circuit is the compensation pneumatic circuit with tube jets 3(1) and 3(2). From each tube jet goes out the stream of the reference gas RG under the flow pressure \( P \), the adjustment and regulation of which is provided by variable throttles 6 and controlled by micromanometers 7. The tube jet 3(2) is connected to the doser 8, consisting of the membrane pneumatic switch 9 and the dosing volume 10 for the analyzed gas AG, which goes in impulses into the RG flow by means of switching valve 11 and control signals \( t \) and \( t̅ \). Between the tube jet 4 and the inlet throttle 12 there is the inter-throttle chamber 13 connected to the inlet of the membrane power amplifier 14 with a gain greater than unity. The output channel of the amplifier 14 is connected to the secondary pressure gauge 15 and the feedback tube jet 16. To compensate for the jet force action emanating from the measuring tube jet 4 the tube jet 17 is provided which connected to the inter-throttle chamber 13. The conditional zero signal \( P_0 \) is supplied through the
tube jet 18. The measuring circuit gain change is achieved by the ratio of the arms \( l_1 \) and \( l_2 \) (respectively and the distance from the gas support 2 to the feedback tube jet 16 and the distance from the gas support 2 to tube jets 3) by rotating the screw 19.

In the initial position of the doser 8 (at the signal \( t \)) the AG fills the dosing volume 10 and the RG passes to both tube jets 3 (1) and 3 (2) and exerts the same pressure on the plate 1. When the RG jet flows onto the plate 1, the jet force action \( F_1 \) acting on the plate 1 surface is determined according to (3):

\[ F_1 = k \rho_1 S_{t1} \varphi_0^2, \]

where \( \rho_1 \) - the RG density, \( S_{t1} = S_{c11} \left( 1 + 0.35 \frac{h}{d_{c1}} \right)^2 \) - the jet «trace» area on the plate 1,
when the jet flows out of the tube jet 3 (1), \( S_{c1} = \frac{\pi d_{c1}^2}{4} \) - the tube jet 3 (1) outlet area, \( d_{c1} \) - the tube jet 3 (1) outlet diameter.

When switching the doser 8 (at the signal \( \hat{t} \)), the AG (with a density \( \rho_2 \)) dose from the dosing volume 10 is introduced into the RG flow, which is supplied to the tube jet 3 (2), and the jet force action \( F_2 \) exerts on the plate 1 surface:

\[ F_2 = k \rho_2 S_{t2} \varphi_0^2, \]

where \( S_{t2} = S_{c2} \left( 1 + 0.35 \frac{h}{d_{c2}} \right)^2 \) - the jet «trace» area on the plate 1, when the jet flows out of the tube jet 3 (2), \( S_{c2} = \frac{\pi d_{c2}^2}{4} \) - the tube jet 3 (2) outlet area, \( d_{c2} \) - the tube jet 3 (2) outlet diameter.

As the result of the AG dose passage through the tube jet 3 (2), the mechanical moments of the forces acting on the plate are equal to:

\[ \begin{align*}
M_1 &= k \rho_1 S_{t1} \varphi_0^2 l_2, \\
M_2 &= k \rho_2 S_{t2} \varphi_0^2 l_2, \\
M_c &= k P_{Ex} S_{t16} l_1, 
\end{align*} \]

where \( M_1 \) - the mechanical moment from the force action \( F_1 \), \( M_2 \) - the mechanical moment from the force action \( F_2 \), \( M_c \) - the compensating mechanical moment of the sensor sensing element, \( P_{Ex} \) - the outlet pressure, \( S_{t16} = S_{c16} \left( 1 + 0.35 \frac{h}{d_{c16}} \right)^2 \) - the jet «trace» area on the plate 1, when the jet flows out from the feedback tube jet 16, \( S_{c16} \) - the feedback tube jet 16 outlet area, \( d_{c16} \) - the feedback tube jet 16 outlet diameter.

The condition of the equality of moments is determined by the expression:

\[ M_2 = M_1 + M_c. \]  \hspace{1cm} (5)

According to equations (4) the expression (5) takes the form:

\[ k P_{Ex} S_{t16} l_1 = k \rho_2 S_{t2} \varphi_0^2 l_2 - k \rho_1 S_{t1} \varphi_0^2 l_2. \]  \hspace{1cm} (6)

Considering that the sensor tube jets diameters are selected the same (\( d_{c1} = d_{c2} = d_{c16} \)) it follows that \( S_{c1} = S_{c2} = S_{c16} \) and \( S_{t1} = S_{t2} = S_{t16} \). Including this the expression (6) can be reduced:

\[ P_{Ex} l_1 = \rho_2 \varphi_0^2 l_2 - \rho_1 \varphi_0^2 l_2. \]  \hspace{1cm} (7)

From expression (7) the outlet pressure will be equal to:

\[ P_{Ex} = \Delta \rho \varphi_0^2 \frac{ l_2}{l_1}, \]

where \( \Delta \rho = \rho_2 - \rho_1 \) - the density difference between the AG and the RG.

The sensor sensitivity \( H_p \) to the gases density difference will be:
Consequently the pneumatic density sensor sensitivity is constant and depends on the mean square gas molecules velocity $\nu_0$ and the ratio of the distances $l_2$ (the distance from the gas support 2 to tube jets 3) and $l_1$ (the distance from the gas support 2 to the feedback tube jet 16). The important condition for the pneumatic gas density sensor operation is the choice of the optimal distance from the doser 8 to the tube jet 3 (2), which determines the inductive resistance. This makes it possible to exclude the wave effect when switching the doser 8 as well as the dilution of the AG dose from the dosing volume 10 by the RG.

3. The product sealing capacity control

The accumulated statistical data on the sealing capacity degree determining for various types of instrumentation and mechanical engineering products shows that the sealing capacity value lies in the range from $10^{-7} \text{ m}^3\text{Pa s}^{-1}$ to $10^2 \text{ m}^3\text{Pa s}^{-1}$. In this regard the task was set to develop the sealing capacity control sensor, the sensitivity of which would be acceptable for automated assembly line flows.

The principle of the jet photocompensation sealing capacity control sensor (figure 2) operation for binary mixtures is based on the gas analytical determination of the test gas dose in the binary mixture with the reference gas, for example air. The test gas is fed directly into the product and in case of sealing capacity breaches gas molecules penetrate through the product defects into the accumulation volume and then the resulting binary mixture is sent for the jet sensor analysis.

![Figure 2. The jet photocompensation sealing capacity control sensor.](image_url)
differential photoresistance 11. When the electrical circuit fall out from the balance the current \( I \) arises in the feedback circuit and recorded by the milliammeter 12. Micromanometers 16 are used to control the pressure in the RG circuit and located each in two branches of the differential pneumatic circuit. Variable throttles 17 are used to adjust the micromanometers 16.

In the initial position of the membrane pneumatic switch 13 the RG passes to tube jets 7 and the RG jet from each tube jet equally affects the plate 5 while the movable part of the galvanometer lies in the neutral position and the milliammeter 12 registers the conditional zero signal. In case of product sealing capacity breaches the test gas TG accumulates during the control time in the measuring chamber 14 and the dosing volume 15. When switching the membrane pneumatic switch 13, the TG dose accumulated during the sealing capacity breach is fed into the RG line, which pushes it through the tube jet 7(2) to the sensor sensitive element - plate 5. The TG dose which has the different density from the RG density rotates plate 5, mirror 4 and frame 2 of the galvanometer through a certain angle. The reflected light beam changes the illumination of the differential photoresistance 11. As the result of that the current \( I \) appears in the feedback circuit and leads to the magnetoelectric force appearance, which compensates the jet force action change. The current value in the feedback circuit is proportional to the density difference between the TG and the RG. The resulting magnetoelectric moment \( M_E \) compensates for the mechanical moment \( M_M \) from the jet force acting on the plate surface.

When the RG jet affect the plate, the jet force action on its surface is determined by expression (3). As the result of the sealing capacity breach the TG (with the density \( \rho_2 \)) penetrate the RG (with the density \( \rho_1 \)) flow and the jet force action is equal to:

\[
F_S = k_S l_2 v_0^2 \left\{ \rho_1 \left[ 1 - Y_i(t) \right] + \rho_2 Y_i(t) \right\}
\]  

(9)

where \( Y_i(t) \) - the TG concentration in the dosing volume 15 of the measuring chamber 14.

The force difference \( \Delta F \) calculated by (3) and (9) make:

\[
\Delta F = k_S l_2 v_0^2 |\rho_1 - \rho_2| Y_i(t).
\]

(10)

The TG concentration in the dosing volume 15 of the measuring chamber 14 will be measured:

\[
Y_i(t) = \frac{N_i}{N} = \frac{Q_i \Delta t}{N V P}.
\]

(11)

where \( N_i = Q_i \Delta t \) - the number of TG molecules that penetrated into the measuring chamber 14 as the result of the sealing capacity breach during the monitoring time \( \Delta t \), \( Q_i \) - the TG molecular flow rate, \( N = n V \) - the total number of molecules in the measuring chamber 14, \( n \) - the molecular gas density in the measuring chamber 14 capacity \( V \)[12].

The molecular gas density in the measuring chamber 14 is equal to:

\[
n = P / (k_B T),
\]

(12)

where \( P \) - the gas pressure in the measuring chamber 14, \( k_B \) - Boltzmann constant, \( T \) - absolute temperature.

Considering the equation (12) the expression (12) is equal to:

\[
Y_i(t) = \frac{Q_i \Delta t}{V P} k_B T.
\]

(13)

As the indicator of sealing capacity breaches can be used the TG flow rate \( Q \) equal to:

\[
Q = Q_i k_B T.
\]

(14)

From equations (10)-(14) it follows that the force difference \( \Delta F \) acting on the plate is equal to:

\[
\Delta F = k_S l_2 v_0^2 |\rho_1 - \rho_2| \frac{Q_i \Delta t}{V P}.
\]

Mechanical moment from the jet force action on the plate movable part:

\[
M_M = \Delta F S l_c,
\]

(15)
where \( l_c \) - the distance of the jet «trace» area \( S_{t2} \) symmetry axis to the galvanometer 1 moving part symmetry axis.

The magnetoelastic moment is determined by the expression:

\[
M_E = \psi l,
\]

(16)

where \( \psi \) - flux linkage.

Neglecting the moving part elastic elements stiffness the sensor operating condition in a steady state is equal to: \( M_M = M_E \). Taking into account equations (15) and (16) the sensor operating condition in a steady state is possible to write down as:

\[
\Delta F S_{t2} l_c = \psi l.
\]

The leakage change sensitivity \( H_Q \) is:

\[
H_Q = \frac{\partial F}{\partial q} = k v_0^2 |\rho_1 - \rho_2| \frac{S_{t2} l_c \Delta t}{\psi v P}.
\]

(17)

Overall by changing the jet photocompensation sensor parameters the leakage change sensitivity can be varied.

4. Conclusion

In the course of this research the following was carried out and revealed: the research data on gas parameters when it flows out onto the limited dimensions plate, commensurate with the jet force action section dimensions acting on it; proposed the pneumatic density sensor use for single-component gases and the jet photocompensation sealing capacity control sensor use for binary mixtures, both operation of which based on the jet force action effect and the impulse injection of the analyzed gas dose into the reference gas flow; determined the sensors static characteristics and the physical, technical and design parameters affecting them, which allow qualify that both devices has the acceptable sensitivity for automated assembly line flows.

To ensure the high sensor accuracy and high sensor sensitivity special requirements are imposed on the sensor design:

- The plate width and the corresponding tube jet diameter as well as the distance between them are selected taking into account the maximum perceiving force action of the normally incident jet.
- To increase the sensor merit figure (the combination criterion of the speed and the sensitivity) it is required to reduce the plate thickness and use the lower density plate material.

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