The research of gas leak from the pipeline

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Abstract

There are presented the research results of gas leak from the pipeline under pressure through a small hole in a thin wall. The analysis of equations of gas flow energy in the process of gas leak allows making under certain assumptions a formula for the mass flow of gas through a small hole in a wall.

However, the experience shows that the assumptions significantly distort the actual state of physical process that ultimately leads to uncertainty in the obtained results. In this regard, there are made a number of analytical and experimental studies to assess the adequacy of theoretical statements with restrictions and the actual results of experiments. The result of the research is an adjustment for the theoretical dependence for the mass flow rate of gas, which flows through a small hole from the tank. There is also showed the dependence of the adjustment on the pressure and temperature of gas in the tank.

Keywords: *adjustment for reality, equation of gas flow energy, gas leak, mass flow.*

The gas leak from the tank, where it is under redundant pressure, is extremely difficult, as it is characterized by parameters, which ambiguously determine the consumption of gas. The following parameters primarily include:

absolute pressures in the tank and out of it and their correlation;

the gas temperature;

dimensions of the hole through which gas is leaked;

gas properties.

The mode of leakage can be critical, or under critical depending on the pressure ratio. It has a significant effect on the cost of gas.

The classical principles in research of gas leak under pressure are researched by I. A. Charnyi [1]. He offered analytical framework of mathematical modelling of the process that is based on the equation of energy. The outstanding researches were also made by L. D. Landau [2], L. G. Loicianskyi [3], G. Yu. Stepanova [4], G. G. Chernyi [5], S. G. Shcherbakov [6], E. I. Yakovleva [7], G. N. Abramovič [8], J. L. Campbell [9], R. Kantola [11], F. A. Lang [12], W. Zielke [13]. Their studies show the results of the researches in thermo gas dynamics of the leakage process, provide the analysis of the factors that have an impact on the flow of the process, define the boundaries of critical and subcritical leakage, offer settlement formula and methodologies. However, the real influence of the process parameters on gas consumption turns out to be more difficult compared to the theoretically predicted influence. Therefore, the actual gas leakage is significantly different from the estimated, distorting the projected estimates. Therefore, an important task for the practice of research of the leakage process is comparing the actual and projected results.

As we know from [1], the equation of the gas flow energy is the basis for the calculation of gas leak under pressure from the tank. In our case it can be the following:

$$i_1 - i_2 = \frac{w_1^2 - w_2^2}{2}. \qquad (1)$$

Where i_1, i_2 is an enthalpy of gas in the tank and in the flow through the hole with the diameter d, respectively; w_1, w_2 are linear velocities of gas in the tank and the hole.

For calculation of a dependence relation of the gas leak on the process parameters we make the following assumptions:

the process of gas leak is adiabatic, i.e. it occurs without heat exchange with the environment;

the linear velocity of gas in a tank is negligible in comparison to the gas velocity, and it is neglected;

the hole diameter in a thin wall is considered to be substantially greater than the wall thickness, thus the energy losses during the leakage are neglected.

gas is considered to be ideal, thus non-pressing phenomenon is neglected.

As a result of simple mathematical transformations [1] there is a dependence that links the mass flow with parameters of the leakage. This dependence is Saint-Venant`s equation:

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$$m = \frac{\pi d^2}{4}\sqrt{\frac{2k}{k-1}\, p_0 \rho_0 \left[\left(\frac{p_a}{p_0}\right)^{\frac{k-1}{k}} - \left(\frac{p_a}{p_0}\right)^{\frac{2}{k}} \right]}. \qquad (2)$$

Where k is a rate of adiabatic process; p_0, p_a are the pressures inside and outside the tank; ρ_0 is the density of gas at certain conditions inside the tank.

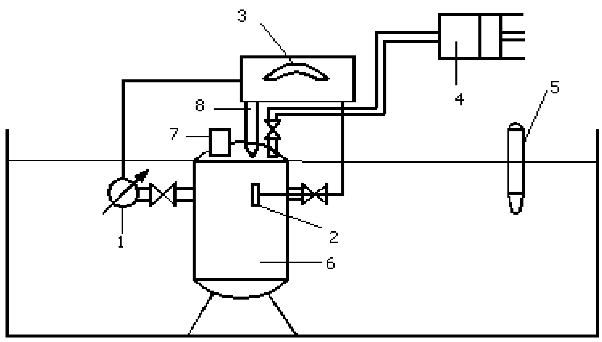
Apriori comparisons of actual values of gas leak are calculated in [2], and they show that their values are overestimated by up to 30 % [8]. However, the scientific justification for the mentioned conclusion is not provided.

It should be shown that during the study of fluid leak from the tank through a hole in a thin wall we have taken for the theoretical basis the Bernoulli equation, which is the law of conservation of energy formula. There is introduced the concept of expense ratio and compression ratio, which depend on the leak conditions, to adapt the theoretical dependence and practice.

Obviously, in order to adapt the theoretical relations and practical result in case of gas leak from the tank under pressure it is necessary to use certain coefficients derived from the studies.

These studies will, firstly, assess the impact of the assumptions, mentioned above, on the value of the mass flow rate of gas. It is obvious that these studies can only be based on comparison of theoretical and actual results.

For the experimental part of the study we have set up a stand, its scheme is shown in Fig. 1.



1 – manometer HO8EM011ШТ 3051 C with the range of 25 Pa – 13.8 MPa, 2 – resistance thermometer POL, 3 – automatic balancing bridges, 4 – compressor, 5 – scales thermometer, 6 – receiver, 7 – nozzle, 8 – thermocouple

Figure 1 – Experimental stand

The cylindrical container, placed in a water thermostat, was filled up with air by a compressor to the maximal pressure 1.0 MPa. The pressure in the container was monitored and recorded using the manometer H08EMO11ШТ 3051C with a range of measurement of 25 Pa – 13.8 MPa. For measuring and recording the temperature of the gaseous medium there is used a ТСП-1088 thermometer. For a gas leak in a container there are mounted removable nozzles with small holes of various shapes in a thin wall, the area of which is 0.2 cm^2. The temperature of the wall at a distance of 12mm from the nozzle was measured and written by the thermocouple ТХА-2088.

Based on the conducted series of experiments, which differed by values of gas temperature in a receiver, there were built dependency graphs of gas temperature in a tank and the wall surface during emptying the battery gas. The variation of temperature in gas environment and changes in wall temperature are shown in Fig. 2.

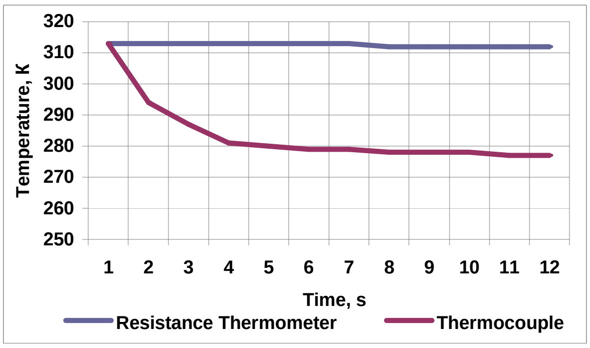


Figure 2 – The change of gas temperature during the leak

Their analysis shows that despite the almost constant temperature of gas in the receiver the wall temperature changes significantly even for a short emptying time. Therefore, the assumption of the adiabatic nature of the process is not adequate, which is obviously reflected in results of prediction.

To evaluate the following assumptions that the velocity of gas in a container is approximately equal to zero, there is made a mathematical model of the process of leaking.

The mathematical model is made for the linear section of the pipeline length of $L = 12$ m. The gas with a constant mass flow of $m = 50$ kg/s is extracted at the beginning of this section. The aim of the research is to define the distribution of gas velocities in the pipeline. The basis of the mathematical model makes the equation of motion and continuity in the following form

$$\begin{aligned} &\frac{\partial p}{\partial x} + \frac{\lambda \rho w^2}{2d} = 0, \\ &-\frac{\partial p}{\partial t} = c^2 \frac{\partial (\rho w)}{\partial x}, \end{aligned} \qquad (3)$$

where $p(x,t)$ is the pressure in the pipeline; ρ is the density of gas; w is the linear velocity; d is the diameter of the pipeline; λ is the coefficient of hydraulic resistance; c is the speed of sound in gas.

Implementation of this system of equations was carried out under the following initial and boundary conditions

$$\begin{aligned} &p(x,0) = p_0, \\ &\left.\frac{\partial p^2}{\partial x}\right|_{x=0} = -\mu m^2, \\ &\left.\frac{\partial p^2}{\partial x}\right|_{x=L} = 0. \end{aligned} \qquad (4)$$

The system of equations (3) can be reduced by differentiation in time to the equation of heat conductivity relatively to mass velocity of gas

$$\frac{\partial(\rho w)}{\partial t} = æ\frac{\partial^2(\rho w)}{\partial x^2}. \qquad (5)$$

The boundary value problem for this equation is chosen for the following reasons: there is a balance during the initial time ($t = 0$) in the pipeline, therefore $\rho w(x,0) = 0$. From some point of time ($t > 0$) we extract gas with a constant mass flow $m = \text{idem}$ on the left side, resulting in $\rho w(0,t) = \frac{m}{F}$ (where F is the sectional area of the pipeline) and the right end of the pipeline is isolated, so $\rho w(L,t) = 0$.

In order to solve the equation (5) we summarize the boundary value problem to homogeneous. For this reason we introduce a new function $\varphi(x,t)$, built with the required $\rho w(x,t)$ by the ratio

$$\rho w(x,t) = \varphi(x,t) + \gamma + \gamma_1 x, \qquad (6)$$

where γ, γ_1 are the constant coefficients that are to be calculated. Function $\varphi(x,t)$ must satisfy the equation (5) with homogeneous boundary conditions $\varphi(0,t) = 0$ and $\varphi(L,t) = 0$.

Therefore the constant coefficients from (6) have the following values

$$\gamma_1 = \frac{m}{f},$$

$$\gamma = -\frac{m}{FL}.$$

The initial condition

$$\varphi(x,0) = -\frac{m}{F}(1 - \frac{x}{L}).$$

Implementation of homogeneous boundary value problem is performed by Fourier method. The variables are divided:

$$\varphi(x,t) = X(x)T(t).$$

The equation (5) can be written as

$$\frac{1}{æ}\frac{T'}{T} = \frac{X''}{X} = -\lambda_n^2. \qquad (7)$$

Based on (7) we obtain two linear differential equations

$$X'' + \lambda^2 X = 0,$$
$$\frac{dT}{T} = \lambda^2 æ\, dt. \qquad (8)$$

From the first equation of the system (8) we find

$$\lambda_n = \frac{\pi n}{L}.$$

So the general solution of the homogeneous problem has the form

$$\varphi_n(x,t) = a_n \sin\frac{\pi n x}{L} e^{-\frac{\pi^2 n^2 æ t}{L^2}}.$$

By integrating the constant we obtain

$$a_n = \frac{2}{L}\int_0^L \varphi(x,0)\sin\frac{\pi n x}{L}.$$

Therefore the final solution is the following

$$\varphi(x,t) = \frac{2m}{F\pi}\sum_{n=1}^{\infty}\left[\frac{1-(-1)^n}{n} + (-1)^n\right]\sin\frac{\pi n x}{L} e^{-\frac{\pi^2 n^2 æ t}{L^2}}.$$

The mass velocity is the following

$$\rho w(x,t) = \frac{m}{F}\left\{\left(1 - \frac{x}{L}\right) + \right.$$
$$\left. + \frac{2}{\pi}\sum_{n=1}^{\infty}\left[\frac{1-(-1)^n}{n} + (-1)^n\right]\sin\frac{\pi n x}{L} e^{-\frac{\pi^2 n^2 æ t}{L^2}}\right\}. \qquad (9)$$

We find the distribution of pressure in the pipeline from the first equation of a system (4)

$$-\int_{P_0}^{P}\frac{\partial p}{\partial x}dx = 2a\int_0^x \rho w(x,t)dx,$$

where $2a = \frac{\lambda \overline{w}}{2d}$ is the linearization coefficient.

In the final form the pressure distribution in the pipeline as a linear function of coordinate and time is expressed by the following dependence

$$p^2(x,t) = P_0 - \frac{\lambda \overline{w} m}{2df}\left\{x\left(1 - \frac{x}{2L}\right) + \right.$$
$$\left. + \frac{2L}{\pi^2}\sum_{n=1}^{\infty}\frac{1 + (n-1)(-1)^n}{n}\left(1 - \cos\frac{\pi n x}{L}\right)e^{-\frac{\pi^2 n^2 æ t}{L^2}}\right\}, \qquad (10)$$

$$æ = \frac{c^2}{2a}.$$

Therefore the linear velocity of gas based on the continuity equation is

$$w(x,t) = \frac{2m}{\pi f \rho(x,t)} \times$$
$$\times \sum_{n=1}^{\infty}\left[\frac{1-(-1)^n}{n} + (-1)^n\right]\sin\frac{\pi n x}{L} e^{-\frac{\pi^2 n^2 x t}{L^2}}, \qquad (11)$$

where $\rho(x,t) = \frac{p(x,t)}{zRT}$.

Based on the latter dependence we have built the graph of the gas linear velocity change in the receiver at different distances from the source of leakage.

The analysis of results, shown in the graphs in Figure 3, proves that gas linear velocity in the pipeline during the non-stationary process varies in length and time in the range up to 29 m/s under the critical conditions for gas leak through a hole with 50 mm in diameter from a pipe with the diameter of 500 mm. If the critical velocity of gas is equal to the speed of sound in air $c = \sqrt{kRT}$, which is 355 m/s at a temperature of $313K$, the ratio of linear velocities of gas is more than 8%. This means that neglect of the gas velocity in the pipeline causes a certain error by calculating the mass flow rate of gas leak.

Two of these assumptions, used for the dependence (2), can be confirmed or refuted only by experimental studies. Therefore there were conducted a series of experiments on the experimental stand (Fig. 3).

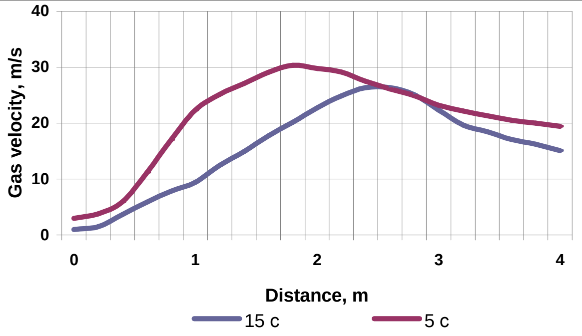


Figure 3 – The change of the linear velocity of gas in the pipeline during the leak

During the air bleed from the tank through the holes with the same cross-sectional area and different shape (circle, square, and cleft) there was recorded the process of pressure reduction in receiver in time (Fig. 4).

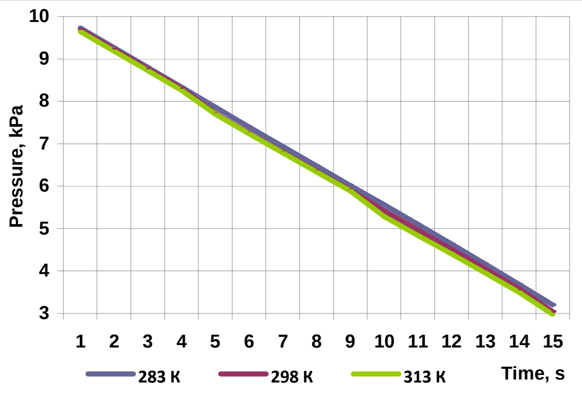


Figure 4 – The pressure change in receiver during the gas leak

There was chosen a random period of time Δt at the graph and there were recorded the pressures at the beginning of period $p_1(t)$ and the end of it $p_2(t+\Delta t)$. The mass flow of gas during the (average) time interval Δt was calculated on the basis of the equation of state for gas

$$m_0 = \frac{\Delta M}{\Delta t} = \left(p_1^*(t) - p_2^*(t+\Delta t)\right)\frac{V}{RT}, \qquad (12)$$

where V is the geometric volume capacity; R is the gas constant of air; T is an absolute gas temperature, which was considered constant, at the interval Δt; $p_1^*(t)$, $p_2^*(t+\Delta t)$ are the pressures in the receiver at the beginning and the end of the period of time Δt

$$p^* = \frac{p}{z},$$

where z is the coefficient of air compressibility.

For calculating the average theoretical mass of the flow rate of air for a certain period of time Δt we computed the density of air at the beginning and the end of the certain period of time

$$\rho_{1,2} = \frac{p_{1,2}}{zRT}. \qquad (13)$$

There was calculated the mass flow of air leak at the beginning of m_t and the end of $m_{t+\Delta t}$ of the time period Δt based on (2). Since the time interval Δt was small, the change of the leak at this time could be close to linear. Therefore, the average air mass flow during the time interval Δt was calculated as an average

$$m_m = \frac{1}{2}\left(m_t + m_{t+\Delta t}\right). \qquad (14)$$

The results, obtained in (14), were considered theoretical and that was why they were compared with those obtained in (12), which were considered factual. As a result we obtained the coefficient of leak

$$C_\mu = \frac{m_0}{m_m}. \qquad (15)$$

The graphics, built based on the research results, are shown in Fig. 5.

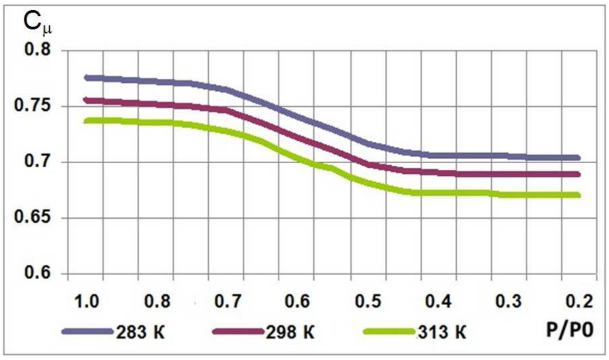


Figure 5 – The change of the coefficient of the leakage flow depending on pressure and temperature

When analyzing the graphs shown in Fig. 5, we can draw the following conclusions.

The assumptions, which are the basis of the dependence of the mass flow during gas leak from the tank through a hole in a thin wall, have a significant influence on the results of the simulation process, as a real mass flow differs significantly from the calculated one. If the absolute pressure changes in the receiver from 1.0MPa up to 0.54MPa (the end of the critical outflow zone), the flow coefficient varies from 0.776 to 0.709 at the temperature of $288K$ in the receiver. The rise of the gas temperature in the receiver results in a significant deviation of actual flow from the theoretical flow. So at the temperature of $283K$ and the pressure of 1.0MPa in the receiver the flow coefficient is 0.776, when the temperature rises up to $298K$ the coefficient decreases to 0.756, when the temperature rises to $313K$ the coefficient decreases to 0.738. The flow coefficient is 0.709 at the pressure of $0.54MPa$ and the temperature of $283K$, when the temperature rises to $298K$ the coefficient decreases to 0.696, and when the temperature rises to $313K$ the coefficient decreases to 0.678.

The change of the shape of hole, through which the leak occurs, isn't of great importance during the critical process.

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Дослідження витоку газу з трубопроводу

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Наведено результати досліджень процесу витікання газу з газопроводу під тиском через отвір у тонкій стінці. Аналіз рівнянь енергії газового потоку в процесі витікання газу дає можливість одержати за певних припущень формулу для масової витрати газу через отвір у тонкій стінці.

Водночас досвід свідчить, що прийняті припущення суттєво спотворюють реальну картину фізичного процесу, що в кінцевому рахунку приводить до похибки в одержаному результаті. У зв'язку з цим проведено низку аналітичних і експериментальних досліджень з оцінки адекватності теоретичних положень з прийнятими обмеженнями реальним результатом, одержаним через проведені експерименти. Наслідком проведених досліджень є поправка, яку запропоновано внести в теоретичну залежність для масової витрати газу, що витікає через малий отвір з ємності. Показано залежність одержаної поправки від тиску і температури газу в ємності.

Ключові слова: *витікання газу, масова витрата, поправка на реальність, рівняння енергії газового потоку.*