Calculation Method for the Energy Loss in the Pneumatic Mining Networks

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Abstract: We propose a calculation method by we can estimate the value of the loss of pressure along the pipeline, the loss of pressure per length meter of network and the cost of the pneumatic energy loss in the case of the horizontal and vertical pneumatic network. The proposed method is validated by a study case.

Key-Words: pneumatic network, loss of pressure, drop of temperature, cost of pneumatic energy loss, energy loss

Nomenclature:

B – barometric pressure at the surface (mmHg);

C_l – cost of energy loss per meter and hour (lei/(m·h))

C_l^o – cost of energy loss per meter and hour in the case of the horizontal network (lei/(m·h))

C_l^v – cost of energy loss per meter and hour in the case of the vertical network (lei/(m·h))

C_e – cost of the pneumatic energy;

c_p – mass specific heat of the air at constant pressure(J/(kg·K))

d- diameter of the pneumatic pipeline (m);

d_e – outer diameter of the pipe (m);

H – depth of the vertical work (m);

k – adiabatic exponent;

k_o – coefficient of energy loss for the horizontal network;

k_v – coefficient of energy loss for the vertical network;

$\dot{m}$ - mass flow (kg/min);

Δp - loss of pressure (bar);

P – area of the mining work (m);

p_1 – inlet pressure of the pneumatic network section (N/m^2);

p_2 – outlet pressure of the pneumatic network section (N/m^2);

$\bar{p}$ - average pressure per meter of air column (mmHg/m);

Re – invariant Reynolds;

R – constant nature of air (J/(kg·K));

t_a – temperature of the compressed air;

t_{in} – temperature of the air inside the pipe;

T_1 – inlet temperature of the compressed air the pneumatic network section (K);

T_2 – outlet temperature of the compressed air the pneumatic network section (K);

T_{cond} – external temperature of the compressed air pipeline for a certain length of the pipe

S – surface (m^2);

r – water vaporization latent heat (J/(kg·K))

$\dot{V}$ - volume flow of compressed air (m³/s);

Δx_l - change of the absolute humidity per length meter;

x – absolute humidity;

x_1 – absolute humidity at the surface of the mine;

α_e – coefficient of thermal convection at the outer side of the pipe (W/(m²·K));

η_{ad} - adiabatic efficiency;

λ – coefficient of thermal conduction (W/(m·K));

ζ - the coefficient of friction;

1 Introduction

The energy required for operating the pneumatic equipment and machines from the underground mining works is provided by the pneumatic energy generator through a pipeline network.

In order to argue the importance of the study, we remind that the temperature, the pressure, the flow of the compressed air are basic parameters of the pneumatic networks and determining them is useful as well as necessary for the rational operation of the pneumatic energy consumers.

The pipeline network can be extremely complicated in its extension horizontally as well as vertically. The diameters of the pipes vary depending on the distance and the type of the equipment they serve. The network has losses of energy (power) on the way from the compressor until the consumer.

The problem of determining the loss of pressure, flow and energy (power) within the networks of compressed air was presented in [1], [2], [3] si [4]. The results obtained show a significant percentage of the mass debit losses when connecting the consumers (27.98%), major loss on the distribution network (14,99%) and smaller losses on the main network (4,89%)[1]. The most significant energy losses on the network are recorded due to flow loss through non-tightness spots – at a flow loss of 50.702% (36.661% network losses and 14.041% consumer losses), corresponds an energy loss of 48.938% (36.958% network losses 12.34% consumer losses); the influence of pressure losses is insignificant as a percentage in the energetic balance of the system compressor – network – consumer [5].

The energetic changes in the network are due to the variation of the kinetic, potential and internal energy and on the other hand to the changes of energy. We use the classical method to determine the parameters of the network, through iterative computing, using average values for the section of pipe, knowing the parameters of the initial stage at exiting the compressor and the final one at the last pneumatic consumer [3]. This method requires pressure and temperature measurements in the initial and final points of the pneumatic network, being significantly different as compared with the proposed method.

This study is realised in time for only one space coordinate. The elements of novelty in this paper consist of:

1. the loss of pressure in the compressed air pipelines can be computed depending on the initial parameters without mediations on the considered section, as it usually is done. This is the novelty of the proposed method;

2. distinct computing methods for the loss of pressure and temperature for the case of horizontal and vertical pneumatic network. In view of determining the fall of temperature we get a solution as integral (relation 16).

The validation of the results obtained is realised through a case study.

2 Model overview

2.1 The case of the horizontal pneumatic network

The fundamental parameters of a pneumatic network are its diameter and its flow. Depending on these parameters, the loss of energy in relation to the pipe length and to the time is calculated by the following relation [7]:

$$C_l = k_l \cdot \frac{\dot{V}^{2,852}}{d^5} \qquad \left[\frac{lei}{m \cdot h} \right] \qquad (1)$$

where:

$$k_l = 0.0187 \cdot 10^{-6} \left(\frac{p_1}{T_1} \right)^{2.852} \cdot \frac{T_2^{1.852}}{p_2^2} \cdot \frac{C_e}{\eta_{ad}} \left(0.098 \cdot T_2 - 13.5 \right)^{0.148}$$

(2)

For a given (known) diameter and flow, the cost of the lost pneumatic energy depends on the parameters of the environmental air as well as on the specific condition of the installation.

The pressure along the pipeline depends on the loss of pressure, which can be de3terminede by the known relation:

$$\Delta p = p_1 \left[1 - \sqrt[\frac{k+1}{k}]{1 - \frac{k+1}{k} \cdot \frac{\zeta \cdot \lambda \cdot l}{d \cdot R \cdot T_1} \cdot \frac{w_1^2}{2}} \right] \quad (3)$$

as the friction coefficient on (3) depends on the pipe rugosity and on the Re and is calculated by the relation:

$$\zeta = 0.0624 \cdot d^{-0.148} \cdot Re^{-0.148} \quad (4)$$

Due to the length of the distribution network, an inherent loss of pressure (energy) occurs. Just after the compressor, the cooling is more intense due to the high difference of temperature between the compressed air and the environment and is lower for the rest of the network. The polytropic index that characterizes the transformation is variable. As we measure the initial and the final parameters, we can determine an average polytrope exponent.

The measurements „in situ", that were carried out in a great number of stations for screw compressor in Jiu Valley [1], [2], [3] led to the conclusion that the process is polytropic and almost adiabatic, so that n ≈ k. The pneumatic network inside the mines is heating the surrounding air, as it has a higher temperature.

Identically, the thermal resistance of the wall is omitted, because the wall is thin and the coefficient of conduction for the metal is high. In the systems for air ventilation in mines, the speed of the air is low compared with other branches of the industry, both in shafts and in the galleries and ranges between $0.2 \div 11.0$ m/s [3],[4]. The coefficient of conduction of the rock λ was experimentally determined through laboratory trials for hard sandstone, predominant in Jiu Valley's coal basin, $\lambda = 1.2 \div 2.0 \quad W /(m \cdot K)$ [6].

Generally, the technical literature considers for the usual mine works the coefficient of convection $\alpha = 12 \div 25 \quad W /(m^2 \cdot K)$ [6].

The value of the coefficient of convection results from the research of M.A. Miheev and W.H. McAdams as criterion[6]:

$$Nu = 0.0195 \cdot Re^{0.8} \quad (5)$$

out of which:

$$\alpha_e = 2.3 \cdot \frac{\dot{m}^{0.8} \cdot P^{0.2}}{S} \quad (6)$$

For three types of standard mining works we have measured and determined the values of the mass flow, the perimeter, the cross section and the coefficient of convection (relation (6)). The values we got are in table 1.

Table 1. Mass flow, area, cross section and coefficient of convection

Type of work	Mass flow [kg/s]	Perimeter of the work [m]	Area of the cross section [m²]	Coefficient of convection on the surface of the objects $[\frac{W}{m^2 \cdot K}]$
PB-5,0 Concrete shaft 5 m	181 – 340	15.7	19.25	13.146 ÷ 21.766
GDZ-9,7 Double-builded gallery	87 – 167	11.6	9.7	13.93 ÷ 23.467
SB-2,8 Concrete raised shaft	25 – 47	5.9	2.8	15.549 ÷ 25.764

The temperature along the pipeline results from the equality between the internal and external energies:

$$dE = \dot{V} \cdot \rho \cdot c_p dt = \pi \cdot \alpha_e \cdot d_e (t_i - t_a) dl \quad (7)$$

The drop of temperature for the pipe with constant diameter (hermetically closed pipes, very well welded or flanged) is determined by the expression:

$$\frac{dt}{dl} = \frac{\pi \cdot \alpha_e \cdot d_e (t_i - t_a)}{\dot{m} \cdot c_p} \qquad \frac{K}{m} \quad (8)$$

But the network of a mine is extending vertically too, in the extraction shafts or inclines.

2.2. The case of the vertical pneumatic network

In reality, in the underground works, the air enters the network from the surface, gets humid on its way as compared with the atmospheric air, evolving almost to a state of saturation.

The evaporation occurs by transfer of heat with the environment according to the relation:

$$r \cdot dx = c_v \cdot dT + p \cdot dv \quad (9)$$

Analysing this equation on the route of a mine shaft having a length of *dy* we will determine the function related to *y* (distance from the surface to the chosen free element) *x, dx, p, dp*.

We admit that the absolute humidity *x* and the pressure *p* change in a linear manner:

$$x = x_1 + \Delta x_l \cdot y \qquad (10)$$

$$p = p_1 + \overline{p} \cdot y \qquad (11)$$

Further we find:

$$\frac{x \cdot \Delta x_l}{R} dy = \frac{c_p}{R} dT - \frac{\overline{p} \cdot dy}{p_1 + \overline{p} \cdot y} \qquad (12)$$

notations: $\quad \dfrac{x \cdot \Delta x_l}{R} = D$; $\dfrac{c_p}{R} = Z$; $\dfrac{p_1}{\overline{p}} = \rho$.

or

$$\frac{dT}{dy} - T\,f(y) = \frac{D}{Z} \qquad (13)$$

in which: $f(y) = \dfrac{1}{Z(\rho + y)}$.

The general integral of the equation is:

$$T = exp^{\int f(y)dy} \left[\frac{D}{Z} \int exp^{-f(y)dy} + C \right] \qquad (14)$$

Taking into account that:

$$f(y)dy = \int \frac{dy}{Z(\rho + y)} = \frac{1}{Z} ln\,Z(\rho + y) \qquad (15)$$

$$T = exp^{\frac{1}{Z}ln(\rho+y)} \left[\frac{D}{Z} \int exp^{-\frac{1}{Z}ln\,Z(\rho+y)} dy + C \right] \qquad (16)$$

At Z = 0, T = T_1 , we determine the constant C and because Z = H (depth of the vertical work) we get:

$$T = \left\| \left[Z(\rho + H)^{\frac{1}{Z}} \right] \cdot (Z \cdot \rho)^{-\frac{1}{Z}} \right| T_1 +$$

$$+ \frac{D[Z(\rho+H)]}{\Psi} - \frac{D\left| [Z(\rho+H)]^{\frac{1}{Z}} \cdot (Z \cdot \rho)^{1-\frac{1}{Z}} \right|}{\Psi} \qquad (17)$$

in which $\Psi = Z^2 - Z$.

In the ratio $Z = \dfrac{c_p}{R}$, the average specific heat in the underground can be calculated by the relation:

$$c_p = (1-x)c_{pa} + x \cdot c_{pv} = 1017 \quad \frac{J}{kg \cdot K}$$

for the domain p = 1 bar and temperature between 0 ÷ 50°C.

And for the nature constant R, we can take the value of the dry air (without a significant influence on the results).

The average pressure per meter of air column is calculated by the relation:

$$\overline{p} = 0.0475 \frac{\left(\dfrac{273}{T_1} + \dfrac{273}{T_2} \right) \dfrac{B}{760}}{1 - 0.0175 \dfrac{H}{T_2}} \quad \frac{mmHg}{m} \qquad (18)$$

3 Validation of the method. Study case

In view of the validation of the proposed method, there are required status parameters within a screw compressor station together with the pneumatic network at which we study the relevant energetic parameters.

Thus, based on the parameters of status measured in a screw compressor station (Atlas Copco GA 250) in the Jiu Valley, we determined the drop of temperature along the work, the drop of pressure, the coefficient of energy loss and the cost of the lost pneumatic energy for the situation of the horizontal and vertical network.

The measured values in the screw compressor station are[2]:
- the inlet temperature of the air 14°C;
- the outlet temperature of the air compressor 88°C;
- the outlet temperature of the air after cooler 40°C;
- the inlet temperature of the air into pneumatic network 39,87 ^{0}C
- the pressure of the aspiration air 0.927 bar
- the outlet pressure of the compressed air 5 bar;
- the difference of pressure in the diaphragm 123 mmHg;
- the temperature of the dry air 14°C;
- the temperature of the moist air 11°C;
- the relative moisture φ ~ 70%;
- the volume flow 0.7 m^3/s.

3.1. The case of the horizontal network
The compressor exit flow was measured by a diaphragm device-differential manometer with Hg. The average measured value was 42

m³/min [2] and is overtaken by the main pipe network with a diameter of 100 mm and length of 100 m. For the analysed section the pressure and the temperature remain equal with those at the exit. The status parameters of the air at the inlet in the horizontal section are 287 K and 0.927 bar[2].

The cost of the pneumatic energy, based on the information from the C.N.H. S.A. (National Coal Company) is $C_e = 0.5$.

Using the relation (3) appropriately modified, the loss of pressure on the analyzed length can be written as:

$$\Delta p = p_1 \left[1 - \sqrt[\frac{k+1}{k}]{1 - \frac{k+1}{k} \frac{\lambda \cdot l}{d \cdot R \cdot T_1} \frac{\dot{V}^2}{15^2 \pi^2 d^4} \cdot \frac{1}{2}} \right] = 4.99 \, bar$$

where $\lambda = 0,0234$ for the roughness of 0,2 mm was found in [3].

On the horizontal length the difference of pressure becomes $p = 5 - 4,99 = 0,01$ bar

As applied to GDZ-97(see table 1), the relevant measured are: $\dot{m} = 120 \, kg/s$; $P = 11.6 \, m$ and $S = 9.7 \, m^2$. Using (6), we get

$$\alpha_e = 17.824 \quad \frac{W}{m^2 \cdot K} .$$

The drop of temperature for the case of the horizontal network becomes, according to (10):

$$\frac{dT}{dl} = 0.0013 \quad \frac{K}{m} = 0.13 \quad \frac{K}{100 \, m}$$

In this situation, according to relation (2), considering the drop of temperature/100m and the loss of pressure on the horizontal network $k_l^o = 0.0422 \cdot 10^{-6}$.

The cost of the lost energy for the case of the horizontal network, taking into account the drop of temperature/100 m and the loss of pressure is determined by (1):

$$C_l^o = 0,00152 \quad \frac{lei}{m \cdot h} = 1.52 \quad \frac{lei}{km \cdot h} = 0.34 \frac{Eur}{km \cdot h}$$

3.2. The case of the vertical network

Generally, the air temperature increases underground as compared with the one at the surface and can be expressed by the relation (17), in which: $Z = c_p / R = 3.5$; $\Psi = Z^2 - Z = 8.75$. The status parameters of the air entering the vertical segment are 287 K and 0.927 bar.

The gradient of temperature was determined by multiple measurements, the average value was 1 degree for 100 m of depth. Using the relation (18) for the depth of 100 m, the average pressure on the air column becomes $\overline{p} = 0,0847 \, mmHg/m$. The values ρ and D necessary to calculate the absolute temperature are:

$$\rho = 8382,526 \, ; \, D = \frac{r \cdot \Delta x_l}{R} = \frac{2500 \cdot 0,01}{287} = 0.0871$$

It has been taken $\Delta x_1 = 0,01$ from [3].

As a result, as we know the values of the parameters in the relation (17), the absolute temperature at the other end of the segment becomes 288,474 K. The value of the temperature entering the network segment was 287 K(14⁰C). We notice, taking into account the value obtained at the other end of the segment, that the temperature at 100 m depth increases by almost 1,5°C, so it will be 15,5 ⁰C.

As a result, the drop of temperature for the case of the vertical network becomes according to the relation (8):

$$\frac{dT}{dl} = 0.00123 \frac{K}{m} = 0.123 \quad \frac{K}{100 \, m}$$

The value for the coefficient of the energy loss for the vertical network is $k_l^v = 0,0444 \cdot 10^{-6}$.

The cost of the lost energy on the vertical network, taking into account the relation (1) is:

$$C_l^v = 0,0016 \quad \frac{lei}{m \cdot h} = 1.6 \quad \frac{lei}{km \cdot h} = 0,36 \frac{Eur}{km \cdot h} .$$

4 Conclusion

The paper can be seen as a method of providing data for the validation of other analytical analyses and/or numerical methods.

The method may prove its efficiency in the design or economic calculus for works opening/preparation the mine where the problem of establishing the air flow as well as the value of the temperature arises.

Based on the results obtained in the paper we can draw the following conclusions:

- the suggested method regarding the calculation of the losses of pressure is suitable for complex pneumatic networks without the need to canonize the network, procedure that

cannot be used for circular or very complex networks;

- the loss of pressure in the compressed air pipes can be calculated depending on the initial parameters without using mediations on the analysed segment, as it is done by classical means;

the cost of lost energy on the vertical network is slightly higher than in the case of the horizontal network due to the contribution of the condensate.

Acknowledgment

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