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January 2013

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Abstract: We popose a calculation method by which 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

List of used symbols:
d- diameter of the pneumatic pipeline (m);
$\dot{V}$ - volume flow of compressed air (m^3/s);
$\dot{m}$ - mass flow (kg/min);
P – area of the mining work (m);
S – cross section (m^2);
k_o – coefficient of energy loss for the horizontal network;
k_v – coefficient of energy loss for the vertical network;
t_a – temperature of the compressed air;
t_{in} – temperature of the air inside the pipe;
C_e – cost of the pneumatic energy;
p_1 – incoming pressure in the pneumatic network section (N/m^2);
T_1 – temperature of the incoming compressed air entering the pneumatic network section (K);
p_2 – pressure of the compressed air exiting the pneumatic network section (N/m^2);
T_2 – temperature of the compressed air exiting the pneumatic network section (K)
η_{ad} - adiabatic efficiency of the flow;
Δp - loss of pressure (bar);
ζ - coefficient of friction;
Re – invariant Reynolds;
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))
k – adiabatic exponent;
R – natural constant for the air (J/(kg·K))
T_{cond} – external temperature of the compressed air pipeline for a certain length of the pipe
λ – coefficient of thermal conduction (W/(m·K));
α_e – coefficient of thermal convection at the outer side of the pipe ($W/(m^2\cdot K)$);
d_e – outer diameter of the pipe (m);

c_p – isobar massic specific heat of the air (J/(kg·K))
x – absolute humidity;
x_1 – absolute humidity at the surface of the mine;
r – water vaporization latent heat (J/(kg·K))
Δx_1 - change of the absolute humidity per length meter.
$\bar{p}$ - average pressure per meter of air column (mmHg/m)
H – depth of the vertical work (m);
B – barometric pressure on the surface (mmHg);

1 Introduction

The energy reuired for operating the pneumatic euipment 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 hrozontally 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 enery (power) within the networks of compressed air was presented in [1], [2], [3] si [4]. The results obtained show a significant percentage of the massic 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 determin 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 are calculated by the following relation[7]:

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

where:

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

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 calculate 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:

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

Certain parameters p and T of the network, must be found for any lengths of pipes.

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 helicoidal compressor in Jiu Valley [1], [2], [3] led to the conclusion that the process is polytropic and almost adiabatic, so that $n \approx k$. 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 sistems 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 ÷ 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 $\alpha = 12 \div 25 \quad W/\left(m^2\cdot K\right)$[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 massic flow, the perimeter, the cross section and the coefficient of convection (relation (6)). The values we got are in table 1.

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

Type of work	**Massic flow [kg/s]**	**Perimeter of the work [m]**	**Area of the cross section [m^2]**	**Coefficient of convection on the surface of the objects** $[W/(m^2\cdot K)]$
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:

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

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

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

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:

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

Analysing this euation 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:

$$\mathrm{x} = \mathrm{x}_1 + \Delta \mathrm{x}_1 \cdot \mathrm{y} \qquad (10)$$

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

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

or

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

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

The general integral of the equation is:

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

Taking into account that:

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

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

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 $\Psi = \mathrm{Z}^2 - \mathrm{Z}$.

In the ratio $\mathrm{Z} = \frac{\mathrm{c_p}}{\mathrm{R}}$, 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 natural 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:

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

3 Validation of the method. Study case

In view of the validation of the proposed method, there are required status parameters within a helicoidal 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 helicoidal 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 helicoidal compressor station are[2]:

- the temperature of the aspiration air 14°C;
- the temperature of the air exiting the compressor 88°C;
- the temperature of the entering the cooler 88°C;
- the temperature of the air exiting the cooler 40°C;
- the temperature of the air entering the pneumatic network T 39,87 ^{0}C
- the pressure of the aspiration air 0.927 bar
- the pressure of the compressed air when exiting 5 bar;
- the difference of pressure in the diaphragm 123 mmHg;
- the temperature of the dry air 14°C;
- the temperature of the humid air 11°C;
- the relative humidity φ ~ 70%;
- the volumic 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 m^3/min [2] and is overtaken by the main pipe network with a dameter 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 si 0.927 bar[2].

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

Using the relation (3) appropriately modified, the loss of pressure on the analized 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 $\mathrm{p} = 5 - 4{,}99 = 0{,}01$ bar

As applied to GDZ-97(see table 1), the relevant measured are: $\dot{m} = 120\ kg/s$; $P = 11.6\ m$ şi $S = 9.7\ m^2$. Using (6), we get $\alpha_e = 17.824\ \frac{W}{m^2\cdot K}$.

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

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

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):

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

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 transom are 287 K si 0.927 bar.

The gradient of temperatur 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 $\Delta \mathrm{x}_1 = 0{,}01$ 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 transom becomes $288{,}474\ K$. The value of the temperature entering the network transom was 287 K(14^{0}C). We notice, taking into account the value obtained at the other end of the transom, that the temperature at 100 m depth increases by almost 1,5°C, so it will be 15,5 ^{0}C.

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

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

The value for the 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:

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

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 analised transom, 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

"This work was partially supported by the strategic grant POSDRU 107/1.5/S/77265 (2010) of the Ministry of Labor, Family and Social Protection, Romania, co-financed by the European Social Fund – Investing in people."

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