The Minimum Pressure Drop Caused by the Condensation of Water Vapor in the Cooled Air Flowing in the Inclined Conduit

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Abstract

The paper presents methodology for determining water mass and pressure drop in ducts with fixed co-current and no-slip two-phase flow. The dispersed liquid phase (water) is present in the air as a result of wet air from underground excavations being distributed in some sections of a discharge pathway, or local water mass sources (or its local outlets) formed by the natural phenomenon of water vapor condensation. For such cases, static pressure losses were determined, which resulted from the force of gravity of the mass of water droplets occurring in the air stream in the duct.

Keywords: two-phase no-slip flow, pressure loss, flow characteristics of a duct, water mass sources from water vapor condensation

Introduction and Study Objective

Wet air discharged to the surface from deep excavations of underground mines, flows through vertical and inclined ducts. In order to force such flows, mechanical energy sources are used, called main ventilation fans. They usually work in a suction mode, producing static pressure by air flow, which increases its value along the pathway traveled by the flowing air. In the research study (Ptaszyński, 2016), the author presents the methods of using the Mollier diagram to determine thermodynamic processes of the wet air stream occurring at substantially varying static pressure. This allowed to analyze thermodynamic changes of the air along its discharge pathway from a mine (Ptaszyński, Łuczak, Życzkowski, & Kuczera, 2018). Therefore, for the known parameters of thermodynamic air streams (defined by standard ventilation measurements in underground excavations), it is possible to determine whether there exist sections of air discharge ducts where the phenomenon of water vapor condensation occurs, and what the mass flow rate of water is, if referred to the unit of length in a given duct. From the considerations presented in the paper (Ptaszyński et al., 2018), it can be concluded that positive water mass sources from water vapor condensation, which are distributed sources on the finite sections of the ducts, as well as locally located water mass sources or their outlets, resulting from the condensation of water or evaporation of water droplets from the mixing of wet air streams and haze air streams containing water mist, may occur on the pathways of air discharge through the ducts. Some of these values of water mass flow rate depend on the time of the year (summer/winter). In the course of a year, the character of the source may change, which in one period may be positive (source) and in another negative (outlet). The author also identified those ducts on the analyzed air pathway, whose only function was to carry a fluid, i.e. those with no source or outlet of water mass from the condensation of water vapor.

In the discussed example, the output values of water mass sources from water vapor condensation, on the analyzed pathway of air discharge to the surface, were determined for the extreme seasons. The flow of air through a duct as a single-phase fluid is subject to considerations in mining aerology. The concepts of resistance (specific or equivalent) of a duct, its characteristics, and loss of pressure are utilized then. The fixed flow of the two-phase medium in the transportation duct makes it difficult to apply some of the previously mentioned terms. This mainly concerns the characteristics of the duct, its graphical representation and the method of determining resistance of the duct (Ptaszyński, 2015). The notion of flow characteristics of the duct has been introduced and specified, where a fixed, co-current and no-slip two-phase flow occurs. This notion contains the value of $A_{\dot{m}}$, which is the pressure that the force of gravity of water droplets contained in the flowing air exerted on the plane perpendicular to the velocity vector. Due to the fact that on the discharge pathway of the wet from the mine, the phenomenon of water vapor condensation occurs, water droplets are transported with the air to the surface.

The objective of this research study is to determine the value of the above-mentioned $A_{\dot{m}}$, occurring in flow characteristics of ducts, through which a two-phase medium, composed of air and water, flows along a discharge pathway from the mine.

The example of a pathway and the results of calculations presented in (Ptaszyński, 2015) were used in this study.

Flow Characteristics of the Duct Transporting Two-Phase Medium

With the fixed two-phase flow of air and water through a vertical duct in the upward direction, where the phases move in the same direction and with the same velocity (no velocity of the slip), it is insufficient to use the term of the duct re-

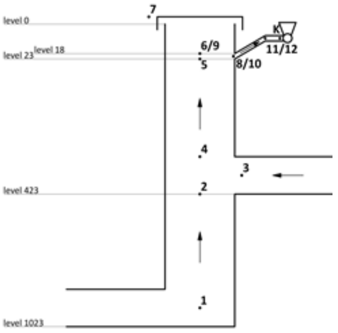

Fig. 1. Pathway of air discharge from the mine with marked points assigned to the corresponding cross-section of the flowing air stream (Ptaszyński et al., 2018)

Rys. 1. Droga odprowadzenia powietrza z kopalni z zaznaczonymi punktami przypisanymi do odpowiedniego przekroju przepływającego strumienia powietrza (Ptaszyński i in., 2018)

sistance in order to correctly determine the mechanical energy loss in it (Ptaszyński, 2015). It is important in such a case to use the concept of flow characteristics of the duct which, according to (Ptaszyński, 2015), can be presented in the form of the value w^* being the following function:

$$w^* = f(A_{\dot{m}}, R_{\dot{m}}, {}_{\dot{m}}) \text{ , } N/m^2 \tag{1}$$

The characteristics of flow can be represented by the following equation:

$$w^* = A + R_{\dot{m}} \cdot \dot{m}^2, N/m^2 \tag{2}$$

In case of a one-phase air flow, the value of A = 0, and the value of $R_{\dot{m}}$ represents the specific resistance of the duct with a fully developed turbulent flow in it. If the characteristics referred to the flow of water through this duct (one-phase medium), then the value of A would be the pressure that the water exerts on the plane perpendicular to the direction of the flow. This amount does not depend on the mass output of the water flowing in it. In this case, the value of $R_{\dot{m}}$ is also the specific resistance of the duct, but with the turbulent flow of water through it. Regarding the flow characteristics of this duct for a two-phase medium with constant mass concentration flowing through it, equation (2) still defines it correctly, but the value of $A = A_{\dot{m}}$ represents the pressure exerted on the plane perpendicular to the flow direction of water contained in this duct. In this case, however, the value depends on the mass output $\dot{m}$ of the mixture with the specific mass concentration of water, and it can be calculated from the following dependence (Ptaszyński, 2015):

$$A_{\dot{m}} = w_{\dot{m}=0} = (z_2 - z_1)\, \rho_w\, g\, c, N/m^2 \tag{3}$$

It is similar with the a value of $R_{\dot{m}}$, which also depends on the mass output of the mixture $\dot{m}$ and on the specific mass concentration of water in it.

As it was already mentioned, the objective of this research study is to determine the value of $w_{\dot{m}=0} = A_{\dot{m}}$ for the ducts located in the air discharge pathway and therefore also for those in which there are internal mass sources of the heavier phase (water) supply from the condensation of water vapor in the cooling wet air stream, and for those in which the process of mixing the wet air streams occurs.

For this purpose, ventilation and thermodynamic data on the air discharged to the surface from the underground mine, obtained in the paper (Ptaszyński et al., 2018), were used to determine:

- location and character (distributed, local) of the occurrence of the phenomenon of water vapor condensation on the air discharge pathway,
- mass output of internal water sources from the condensation of water vapor on the air discharge pathway,
- mass output of water transported with the air through individual sections of the air discharge pathway.

Using such values, the article specifies the water mass contained in the air and discharged with the air, with no slip, through the ducts, to the surface. The pressure $A_{\dot{m}}$ was also calculated, with which the weight of this water affects the air at a given section of the duct being a part of the air discharge pathway, and it was indicated what this value depends on. These values were specified for a predetermined flow of the analyzed medium at each section of the analyzed flow discharge pathway.

Exemplary Pathway of Air Discharge from the Mine

Figure 1 illustrates a discussed pathway of air discharge from the mine. It consists of a two-level ventilation shaft, a ventilation pipe and a ventilation duct.

The ventilation shaft has a circular cross-section, a diameter of 7 m, cross-sectional area F = 38,48m² and a depth of 1030 m. The bottom of the lower level with the air stream inlet is located at 1023 m, and the bottom of the upper level is at 423 m. The bottom of the inlet to the ventilation pipe is located at 23 m. Linear pressure loss coefficient λ = 0.02 (for fully developed turbulent flow) (Wacławik, 2010). The height of the two shaft bottoms is 6 m, and the diameter of the ventilation pipe is 5 m. The length of the ventilation pipe is l_{pipe} = 28 m, and its angle of inclination is α = 45°. The ventilation duct has a length of 45 m, a rectangular cross-section measuring 4×5 m and its angle of inclination β = 5°. The results of measurements and calculations of ventilation as well as thermodynamic parameters are as follows (Ptaszyński, 2016; Ptaszyński et al., 2018):

- air stream flowing in at the 1023 level: barometric pressure p_1 = 110,000 Pa; dry-bulb temperature

t_{s1} = 29°C; wet-bulb temperature t_{w1} = 28.5°C; specific humidity of wet air X_1 = 0.02258 kg/kg; wet air density ρ_1 = 1.2517 kg/m³; volumetric flow rate of wet air flowing into the shaft $\dot{V}_1$ = 166.67 m³/s; wet air mass flow rate $\dot{m}_1$ = 208.62 kg/s; dry air mass flow rate $\dot{m}_{s1}$ = 204.01 kg/s,

- air stream flowing in at the 423 level: barometric pressure p_3 = 98,500 Pa; dry-bulb temperature t_{s3} = 26°C; wet-bulb temperature t_{w3} = 25°; specific humidity of wet air X_3 = 0.02024 kg/kg; wet air density ρ_3 = 1.1336 kg/m³; volumetric flow rate of wet air flowing into the shaft $\dot{V}_3$ = 166.67 m³/s; wet air mass flow rate $\dot{m}_3$ = 188.93 kg/s; dry air mass flow rate $\dot{m}_{s3}$ = 185.18 kg/s,

- the outside air is sucked into the shaft through the sealed-off outset of the shaft. The barometric pressure at the surface is p_7 = 98,600 Pa. The conducted research took into account air parameters characteristic for winter and summer periods, which are as follows:

  In winter: dry-bulb temperature t_{s7} = -20°C; wet-bulb temperature t_{w7} = -20°C; specific humidity of wet air X_7 = 0.0079 kg/kg; wet air density ρ_7 = 1.35645 kg/m$_3$; volumetric flow rate of external air intake accounts for 10% of the volumetric flow rate of the air discharged through the shaft (section 4–5), i.e. $\dot{V}_7 = 0.1\ (\dot{V}_1 + \dot{V}_3)$.

  In summer: dry-bulb temperature t_{s7} = 24°C; wet-bulb temperature t_{w7} = 21°C; specific humidity of wet air X_7 = 0.01484 kg/kg; wet air density ρ_7 = 1.14597 kg/m³; volumetric flow rate of external air intake accounts for 10% of the volumetric flow rate of the air discharged through the shaft (section 4–5), i.e. $\dot{V}_7 = 0.1\ (\dot{V}_1 + \dot{V}_3)$.

Additional measurement results at the end of sections (1–2 and 4–5), at the cross section of the shaft below the air inlet at a higher level (cross-section 2) as well as below the ventilation pipe inlet (cross-section 5) are as follows: barometric pressure $p_2 = p_3 = p_4$ = 98,500 Pa; dry-bulb and wet-bulb temperatures $t_{s2} = t_{w2}$ = 24°C; wet air density ρ_2 = 1.14332 kg/m³; volumetric flow rate of wet air $\dot{V}_2 = \dot{m}_2/\rho_2$ = 182.469 m³/s; barometric pressure $p_5 = p_6 = pK$ = 93,600 Pa; dry-bulb and wet-bulb temperatures $t_{s5} = t_{w5}$ = 22°C; wet air density ρ_5 = 1.0941 kg/m³, volumetric flow rate of wet air $\dot{V}_5 = (\dot{m}_2 + \dot{m}_3)/\rho_5$ = 363.358 m³/s.

If the airflow at the cross-sections 2 and 5 was a single-phase one (saturated wet air), then the average air velocity in those cross-sections would be equal to $v_2 = \dot{V}_2/F$ = 4.74 m/s and $v_5 = \dot{V}_5/F$ = 9.44 m/s.

The measurements recorded at the cross-sections of the shafts 2 and 5 do not determine unambiguously whether there is a single-phase flow of saturated wet air or a two-phase one, where in addition to the vapor-saturated air stream constituting the carrier gas phase, there is a stream of fluid produced in the process of water vapor condensation in the air pathway. Ventilation measuring instruments commonly used in mining are not capable of solving this problem. The method involving the Mollier diagram presented in the research paper (Ptaszyński, 2016) allowed to determine locations of water mass sources or water mass outlets formed from water vapor condensation in the air stream, and to specify them quantitatively. It was found that in the discussed pathway of air discharge from the mine, there are water mass sources and water mass outlets resulting from water vapor condensation. The condensation phenomenon occurring in the duct was described by the unit water mass flow rate that is condensed at the unit length of the duct, and it is a constant value at a given section of the duct. At places where mixing of two or more wet air streams, or mixing of haze air stream and wet air stream, takes place on the pathway, a local water mass source or outlet from condensation may occur. The output of such a local source or outlet was determined for the exemplary discharge pathway in (Ptaszyński et al., 2018) in the form of a value of its mass flow rate, kg/s.

In this research paper, the author used the previously determined unit mass flows of condensed water in the ducts forming the examined pathway of air discharge from the mine. The mass flow of water condensed in a given duct, referenced to the unit length of the condensation zone in the duct, is the unit mass flow rate of water and its physical quantity is kg/(s·m). The knowledge of these values will allow to determine the aforementioned loss of pressure caused by the component of weight of the water droplets resulting from the vapor condensation, flowing with air at the same velocity. For this purpose, for each duct located within the discharge pathway, mathematical forms of the mass flows of water sources or outlets existing in the ducts must be provided as functions of the independent variable "s", which is the distance.

The analyzed ducts include those, where:

a) there is a local water mass source or local water mass outlet located at the inlet cross-section of the duct, as a result, e.g. of water condensation when wet air streams are mixing. Examples include the ducts: (5–10) with the local source (in winter) and (2–4) with the local outlet, located within the air discharge pathway analyzed in this paper (Ptaszyński et al., 2018).

b) there is a water mass source that is distributed throughout the length of the duct, resulting from the condensation of water vapor in the air flowing through this duct. Examples of such ducts located within the analyzed air discharge pathway include: (4–5), (10–12).

c) on a finite section of a given duct there is a distributed water mass source resulting from the condensation of water vapor in the air flowing through this duct. An example of such a duct located within the analyzed air discharge pathway is: (1–2), in which the condensation phenomenon occurs in the section (W-2), which is the above-mentioned distributed water mass source, whereas in the section (1-W) of this duct there is no water mass source.

d) the condensation of water vapor contained in the flowing air does not occur throughout the entire length of the duct, and therefore, there is no water mass source in it. An example of such a duct located within the analyzed air discharge pathway is: (12-K).

The water mass flow rate, flowing through a given duct, depends on the presence of water sources from the condensation of water vapor contained in the flowing air, and from the position of a specific duct on the air discharge pathway, which determines which water mass flow flows into this duct from the preceding duct. Therefore, in the calculation of the water mass flow rates, it is important to assign them to the specific ducts located within the discharge pathway. Figure 2 illustrates the air discharge pathway from the mine, whereas the position of a given duct within this pathway is specified by the number of the initial point (cross-section) and the number of the terminal point of the duct, separated by a hyphen, provided in brackets. Such designation of the duct is present in the physical quantity subscripts that apply to these ducts.

In this research paper, the value of unit mass flow of condensed water $\dot{m}_{wj}$(s) in the local source/outlet is determined mathematically using the Dirac pseudo function δ(s), hence it is mathematically written as

$$\dot{m}_{wj(a\text{-}b)}\ (s) = \pm\ c\ \delta\ (s\text{-}a),\ kg/(s{\cdot}m), \tag{4}$$

where the subscript (a-b) of $\dot{m}_{wj}$(s) means that the unit mass flow of the condensed water being the function of distance “s” refers to the duct with the nodes (a-b), of which the “a” node is the initial node, and the other one is the terminal node. The physical unit of the quantity $\dot{m}_{wj(a\text{-}b)}$(s) is kg/(s·m). The value of “c” on the right of the formula (4) denotes the mass flow rate of this local source expressed in kg/s when preceded by the “+” sign, and when “c” is preceded by the “-” sign, it denotes the local outlet mass flow rate. It should be noted that if local sources or outlets are present on the analyzed discharge pathway, they are located in the initial node s = a of a specific duct (a-b). If, in addition to the already discussed local source (outlet) located in the “a” node, there is a continuous water source from the condensation of water vapor in the flowing and cooling air in the duct (a-b), then knowing the unit water mass flow “d” of this source distributed on the pathway, the constant value on the pathway in a given duct, expressed in kg/(s·m), the resultant unit water mass flow rate from the sources acting in the analyzed duct, can be determined in the form of the formula (5):

$$\dot{m}_{wj(a\text{-}b)}\ (s) = \pm\ c\ \delta\ (s\text{-}a),\ d\ kg/(s{\cdot}m), \tag{5}$$

Formula (5) demonstrates that the value of the unit water mass flow rate in such a duct is the algebraic sum of the individual water mass flow rates of the sources and outlets acting in the duct.

For the ducts examined in (Ptaszyński et al., 2018), in general, the unit mass output of a water source in a duct can be described by the formula (5), but depending on the position of the duct on the discharge pathway and whether there are water mass sources or outlets in the duct, “c” and “d” may take different values. As an example, let us consider the duct (a-b), deprived of mass water sources, but located in the discharge pathway in such a way that there is a water stream in the flowing air in the preceding duct. This means that the duct (a-b) has only a transportation function for the wet air stream and for the water stream. This means that in Formula (5) describing the unit water mass source in this duct, the value of “d” = 0 (no sources in the duct), while the value of “c” is equal to the mass flow rate (kg/s) of the water flowing from the preceding duct to the duct (a-b).

Then, the mass flow rate of the water that is fed to the analyzed duct by the duct (or a sequence of connected ducts) preceding it, may be considered to be the mass flow rate of the local source located in the studied duct at its initial section (point) “a”. Knowing the value of the unit mass flow rate of water in the exemplary duct (a-b), i.e. the value of $\dot{m}_{wj(a\text{-}b)}$(s), it is necessary to determine the water mass flow rate $\dot{M}_{W(a\text{-}b)}$(s) in this duct as a function of the distance “s”. The mass flow rate of the water flowing in the exemplary duct (a-b), at the cross-section located in a position described by the coordinate “s”, is determined by the following Formula:

$$\dot{M}_{W(a\text{-}b)}(s) = \int_a^s \dot{m}_{wj(a\text{-}b)}(s)\ ds,\ kg/s \tag{6}$$

where the variable “s” ϵ <a, b>. The quantity $\dot{M}_{W(a\text{-}b)}(s)$ is a function which is continuous on an interval in definition interval, and its jump at the point of discontinuity is finite.

The above-mentioned quantity $\dot{M}_W$(s=b) of the mass flow rate of water from condensation at the end of the duct <a, b> is determined using the relationship (6) as:

$$\dot{M}_{W(a\text{-}b)}(s{=}b) = \int_a^s \dot{m}_{wj(a\text{-}b)}(s)\ ds,\ kg/s \tag{7}$$

For the discussed example of air discharge from the mine, it can be written that:

1. Condensation of water vapor in the wet air stream, flowing in the vertical duct 1–2, occurs at the last 520 meters of its length. The unit flow rate of the distributed water mass source $\dot{m}_{wj(w\text{-}2)}(s)$ is equal to 0.001240 kg/(s·m) throughout the entire length of 520 meters (Ptaszyński et al., 2018).

For such a value of the unit water flow rate, it is possible to determine a form of the water mass flow $\dot{M}_{w(1\text{-}2)}(s)$, flowing concurrently in the analyzed duct, using the Formulas (6) and (7):

$$\dot{M}_{w(1\text{-}2)}(s) = \int_{s1}^{s} \dot{m}_{wj(1\text{-}2)}(s)\ ds = \int_{s1}^{sw} \dot{m}_{wj(1\text{-}W)}\ (s)\ ds + \int_{sw}^{s} \dot{m}_{wj(w\text{-}2)}(s)\ ds$$
$$= 0 + 0.001240\ (s - s_w),\ \text{kg/s} \tag{8}$$

$$\dot{M}_{w(1\text{-}2)}(s = s_2) = 0.001240\ (s_2 = s_w) = 0.001240 \cdot 520 =$$
$$0.6448\ kg/s \tag{9}$$

This quantity is the function of distance, but it is independent of the season since thermodynamic parameters of this wet air stream do not change throughout the year. At the initial cross-section 1, the mean air velocity is v_1=4.33 m/s, in the cross-section W, where water vapor condensation begins, it is v_w=4.38 m/s, and at the end point 2: v_2=4.73 m/s. The wet air density at the cross-section 1 is equal to ρ_1=1.2517 kg/m³, in the cross-section W: ρ_W=1.2370 kg/m³, and in the cross-section 2: ρ_2=1.1433 kg/m³. The mean values of wet air velocity and density at the section W-2 are, respectively:

$$v_{śr(W\text{ - }2)} = (v_w+v_2)/2 = 4.56\ m/s,\ \rho_{śr(W\text{ - }2)} = (\rho_w+\rho_2)/2 = (1.2370$$
$$+ 1.1433)/2 = 1.1902\ kg/m^3$$

2. In the 6-meter-long duct 2–4, there is a mixing of the two-phase stream of saturated wet air and water droplets (water mist) with a stream of wet air, resulting in a two-phase

mixture. However, as demonstrated in the calculations in (Ptaszyński et al., 2018), at the initial cross-section of this short duct, there is a water mass outlet with a unit mass flow rate $\dot{m}_{wj(2\text{-}4)}(s) = -0.09977\ \delta(s\text{-}s_2)$, where $\delta(s\text{-}s_2)$ is Dirac's pseudo-function. In this duct, the mass flow rate $\dot{M}_{w(2\text{-}4)}$(s) of the water flowing co-currently, with no slip, is expressed by the following Formulas:

$$\dot{M}_{w(2\text{-}4)}(s) = \dot{M}_{w(1\text{-}2)}(s_2) + \int_{s2}^{s} [-0.09977\ \delta(s_2)]\ ds = 0.6448 - 0.09977\ H(s - s_2),\ \text{kg/s} \tag{10}$$

where $H(s - s_2)$ is a Heaveside'a function.

$$\dot{M}_{w(2\text{-}4)}(s = s_4) = 0.6448 - 0.09977H(s_4 - s_2) = 0.54503\ kg/s \tag{11}$$

The quantity $\dot{M}_{w(2\text{-}4)}(s)$ is constant on the pathway 2–4, because the outlet is located at the inlet cross-section of the duct, and its value does not depend on the season, since thermodynamic parameters of the wet air stream affecting it do not change during the year. In any cross-section of this section, the mean air velocity is v_4=9.055 m/s, and the wet air density is ρ_4=1.1394 kg/m³.

3. Condensation of water vapor in the wet air stream, flowing in the vertical duct 4–5, occurs at its entire length. The unit flow rate of the distributed water mass source $\dot{M}_{w(4\text{-}5)}(s)$ is constant throughout this 400-meter-long section, and it is equal to 0.00185 kg/(s·m) (Ptaszyński et al., 2018). The form of the water mass flow rate $\dot{M}_{w(4\text{-}5)}(s)$, flowing concurrently in the considered duct, is expressed by the following Formulas:

$$\dot{M}_{w(4\text{-}5)}(s) = \int_{s4}^{s} \dot{m}_{wj(4\text{-}5)}(s)\ ds = \int_{s4}^{s} [0.54503\ \delta\ (s_4) + 0.001850]\ ds = 0.54503\ H(s - s_4) + 0.001850\ (s - s_4)\ kg/s \tag{12}$$

$$\dot{M}_{w(4\text{-}5)}(s = s_5) = 0.54503 + 0.001850\ (s_5 - s_4) = 1.28503\ kg/s \tag{13}$$

The quantity $\dot{M}_{w(4\text{-}5)}(s)$ is the function of distance but it is independent of the season, since thermodynamic parameters of this wet air stream do not change over the year. At the initial cross-section 4, the mean air velocity is v_4 = 9.055 m/s, and at the cross-section 5, it is v_5 = 9.420 m/s. The mean air velocity at this section of the shaft is equal to $v_{śr(4\ -\ 5)} = (v_4 + v_5)/2$ = 9.238 m/s, and the mean wet air density at this section is:

$$\rho_{śr(4\ -\ 5)} = (\rho_4+\rho_5)/2 = (1.1394 + 1.0932)/2 = 1.1163\ kg/m^3$$

At the further sections of air discharge pathway in the example provided in the research paper (Ptaszyński et al., 2018), the flow rate parameters of the medium depend on the time of the year. Therefore, in the paper (Ptaszyński et al., 2018) two periods were considered: summers and winters. In the summer season, further ducts were described by the numbers of the points representing the thermodynamic states of the discharged stream, denoted on the Mollier diagram as: 5–8, 8–11, 11–K. In the winter period, further ducts were denoted in the Mollier diagram with the numbers of the points representing the thermodynamic states of the discharged stream: 5–10, 10–12, 12–K. Point K denoted the thermodynamic state of the stream at the inlet of the main ventilation fan.

4. In summer, in the 6-meter-long duct 5–8, there is a mixing of the two-phase stream of wet air and water droplets (water mist) with the wet air stream drawn through the shaft outset seal. In the analyzed case, external losses accounted for 10% of the volumetric output of the air discharged from the mine, expressed as dry air stream. As a result, a two-phase mixture was produced, but as demonstrated in the calculations included in (Ptaszyński et al., 2018), at the initial cross-section of this short duct, there was a water mass outlet with a unit mass flow rate equal to $\dot{m}_{wj(5\text{-}8)}(s) = -0.04281\ \delta(s\text{-}s_5)$. In this duct, the mass flow rate $\dot{M}_{w(5\text{-}8)}(s)$ of the water flowing co-currently, with no slip in the examined duct, is expressed by the following Formulas:

$$\dot{M}_{w(5\text{-}8)}(s) = \dot{M}_{w(4\text{-}5)}(s_5) + \int_{s5}^{s} [-0.04281\ \delta\ (s_5)]\ ds = 1.28503 - 0.04281\ H\ (s - s_5),\ kg/s \tag{14}$$

$$\dot{M}_{w(5\text{-}8)}(s = s_8) = \dot{M}_{w(4\text{-}5)}(s_5) + \int_{s5}^{s8} [-0.04281\ \delta\ (s_5)]\ ds = 1.28503 - 0.04281\ H\ (s_8 - s_5) = 1.24222\ kg/s \tag{15}$$

The quantity $\dot{M}_{w(5\text{-}8)}(s)$ is constant on the pathway 5–8, because the outlet is located at the inlet cross-section of the duct, and the parameters of the outside air were assumed to remain constant during the summer season. At any cross-section of this section, the mean air velocity is v_8 = 10.173 m/s, and the wet air density is ρ_8 =1.0936 kg/m³.

In winter, in the 6-meter-long duct 5–10, there is a mixing of the two-phase stream of wet air and water droplets (water mist) with the wet air stream drawn through the shaft outset seal.

As a result, a two-phase mixture is produced, but as demonstrated in the calculations included in (Ptaszyński et al., 2018), at the initial cross-section of this short duct, there is a local water mass source with a unit mass flow rate $\dot{m}_{wj(5\text{-}10)}(s) = 0.29968\ \delta\ (s - s_5)$. In this duct, the mass flow rate $\dot{M}_{w(5\text{-}10)}(s)$ of the water flowing co-currently in the examined duct, is expressed by the following Formulas:

$$\dot{M}_{w(5\text{-}10)}(s) = \dot{M}_{w(4\text{-}5)}(s_5) + \int_{s5}^{s} [0.29968\ \delta\ (s_5)]\ ds = 1.28503 + 0.29968\ H\ (s - s_5),\ kg/s \tag{16}$$

$$\dot{M}_{w(5\text{-}10)}(s = s_{10}) = \dot{M}_{w(5\text{-}10)}(s_5) + \int_{s5}^{s10} [0.29968\ \delta\ (s_5)]\ ds = 1.28503 + 0.29968\ H\ (s_{10} - s_5) = 1.58471\ kg/s \tag{17}$$

The quantity $\dot{M}_{w(5\text{-}10)}(s)$ is constant on the pathway 5–10, because the local water mass source is located at the inlet cross-section of the duct, and the parameters of the outside air were assumed to remain constant during the winter season. At any cross-section of this section, the mean air velocity is v_{10}=10.447 m/s, and the wet air density is ρ_{10}=1.0805 kg/m³.

5. In the ventilation pipe, the flowing two-phase stream gets cooled in summer. Therefore, on the pathway 8–11, there is a fixed distributed unit water mass source equal to $\dot{m}_{wj(8\text{-}11)}(s) = 0.0306\ kg/(s\cdot m)$ (Ptaszyński et al., 2018). The volume of the water mass flow rate $\dot{M}_{w(8\text{-}11)}(s)$, flowing out of this duct, co-currently with the air, can be calculated from the Formula:

$$\dot{M}_{w(8\text{-}11)}(s) = \int_{s8}^{s} [\dot{M}_{w(5\text{-}8)}(s = s_8)\ \delta\ (s - s_8) + \dot{m}_{wj(8\text{-}11)}(s)]\ ds = \int_{s8}^{s} [1.24222\ \delta\ (s - s_8) + 0.0306]\ ds = 1.24222\ H\ (s - s_8) + 0.0306\ (s - s_8),\ kg/s \tag{18}$$

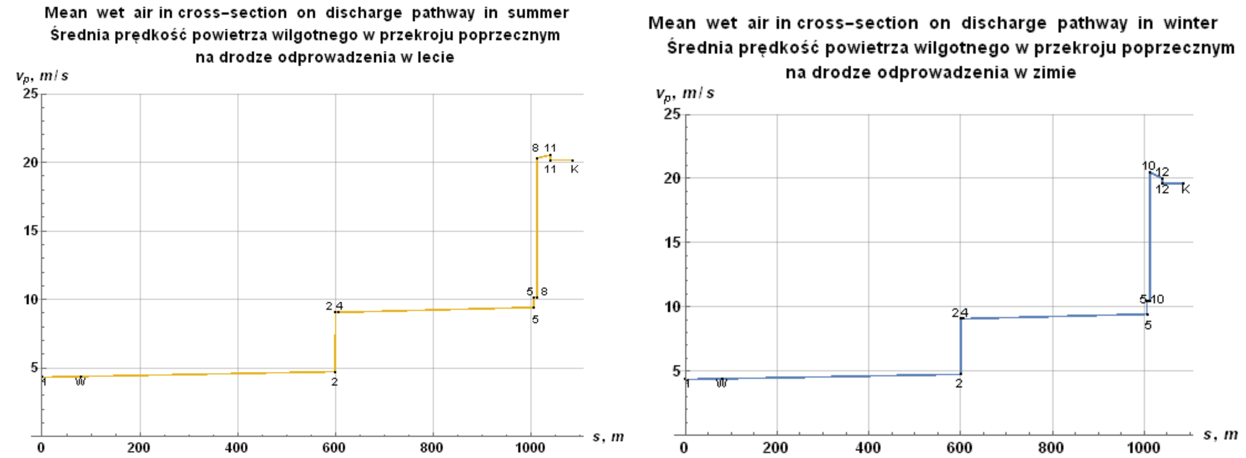

Fig. 2. Change in wet air velocity on discharge pathway in a) summer, b) winter
Rys. 2. Zmiana prędkości powietrza wilgotnego na drodze odprowadzenia w a) lecie, b) zimie

$$\dot{M}_{w(8-11)}(s = s_{11}) = \int_{s8}^{s11} [\dot{M}_{w(5-8)}(s = s_8)\ \delta\ (s - s_8) + \dot{m}_{wj(8-11)}(s)]\ ds = \int_{s8}^{s11} [1.24222\ \delta\ (s - s_8) + 0.0306]\ ds = 1.24222\ H\ (s_{11} - s_8) + 0.0306\ (s_{11} - s_8) = 2.0990\ kg/s \tag{19}$$

The quantity $\dot{M}_{w(8-11)}(s)$ is a function of distance and relates to the summer period. In the initial cross-section 8 of the ventilation pipe, the mean air velocity is v_8=20.293 m/s, and in the cross-section 11: v_{11}=20.539 m/s. The mean air velocity at this section of the shaft is equal to $v_{śr(8-11)} = (v_{8+11})/2 = 20.416\ m/s$, and the mean wet air density at this section is $\rho_{śr(8-11)} = (\rho_{8+11})/2 = (\rho_8+\rho_{11})/2 = (1.0936 + 1.0805)/2 = 1.0871\ kg/m^3$.

In winter, in the ventilation pipe, the flowing two-phase stream also gets cooled. Therefore, on the pathway 10–12, there is a fixed distributed unit water mass source equal to $\dot{m}_{wj(10-12)}(s) = 0.0275\ kg/(s{\cdot}m)$ (Ptaszyński et al., 2018). The volume of the water mass flow rate $\dot{M}_{w(10-12)}(s)$, flowing with no slip, co-currently with the air, can be calculated from the formula:

$$\dot{M}_{w(10-12)}(s) = \int_{s10}^{s} [\dot{M}_{w(5-10)}(s = s_{10})\ \delta\ (s - s_{10}) + \dot{m}_{wj(10-12)}(s)]\ ds = \int_{s10}^{s} [1.58471\ \delta\ (s - s_{10}) + 0.0275]\ ds = 1.58471\ H\ (s - s_{10}) + 0.0275\ (s - s_{10}),\ kg/s \tag{20}$$

$$\dot{M}_{w(10-12)}(s = s_{12}) = \int_{s10}^{s12} [\dot{M}_{w(5-10)}(s = s_{10})\ \delta\ (s - s_{10}) + \dot{m}_{wj(10-12)}(s)]\ ds = \int_{s10}^{s12} [1.58471\ \delta\ (s - s_{10}) + 0.0275]\ ds = 1.58471\ H\ (s_{12} - s_{10}) + 0.0306\ (s_{12} - s_{10}) = 2.35471\ kg/s \tag{21}$$

The quantity $\dot{M}_{w(10-12)}(s)$ is a function of distance and relates to the winter period. In the initial cross-section 10 of the ventilation pipe, the mean air velocity is $v_{10}=20.474\ m/s$, and in the cross-section 12: $v_{12}=19.994\ m/s$. The mean air velocity at this section of the shaft is equal to $v_{śr(10-12)} = (v_{10+12})/2 = 20.234\ m/s$, and the mean wet air density at this section is $\rho_{śr(10-12)} = (\rho_{10-12})/2 = (1.0805 + 1.1065)/2 = 1.0935\ kg/m^3$.

6. In summer, the two-phase stream 11–K in the ventilation duct is not cooled. Therefore, the unit distributed water mass source from the condensation is $\dot{m}_{wj(11-K)}(s) = 0$. In winter, the situation is the same: $\dot{m}_{wj(12-K)}(s) = 0$. There is no internal water mass source in the duct, but the water from the condensation occurring in the preceding ducts is discharged through it. The water mass flow rate $\dot{M}_{w(11-K)}(s)$, $\dot{M}_{w(12-K)}(s)$, flowing in the air stream in the duct is constant over its entire length and the value depends on the period of the year. For the summer:

$$\dot{M}_{w(11-K)}(s) = \int_{s11}^{s} [\dot{M}_{w(8-11)}(s = s_{11})\ \delta\ (s - s_{11}) + \dot{m}_{wj(11-K)}(s)]\ ds = \int_{s11}^{s} 2.0990\ \delta\ (s - s_{11})\ ds = 2.0990\ H\ (s - s_{11}),\ kg/s \tag{22}$$

$$\dot{M}_{w(11-K)}(s = s_K) = \int_{s11}^{SK} [\dot{M}_{w(8-11)}(s = s_{11})\ \delta\ (s - s_{11}) + \dot{m}_{wj(11-K)}(s)]\ ds = 2.0990\ H\ (s_K - s_{11}) = 2.0990\ kg/s \tag{23}$$

The air velocity in the shaft duct in summer is equal to $v_{śr(11-K)} = 20.165\ m/s$, and the wet air density at this section is $\rho_{r(11-K)} = 1.0805\ kg/m^3$.

For winter:

$$\dot{M}_{w(12-K)}(s) = \int_{s12}^{s} [\dot{M}_{w(10-12)}(s = s_{12})\ \delta\ (s - s_{12}) + \dot{m}_{wj(12-K)}(s)]\ ds = \int_{s12}^{s} [2.35471\ \delta\ (s - s_{12}) + 0]\ ds = 2.35471\ H\ (s - s_{12}),\ kg/s \tag{24}$$

$$\dot{M}_{w(12-K)}(s = s_K) = \int_{s12}^{SK} [\dot{M}_{w(10-12)}(s = s_{12})\ \delta\ (s - s_{12}) + \dot{m}_{wj(12-K)}(s)]\ ds = \int_{s12}^{SK} [2.35471\ \delta\ (s - s_2)+ 0]\ ds = 2.35471\ H\ (s_K - s_{12}) = 2.35471\ kg/s \tag{25}$$

The air velocity in the shaft duct in winter is equal to $v_{śr(1-K)} = 19.629\ m/s$, and the wet air density at this section is $\rho_{r(11-K)} = 1.1065\ kg/m^3$.

Figs. 2a and 2b illustrate how the mean wet air velocity changes in the cross-section of the pathway of the air discharged in summer and winter, respectively. Figs. 3a and 3b illustrate the change in the water mass flow rate from the condensation of water vapor carried away to the surface along the air discharge pathway in summer and in winter.

Water Mass Flow Rate and Pressure Drop at Individual Sections of Air Discharge Pathway

In a co-current flow upward, in which the velocity of water droplets and the velocity of the air stream carrying them away are the same (no-slip flow), the water mass mw in the vertical duct (W–2) is defined by the following Formula:

$$m_{w(1-2)} = \int_{s1}^{s2} [\dot{M}_{w(1-2)}(s) / v_{śr(1-2)}]\ ds = \int_{sw}^{s2} [0.001240\ (s-s_w) /$$

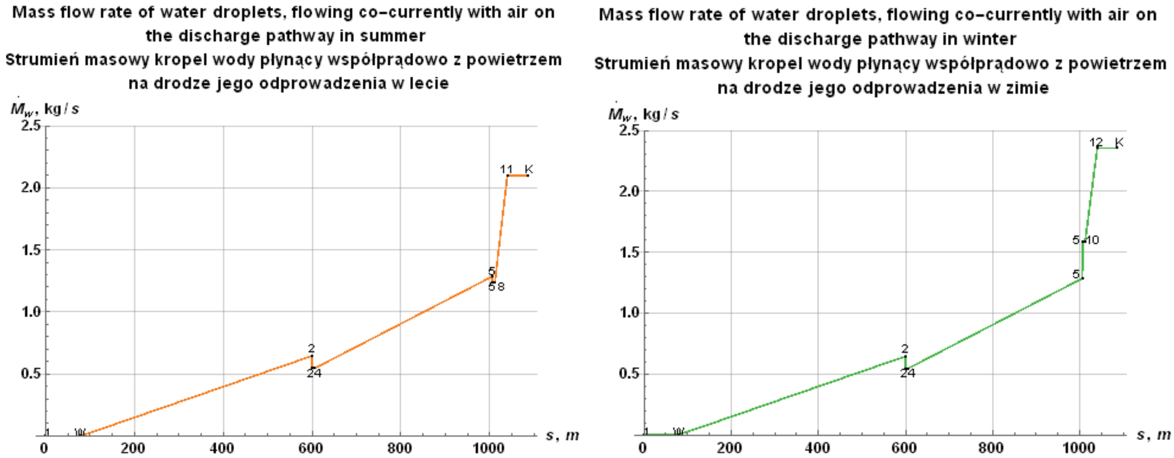

Fig. 3. Change in the mass flow rate of water droplets from water vapor condensation carried away along the air discharge pathway in a) summer, b) winter
Rys. 3. Zmiana strumienia masowego kropel wody powstałych z kondensacji pary wodnej na drodze odprowadzenia powietrza w a) lecie, b) zimie

$$v_{\text{śr}(w-2)}\,]\,ds = [0.001240 / 2\,(v_{\text{śr}(w-2)})]\,(s_2 - s_w)^2,\ \text{kg} \tag{26}$$

Having substituted appropriate data, it was obtained as follows: $m_{w(1-2)} = 36.81$ kg.

In the next duct (2–4) located on the discharge pathway, the mass of water droplets is determined by the relationship:

$$m_{w(2-4)} = \int_{s2}^{s4} [\dot{M}_{w(2-4)}(s) / v_{\text{śr}(2-4)}\,]\,ds = \int_{s2}^{s4} [0.54503\,H\,(s-s_2) / v_{\text{śr}(2-4)}\,]\,ds = 0.54503\,(s_4-s_2) / v_{\text{śr}(4-2)},\ \text{kg} \tag{27}$$

Having substituted appropriate data, it was obtained as follows: $m_{w(2-4)} = 0.36$ kg.

In the vertical duct (4–5), the mass of water droplets is determined by the relationship:

$$m_{w(4-5)} = \int_{s4}^{s5} [\dot{M}_{w(4-5)}(s) / v_{\text{śr}(4-5)}\,]\,ds = \int_{s4}^{s5} [0.54503\,H\,(s-s_4) + 0.00185\,(s-s_4) / v_{\text{śr}(4-5)}\,]\,ds = [0.54503\,(s_5-s_4) / v_{\text{śr}(4-5)}] + [0.00185/2\,v_{\text{śr}(4-5)}]\,(s_5-s_4)^2,\ \text{kg} \tag{28}$$

Having substituted appropriate data, it was obtained: $m_{w(4-5)} = 39.62$ kg.

In the vertical duct (5–8), the mass of water droplets can be calculated from the Formula:

$$m_{w(5-8)} = \int_{s5}^{s8} [\dot{M}_{w(5-8)}(s) / v_{\text{śr}(5-8)}\,]\,ds = \int_{s5}^{s8} [1.28503 - 0.0481\,H\,(s-s_5) / v_{\text{śr}(5-8)}\,]\,ds = 1.24222\,(s_8-s_5) / 10.173,\ \text{kg} \tag{29}$$

Having substituted appropriate data, it was obtained: $m_{w(5-8)} = 0.74$ kg.

In the duct (ventilation pipe) (8–11) inclined by the angle α to the horizontal plane, the mass of water droplets in summer can be calculated from the Formula:

$$m_{w(8-11)} = \int_{s8}^{s11} [\dot{M}_{w(8-11)}(s) / v_{\text{śr}(8-11)}\,]\,ds = \int_{s8}^{s11} [1.24222\,H\,(s-s_8) + 0.0306\,(s-s_8) / v_{\text{śr}(8-11)}]\,ds = [1.24222\,(s_{11}-s_8) / 20.416] + 0.0306\,(s_{11}-s_8)^2 / 2 \cdot 20.416,\ \text{kg} \tag{30}$$

Having substituted appropriate data, it was obtained as follows: $m_{w(8-11)} = 2.29$ kg.

In the duct (ventilation pipe) (11-K) inclined by the angle β to the horizontal plane, the mass of water droplets in summer can be calculated from the Formula:

$$m_{w(11-K)} = \int_{s11}^{SK} [\dot{M}_{w(11-K)}(s) / v_{\text{śr}(11-K)}\,]\,ds = \int_{s11}^{SK} [2.0990\,H\,(s-s_{11}) / v_{\text{śr}(11-K)}\,]\,ds = [2.0990\,(s_K-s_{11}) / 20.165,\ \text{kg} \tag{31}$$

Having substituted appropriate data, it was obtained: $m_{w(11-K)} = 4.68$ kg.

Fig. 2b and Fig. 3b demonstrate that during the winter season, in the three final ducts of the discharge pathway, the water mass flow rate from the water vapor condensation on the air discharge pathway is greater than that for the summer period. Therefore, the water mass present in these ducts in winter will be different than previously calculated. The water mass in these ducts is determined as follows:

In the vertical duct (5–10), the mass of water droplets can be calculated from the Formula:

$$m_{w(5-10)} = \int_{s5}^{s10} [\dot{M}_{w(5-10)}(s) / v_{\text{śr}(5-10)}]\,ds = \int_{s5}^{s10} [1.28503 + 0.29968\,H\,(s-s_5) / v_{\text{śr}(5-10)}\,]\,ds = [1.58471\,(s_{10}-s_5) / 10.447,\ \text{kg} \tag{32}$$

Having substituted appropriate data, it was obtained: $m_{w(5-10)} = 0.91$ kg.

In the duct (ventilation pipe) (10–12) inclined by the angle α to the horizontal plane, the mass of water droplets in winter can be calculated from the Formula:

$$m_{w(10-12)} = \int_{s10}^{s12} [\dot{M}_{w(10-12)}(s) / v_{\text{śr}(10-12)}]\,ds = \int_{s10}^{s12} [1.58471\,H\,(s-s_{10}) + 0.0275\,(s-s_{10}) / v_{\text{śr}(10-12)}\,]\,ds = [1.58471\,(s_{12}-s_{10}) / 20.234] + [0.0275\,(s_{12}-s_{10})^2 / 2 \cdot 20.234],\ \text{kg} \tag{33}$$

Having substituted appropriate data, it was obtained: $m_{w(10-12)} = 2.73$ kg.

In the duct (ventilation pipe) (12–K) inclined by the angle β to the horizontal plane, the mass of water droplets in summer can be calculated from the Formula:

$$m_{w(12-K)} = \int_{s12}^{SK} [\dot{M}_{w(12-K)}(s) / v_{\text{śr}(12-K)}\,]\,ds = \int_{s12}^{SK} [2.35471\,H\,(s-s_{12}) / v_{\text{śr}(12-K)}\,]\,ds = [2.35471\,(s_K-s_{12}) / 19.629,\ \text{kg} \tag{34}$$

Having substituted appropriate data, it was obtained as follows: $m_{w(12-K)} = 5.40$ kg.

The consequence of the occurrence of the water mass in the discussed vertical and variously inclined ducts is the loss of static pressure of the air caused by the weight of the calculated water mass. These pressure losses, determined for the individual ducts, constitute the quantities $A_{\dot{m}}$, sought in this research paper, describing the flow characteristics of each of the analyzed ducts. They can be determined from the following relationships:

$$A_{\dot{m}(1\text{-}2)} = m_{w(1\text{-}2)}\, g / F_{(1\text{-}2)} = (36.81 \cdot 9.81) / 34.84 = 10.36 \text{ Pa} \tag{35}$$

$$A_{\dot{m}(2\text{-}4)} = m_{w(2\text{-}4)}\, g / F_{(2\text{-}4)} = (0.36 \cdot 9.81) / 34.84 = 0.10 \text{ Pa} \tag{36}$$

$$A_{\dot{m}(4\text{-}5)} = m_{w(4\text{-}5)}\, g / F_{(4\text{-}5)} = (39.62 \cdot 9.81) / 34.84 = 11.16 \text{ Pa} \tag{37}$$

$$A_{\dot{m}(5\text{-}8)} = m_{w(5\text{-}8)}\, g / F_{(5\text{-}8)} = (0.74 \cdot 9.81) / 34.84 = 0.21 \text{ Pa (in summer)} \tag{38}$$

$$A_{\dot{m}(5\text{-}10)} = m_{w(5\text{-}10)}\, g / F_{(5\text{-}10)} = (0.91 \cdot 9.81) / 34.84 = 0.26 \text{ Pa (in winter)} \tag{39}$$

$$A_{\dot{m}(8\text{-}11)} = m_{w(8\text{-}11)}\, g \sin\alpha / F_{(8\text{-}11)} = (2.29 \cdot 9.81 \cdot 0.7071) / 19.63 = 0.81 \text{ Pa (in summer)} \tag{40}$$

$$A_{\dot{m}(10\text{-}12)} = m_{w(10\text{-}12)}\, g \sin\alpha / F_{(10\text{-}12)} = (2.73 \cdot 9.81 \cdot 0.7071) / 19.63 = 0.96 \text{ Pa (in winter)} \tag{41}$$

$$A_{\dot{m}(11\text{-}K)} = m_{w(11\text{-}K)}\, g \sin\beta / F_{(11\text{-}K)} = (4.68 \cdot 9.81 \cdot 0.0872) / 20 = 0.20 \text{ Pa (in summer)} \tag{42}$$

$$A_{\dot{m}(12\text{-}K)} = (m_{w(12\text{-}K)}\, g \sin\beta / F_{(12\text{-}K)} = (5.40 \cdot 9.81 \cdot 0.0872) / 20 = 0.23 \text{ Pa (in winter)} \tag{43}$$

The values of $A_{\dot{m}(a\text{-}b)}$ calculated above, in the exemplary ducts (a-b), which represent the air discharge pathway, refer to a no-slip flow in which all the condensed water is brought to the surface. These are the theoretically smallest values possible.

Conclusions

1. The procedure and calculation Formulas presented in this research paper allow to determine the value of $A_{\dot{m}}$ for the analyzed ducts. This quantity is essential for determining the flow characteristics of the duct in which a fixed no-slip co-current two-phase flow occurs.
2. The calculations were carried out in the following ducts:
   - vertical, in which the water mass flow rate was constant over their entire lengths (transporting ducts),
   - vertical, in which the mass sources of the liquid phase were distributed over the length of the flow pathway,
   - in which the mass sources resulted from the condensation of water vapor contained in the air. As a consequence, the mass flow of the liquid phase changed along the flow pathway,
   - inclined at a certain angle, in which the water mass flow rate remained constant throughout its entire length,
   - inclined at a certain angle, in which the water mass flow rate was changing along the flow pathway in the duct.

In each of the above-mentioned cases, the calculation Formulas for the water mass contained in the air in the analyzed duct and for the quantity $A_{\dot{m}}$ were different, and were provided in the paper.

3. In all types of the studied ducts, the values of the water mass and pressure losses $A_{\dot{m}}$, calculated for fixed two-phase no-slip flows are theoretically the smallest.
4. Theoretically, the smallest pressure loss $A_{\dot{m}}$ on the air discharge pathway, expressed in Pa, is the sum of the calculated pressure losses $A_{\dot{m}}$ for the individual ducts of this pathway, and its value (as indicated by the performed calculations for the presence of the liquid phase in the discharge pathway only due to the phenomenon of water vapor condensation) does not exceed several dozen Pa. However, one should be aware that, in fact, these values can be much larger.
5. The largest contribution to the total pressure losses $A_{\dot{m}}$ occurring on the discharge pathway, have those long sections of vertical ducts in which the water mass in the air is the greatest.

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Nomenclature

$A_{\dot{m}}$ – pressure exerted by the weight of water droplets in an inclined duct being a pathway for the discharge of air from the mine to the surface, N/m²,

c – volumetric concentration (volume) of water in air (constant value throughout the entire length of the duct), m³/m³,

$\dot{m}$ – mass flow rate of air and water in a duct, kg/s,

$\dot{m}_{wj}(s)$ – the unit mass flow of the condensed water being the function of distance "s" , kg/(s·m),

$\dot{M}_W(s)$ – the mass flow rate of the water flowing in the exemplary duct being the function "s", kg/s,

$H(s\text{-}s_2)$ – the Heaveside'a function,

$R_{\dot{m}}$ – duct resistance for a two-phase mass flow rate, with constant mass concentration of water at the length of the duct, $(\text{m}\cdot\text{kg})^{-1}$,

w^* – mechanical energy loss, N/m²,

$(z_1\text{-}z_2)$ – difference between height of inlet and outlet of the duct, m.

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Minimalna strata ciśnienia spowodowana kondensacją pary wodnej w chłodzonym powietrzu płynącym przewodem nachylonym

W pracy przedstawiono metodologię wyznaczania masy wody i spadku ciśnienia w przewodach z ustalonym współprądowym bezpoślizgowym przepływem dwufazowym. Zdyspergowana faza ciekła (woda) występuje w powietrzu w wyniku ochłodzenia strumienia wilgotnego powietrza na niektórych odcinkach drogi jego odprowadzenia z wyrobisk podziemnych lub w miejscach występowania lokalnych źródeł masy wody (lub jej lokalnych upustów) utworzonych przez naturalne zjawisko kondensacji pary wodnej przy mieszaniu się strumieni powietrza wilgotnego. Dla takich przypadków określono straty ciśnienia statycznego, które wynikały z siły grawitacji masy kropelek wody występujących w strumieniu powietrza w szybie wydechowym.

Słowa kluczowe: dwufazowy przepływ bezpoślizgowy, strata ciśnienia, charakterystyka przewodu, masowe źródła wody z kondensacji pary wodnej