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VERIFICATION OF MATHEMATICAL DESCRIPTION OF CHANGES IN AIR TEMPERATURE AND HUMIDITY IN HEADINGS VENTILATED WITH AUXILIARY VENTILATION SYSTEM

WERYFIKACJA METEMATYCZNEGO OPISU ZMIAN TEMPERATURY I WILGOTNOŚCI POWIETRZA W WYROBISKACH PRZEWIETRZANYCH LUTNICIĄGIEM TŁOCZĄCYM Z DADATKOWYM WENTYLATOREM O ZMIENIANEJ PRĘDKOŚCI OBROTOWEJ

The article presents verification of the mathematical model which was developed in earlier works, describing, through distributions of temperature, specific humidity, and flow rate of both fresh and exhaust air in the dead end headings ventilated with forcing duct line ventilation system, the climatic conditions existing in those headings. On the route of the considered duct line, an additional fan with a variable rotational speed was installed in order to avoid recirculation of the air between the inside of the duct line and the heading. The task of this auxiliary fan is an increase in the volumetric flow rate of fresh air at the mine face. The above-mentioned verification was based on a comparison of the calculation results obtained from the numerical solution of ordinary differential equations of the first order and algebraic equations with the results of measurements carried out in the selected mine heading. Wide comparative material was obtained by changing the location of the auxiliary fan in the duct line for a given heading length, and the heading length itself. 14 research variants were obtained in this way, in which, in addition to the already mentioned temperatures and humidity of the air, also the rotor speeds of the auxiliary fan were compared. The results of calculations and measurements have been presented in a graphical form. Their comparison was carried out using statistical methods.

Keywords: mining aerology, auxiliary ventilation, duct lines, comfort of work

W artykule przeprowadzono weryfikację, wyprowadzonego we wcześniejszych pracach, modelu matematycznego opisującego, poprzez rozkłady temperatury, wilgotności właściwej oraz prędkości przepływu zarówno świeżego jak i zużytego powietrza w ślepych wyrobiskach przewietrzanych tłoczącą wentylacją lutniową, istniejące w tych wyrobiskach warunki klimatyczne. Na trasie rozważnego lutniociągu zabudowano dodatkowy wentylator o zmienianej, w celu uniknięcia recyrkulacji powietrza między wnętrzem tego lutniociągu a wyrobiskiem, prędkości obrotowej. Zadaniem dodatkowego wentylatora jest wzrost wydatku objętościowego powietrza świeżego w przodku. Wspomniana weryfikacja polegała na porównaniu wyników obliczeń otrzymanych z numerycznego rozwiązania układu równań różniczkowych

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zwyczajnych pierwszego rzędu i równań algebraicznych z wynikami pomiarów przeprowadzonymi w wybranym wyrobisku górniczym. Szeroki materiał porównawczy uzyskano zmieniając lokalizację wentylatora dodatkowego w lutniociągu dla danego wybiegu wyrobiska jak i sam wybieg wyrobiska. Uzyskano w ten sposób 14 wariantów badawczych, w których oprócz wymienionych już temperatur i wilgotności powietrza porównywano także prędkości obrotowe wirnika dodatkowego wentylatora. Wyniki obliczeń i pomiarów przedstawiono w formie graficznej. Ich porównanie przeprowadzono stosując metody statystyczne.

Słowa kluczowe: aerologia górnicza, wentylacja odrębna, lutniociągi, komfort pracy

1. Introduction

The increase in thermal hazard in mine headings induced many researchers to involve in this issue. Numerous methods have been developed, forecasting temperature and humidity of the air in mine headings ventilated both with streamlined ventilation and auxiliary exhaust ventilation. They also considered various ways to improve the climatic conditions in mining crew places of work, ranging from the increase in the intensity of ventilation of the headings to artificial cooling of the air there, using, among others, air compression refrigerators. In the last three years, the work of (Zapletal et al., 2012) is worth mentioning. Heat transfer in refrigerators is done through phase transitions of a environmentally friendly refrigerant (usually a zeotropic one), circulating in a closed circuit between the evaporator and the condenser as a result of the work of a compressor. The effect of the temperature glide of such a refrigerant on the power of an evaporator in air refrigerators, and thus on the enthalpy of the cooled air has been discussed in (Nowak & Życzkowski, 2013). This article discusses the improvement of working conditions in mine workings ventilated with auxiliary exhaust ventilation.

In the works of (Piątek, 2000; Piątek & Nowak, 2002), having adopted simplifying assumptions, comparing, as in (Nowak, 1997; Sinha, 1996; Nowak & Sinha, 1999), the mass of the dry air, the mass of the the water vapor contained in the air, the energy of the flowing air, and taking into account local and distributed sources of heat and moisture, a system of ordinary differential equations of the first order and algebraic equations was given, describing the distribution of the volumetric flow rate of the air in a duct line, as well as distributions of temperature and specific humidity of the air in a duct line, at the mine face zone and in the heading. These distributions concern ventilation of roadways with untight forcing duct line with a built-in additional (auxiliary) fan (W_2) along its route, thus defining the prevailing climatic conditions in them. The presented method of ventilation of dead end headings increases the flow rate of fresh air at its face. The motor of an auxiliary fan is powered by an electronic device (inverter). It allows to change the frequency of the voltage supplied to the fan motor, and thus the appropriate (less than nominal) change in the rotor speed in order to avoid uncontrolled recirculation of the air between the inside of the duct line and the heading. The rotational speed of the main fan (W_1), installed at the inlet of the duct line, is equal to the nominal value. The work of (Piątek, 2000) also defines the limiting minimum distance between the main and auxiliary fans.

The objective of this article is to determine the correctness of the discussed mathematical model by comparing its numerical solutions with the results of measurements in natural conditions in one of the coal mine workings.

2. The results of in situ measurements and numerical calculations

This heading was a research gallery 42[a] (Piątek, 2000), hollowed out with the AM-50 shearer with an average progress of the works of about 15 m/day. It operated in the rock mass at the initial temperature equal to the 19.2°C. The area of the cross section of this gallery was 12.4 m^2. The heading had two pipelines installed: fire protection and drainage, with diameters of 0.1 m and 0.15 m, respectively. Fresh air was supplied to the face with the forcing duct line, built with the "Teseco" ducts with a diameter of 0.8 m. The exception was the 34-meter section, composed of metal ducts with a diameter of 1.0 m, which was installed directly behind the main fan WLE – 1003B. On the route of the duct line, an auxiliary fan of the WLE – 803AM type was installed, with a speed variable by an inverter. These fans were local heat source in the duct line. However, in the heading and at the mine face, the role of heat sources was performed by the following machines and equipment, as indicated in Figures 1÷14: PTG conveyor belt engines with a capacity of 55 kW, SKAT scraper conveyor engines with a capacity of 2·15 kW, ITSb-type transformers with the power of 400 kW each, and the AM-50-type shearer with the engine power of 170 kW.

Experimental studies were carried out at the measurement points located along the flow path of the air in the duct line and in the analyzed dead end heading in four (I, II, III and IV) different stages of its drilling (four values of the L_2 heading strip L_2 = 725 m (variant I), L_2 = 785 m (variant II), L_2 = 1015 m (variant III), L_2 = 1070 m (variant IV)). For each of the four strips, several variants were tested, differing in the location of the auxiliary fan W_2 (i.e., the distance between the main and the auxiliary fan, hereinafter denoted by L_0). Thus, 14 test variants were obtained. During the first stage of drilling the heading (L_2 = 725 m), the location of the auxiliary fan W_2 was changed twice (L_0 = 650 m (variant I.1) and L_0 = 550 m (variant I.2)); in the second stage (L_2 = 850 m) this location was changed three times: L_0 = 775 m (variant II.1), L_0 = 680 m (variant II.2) and L_0 = 585 m (variant II.3); in the third stage (L_2 = 1015 m) – five times: L_0 = 945 m (variant III.1), L_0 = 850 m (variant III.2), L_0 = 740 m (variant III.3), L_0 = 645 m (variant III.4) and L_0 = 550 m (variant III.5); and in the last, fourth, stage (L_2 = 1070 m) – four times: L_0 = 905 m (variant IV.1), L_0 = 805 m (variant IV.2), L_0 = 705 m (variant IV.3) and L_0 = 590 m (variant IV.4). At the measurement points of each of the mentioned ventilation variants of the dead end heading, the following were measured: the absolute air pressure (b) with a pressure gauge, dry temperature (t) and wet (t_w) of this air with Assmann aspiration psychrometer, the average speed of air flow in a duct line with a wing anemometer of the μAS type, and the rotational speed (n_d) of the auxiliary cooling fan was read out from the inverter. Before the commencement of the measurements, the rotational speed of the auxiliary fan W_2 was reduced to exclude recirculation of the air between the duct line and its surroundings. For this purpose, observing the readings of the U-shaped tube, using the inverter, the difference of static pressures between the inside of the duct line immediately before the fan W_2 and the heading next to the fan was brought to zero. At the same time, the actual rotational speed of the auxiliary fan was read out. In this work, it was assumed that the thermodynamic state of the air (besides the absolute pressure b) is determined by two values – the temperature t and the specific humidity x. Accordingly, its specific humidity (x) was assumed as a measure of the moisture content in the air, rather than the wet bulb temperature (t_w). Therefore, instead of analyzing the pairs of temperatures (t, t_w) obtained from the measurements, the pairs of values (t, x) are analyzed. Appropriate calculations were performed according to the following formula (Filek & Nowak, 1993; Nowak, 1997).

$$x = \frac{379,8 \cdot 10^{\frac{7,5 \cdot t_w}{237,29+t_w}} - 4,1161 \cdot 10^{-4} \cdot \left(t - t_w\right) \cdot b}{b - 610,6 \cdot 10^{\frac{7,5 \cdot t_w}{237,29+t_w}} + 6,6176 \cdot 10^{-4} \cdot \left(t - t_w\right) \cdot b} \tag{1}$$

Location of the measurement points in the duct line was clearly specified, and these were always: main and auxiliary fans inlets and the duct line outlet. However, in the heading, it was attempted to select the location of those measurement points in such a way as to perform the measurements at the outlet of the mine face zone and at a distance of several dozen meters in front of each of the local heat sources found in the heading, as well as several dozen meters behind it. The results of the measurements and calculations obtained from the numerical solution of the adopted mathematical model have been presented graphically in the form of graphs (Fig. 1÷14). Each test variant is represented by three graphs constituting a single Figure. The graph "a" shows the course of the air temperature as a function of the current coordinate s in the duct line $t_1(s)$ and in the heading $t_2(s)$, the graph "b" in the same way shows the course of specific humidity of the air $x_1(s)$ and $x_2(s)$, and the graph "c" presents the course of volumetric flow rate of the air in the duct line $Q_1(s)$. Index "1" denotes the parameters of the air in the duct line, and index "2" the parameters in the headings. Results of the calculations have been plotted on the graphs as lines, and the measurement results in the form of points. Solid lines and points in the form of circles refer to the duct line, and dashed lines and points marked as full squares – to the heading. The Figures also include fans forcing air flow in the test duct line, as well as devices which are local heat sources, plotted in the right places and signed, operating in the analyzed heading and at the face at the time of the measurements. Each of these elements was located precisely on the axis of abscissas using a short vertical section. At this point, it should be mentioned, that due to a significant extension of the measurements for a given heading in time, and with no intention to disturb the production process, the measurements were carried out on non-working days, when the devices which are at the face and in the heading, and which constitute the heat source, worked at idle speed.

For the test values – the temperature, specific humidity and air flow, and the rotational speed of the auxiliary fan – the absolute (D) and relative (d) deviations were calculated of the measured values from the calculated ones. Absolute deviations were statistically analyzed to determine their statistical significance.

3. A comparison of the results of measurements and calculations

As it was mentioned, the differences in the values of temperatures, specific humidity, volumetric flow rates of the air and rotational speed of the fan W_2, calculated from the equations of the mathematical model and obtained from the measurements were subjected to statistical analysis (Greń, 1976). For this purpose, from a selected series of calculated absolute deviations, arithmetic means ($\overline{\Delta t}$, $\overline{\Delta x}$, $\overline{\Delta Q_1}$, $\overline{\Delta n_d}$), standard errors ($S_{\Delta t}$, $S_{\Delta x}$, $S_{\Delta Q_1}$, $S_{\Delta n_d}$) were calculated and, using the Student's t-distribution, the value of the statistics t. These values were calculated using equations (2)÷(4), which based on the example of the absolute deviations of the air temperature

Δt_r can be written as:

$$\overline{\Delta t} = \frac{1}{u} \cdot \sum_{r=1}^{u} \Delta t_r \tag{2}$$

$$S_{\Delta t} = \sqrt{\frac{1}{u-1} \cdot \sum_{r=1}^{u} \left(\Delta t_r - \overline{\Delta t} \right)^2} \tag{3}$$

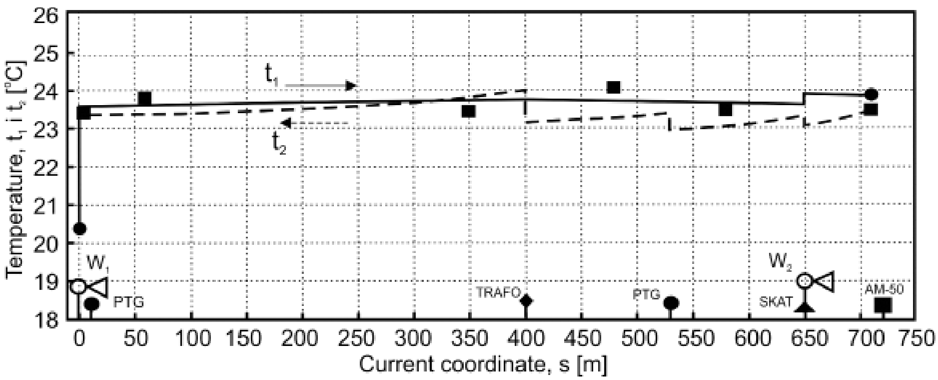
$$t = \frac{\overline{\Delta t}}{S_{\Delta t}} \cdot \sqrt{u} \tag{4}$$

where u denotes a number of elements in the selected series. The resulting value of the statistics t in each case was compared with the critical value of the statistics t_{kr}, read from the tables of this distribution for $(u - 1)$ degrees of freedom at a significance level of $\alpha = 0.05$. The statistical significance of deviations was found in the case $|t| > t_{kr}$, while at the opposite inequality sign, lack of statistical significance was observed (randomness of the source of deviations).

For the temperature and specific humidity of the air, the series included results of the measurements and calculations for the outlet of the duct line and the measurement points in the heading, separately for each of the fourteen variants. And for the air flow rate in the duct line and for the auxiliary fan rotational speed, the series created results from all 14 variants, wherein the flow rate was studied separately for the main fan inlet, auxiliary fan inlet, and for the duct line outlet. The results of the statistical analysis have been presented in Tables 1 to 4.

Based on the distributions of the air temperature in the duct line and in the heading, i.e. the functions $t_1(s)$ and $t_2(s)$, denoted as “a” in Figures 1÷14, it is possible to make the following statements:

The depth of the drilled research gallery 42^a is relatively small. This significantly affects the initial temperature of the surrounding rock mass which does not exceed 20°C. Due to this relatively low temperature of the rock mass which, besides, is close to the air temperature at the inlet to the duct line, the waveforms $t_1(s)$ and $t_2(s)$ are flat. The main fan causes large local increase in the air temperature in the duct line – in the tested variants it was about 3 to 3.5°C; the auxiliary fan causes lower increase in the air temperature – depending on its location, from about 0.2°C to about 1.1°C. The heat sources located in the headings also cause step increases in temperature of the exhaust air, which in some cases (with large lengths of a dead end heading with additional, high-power local sources of heat) makes the duct line surrounded by warmer air, in the part closer to the streamlined current, and an increase in the air temperature in the duct line along the coordinate s can be observed there. However, in the part closer to the mine face (and thus before these sources), a slight decrease in its temperature is observed, caused by heat exchange with the exhaust air, which is cooler. Thus, the measured and calculated air temperature increase at the face of the test heading is always negative (due to a cool rock mass and low engaged power of the shearer – idle speed), and their absolute values do not exceed 0.6°C (measured) and about 0.7°C (calculated).



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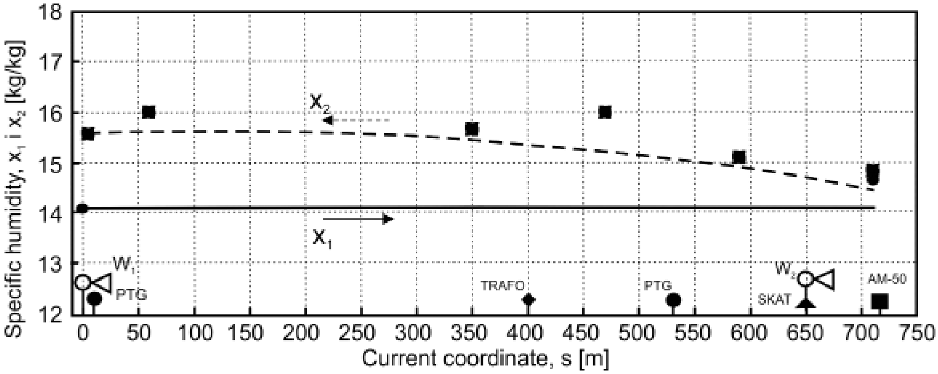

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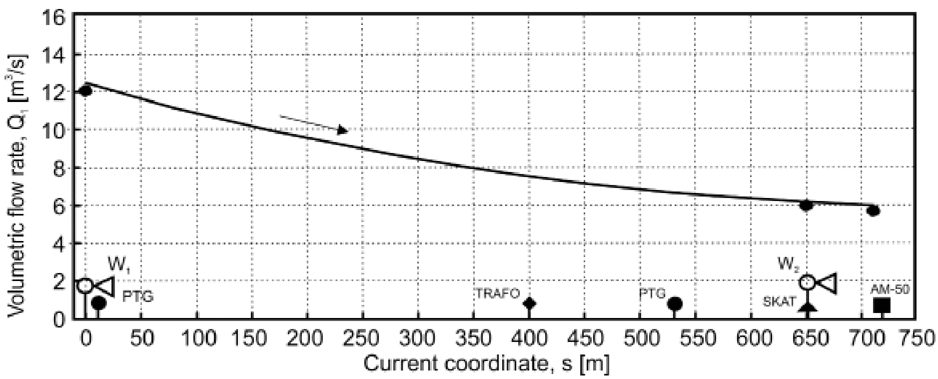

c)

Fig. 1. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant I.1

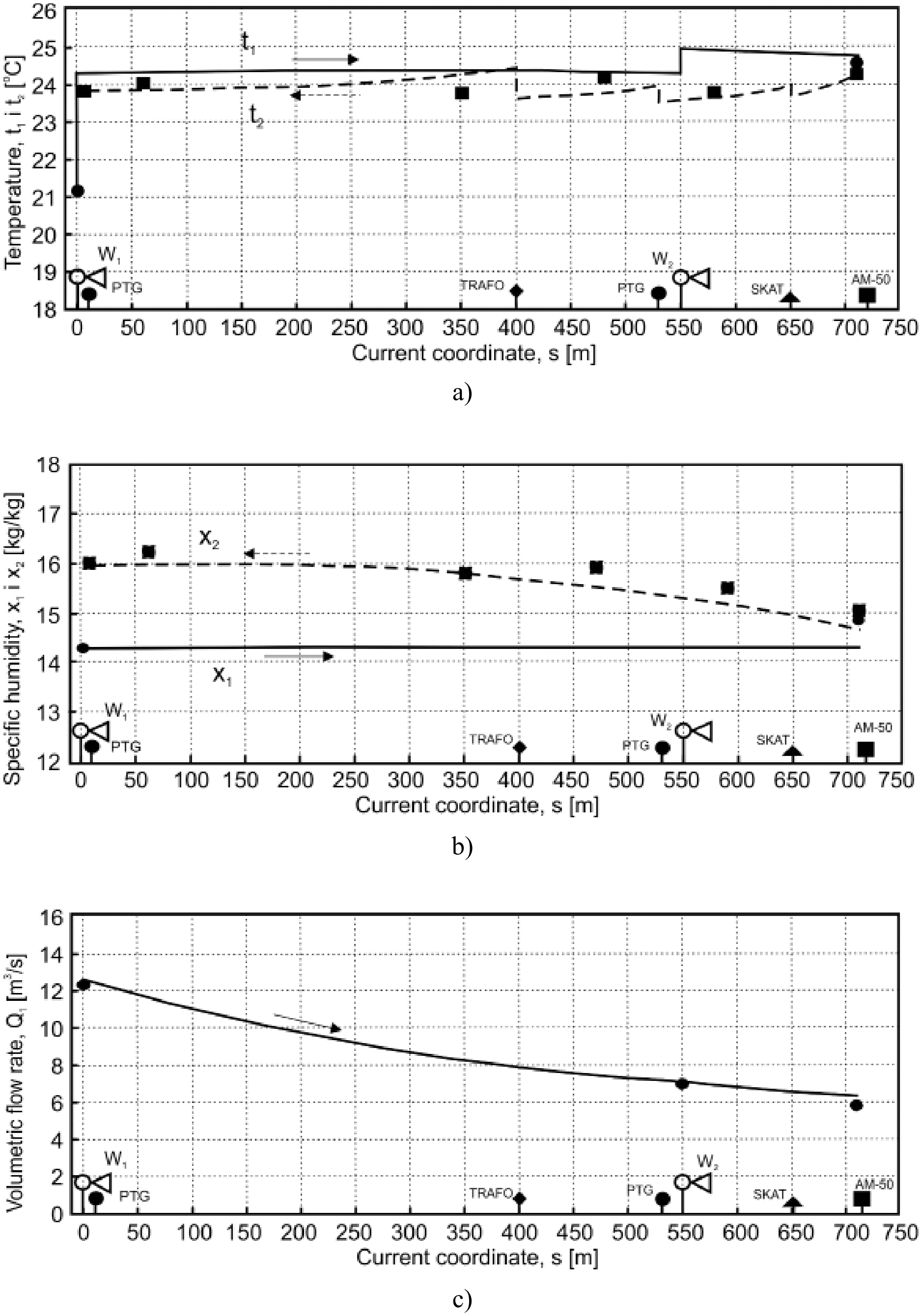

Fig. 2. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant I.2

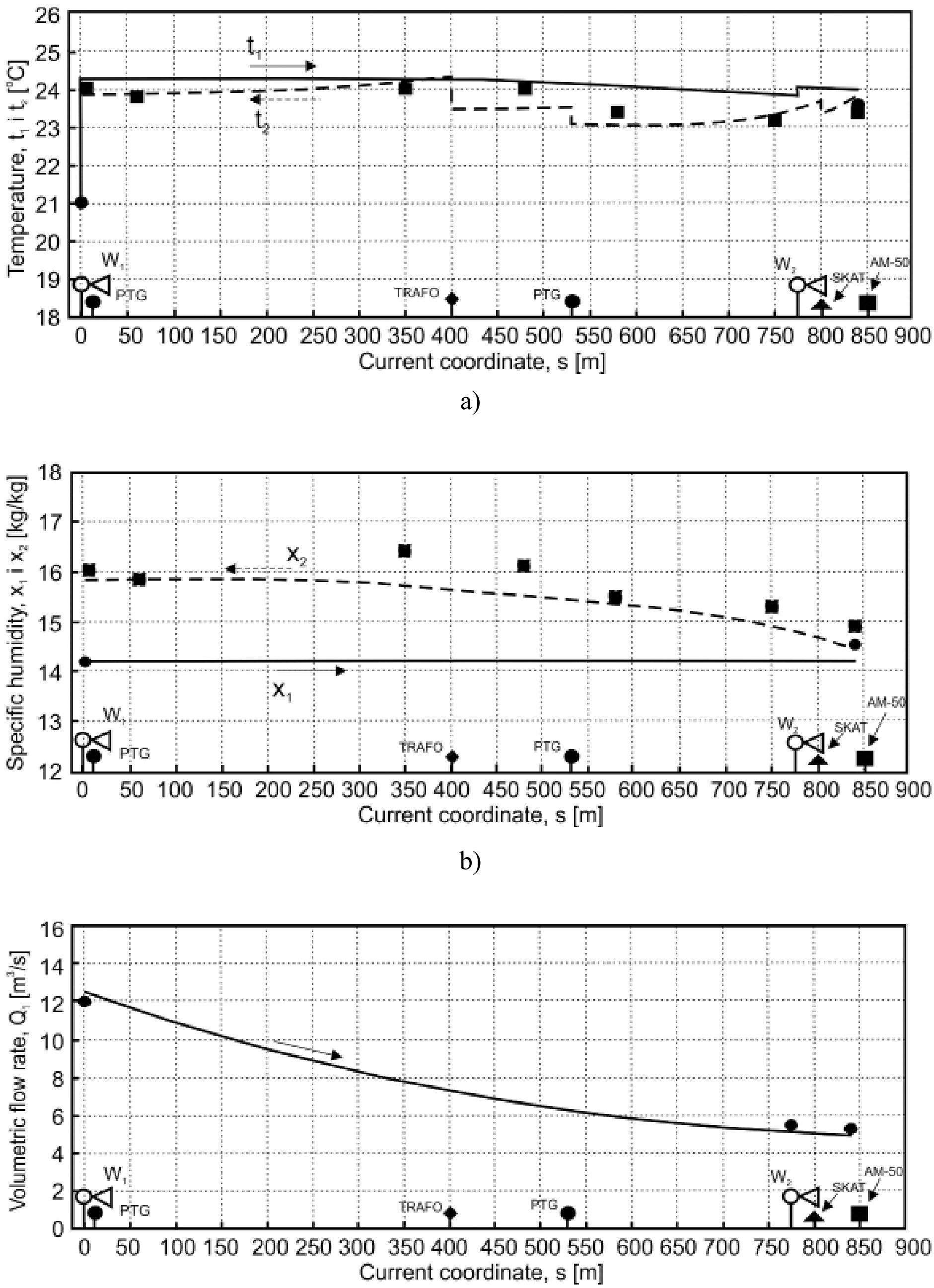

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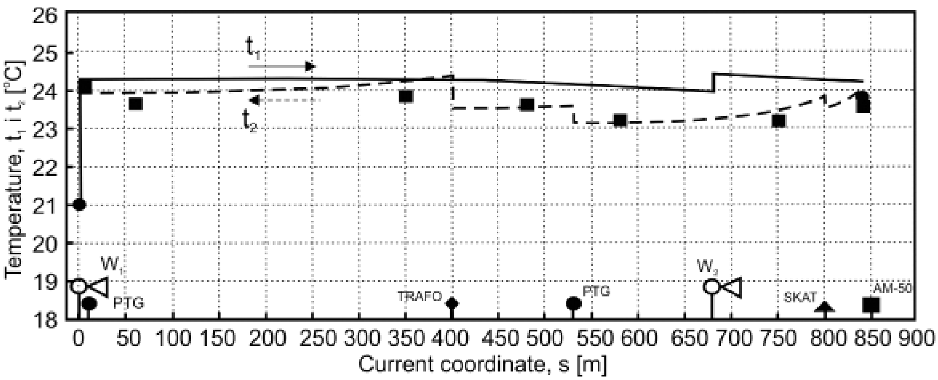
Fig. 3. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant II.1



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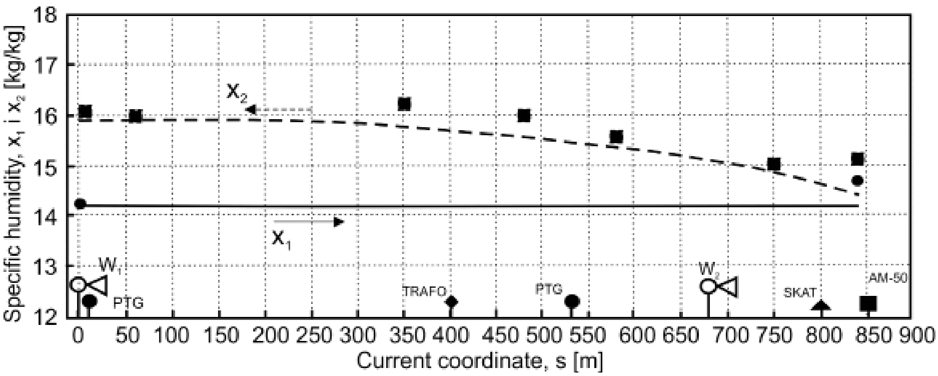

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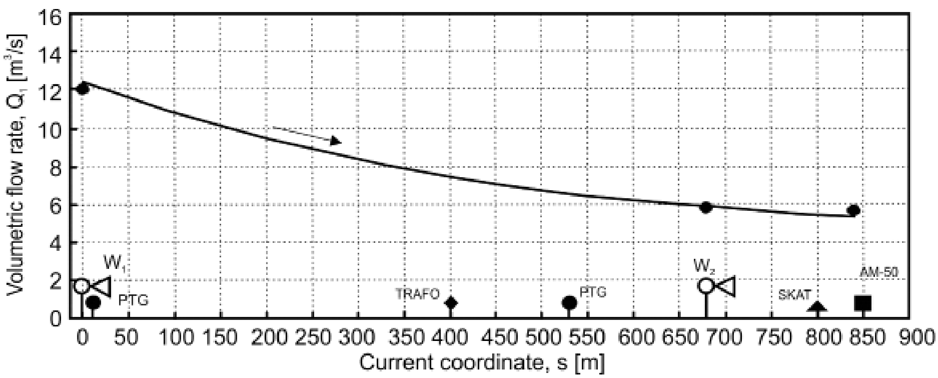

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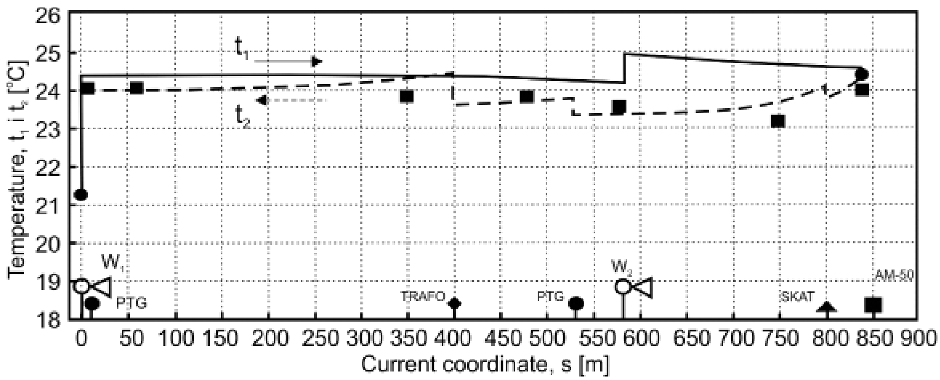
Fig. 4. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant II.2



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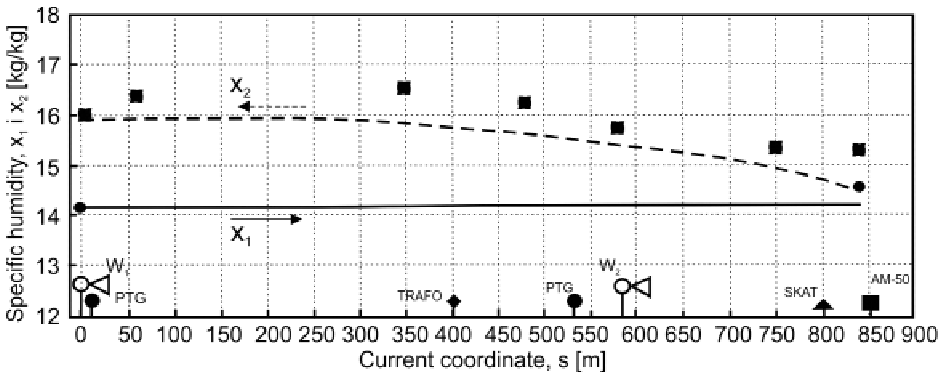

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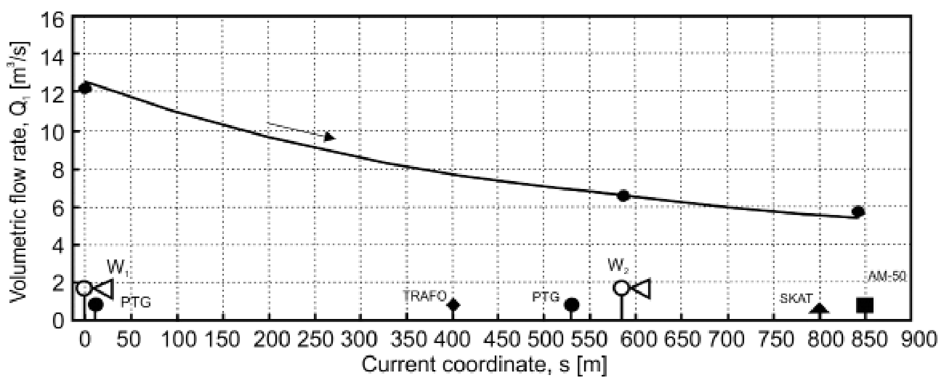

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Fig. 5. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant II.3

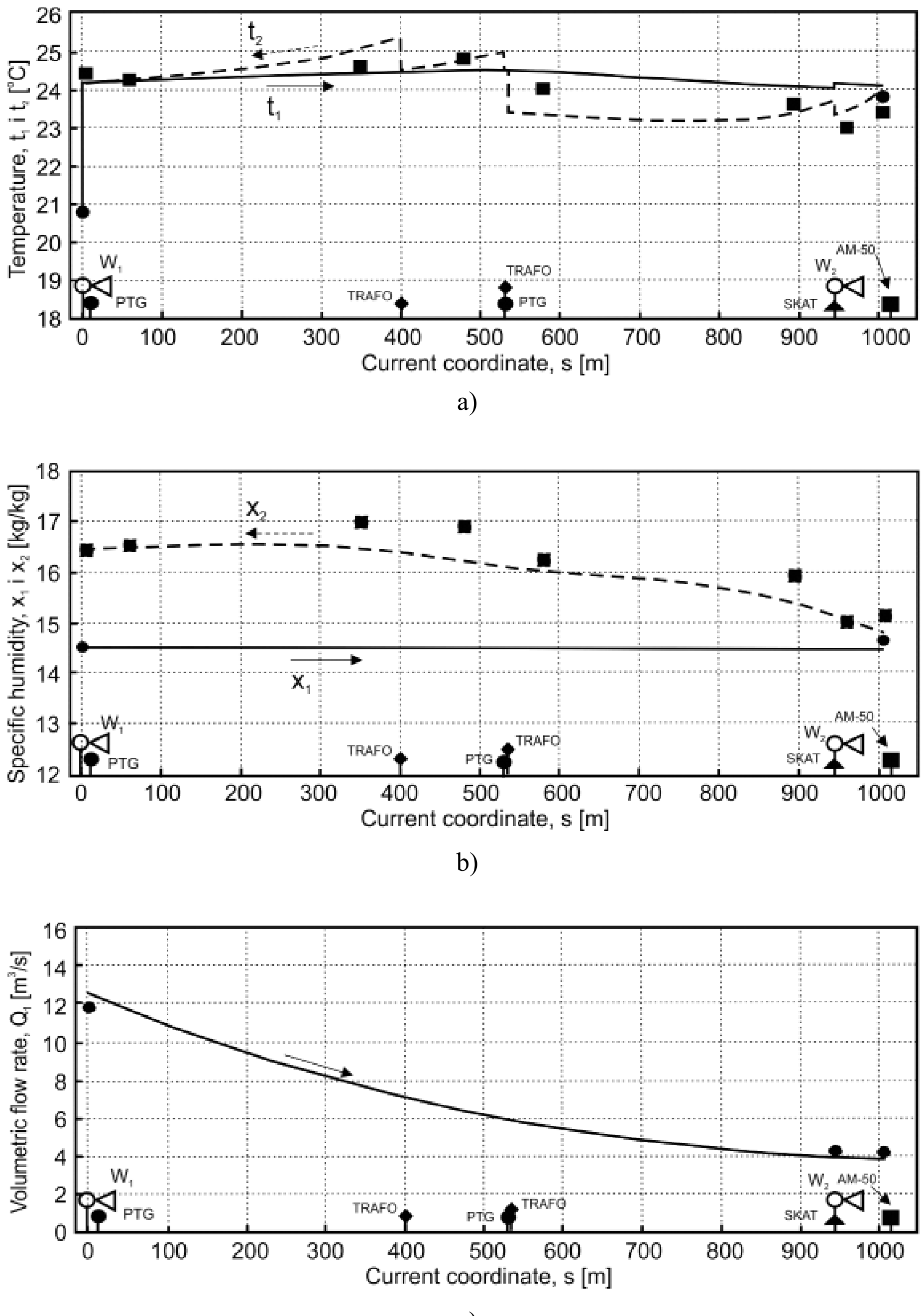

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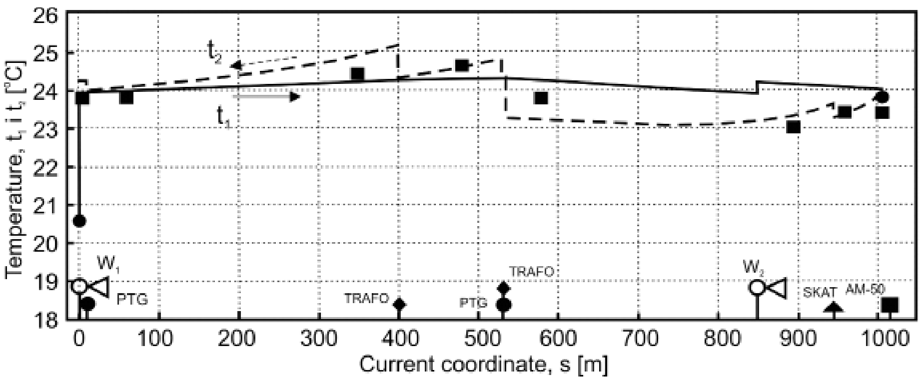
Fig. 6. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant III.1



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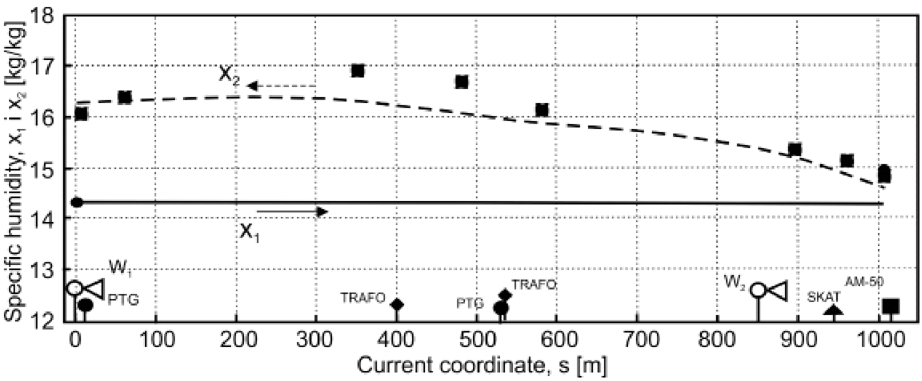

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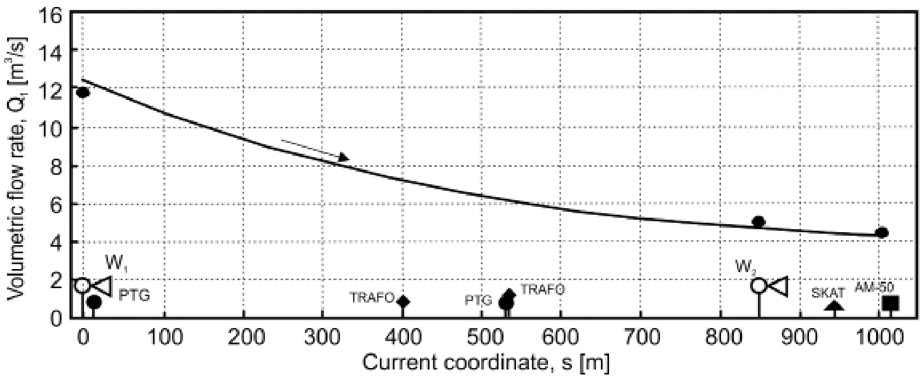

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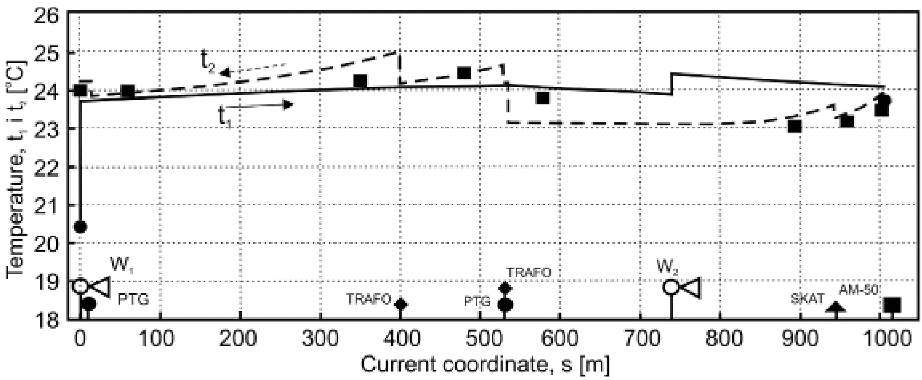
Fig. 7. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant III.2



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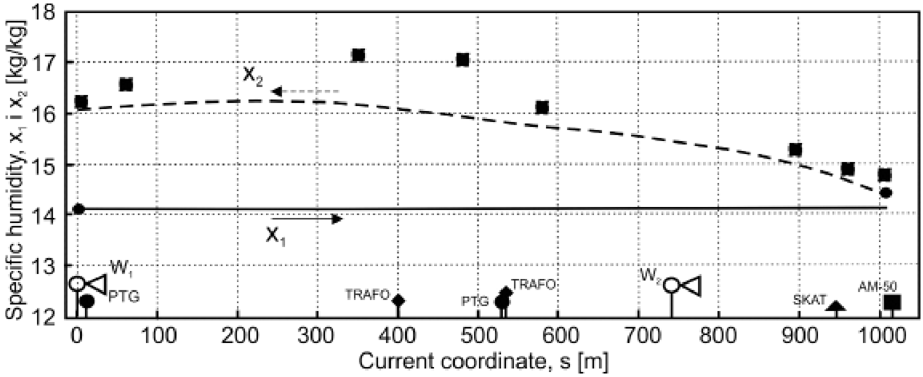

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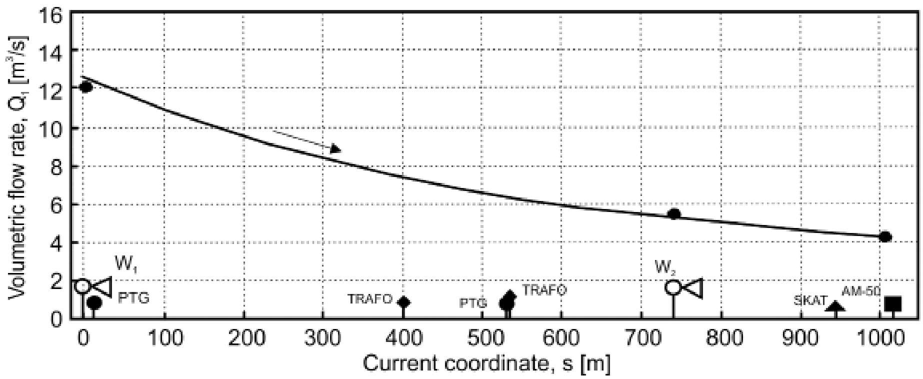

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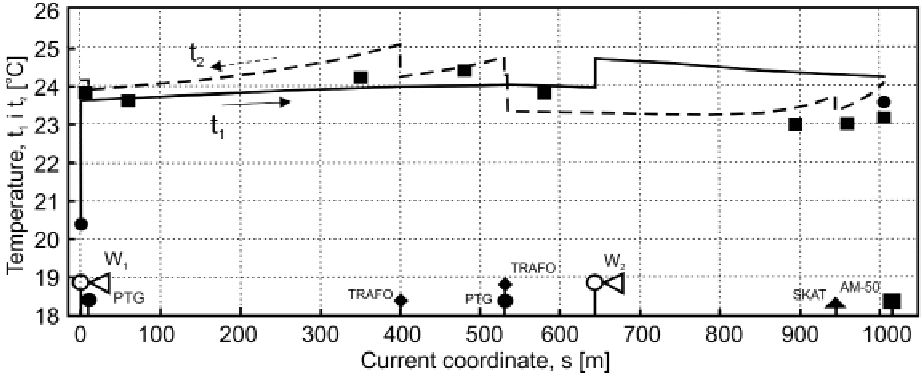
Fig. 8. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant III.3



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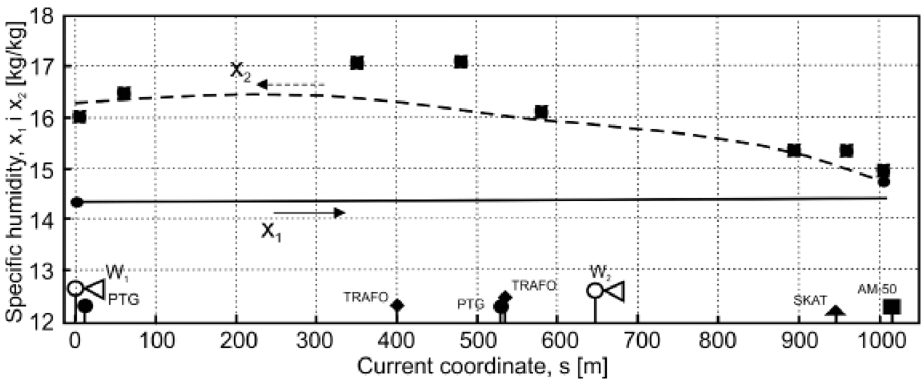

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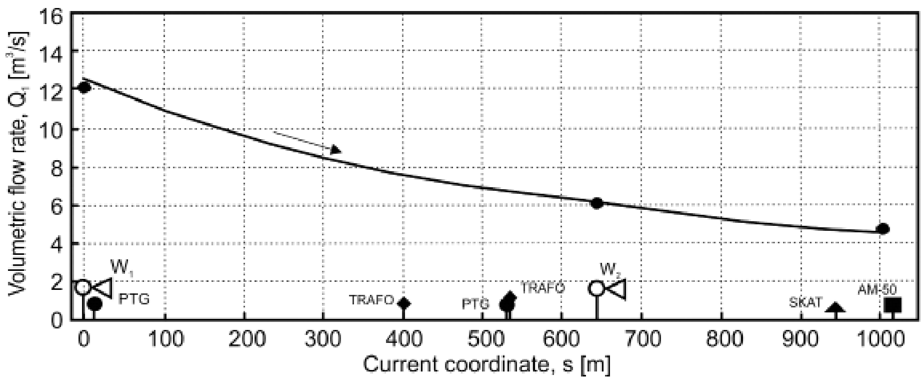

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Fig. 9. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant III.4

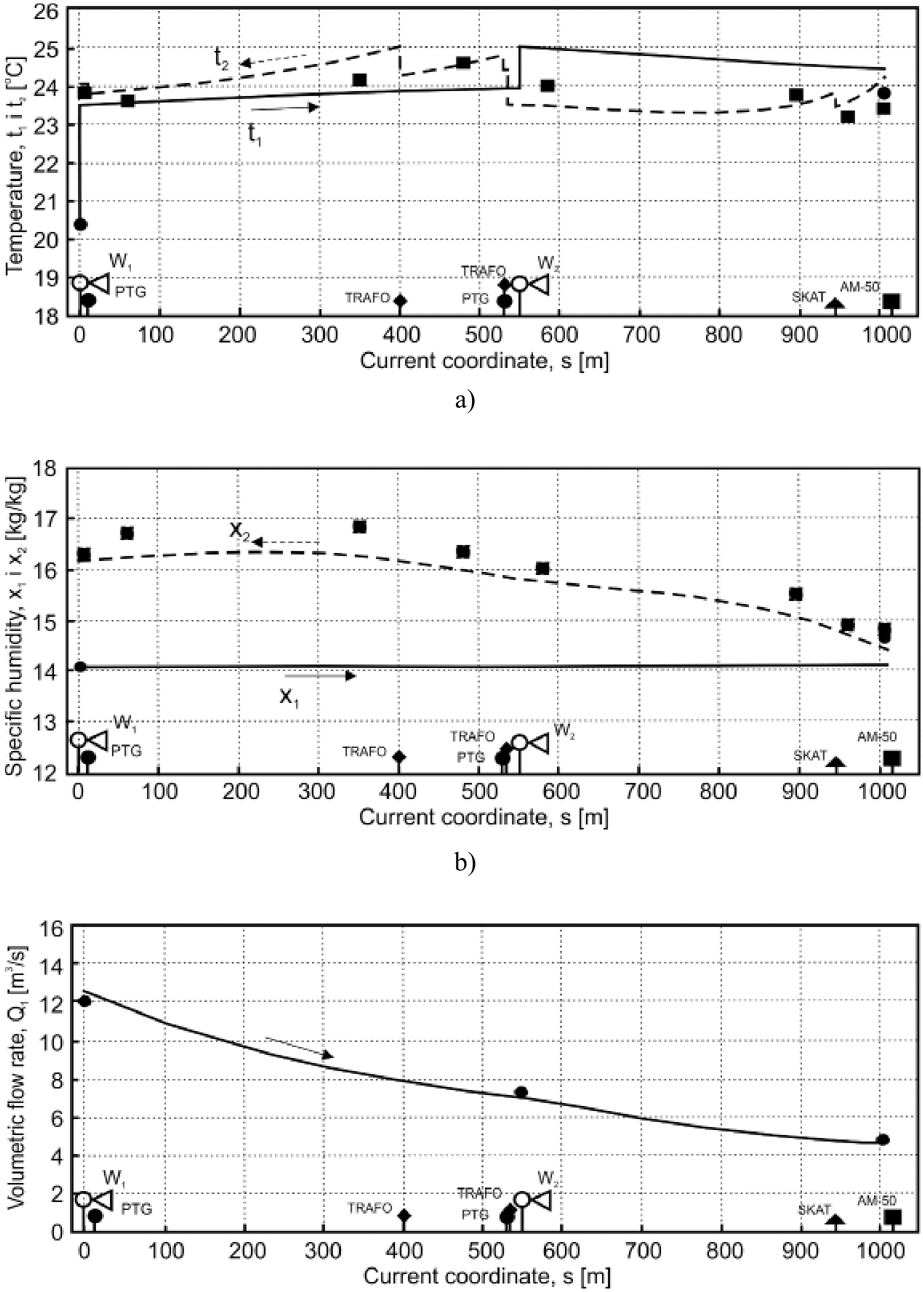
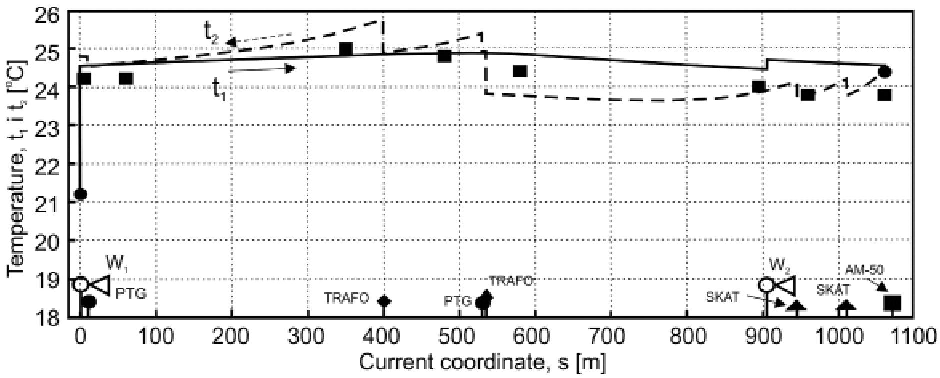


Fig. 10. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant III.5



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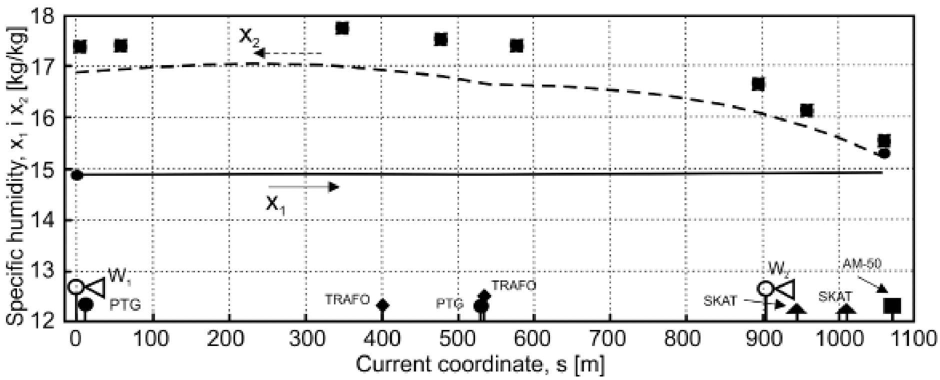

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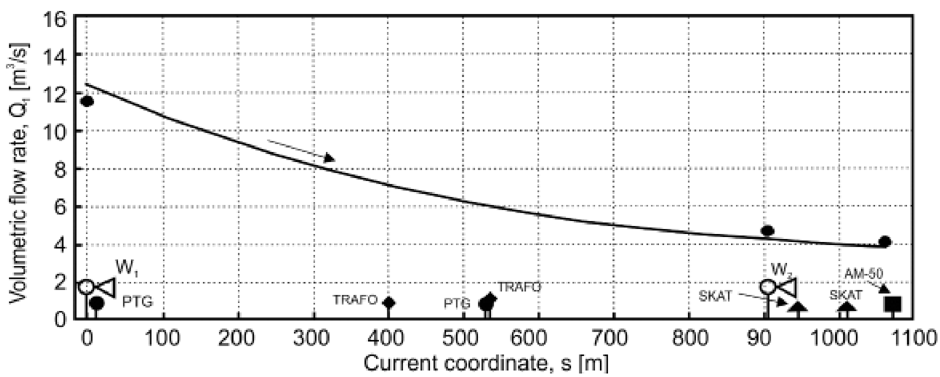
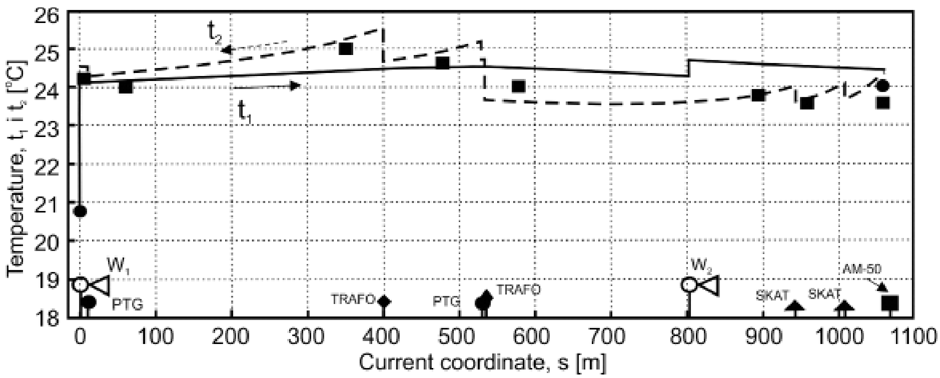


c)

Fig. 11. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant IV.1



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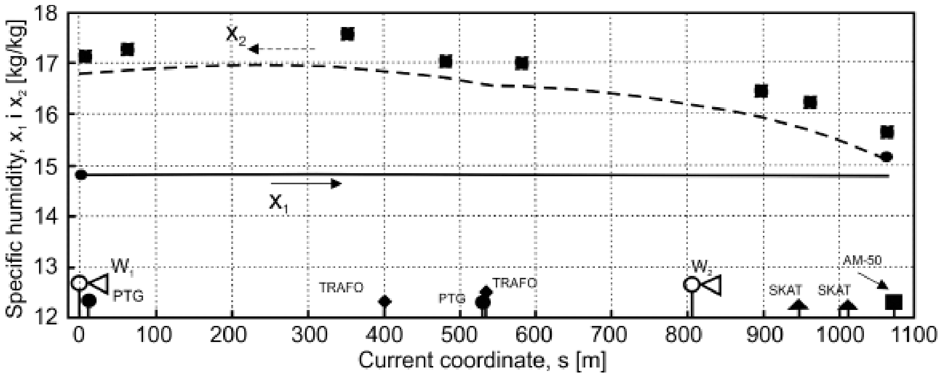

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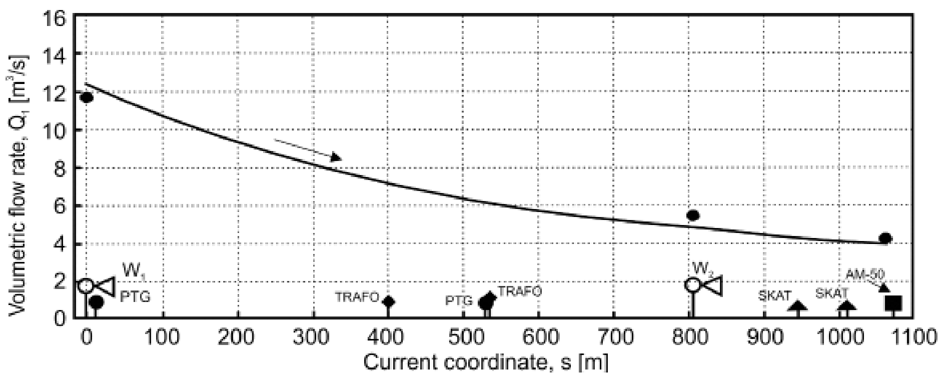


c)

Fig. 12. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant IV.2

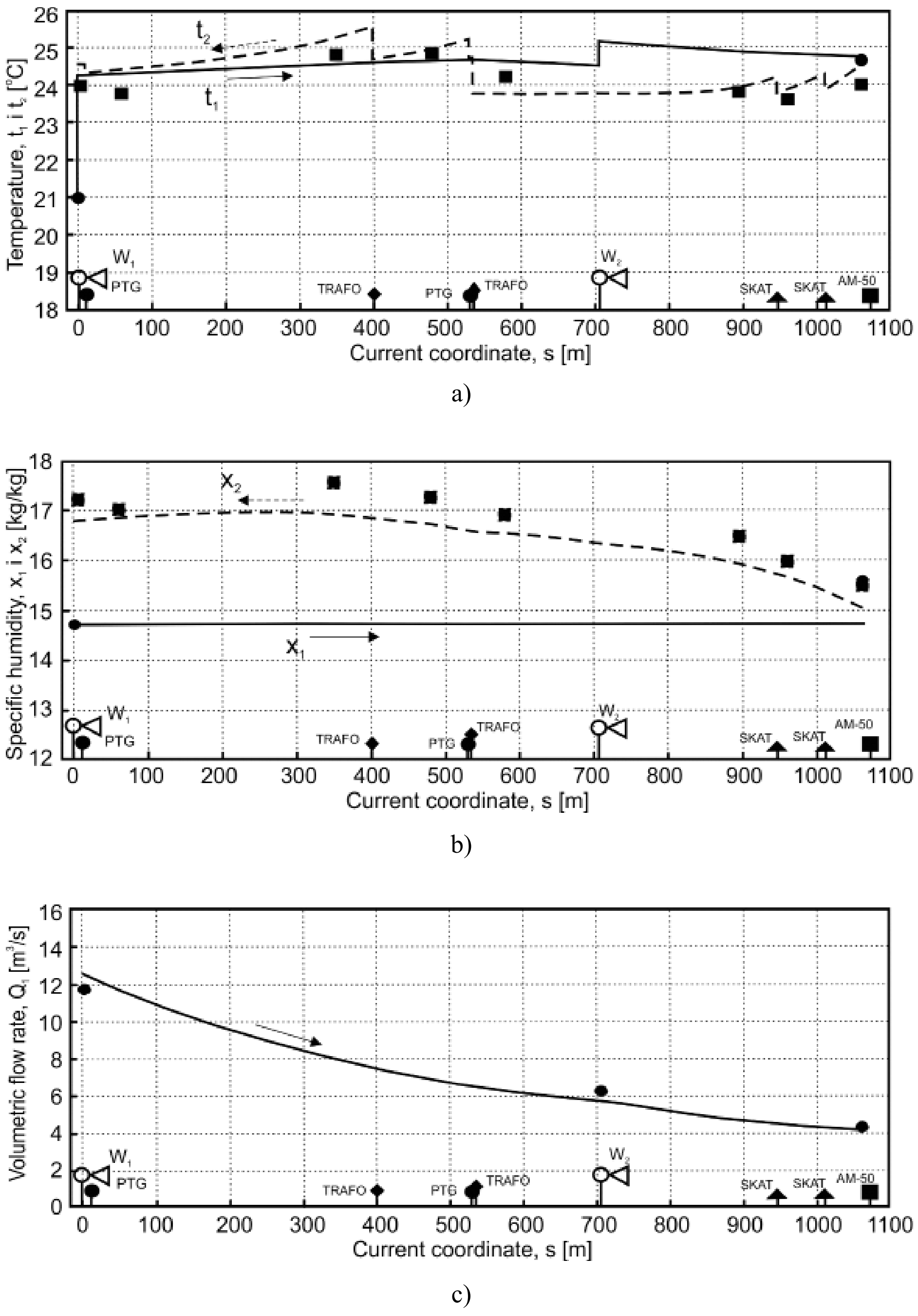
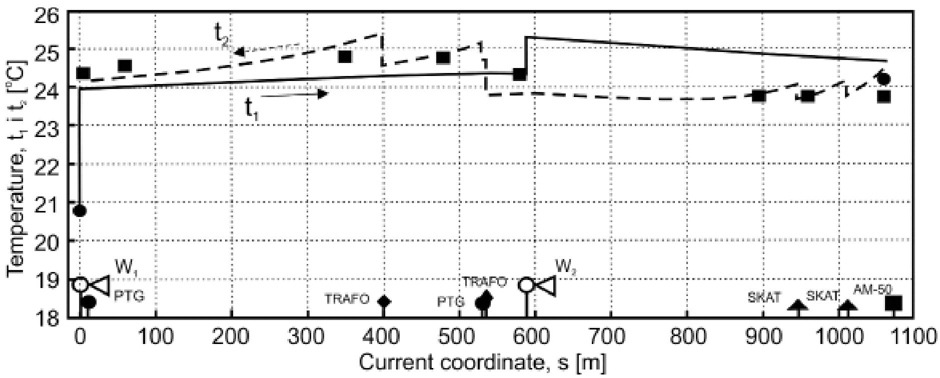
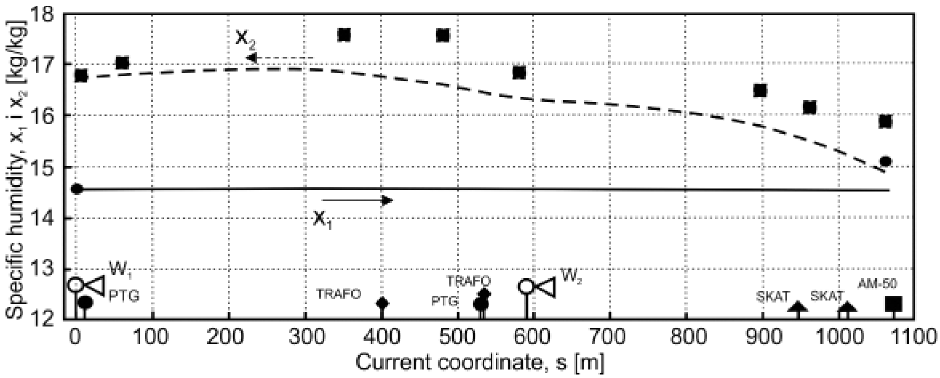


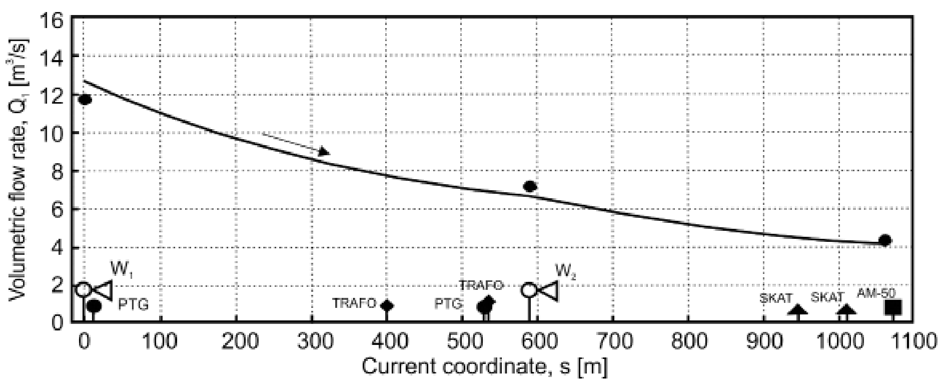
Fig. 13. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant IV.3



a)



b)



c)

Fig. 14. A comparison of the results of the temperature measurement (a), specific humidity of the air (b) in the heading and in the duct line, and the volumetric flow rate of the air (c) in the duct line with the results of numerical calculations for variant IV.4

TABLE 1

The air temperature – statistical analysis of deviations of the calculated values from the measured ones

Mea-surement variant	**Number of data** u	**Critical value of statistics** t_{kr}	**Maximum absolute deviation** $\lvert\Delta t\rvert_{max}$	**Maximum relative deviation** $(\delta t)_{max}$	**Mean absolute deviation** $\overline{\Delta t}$	**Standard error** $S_{\Delta t}$	**Calculated value of statistics** t	**Signi-ficance**
-	-	-	°C	%	°C	°C	-	-
I.1	7	2.447	0.79	–3.29	–0.149	0.403	–0.975	–
I.2			0.48	–1.98	–0.006	0.300	–0.050	–
II.1	8	2.365	0.49	–2.04	0.073	0.336	0.610	–
II.2			0.43	1.82	0.218	0.210	2.932	+
II.3			0.51	2.20	0.159	0.267	1.682	–
III.1	9	2.306	0.65	–2.71	0.090	0.386	0.700	–
III.2			0.59	–2.48	0.177	0.352	1.504	–
III.3			0.68	–2.86	0.119	0.376	0.949	–
III.4			0.89	3.84	0.374	0.390	2.879	+
III.5			0.76	3.25	0.211	0.427	1.482	–
IV.1	9	2.306	0.66	2.77	0.214	0.399	1.612	–
IV.2			0.73	3.09	0.263	0.312	2.535	+
IV.3			0.64	2.69	0.262	0.340	2.311	+
IV.4			0.72	3.03	0.118	0.387	0.913	–

TABLE 2

Specific humidity of the air – statistical analysis of deviations of the calculated values from the measured ones

Measu-rement variant	**Number of data** u	**Critical value of statistics** t_{kr}	**Maximum absolute de-viation** $\lvert\Delta x\rvert_{max}$	**Maximum relative de-viation** $(\delta x)_{max}$	**Mean absolute deviation** $\overline{\Delta x}$	**Standard error** $S_{\Delta x}$	**Calculated value of statistics** t	**Signi-ficance**
-	-	-	g/kg	%	g/kg	g/kg	-	-
I.1	7	2.447	0.78	–4.88	–0.354	0.258	–3.628	+
I.2			0.57	–3.83	–0.274	0.204	–3.551	+
II.1	8	2.365	0.67	–4.09	–0.348	0.224	–4.387	+
II.2			0.65	–4.29	–0.325	0.216	–4.262	+
II.3			0.83	–4.17	–0.480	0.219	–6.193	+
III.1	9	2.306	0.67	–3.96	–0.310	0.282	–3.297	+
III.2			0.64	–4.28	–0.258	0.266	–2.905	+
III.3			1.10	–6.45	–0.474	0.331	–4.299	+
III.4			0.90	–5.28	–0.250	0.324	–2.315	+
III.5			0.57	–3.62	–0.380	0.151	–7.562	+
IV.1	9	2.306	0.88	–4.37	–0.534	0.176	–9.124	+
IV.2			0.76	–3.76	–0.464	0.112	–12.420	+
IV.3			0.66	–5.15	–0.469	0.187	–7.512	+
IV.4			0.98	–5.57	–0.576	0.290	–5.963	+

TABLE 3

Volumetric air flow rate in the duct line – statistical analysis of deviations of the calculated values from the measured ones

Measurement point	Number of data u	Critical value of statistics t_{kr}	Maximum absolute deviation $\|\Delta Q_1\|_{max}$	Maximum relative deviation $(\delta Q_1)_{max}$	Mean absolute deviation $\overline{\Delta Q_1}$	Standard error $S_{\Delta Q_1}$	Calculated value of statistics t	Significance
-	-	-	**m³/s**	**%**	**m³/s**	**m³/s**	-	-
Inlet to W_1	14	2.160	0.91	7.81	0.595	0.219	10.166	+
Inlet to W_2	14	2.160	0.50	–9.17	–0.144	0.302	1.777	–
Outlet of the duct line	14	2.160	0.54	9.25	–0.0057	0.291	0.733	–

TABLE 4

Auxiliary fan rotational speed (W_2) – statistical analysis of deviations of the calculated values from the measured ones

Measurement point	Number of data u	Critical value of statistics t_{kr}	Maximum absolute deviation $\|\Delta n_d\|_{max}$	Maximum relative deviation $(\delta n_d)_{max}$	Mean absolute deviation $\overline{\Delta n_d}$	Standard error $S_{\Delta n_d}$	Calculated value of statistics t	Significance
-	-	-	**r/min**	**%**	**r/min**	**r/min**	-	-
Fan W_2	14	2.160	212	–10.08	–77.8	100.1	–2.909	+

The "+" sign in the last columns of the Tables 1÷4 denotes respectively the observed statistical significance of deviations of the air temperature, the specific humidity, the volumetric flow rate and the rotational speed of the auxiliary fan, and the "-" sign – no such significance.

Due to the lack of local sources of moisture, both in the duct line as well as in the heading, the calculated curves $x_1(s)$ and $x_2(s)$ – denoted by "b" in Figures 1÷14, do not have the discontinuities, characteristic of t_1 and t_2. Discontinuity occurs only at the face, which is caused by the adopted assumption that at the face all the sources, including moisture sources, are of a local character. On the curves $x_2(s)$, depicting distribution of specific humidity of the air in the heading, deflection points are visible, i.e. the discontinuity of the first derivatives, in the section of the location of the local sources of heat. This is particularly clearly seen where the efficiency of these sources is high. This can be explained by an increased evaporation of water in the heading and an increased inflow of water vapor from the rock mass in the event of a sudden increase in temperature (and hence in the saturation humidity) of the air. As it was expected, the waveform of the calculated relationship $x_1(s)$ is presented by a constant function. As to the measured values, some slight differences in specific humidity of the air at the beginning and end of the duct line can be observed. When the air flows through the face zone and the heading, the specific humidity increases, but the difference in the specific humidities calculated from the equations for the initial and final sections is about 1.5÷2 g/kg. Changes in the humidity of the air flowing through the heading do not always happen monotonically; in most cases, especially at larger heading lengths, the exhaust air at the end of its flow in the gallery 42[a] is subject to a partial secondary drying as a result of the mixing with the intensive supply of drier air flowing through the leaks in the duct line. At this point it is worth mentioning that all the values of specific humidity of the air obtained from the calculations were tested with a positive result in terms of their compliance with the premise of not reaching a dew point by the air.

Regarding the calculated volumetric flow rate of the air in the duct line – the curves denoted by "c" in Figures 1÷14 – deflection points can be seen in sections of the casings of the auxiliary fan. It should be mentioned that the flow curve before them falls more gently than behind them. The resulting curves apply to situations in which, by reducing the auxiliary fan rotational speed, the phenomenon of recirculation of the air between the heading and the inside of the duct line was eliminated.

The observed in most cases lack of significance of deviations (of the calculated values from the measured ones) for the air temperature (Table 1) proves that their main cause is a random dispersion of the measurement results. Small values of deviations (the largest of 0.89°C) and their statistical insignificance in ten out of fourteen cases, as well as small exceeding of the critical value of statistics t_{kr} by the absolute value of the calculated statistics t in the other four cases, are a proof of a good matching of the equations of the mathematical description to the real conditions.

With respect to the specific humidity of the air, it was found that for all the studied variants similar results were obtained - the deviation of the air specific humidity from the measured values, calculated from the equations of the mathematical model, are negative and statistically significant (Table 2). This effect is also visible in the "b" graphs in Figures 1÷14, where the results of the measurements in the heading and at the outlet of the duct line are located above the corresponding lines calculated from the equations. As an argument in favor of the mathematical description, the values of the relative deviations dx never exceeding 6.5% can be provided. It can therefore be concluded that such a clear significance of the air humidity deviations discussed here is more a result of a small dispersion of their values in each series than their large absolute values.

The results of the measurements and calculations of the air flow rate in the duct line in front of the auxiliary fan and at the outlet from the face zone are similar. At these points in the series regarding all variants, at the level of significance $\alpha = 0.05$, no statistical significance of deviations of the calculated values from the measured ones was determined – Table 3. These deviations should therefore be attributed to random factors. In contrast, before the inlet to the main fan, the deviations of these values which could not be explained by random causes were noted. These deviations, however small (relative maximum deviation did not exceed 7.9%), are statistically significant, due to their small dispersion in a series of fourteen values. It must therefore be assumed, that the calculation method somehow overestimates the fan efficiency. It seems that this can be attributed, among others, to rejecting additional local motion resistances in the equations, e.g. the arc of the duct line at the outlet of the heading, or the above-mentioned change in the duct line diameter, as well as omitting a short segment of the duct line located in the gallery with streamlined current. Despite the significance of the deviations of the air flow rate before the inlet to the main fan due to their small values, it can be concluded that the volumetric flow rate of the air in the duct line is sufficiently well described by the developed equations.

Deviations of the calculated rotational speeds of the auxiliary cooling fan, installed at the duct line route, from the measured ones, do not exceed 10% as a rule (in one case they were 10.1%). At the level of $\alpha = 0.05$, their statistical significance was noted. Their mean value of the fourteen tested variants is negative, which means that the actual rotational speeds of this fan are usually higher than those calculated ones. The values obtained from the measurements were considered actual here – a potential error introduced by the measuring instrument – frequency meter (and therefore rotations as well), installed in the housing of the inverter – was omitted. The effect of advantage of the measurement results over calculations can be seen especially clearly in the case of large heading lengths – L_2 = 1015 m and L_2 = 1070 m, while for smaller heading lengths L_2 = 725 m and L_2 = 840 m, the calculated values are greater than those obtained from the measurements. It is difficult to unambiguously state what the cause is. It seems that this may be due to systematic errors which were not taken into account. However, due to high compliance of the calculations and measurements of the most important, from the safety point of view, ventilation parameter, which is the volumetric flow rate of the air at the face, the maximum 10 per cent deviation of the auxiliary fan rotational speed is acceptable.

In conclusion it can be stated that the studied in this work and described in the works (Piątek, 2000; Piątek & Nowak, 2002), a mathematical description of the temperature and specific humidity of the air in the duct line and in the heading, as well as of the air flow rate in the duct line and the rotational speed of the auxiliary fan installed at the route of the duct line, sufficiently reflect the reality. This statement is based primarily on small deviations of the calculated values from the measured ones.

References

Greń J., 1976. *Statystyka matematyczna. Modele i zadania.* PWN. Warszawa.

Filek K., Nowak B., 1993. *Model matematyczny zmian temperatury i wilgotności chłodzonego powietrza w wyrobisku górniczym*. Arch. Min. Sci., Vol. 38, No 2, p. 147-157.

Nowak B., 1997. *Temperatura i wilgotność powietrza w wyrobiskach korytarzowych przewietrzanych nieszczelnymi lutniociągami*. Rozprawy, Monografie. Wydawnictwa AGH, z. 56. Kraków.

Nowak B., Sinha A., 1999. *Distribution of temperature and humidity of air in a dog heading gallery ventilated by forcing duct ventilation.* Arch. Min. Sci., Vol. 44, No 3, p. 321-335.

Nowak B., Życzkowski P., 2013. *The effect of temperature glide of R407C refrigerant on the power of evaporator in air refrigerators*. Arch. Min. Sci., Vol. 58, No 4, p. 1333-1346.

Piątek J., 2000. *Wpływ lokalizacji dodatkowego wentylatora zabudowanego w nieszczelnym tłoczącym lutniociągu na warunki klimatyczne w wyrobisku korytarzowym*. PhD disertation. Akademia Górniczo-Hutnicza w Krakowie. Unpublished.

Piątek J., Nowak B., 2002. *Parametry termodynamiczne powietrza w wyrobiskach korytarzowych przewietrzanych lutniociągiem tłoczącym z dodatkowym wentylatorem o zmienianej prędkości obrotowej.* Przegląd Górniczy, 1 (2002), s. 20-25.

Sinha A., 1996. *Variation of temperature and humidity of cooled air in mine dog heading galleries ventilated through leaky duct lines*. PhD disertation. Akademia Górniczo-Hutnicza w Krakowie. Unpublished.

Zapletal P., Prokop P., Košňovský V., 2012. *Evolution of microclimatic conditions in Paskov Mine.* Arch. Min. Sci., Vol. 57, No 4, p. 1045-1055.

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