ISSN 2712-8008
Volume / Том 24 №3 2024
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.4
Article / Статья

Validation of the Heat and Mass Transfer Model in the Atmosphere of a Horizontal Mine Working in the Presence of an Intense Heating Source

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Валидация модели тепломассопереноса в атмосфере горизонтальной горной выработки при наличии интенсивного источника нагрева

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Received / Получена: 01.02.2024. Accepted / Принята: 26.07.2024. Published / Опубликована: 30.08.2024

Keywords:
mine ventilation, exogenous fire, mine workings, laboratory experiment, model validation, turbulent flow, numerical modeling.

The paper describes a laboratory setup developed by the authors, which is a reduced physical model of a mine working and is intended to study the patterns of heat and mass transfer in horizontal and inclined mine workings in the presence of intense heating sources (exogenous fires). The parameters of the setup were substantiated based on scaling according to the Froude similarity criterion. The experimental measurements of the air flow parameters on the setup under the action of an intense heat source were used to validate the mathematical model of heat and mass transfer in a mine working. The mathematical model was based on the Reynolds-averaged continuity equations, Navier-Stokes, energy balance, and ideal gas state. The Realizable k-epsilon turbulence model was used to close the system of equations. The numerical implementation of the model was carried out in the Ansys Fluent software package using the finite volume method and the Simple algorithm for linking the velocity and pressure fields. A comparative analysis of the theoretical calculation results using the proposed model and the obtained laboratory experiment data showed acceptable agreement both at the qualitative and quantitative levels. In addition, the paper provides a comparative analysis of the heat and mass transfer calculation results in a mine working using the Realizable k-epsilon turbulence model with the calculations performed using two other turbulence models based on Reynolds averaging of air flow characteristics – SST k-omega and Reynolds stress model (RSM). It is shown that the Realizable k-epsilon and SST k-omega models are equally applicable for the theoretical analysis of heat and mass transfer processes in the laboratory setup under consideration, while the more complex RSM model has significant differences from the calculation data using the Realizable k-epsilon and SST k-omega models, as well as from the laboratory experiment data.

Ключевые слова:
рудничная вентиляция, экзогенный пожар, горная выработка, лабораторный эксперимент, валидация модели, турбулентное течение, численное моделирование.

Описан разработанный авторами лабораторный стенд, представляющий собой уменьшенную физическую модель горной выработки и предназначенный для исследования закономерностей тепломассопереноса в горизонтальных и наклонных горных выработках в условиях наличия интенсивных источников тепловыделения (экзогенных пожаров). Проведено обоснование параметров стенда, исходя из масштабирования по критерию подобия Фруда. Проведенные экспериментальные измерения параметров воздушного потока на стенде в условиях действия интенсивного источника тепловыделения использованы для валидации математической модели тепломассопереноса в горной выработке. Математическая модель основана на усредненных по Рейнольдсу уравнениях неразрывности, Навье – Стокса, баланса энергии, состояния идеального газа. Для замыкания системы уравнений использована модель турбулентности Realizable k-epsilon. Численная реализация модели осуществлялась в программном пакете Ansys Fluent с использованием метода конечных объемов, а также алгоритма Simple для связывания полей скорости и давления. Сравнительный анализ результатов теоретических расчетов на предложенной модели и полученных данных лабораторных экспериментов показал приемлемое соответствие как на качественном, так и на количественном уровнях. В дополнение к этому в работе проведен сравнительный анализ результатов расчета тепломассопереноса в горной выработке в рамках модели турбулентности Realizable k-epsilon модели с расчетами, выполненными в рамках двух других моделей турбулентности, основанных на усреднении характеристик воздушного потока по Рейнольдсу – SST k-omega и Reynolds stress model (RSM). Показано, что модели Realizable k-epsilon и SST k-omega в равной степени применимы для теоретического анализа процессов тепло- и массопереноса в рассматриваемом лабораторном стенде, в то время как более сложная модель RSM имеет значимые различия с данными расчетов на моделях Realizable k-epsilon и SST k-omega, а также с данными проведенного лабораторного эксперимента.

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Please cite this article in English as:
Levin L.Yu., Semin M.A., Popov M.D., Zhikharev S.Ya. Validation of the heat and mass transfer model in the atmosphere of a horizontal mine working in the presence of an intense heating source. *Perm Journal of Petroleum and Mining Engineering*, 2024, vol.24, no.3, pp.169-176. DOI: 10.15593/2712-8008/2024.3.8

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Валидация модели тепломассопереноса в атмосфере горизонтальной горной выработки при наличии интенсивного источника нагрева / Л.Ю. Левин, М.А. Семин, М.Д. Попов, С.Я. Жихарев // Недропользование. – 2024. – Т.24, №3. – С.169–176. DOI: 10.15593/2712-8008/2024.3.8

Introduction

In the modern world, where the mining industry plays a key role in meeting the energy and raw material needs of our country, the demand for of ensuring safety in mining operations are extremely important. At the same time, the solution of these problems is becoming a progressively difficult task due to the constant process of growth of transport conveyors and power lines, expansion in the number of mine engineering used in mining plants. All this, firstly, indicates an increase in the number of potential sources of underground fires, and secondly, leads to complication in ensuring stable ventilation of mine workings both in normal and emergency modes of operation of the ventilation system [1].

Underground fires in mine systems pose a serious threat to the safety of workers and infrastructure, as well as to the environment. According to [2], even if all reasonable precautions are taken, there are always at least a few plausible scenarios that could lead to a major underground fire in any mine or mine site. Therefore, important areas of research are not only minimising the risks of underground fires [3], but also the development of approaches and methods for localising and eliminating the consequences of fires [4].

Underground fires in shafts and mines are endogenous and exogenous. Endogenous fires occur as a result of spontaneous combustion of rocks [5–7], while exogenous fires are usually caused by malfunctions in electrical equipment, malfunctions in the operation of mechanical elements of ore transport systems (conveyors), non-compliance with safety rules when working underground, etc. [8, 9].

When developing new approaches and methods for localizing and extinguishing exogenous fires in mines, an important aspect is to understand the patterns of underground fire development, as well as their impact on the distribution of aerothermodynamic parameters of air flows in the network of mine workings. The identification of such regularities is carried out both with the use of experimental measurements of the parameters of air flows in the systems of mine workings in the presence of sources of heat emission [10–12] and with the help of modern methods of theoretical analysis. As the latter, both one-dimensional models of ventilation networks of underground mines [1, 13, 14], and three-dimensional models of aerothermodynamic processes in individual sections of ventilation networks are used [15, 16].

At present, the methodology for modeling underground fires is being actively worked out not only for shafts and mines, but also in relation to the problem of ventilation of subway tunnels and vehicles [17, 18]. At the same time, studies of the development of fires in tunnels have their own specifics and therefore do not consider in sufficient detail a number of issues whichh are relevant, first of all, for underground shafts and mines. These include the development of optimal evacuation routes for miners [19–21], the analysis of distributed heat sources in fires (conveyors) [22, 23], and the determination of fires in branched networks of workings based on indirect sensor readings [24, 25]. Another distinctive feature of shafts and mines is the release of combustible gases involved in the combustion process [26, 27]. In addition, correct accounting of the effect of return flows of combustion products in branched networks of mine workings is more difficult than for relatively simple ventilation networks of road and subway tunnels. Studies [13, 28, 29], in particular, are devoted to this issue.

At the same time, the regularities of the distribution of aerothermodynamic parameters of the air in the systems of mine workings have been studied relatively less than in road tunnels and subway tunnels. It was in relation to tunnels that the fundamental laws linking the so-called critical velocity of the air flow with the intensity of heat emissions from the ignition source were first determined. In [10], two modes of variation of the critical velocity are identified when the power of the heat source changes; It is shown that the critical velocity becomes a constant starting from a certain value of thermal power. In [11], the effect of the angle of inclination of the tunnel on the critical speed was investigated. The main result of this work is the conclusion that in the range of inclination angles up to 10°, it is possible to assume a linear dependence of the critical velocity on the angle of inclination. In [12], the influence of the tunnel cross-section on the critical velocity was investigated. It was obtained that in the formulas for the critical velocity, not the height, but the equivalent (hydraulic) diameter should be taken as the characteristic size of the tunnel. At the same time, the authors of the paper [30] came to the conclusion that the characteristic spatial dimension of an inclined tunnel with an ignition source should be taken as a more complex complex H^(3/2)/b^(1/2), which includes both the height H and the width b of the tunnel. The authors of the works [31, 32] studied the regularities of temperature changes at the tunnel roof, thereby clarifying the data of previous studies [30, 33].

In the modern studies of exogenous fires it is used a wide range of software products designed to calculate heat and mass transfer in the conditions of fire sources: MFIRE, Ventgraph, MineFIRE Pro+, VentFIRE™, Fire Dynamics Simulator, "Aeroset" [28, 34, 35]. The authors apply a wide range of possible models of turbulent heat and mass transfer in the air flow near the ignition source: LES [21, 36], k-epsilon [26], SST-k-omega [37], and others. Although the LES model is the more classical model for calculating the unsteady character of air flow in the vicinity of the flame front, simpler two-parameter turbulence models also find their application in solving engineering problems.

At the same time, the issue of applicability of relatively simple turbulence models based on Reynolds averaging of air flow characteristics to determine the regularities of convective stratification of air masses in fires in mine workings systems remains unresolved. The simplest model situation in this case is a fire in a single horizontal or inclined mine workings. The validity of such turbulence models should be checked either by comparison with the data of full-scale in-situ measurements or by comparison with the data of measurements in laboratory conditions on reduced physical models of mine workings systems. The latter approach is applied in the present study, the purpose of which is to validate the mathematical model of heat and mass transfer in turbulent air flow by comparing the calculated data with measurements on the stand developed by the authors, simulating a horizontal mine workings and a local fire source present in its middle.

Bench development

Within the framework of this study a laboratory bench was developed. It is a reduced model of mine workings and is designed for experimental study of convective stratification of air flows in horizontal and inclined workings near an intense source of heat generation. The schematic diagram of the bench is shown in Fig. 1. Photos of the assembled bench are given in Fig. 2. The laboratory bench is a steel duct, which almost throughout its entire length has a rectangular cross-section with dimensions equal to 300 × 500 mm. The exceptions are a small area near the heating source (in the central area of the stand), as well as a small area near the draft source (in the upper part of the stand), where the cross-section changes from a circular profile at the fan outlet to a rectangular profile of 300 × 500 mm.

The air movement in the duct is provided by a duct air conditioner with adjustable capacity. In this case, the average air flow velocity in the duct can vary in the range from 0.5 to 3 m/s. Also, the bench provides the possibility of changing the angle of inclination of the duct in the range from –15° to 15°, which roughly corresponds to the possible range of angles of inclination of real mine workings. In addition, this paper describes the results of experimental measurements and their comparison with model data only at an angle of 0°.

In the central part of the bench the heating source is installed. This is a duct electric heater with a maximum heat output of 22 kW. At the same time, the power of heat emission from the heating source allows step-by-step regulation with a minimum step equal to 2.4 kW. The cross-section of the duct also changes locally at the place of installation of the heating source which is stipulated by the design features of the heaters.

The bench has two ventilation windows, one of which is located in the upper part of the bench and the second one at the bottom. In the framework of the study described in this paper, the ventilation windows were hermetically sealed, and the duct had two aerodynamic connections with the external atmosphere – an inlet section in its upper part and an outlet section in its lower part.

The range of air flow velocities and heat release intensities on the bench were taken in such a way as to comply with the conditions of similarity of heat and mass transfer processes between the laboratory bench and real conditions in the mine. Scaling of velocity and heat flux was performed according to the method described in [10]:

$$\frac{V_{st}}{V_{sh}} = \left(\frac{L_{st}}{L_{sh}}\right)^{1/2}, \qquad (1)$$

$$\frac{W_{st}}{W_{sh}} = \left(\frac{L_{st}}{L_{sh}}\right)^{5/2}, \qquad (2)$$

where V – air flow velocity, m/s; W – heat power of the source, W; L – characteristic size of excavations, m; indices "st" and "sh" denote stand and mine conditions, respectively.

It is noteworthy that the key similarity criterion in problems with thermal convection in individual mine workings (and tunnels) is not the Reynolds number, but the Froude number, provided that the geometric similarity of the computational domain is satisfied. McCaffrey and Kintjer [38] showed that meeting the criterion on the Froude number results in equal corresponding temperatures between the scaled model and the full-scale system.

Nevertheless, in the present work, we also selected the bench parameters in such a way as to observe the range of Reynolds numbers at which the air flow in the duct occurs in the regime of developed turbulence (Re > 10 000).

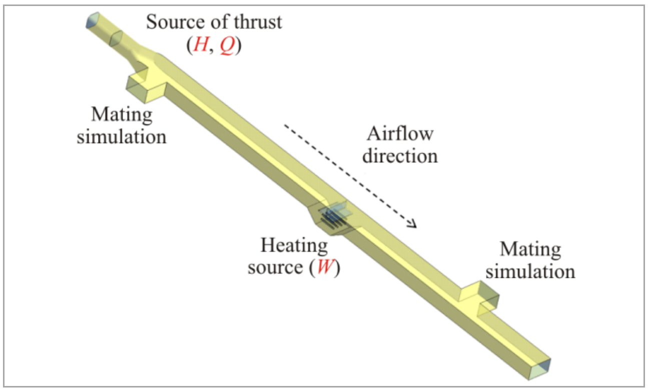

Fig. 1. Schematic diagram of the laboratory bench

Fig. 2. Photographs of the laboratory bench

For typical mine workings of coal mines and undercutting and pumping horizons of polymetallic mines of Krasnoyarsk region, the characteristic diameter of the cross-section varies in the range from 3.6 to 5.2 meters. Air velocity varies between 0 and 8 m/s (if we are not talking about the main ventilation drifts or shafts). Taking into account the characteristic cross diameter of the laboratory ducting (L_{st} = 0.375 m) the air flow velocity in the laboratory duct should vary in the range from 0 to 2.56 m/s. In this case, the mode of developed turbulence in the duct will be provided at a flow velocity of more than 0.4 m/s.

The characteristic power of heat emission from local sources of ignition in mine workings depends significantly on time [39]. The equivalent value of heat emissions from the ignition of various mining equipment (loading and delivery machines, drilling rigs, dump trucks) reaches 8 MW. The equivalent value of heat losses from the ignition of extended heat sources (e.g., conveyor belts) is slightly higher [2, 40], but they are not the subject of this study. For this reason, taking into account formula (2), it is sufficient to reproduce in the laboratory bench the thermal power of the heating source equal to 30.8 kW, and this value corresponds to the smallest characteristic diameter of the mine workings (3.6 m).

This value is slightly higher than the maximum thermal power currently achievable in laboratory conditions (22 kW). This indicates that the developed laboratory bench is applicable primarily to analyze the regularities of heat and mass transfer processes in the excavations of underground horizons with a typical cross-sectional diameter of more than 4 m.

Nevertheless, in our opinion, it can also be useful in the analysis of air exchange in mine workings of smaller cross-section, for which the stand will allow to catch the main regularities of heat and mass transfer processes at a qualitative level.

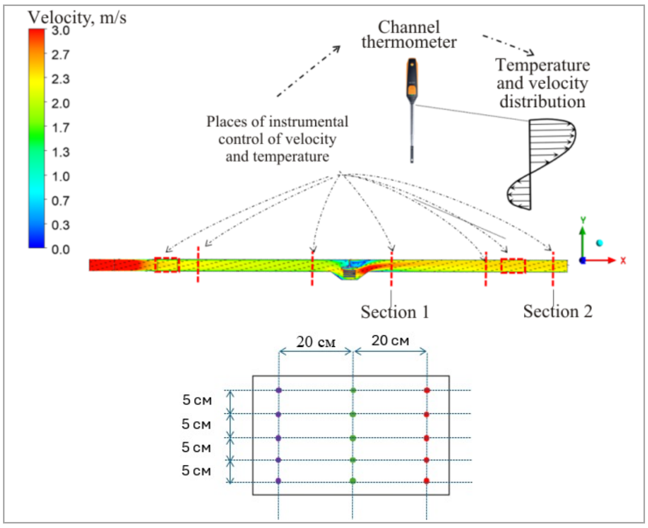

Fig. 3. Places of instrumental control

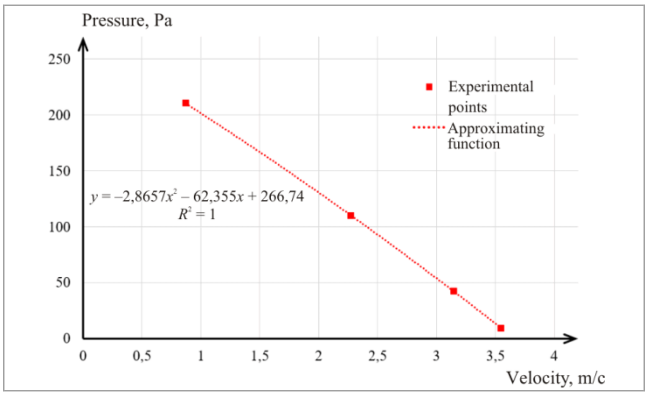

Fig. 4. Determination of the actual characteristic of fan on the Aerodynamic Stand

Mathematical model and its validation

Experimental studies on the laboratory bench were used to validate the mathematical model of air flow in the duct. This model in the future after validation will allow to determine the conditions of return air currents in a wide range of air flow parameters in horizontal and inclined mine workings, geometric parameters of these mine workings, parameters of the heating source.

The mathematical model was based on the equations of continuity, Navier-Stokes, energy balance, and the equation of ideal gas state. Due to the turbulent nature of air flow in the duct, the Reynolds averaging operation was applied to the above equations, and the Boussinesq hypothesis and the two-parameter Realizable k-epsilon turbulence model were used to close the obtained averaged equations. This turbulence model was taken as the main model for numerical calculations, but in addition to it, at the stage of model tuning, calculations on the SST k-omega and Reynolds stress model (RSM) were also performed.

The boundary condition of pressure inlet type was set at the inlet of the design area, and the boundary condition of pressure outlet type was set at the outlet. The presence of a thrust source was specified by means of an internal surface of the "interface" type with a specified pressure drop depending on the flow rate. On both boundaries zero pressure was assumed. On solid walls, the flow adhesion condition was assumed, and standard near-wall functions were used to calculate the flow parameters in the thin boundary layer. The average roughness height of the duct walls was assumed to be 0.8 mm. A uniform heat flux of a given thermal power W was set on the surface of the heating source.

An irregular tetrahedral finite-volume mesh with a prismatic boundary layer near the hard walls was constructed. The mesh parameters were selected in such a way as to ensure the independence of the solution from the mesh. The size of the tetrahedron cell closest to the wall of the air duct was assumed to be 30 mm.

On the surface of the heating source, the size of the nearest cell-tetrahedron was set to 4 mm. The total number of cells was 1,586,296.

Based on preliminary modeling of heat and mass transfer processes in the air duct, the most suitable places for instrumental measurements on the laboratory bench were determined (Fig. 3). Within the framework of this study, when validating the model according to laboratory data the focus was on cross-sections 1 and 2 located further downstream relative to the heating source.

An important aspect necessary for the correct model reproduction of air flows in the laboratory bench is to take into account the actual aerodynamic characteristics of the fan that provides air movement in the experimental stand. In order to determine the characteristics of the fan, a series of full-scale measurements of the air flow velocity and pressure drop on the bench were performed. The difference was determined using a differential pressure gauge as the difference in pressure immediately after the fan and the pressure near the outlet section of the air duct.

Measurements of the air flow velocity were carried out in the section near the outlet of the air duct in three vertical profiles, with a vertical measurement step of 5 cm. The distance between the vertical profiles was 20 cm. 3. For the obtained velocity fields at the measured points, the average air flow velocity in the cross-section at the outlet of the duct system was recalculated.

Four modes of ventilation of the air duct were subject to measurement – at different parameters of the air valve located near the outlet from the air duct. During the measurement, the rotation speed of the installed axial fan was recorded and the degree of closure of the air valve was changed. Variation in the degree of closure of the air valve made it possible to change the aerodynamic drag of the system and thereby obtain different points on the characteristics of the fan.

Based on the results of measurements the points were approximated by a second-degree polynomial dependence of the form P = aV2 + bV + c. The obtained dependence P(V) is presented in Fig. 4. Separate points show experimental measurements on the laboratory bench.

Another important aspect in the initial parameterization of the model is the choice of the heat transfer coefficient through the duct wall. Part of the heat imparted to the flow from the heating source is dissipated through the walls of the air duct into the surrounding atmosphere. Moreover, this thermal factor is more pronounced for the section of the air duct below the heating source. Therefore, in order to take into account this thermal factor, the heat transfer coefficient was selected in such a way as to achieve the best correspondence in terms of the model and measured values of the average air temperatures in sections 1 and 2. The effective value of the heat transfer coefficient was 150 W/(m²•°C).

Validation of the three-dimensional numerical model was performed by comparing the velocity and temperature epuries calculated on the model with the

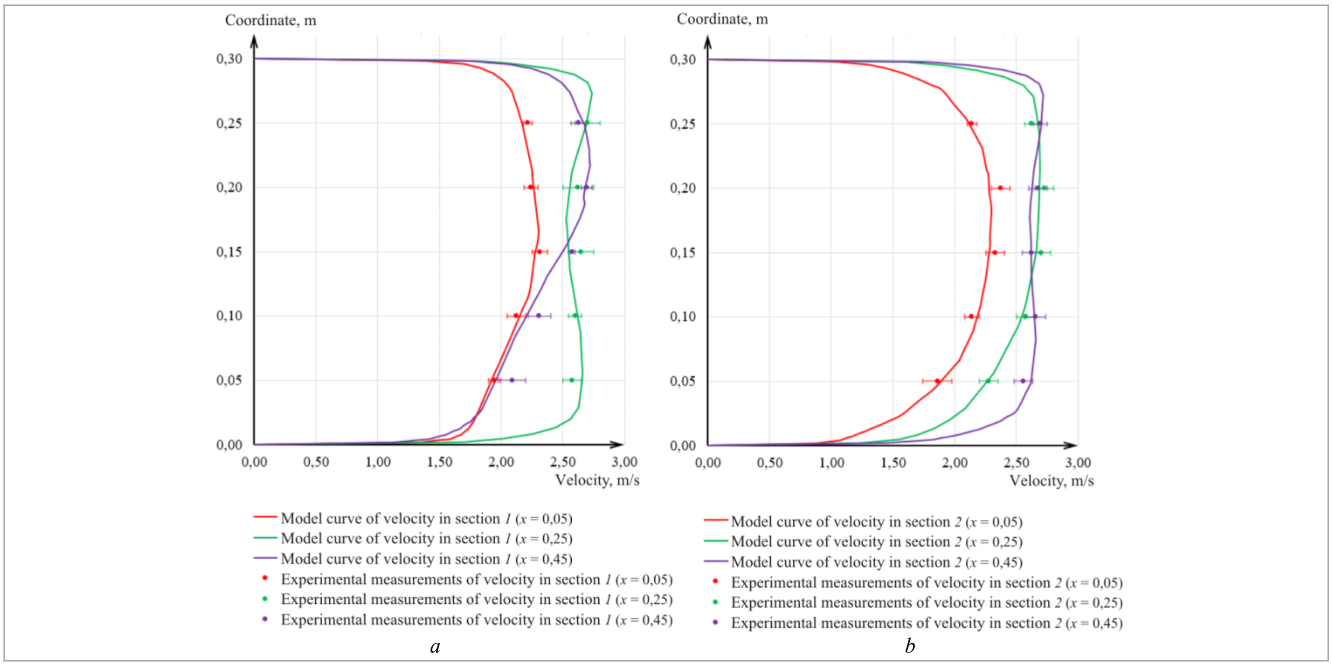

Fig. 5. Comparative analysis of theoretical and experimentally measured values of the longitudinal component of air flow velocity in sections 1 (*a*) and 2 (*b*)

points obtained in field measurements in cross sections 1 and 2 shown in Fig. 3. Fig. 5 shows the theoretical curves and experimental points for the longitudinal component of the airflow velocity, while Fig. 6 shows the theoretical curves and experimental points for the airflow temperature. The situation of source heat power equal to 14.5 kW, duct angle equal to 0° is considered. Taking into account that at intensive heating of the air flow the measured values varied in time (i.e., the distribution of aerothermodynamic characteristics of the air flow was non-stationary), in Figs. 5, 6, in addition to the mean values of the measured airflow velocity and temperature, the minimum and maximum observed data values for a sample of measurement data at individual points were also plotted using the elements of the so-called tendril diagrams.

Comparison of velocity and temperature distributions of the air flow was also carried out at other values of the heat release rate, but the data were not included in this article. In general, the data obtained allow us to judge the good correspondence between numerical modeling and the laboratory experiment at the considered angle of inclination of the air duct. For individual experimental points, insignificant quantitative discrepancies with the numerical simulation data are observed, but in general, at the qualitative level, model curves and experimental points demonstrate the same nature of changes in the velocities and temperatures of the air flow along the cross-section.

In both considered cross-sections, there is also a good correspondence between model and experimental data in terms of average velocity and temperature values. This is largely ensured by the pre-calibration of the mathematical model, while the similar nature of the deviations of the studied flow parameters from the corresponding average values already shows the correct operation of the selected mathematical model.

At the same time, a comparative analysis of different turbulence models has also been carried out in this study: the main Realizable k-epsilon model and two other RANS models, SST k-omega and RSM. The calculated airflow velocity and temperature curves in cross sections 1 and 2 at the three different turbulence models are presented in Fig. 7. The curves are shown only for the central vertical profiles (see Fig. 3, green color) as the most representative ones.

The Realizable k-epsilon and SST *k*-omega models give rather close results to each other both in terms of air velocity (maximum mismatch 0.1 m/s) and temperature (maximum mismatch 2.3 °C). While the RSM model under certain conditions shows a more pronounced differentiation of temperatures by cross-sectional height, and the maximum difference with the model of Realizable *k*-epsilon by temperatures is equal to 8.4 °C. This discrepancy is already quite significant and amounts to more than 25 % of the characteristic temperature difference in the problem. At the same time, the RSM model also has significant discrepancies with the laboratory experiment data both quantitatively and qualitatively.

Conclusion

The developed and assembled laboratory bench is described, presenting a reduced physical model of mine workings with a variable angle of inclination and is designed to study the regularities of heat and mass transfer in horizontal and inclined mine workings in the presence of intensive sources of heat generation.

The series of experimental changes of air flow velocity and temperature carried out on the bench was used to validate the mathematical model of heat and mass transfer in the channel in a three-dimensional formulation using the Realizable k-epsilon turbulence model. Results of comparative analysis data of numerical modeling and laboratory experiments showed an acceptable correspondence at both qualitative and quantitative levels.

A comparative analysis of the results of heat and mass transfer calculation in an inclined channel using three different turbulence models has been carried out. It is shown that the Realizable *k*-epsilon and SST *k*-omega models are equally applicable for the theoretical analysis of heat and mass transfer processes in the considered laboratory bench, while the more complex RSM model has significant differences with the calculation data on the Realizable *k*-epsilon and SST *k*-omega models, as well as with the experimental data.

In the future, it is planned to carry out a comparative analysis of the data of experimental measurements and mathematical modeling at different angles of duct inclination.

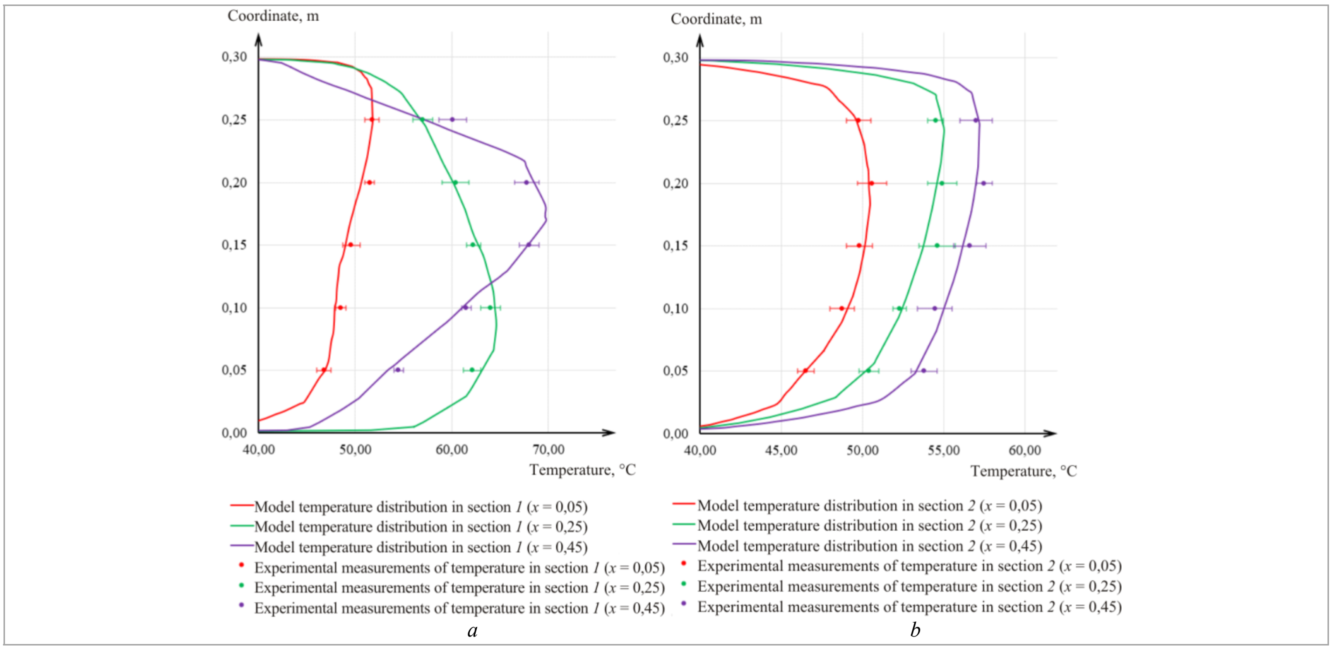

Fig. 6. Comparative analysis of theoretical and experimentally measured values of air flow temperature in sections 1 (*a*) and 2 (*b*)

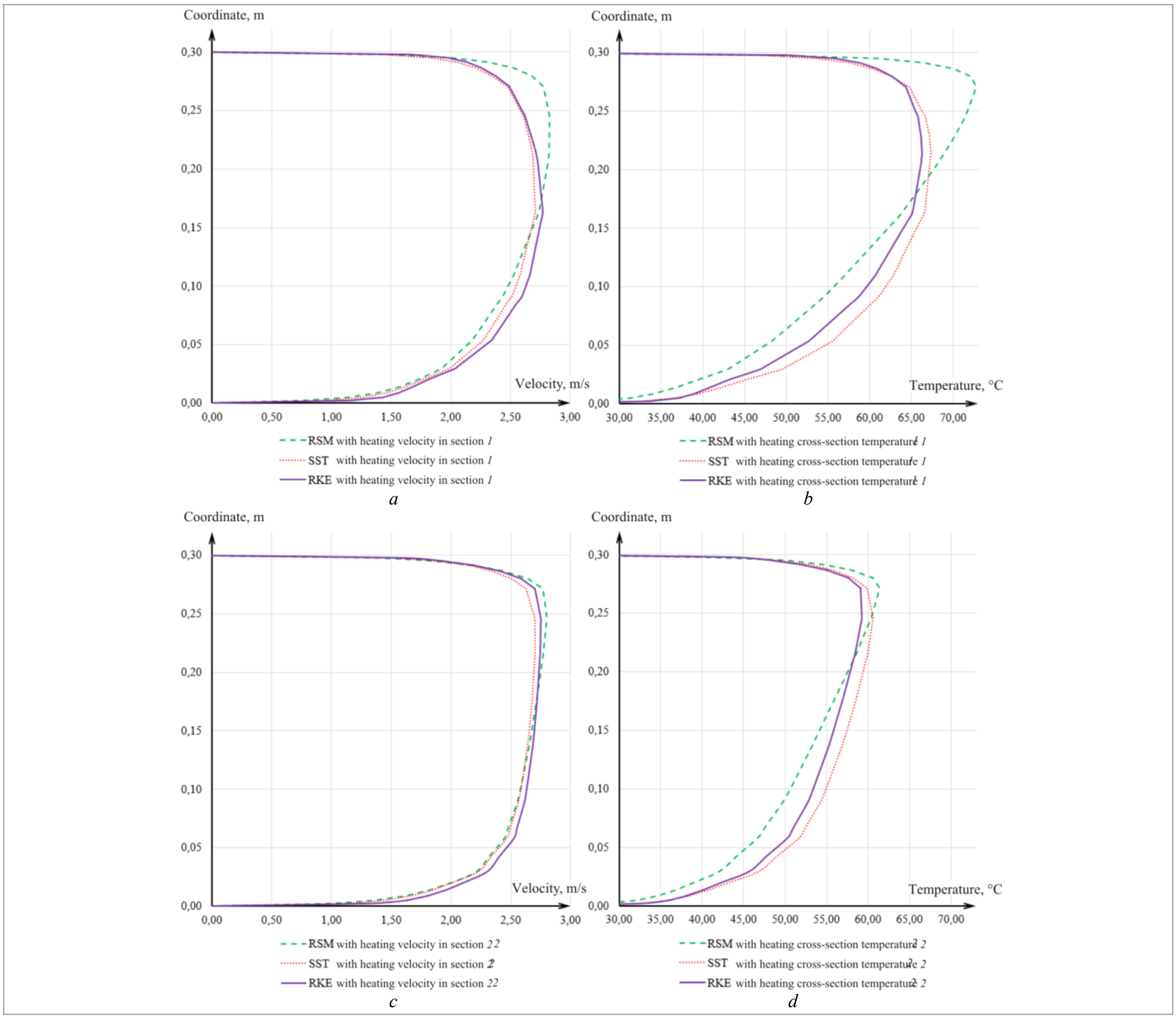

Fig. 7. Comparative analysis of theoretical epiphures of the longitudinal component of velocity and temperature of the air flow in sections 1 (*a, b*) and 2 (*c, d*) for different turbulence models

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Funding. The research was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation within the framework of the state assignment (reg. numbers of R&D: 124020500030-7, 122030100425-6).

Conflict of interest. The authors declare no conflict of interest.

The authors' contribution is equal.