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EFFECT OF GEODYNAMIC SETTING ON SPONTANEOUS COMBUSTION OF COAL WASTE DUMPS

The article considers the hypothesis according to which one of the influences on spontaneous combustion of a coal waste dump is its geodynamic setting. Statistical data show that coal waste dumps located in geodynamically hazardous zones, i.e. at the interfaces of the Earth's crust blocks, suffer from self-ignition more often than dumps set beyond the limits of such zones. The computer modeling of situation at a coal waste dump in the East Donbass reveals a cause-and-effect chain capable to explain this phenomenon. Air permeates into the dump from closely spaced underground mines through the geodynamically hazardous zones as the most permeable areas in rock mass. At fire-hazardous air flow velocity and temperature increment in the dump, its spontaneous combustion takes place. The gas mass transfer process intensifies and promotes further growth of the fire source. The modeling results can be used in coal waste dump planning and monitoring, as well as in combating spontaneous combustions.

Keywords: *coal waste dump, spontaneous combustion, geodynamic zoning, Earth's crust blocks, geodynamically hazardous zone, permeability, porosity, modeling, boundary conditions, higher temperature source, air permeation.*
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Introduction

Spontaneous combustion of coal waste dumps remains a topical problem in many coal-producing countries for a long time [1–5]. Despite preventive control, spontaneous combustions are repeatedly observed after fire suppression in dumps. Researches disclose complexity and multi-factorial nature of this problem, which makes its final solution difficult [6, 7]. At the same time, the common inference says the main promoter of spontaneous combustion is breafing of dumps.

The hypothesis on spontaneous combustion of dumps to be favored by their location in geodynamically hazardous zones (GHZ) was put forward in [8, 9]. Some of such zones represent interfaces of the Earth's crust blocks participating in the modern tectonics. The geodynamically hazardous zones are named so because they make room for mining-induced phenomena—rock bursts, anomalous underground and surface strains, or accidents at engineering structures [10]. The geological interpretation shows that it is often that GHZ are linear zones with increased fracturing and discontinuity, i.e. highly permeable zones. When a dump is located in such zone, air can flow inside the dump through these highly fractured and permeable zones. Considering GHZ as the interfaces of the tectonically active crustal blocks suggests that deformations in such zones can affect engineering structures of ground surface, in particular, contribute to air ingress to dumps from underground mines.

This study deals with computer modeling of mass transfer of gases through GHZ to a local dump. The true of such process is backed by numerous facts of subsoil drainage through fault zones [11] or in subsidence troughs, especially during mine flooding [7, 12]; moreover, the adequate modeling results are available [13].

Geodynamic zoning

Mining practice ascertained the fact of zonal nature of geodynamic phenomena in the 20th century. The related idea of anticipating detection of geodynamically hazardous zone gave birth to the concept and method of geodynamic zoning, which were presented in [10] and then evolved by the authors later on. The concept is based on the interaction of global and local geodynamic processes in the Earth's crust. Large crustal blocks participating in the modern tectonics are composed of lower hierarchical scale blocks which consist of even smaller blocks, etc. In this fashion, it is possible to come up gradually to the block structure of mine fields. Being tectonically active, the blocks and their interfaces are reflected in the modern topographical relief, which allows finding and identifying them. Some interfaces of the modern tectonic blocks in the Earth's crust repeat (i.e. go along) large faults in the subsoil, or the block interfaces can be represented by linear zones of higher faulting and fracturing.

When formulating the problem and performing research in a coal-producing region of Russia, the present authors relied upon that concept of geodynamic zoning. In 2015 the East Donbass (Rostov Region) held 202 coal waste dumps, including 33 dumps in burn. In the region, geodynamic zoning was carried out, and the location of the burning coal waste dumps relative to the interfaces of the crustal blocks was analyzed [8]. The interfaces of the crustal blocks were identified afield, and their width was estimated from the formula [14]

$$B = 10N, \quad (1)$$

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where N is the amplitude of reciprocal displacement of neighbor blocks on the same scale.

Formula (1) is obtained from the practical experience of studying fractured zones nearby faults, and, on the whole, correlates with similar estimates of widths of the influence zones of faults [15–17].

It is found that the total area of GHZ makes 10% of the territory under study while it accommodates 40% of the burning dumps, i.e., the concentration of the burning dumps in these zones is several times higher than the average value inside this entire territory. Such statistical distribution of burning dumps is assumed by the present authors as a proof of the hypothesis on adjacency of burning dumps and GHZ and dictates modeling of gas flow through a geodynamically hazardous zone into a dump body.

Computer model

3.1 Geometrical model. Modeling of air flow nearby dumps is described in [12, 13]. The present study uses the model of a dump located above the permeable rock mass zone intersecting actual mining area.

The computations used ANSYS products. The computational fluid dynamics (CFD) is commonly involved in problems connected with mass transfer in tunnels and mined-out areas in coal and ore mines [18–20].

This study considers three situations with individual geometrical models at a scale of 1:1. The models are used to study gas mass transfer in subsurface and include a rock mass with a geodynamically hazardous zone, a ground surface site, a dump and air. The modeling situations are:

1 — air ingress in the dump from the side of the terrain ledge through GHZ under the action of wind;

2 — air ingress in the dump from mine workings through GHZ intersecting the mining area;

3 — change in air flow velocity in the dump under varying temperature of a heat source in it.

Situation 1 models the process when the source of oxygen required for coal oxidation is air flow toward a terrain ledge 20 m high. The ledge is cut by GHZ through which air permeates into the dump (**Fig. 1**).

Situation 2 assumes the dump is located in GHZ intersecting mined-out stopes. The situation was analyzed using geometrical models in **Figs. 2** and **3**. The width of GHZ was smaller than the width of the dump (**Fig. 2**).

In situation 3 mass transfer was analyzed in the dump with a higher temperature source in it. The model (**Fig. 3**) imaged the dump of Nesvetaevskaya mine, at the interface of blocks belonging to rank III (by classification from [10])—at the Nesvetaevsky Fault (GHZ).

Initial and boundary conditions. Setting of the initial and boundary conditions is explained in **Fig. 2b**. The domain 'Atmosphere' has the boundary conditions as follows: surface 1 — air flow velocity is 10 m/s; surfaces 2–5 — pressure 0 Pa. In the domain 'Geodynamically hazardous zone', the input parameter is set at surface 1 (supposed connection between the mine and geodynamically active zone). The excessive pressure generated by a mine fan is 1000 Pa.

Figure 2b shows the anticipated ways of air flow into the dump:

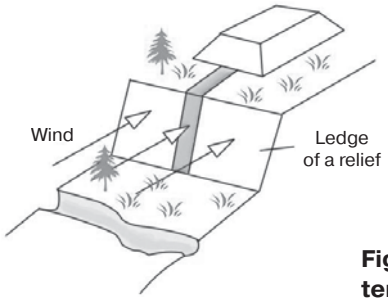

Fig. 1. Air flow toward terrain ledge

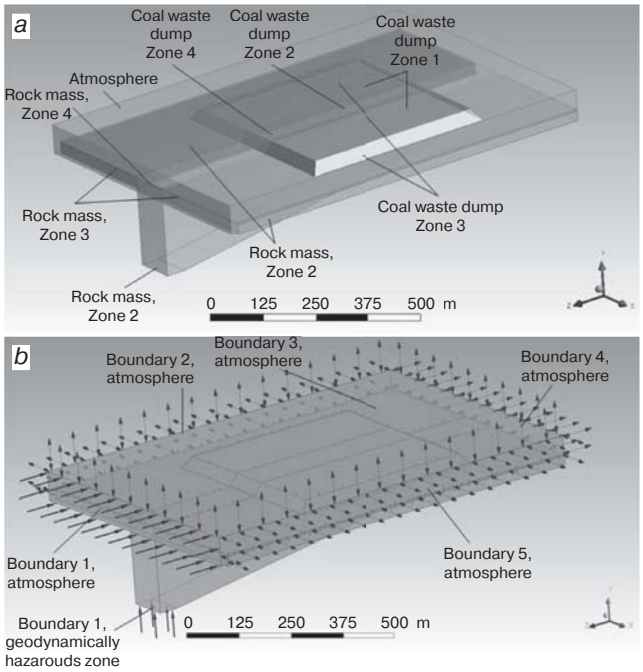

Fig. 2. Geometrical model of dump located in GHZ (*a*); initial and boundary conditions for situation 1 (*b*)

1. Under the action of the wind pressure in the sites of GHZ outcrops;
2. Under the action of the excessive pressure generated by the main mine fans from the mine along the permeable zone GHZ (hypothesis on aerodynamic coupling between the dump and mining area).

In situation 3 (variation in air flow velocity depending on temperature), a surface with preset temperature was assigned in the dump (**Fig. 3c**). The surface temperatures were varied in the modeling as 100, 200 and 400 °C.

Such problem formulation is governed by the increasing velocity of air flow in the dump zone with higher temperature. Consequently, oxygen influx grows, which intensifies heating of the dump. The cycle of the dump temperature increase extends, and the air flow acceleration (oxygen influx) can result in the initiation and development of fire.

Porosity and permeability of rocks in different zones under and inside the dump are compiled in the **table** based on the data from special references [15, 20, 21].

Results and discussion

Modeling of air permeation into the dump from the terrain ledge through GHZ. Modeling of situation 1

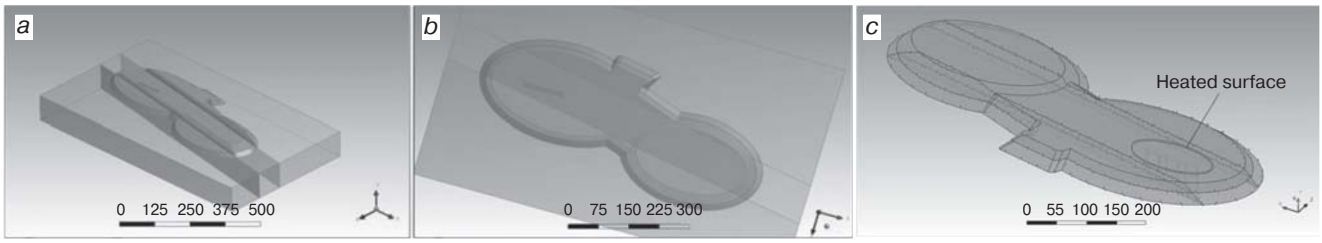

Fig. 3. Geometrical model of dump at the Nesvetaevsky Fault:
(*a*) isometry; (*b*) top view; (*c*) increased temperature surface in the dump of Nesvetaevskaya mine

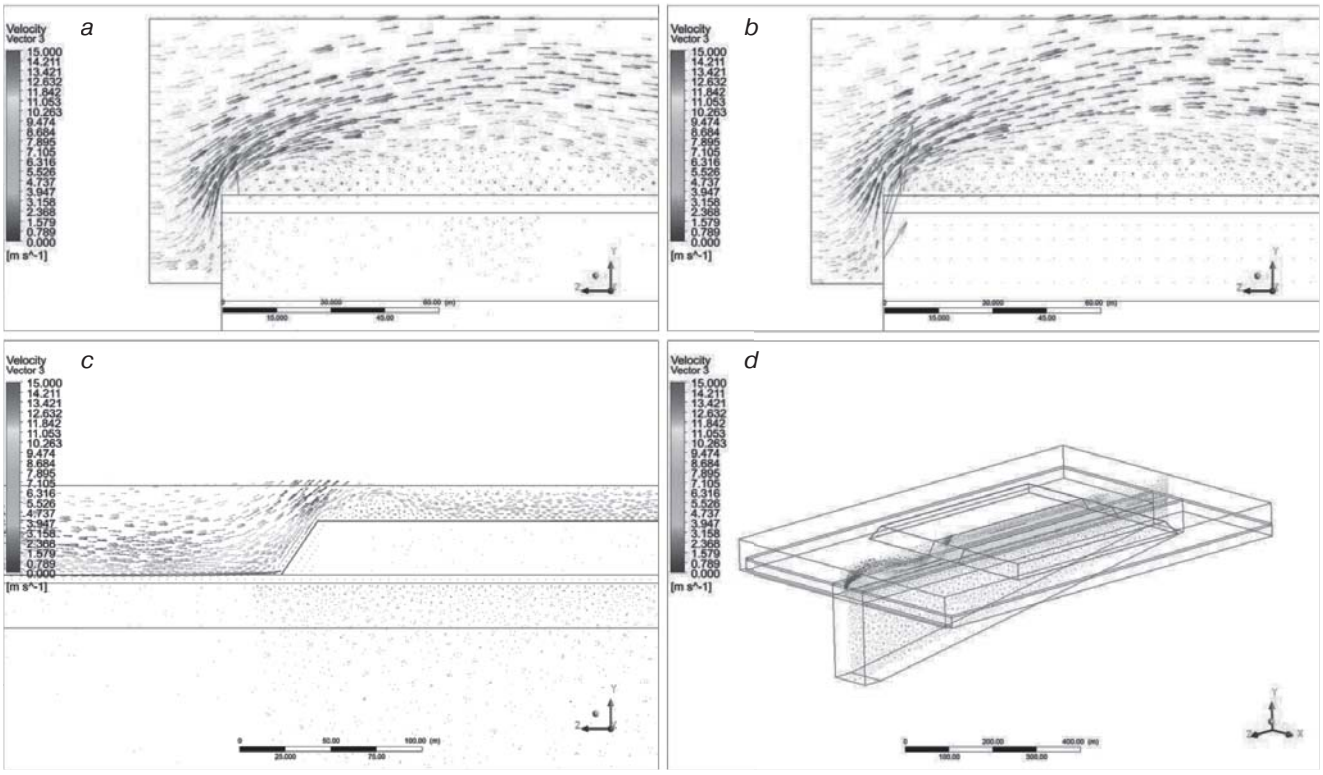

Fig. 4. Modeling of air flow nearby dump (air flow vectors and velocities are shown):
(*a*) in the cross section through GHZ (shelf is drawn nearer); (*b*) in the atmosphere and in rock mass (shelf is drawn nearer); (*c*) in the atmosphere and in the dump (elevation view, dump is drawn nearer, from the air inflow side); (*d*) general view

Porosity and permeability in different zones of rock mass and dump (in accordance with Fig. 2a)

Zone	Porosity, %	Permeability, m^2	References	Note
Rock mass zone 3	16	1e-15	[15]	Top layer
Rock mass zone 4	20	1e-14	[15, pp. 101, 105]	Top layer above GHZ
Coal waste dump zone 1	35	1e-9	[21]	Dump body
Coal waste dump zone 2	35	1e-8	[21]	Dump body above GHZ
Rock mass zone 1	15	1e-14	[15, 20, 21]	
Rock mass zone 2	25	1e-8	[15, 20, 21]	Rock mass in GHZ
Coal waste dump zone 3	16	1e-15	[15, 20, 21]	Top layer above the body of the dump
Coal waste dump zone 4	20	1e-14	[15, 20, 21]	Top layer above the dump body above GHZ

shows that air flow to the terrain ledge permeates through the rock mass (**Fig. 4**). The permeation depth depends on the porosity and permeability of rocks. At the preset initial and boundary conditions, the permeation depth of air through GHZ, where the porosity and permeability are higher, made a few meters (**Fig. 4a**). **Figure 4b** shows the air flow through the terrain shelf into the dump: permeation is minimal, to a few millimeters. **Figures 4c** and **4d** offer the modeling results of air flow to the dump. Due to the low porosity and permeability of the top cover, air fails to

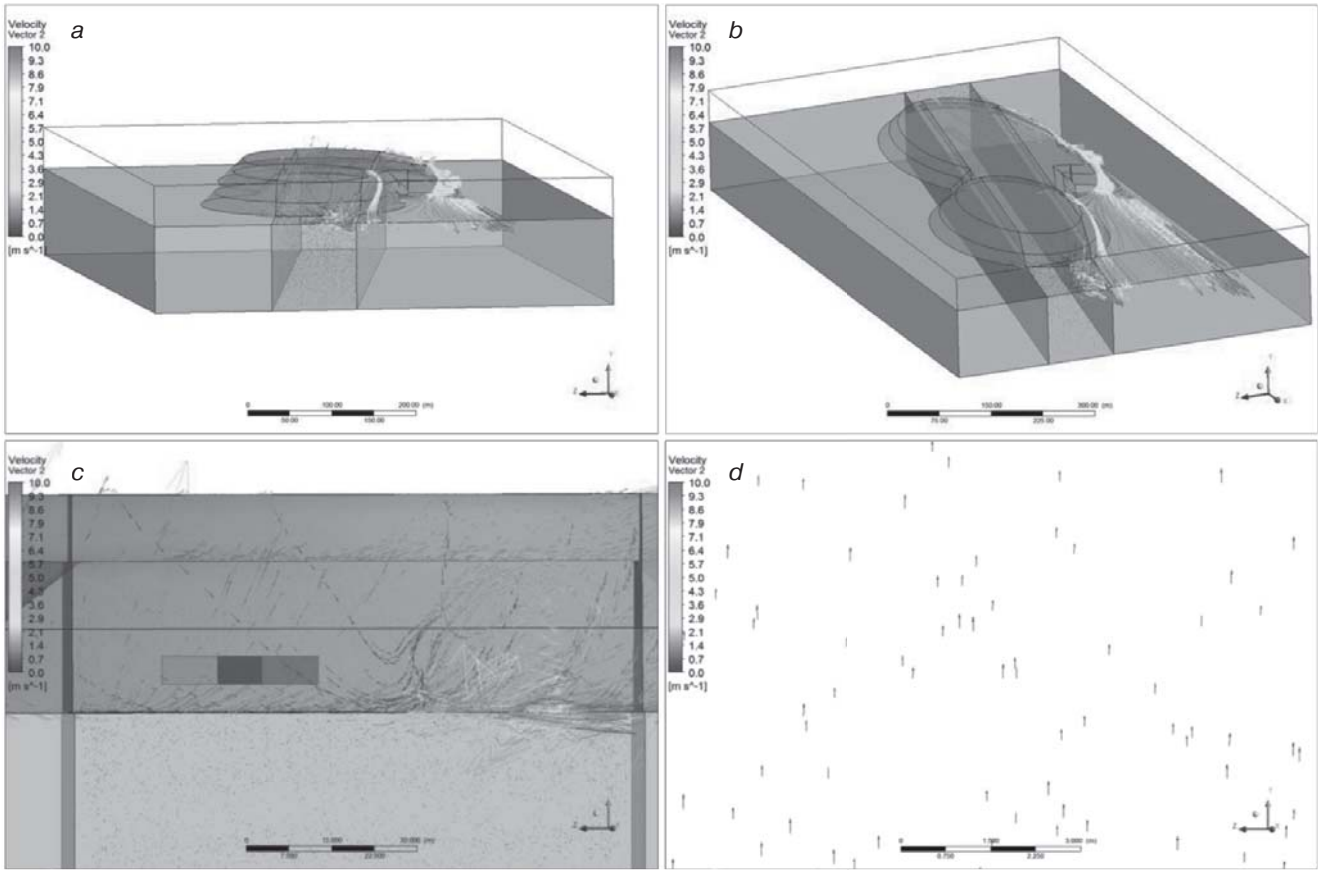

Fig. 5. Modeling of air flow in case of the mine–dump connection via GHZ (air flow vectors and velocities are shown):
(*a*) general elevation view; (general view, isometry; (*c*) GHZ and dump above it are drawn closer; (*d*) air flow vectors inside GHZ and dump

permeate into the dump. However, given no such protective cover, or in case of weak spots in the cover (spots with high porosity and permeability), air can flow in the dump and create conditions of its spontaneous combustion.

On the whole, it is seen in **Fig. 4** that air permeation into the dump from the side of the terrain ledge under the action of wind through GHZ is only possible if the dump is located closely to the ledge, and is impossible in case of the dump location at the distance of hundreds meters from the ledge.

Modeling air permeation into the dump connected with mine via GHZ. These modeling results are demonstrated in **Fig. 5**. The excessive pressure in the mine is taken as 1000 Pa. As seen in the figure, from the lower surface of GHZ, air flows upward under the action of the excessive pressure. Air flows through the dump and into the atmosphere. The air flow is visualized by differently colored vectors depending on the air flow velocity.

From the modeling results obtained with the described geometrical models at the assumed initial and boundary conditions, it is concluded that air permeation into the dump from the mine is possible even under the low excessive pressure (1000 Pa).

Modeling air flow in the dump with a source of increased temperature. In this situation, it is assumed that the higher temperature source creates favorable conditions for gas mass transfer owing to an extra draught provider.

Modeling shows that when the dump contains a heated surface, a thermal gradient field appears around it (**Fig. 6e**). Above the hot surface, owing to the temperature difference, air flows vertically upward (**Figs. 6a–6d**). These ascending air flows promote mass transfer of gases inside the dump (**Fig. 7**).

It is seen in **Fig. 6** that air flows are directed upward from the hot surface. The air flow paths in the figure have colors depending on the velocity. The air flow velocities are selected in the range from 0 to 0.022 m/s for better visualization. The comparison of **Figs. 6a–6d** shows the increase in the air flow velocity versus the heated surface temperature.

It follows from the modeling data in **Fig. 7** that the air flow velocity is both affected by the drag (obstacle avoidance) and temperature variation of the heated surface. With increasing temperature of the heated surface, the air flow velocity in the influence zone of the heat source inside the dump grows.

According to [22], there exists a fire-hazardous velocity range of air permeation in coal, and the conditions of spontaneous heating of coal are the most favorable within

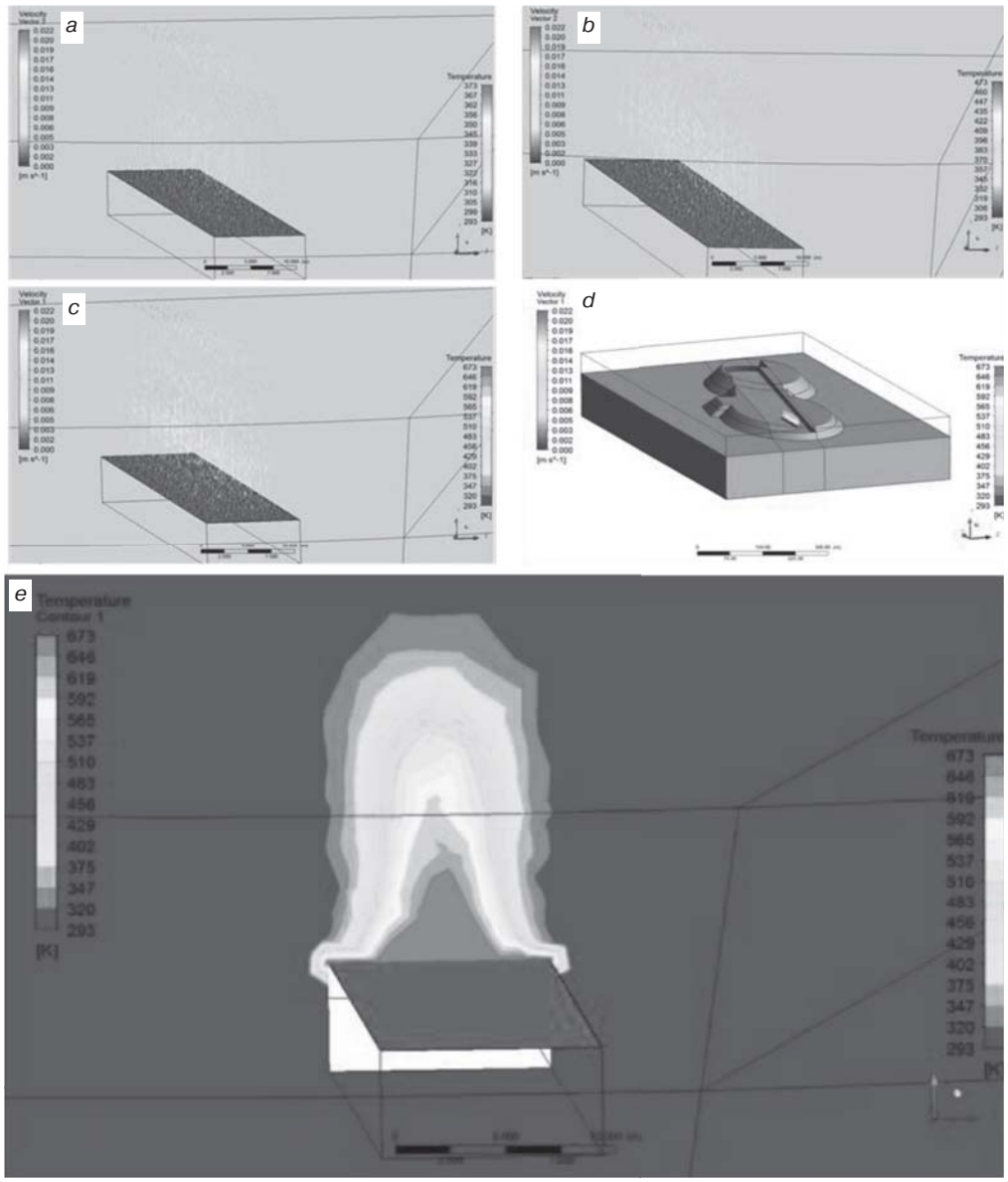

Fig. 6. Air flows above the surface with higher temperature:
(*a*) 100 °C; (*b*) 200 °C; (*c*) 400 °C; (*d*) general view; (*e*) thermal gradient above the heated surface at 400 °C

this range. For example, in Kuzbass mines, the most fire-hazardous velocity range of air permeation is 0.002–0.015 m/s. On evidence of the modeling data in **Figs. 6** and **7**, when air flows in the dump from GHZ, the air permeation velocity can be from 0.009 to 0.014 m/s, i.e. within the fire-hazardous range.

The obtained results enable a conclusion that air flow through the dump sites having the temperature of 100–400 °C creates favorable conditions for increment both in the temperature and in the burning area. The aerodynamic mine–GHZ–dump connection can arise at the moment when a higher temperature source originates in the dump due to any cause. In this case, with increase in the temperature to a threshold governed by permeability of GHZ and dump, GHS 'steps in' the process of active gas mass transfer and contributes to a mushroom growth of the endogenous fire.

Conclusions

1. On the whole, the hypothesis on the geodynamic setting to affect endogenous fire hazard of coal waste dumps is proved by the computer modeling. Adjacency of burning coal waste dumps to GHZ is explained by the aerodynamic connection between dumps and mines through a permeable zone (GHZ) at the dump bottom.

2. The analysis of the possible ways for air flow to dump through GHS at its bottom shows that:

— air permeation in the dump body from the side of the terrain ledge under the action of wind through GHS is only possible if the dump is set directly at the ledge;

— air permeation into the dump body from mines through GHZ intersecting the mining area is possible even at low (1000 Pa) excessive pressure generated by main mine fans. The aerodynamic connection between the mine and dump via GHZ can become the key mechanism of gas

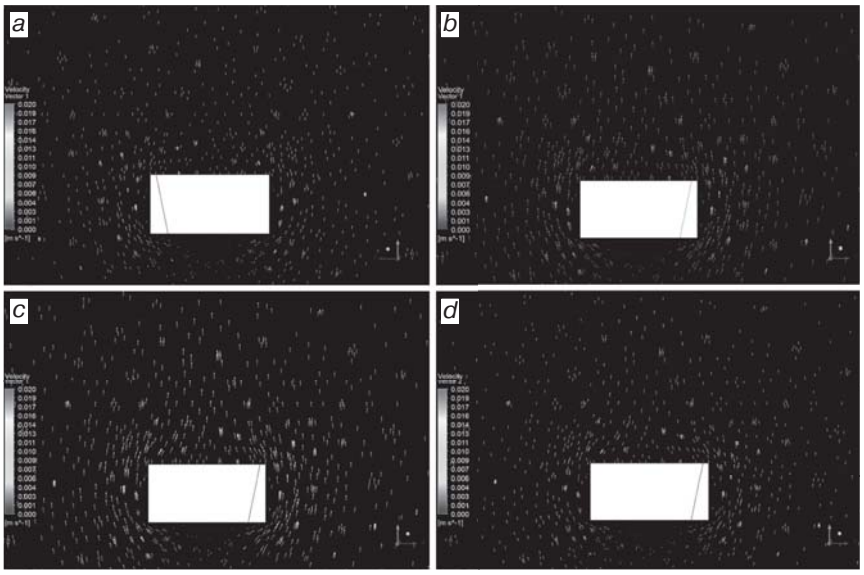

Fig. 7. Air flow vectors plotted in the sectional plane above the surface with higher temperature:
(*a*) 0 °C; (*b*) 100 °C; (*c*) 200 °C; (*d*) 400 °C

mass transfer promoting endogenous fire hazard of coal waste dumps arranged in GHZ.

3. Initiation of a combustion source induced by any cause in dumps can be a trigger to 'switch on' the aerodynamic connection between the dump and ambient environment via GHZ.

4. The research findings emphasize importance of full-scale engineering–geological studies during coal waste dump planning and monitoring, and can be used in combating spontaneous combustions.

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