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COMPLEX USE OF HEAT-EXCHANGE TUNNELS

Aleksandr F. GALKIN
Saint-Petersburg Mining University, Saint-Petersburg, Russia

The paper presents separate results of complex research (experimental and theoretical) on the application of heat-exchange tunnels – in frozen rocks, among other things – as underground constructions serving two purposes. It is proposed to use heat-exchange tunnels as a separate multi-functional module, which under normal conditions will be used to set standards of heat regime parameters in the mines, and in emergency situations, natural or man-made, will serve as a protective structure to shelter mine workers. Heat-exchange modules can be made from mined-out or specially constructed tunnels. Economic analysis shows that the use of such multi-functional modules does not increase operation and maintenance costs, but enhances safety of mining operations and reliability in case of emergency situations. There are numerous theoretic and experimental investigations in the field of complex use of mining tunnels, which allows to develop regulatory design documents on their basis. Experience of practical application of heat-exchange tunnels has been assessed from the position of regulating heat regime in the mines.

***Key words*:** heat-exchange tunnel, heat regime, regulation, safety, design, emergency situations, frozen rocks

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Introduction. Design of modern mines does not provide for the necessity and opportunity of complex use of mining tunnels, although the set of rules, elaborated by Russian Ministry of Emergency Situations, takes it into account [8]. In mine designs, sections dedicated to engineering measures on civil defense and emergency situations usually do not address preservation of mined-out tunnels (or their separate parts, suitable for further use), neither do they cover complex use of mining tunnels. At the same time, scientific community has long since come to the conclusion on feasibility and economic efficiency of secondary use of mining tunnels, including their application as heat-exchange modules. This is especially relevant for underground mines of the North due to high costs of electricity and heat in the region, as well as long duration of the cold period, when the air has to be heated until its temperature reaches a regulated value.

Research objective. Basing on the analysis of main regulatory documents and published results of theoretical and experimental research, feasibility of complex use of heat-exchange tunnels in the mines of the North has been justified. A possibility of module use of heat-exchange tunnels has been reviewed, when a part of them can become a protection construction to shelter operating shift and population in case of a natural or man-made emergency. It has also been assessed to what extent completeness and sufficiency of existing research allow to elaborate a federal-level regulatory document for the design of underground constructions of the module type.

Analysis of research results. Current construction standards and rules on design and construction of underground facilities, operating in Russia, do not apply to permafrost zone which accounts for more than 70 % of Russian territory. Up to this moment, there is only one regulatory document TSN[1]-31-323-2002 «Underground objects in mining tunnels of the permafrost zone in Yakutia» [9]. The document contains the section «Space-planning and constructional solutions», which is the first one to offer design engineers new technical solutions in the field of complex use of mining tunnels, and particularly, in design and construction of module underground facilities. The idea behind this approach is that certain mining tunnels have two purposes, while others only perform their technological function; under normal conditions double-purpose tunnels are used as a part of the

[1] Territorial Construction Standards

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overall technical plan, but in case of emergency there is an option of their autonomous operation. With this being said, there must be minimal interference between double-purpose and conventional tunnels (minimized basing on the achievement of regulated parameters in the process of underground facility operation for its immediate application), i.e. it should not impair overall mine operation for its designated purpose.

From the economic viewpoint, the key requirement to double-purpose tunnels should be their inclusion into the overall technical plan of underground facility operation under normal conditions. In our opinion, in the North, where most technologic processes are characterized by enhanced energy consumption, including processes of heat regime regulation, the most rational choice for double-purpose tunnels is specialized heat-exchange modules [1]. It will permit to include these tunnels into the overall ventilation system of mines and underground facilities as a means of achieving regulated microclimate parameters. Results of theoretical research and experience of underground facilities operation demonstrate that such technical solution allows to reduce energy consumption for air conditioning purposes by way of rational use of heated (cooled) air accumulated by surrounding rocks [3, 4].

Let us consider some typical plans of how to use double-purpose heat-exchange modules on the example of an underground refrigerator. Schemes of underground refrigerators should contain two key modules: frost-accumulating (double-purpose) and basic one (for food storage). The scheme of module connection should provide regulated microclimate parameters, in terms of both protective structure and food storage requirements [1]. When frost-accumulating module is used for its designated purpose, it should provide an amount of frost sufficient for keeping regulated temperature of food storage in all the basic modules for the whole storage period either without any refrigerating equipment, or using low-power devices. When frost-accumulating module is used as a protective structure, it gets isolated from other modules and can quickly be re-equipped to receive people. As analysis suggests, the temperature in basic modules can be maintained at the regulated level through the whole period when the refrigerator is being used as a protective structure. Fig.1 and 2 demonstrate different conceptual schemes of double-purpose module refrigerators for northern conditions. Arrows indicate direction of air flow. As can be seen from Fig.1 and 2, when necessary, the basic module can be rapidly separated from the frost-accumulating one, fully or partially used as a protective structure.

It should be noted that most requirements towards protective structures, located in mining tunnels (SNiP[2] 2.01.54-84), and economic assets in underground spaces (SNiP 2.01.55-85) are identical, which simplifies design and construction using module principle. Under normal conditions, frost-accumulating module can be used without additional frost accumulation in the period of freezing. Besides, due to independent ventilation of the module, frost accumulation can also take place after basic modules are loaded. In order to intensify heat exchange and to increase frost-accumulating properties of the rock mass, large-size wells can be drilled through barrier pillars (Fig.2, *b*)

For low-power refrigerators barrier pillars can be substituted with an air-tight longitudinal wall, dividing the tunnel into two units (Fig.2, *a*) and in such a way creating a geo-accumulator. This technical solution significantly increases efficiency of energy accumulation in heat-exchange tunnels. When the refrigerator is used as a protective structure, it is reasonable to perform reversion of the ventilation stream with simultaneous connection to the energy source, which allows to reach regulated microclimate parameters at a quicker pace.

Results of efficiency assessment show that it is feasible to design frost-accumulating modules in underground refrigerators to maintain regulated parameters of heat regime in the working space.

[2] Construction Rules and Regulations

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Such module systems can also be used in mine design. According to existing classification, they can be categorized as conventional mining-engineering systems [1, 4]. In order to increase energy efficiency of such mining-engineering systems of heat regime regulation, they can be run with specific ventilation modes, among other things providing efficient use of the incoming airflow energy [1, 2, 10].

Earlier complex theoretical research has been carried out for the basic groups of mining-engineering systems: regular, recuperative, regenerative and combined (e.g. recuperative systems operating in regenerative mode) and miscellaneous, including mining tunnels and well reservoirs. The calculation of mining-engineering systems, which have been regarded as systems with distributed parameters, has been based on a designed and implemented mathematical model, allowing to forecast temperature regime of the tunnel and surrounding rocks, taking into account phase changes of the rock moisture. The model takes into account: changes of rock properties in time and space; thermal resistance of the lining, altering with length; presence of absolute and relative heat sources, unevenly distributed along the tunnel; seasonal and daily variations of outside air temperatures and other defining parameters.

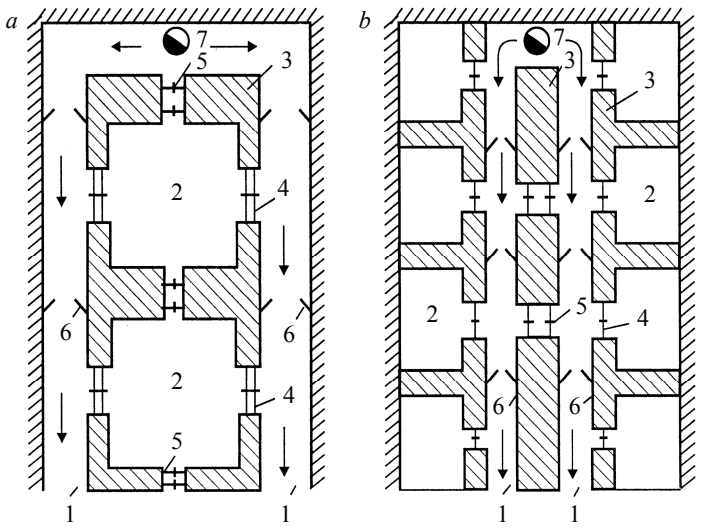


Fig.1. Module schemes of underground facilities (first option):
a – lateral; *b* – central
1 – frost-accumulating module; 2 – basic module; 3 – barrier pillars; 4 – air-tight doors; 5 air-tight entry; 6 – ventilation doors; 7 – ventilation shaft (hole)

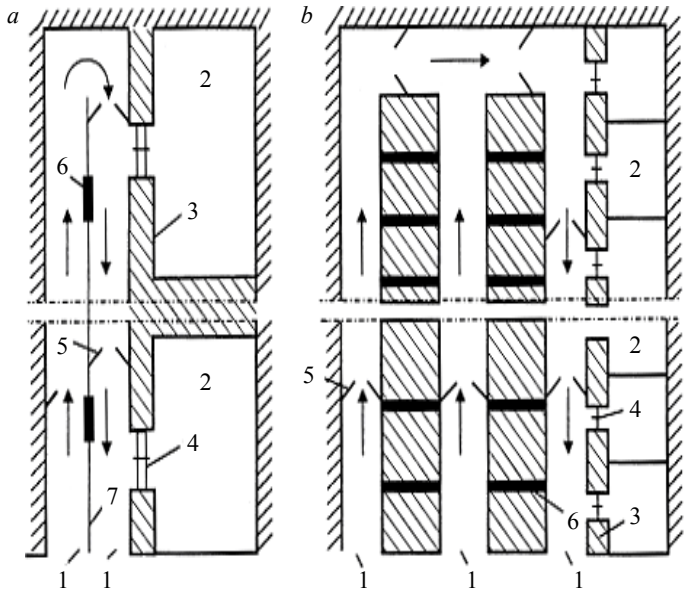


Fig. 2. Module schemes of underground facilities (second option)
1 – frost-accumulating module; 2 – basic module; 3 – barrier pillars; 4 – air-tight doors; 5 – ventilation doors; 6 – ventilation windows (*a*), holes (*b*); 7 – air-tight dividing wall

As a result of theoretical research, new trends have been revealed in heat-exchanging processes of mining-engineering systems of various types and optimal values of defining characteristics, associated with minimal energy consumption and economic costs, have been justified. In particular, it has been identified that, from the position of energy, the most feasible option is a series connection of heat-exchange tunnels in a single network. A method has been developed to carry out comparative assessment of energy and economic efficiency for different options of mining-engineering systems. Fields of rational use have been outlined for each group of systems, depending on geocryological and climate conditions of underground facilities operation. It has been established that mining-engineering regulation systems can also be effectively applied outside permafrost zones.

Experimental tests have been carried out in order to understand how heat regime settles in underground facilities of different types, including operation in full and partial isolation [3, 5].

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A method of joint solutions for the tasks of air distribution and heat regime in the network of mining tunnels in permafrost zone has been developed and realized as an independent software product – among other things, for the case of changing volume of mining tunnels [11, 12, 16].

The main distinction of ventilation in module underground facilities is an opportunity to choose between combined and separate ventilation of basic technological modules and double-purpose tunnels. Complex thermal analysis has been carried out and it showed that in case of emergency it is possible to reach regulated microclimate parameters in protective constructions, located in double-purpose tunnels, on time and without disturbing ventilation mode of basic technological modules. Module principle can also be implemented by operating mining enterprises. In this case, in the course of underground exploitation a certain amount of tunnels should be preserved and reconstructed, if needed, in order to include them in the overall system of mine ventilation as double-purpose heat-exchange tunnels.

Scientific justification has been made to prove that it is feasible to include tunnels of mined-out planes in the systems of ventilation and mine air conditioning. New methods of heat regime regulation, which make allowance for complex use of mining tunnels, have been developed for northern mines. The primary focus has been on energy and economic efficiency of new systems of heat regime regulation, which is important for the implementation of new technical solutions in design practice. In particular, schemes of optimal ventilation modes with periodic airing have been proposed for heat-exchange tunnels. Optimal amounts of air have been found, both from energy and economic perspectives, which have to be supplied to the system in the course of the annual cycle. Carried out estimations of characteristic conditions of mine exploitation in the North demonstrate that in the latter case annual energy efficiency of the mining-engineering system will increase no less than by 30 %.

In order to enhance seasonal energy efficiency of mining-engineering systems, special heat-accumulating coating has been suggested, which effectively suppresses daily and weekly fluctuations of outside air during mid-season. Application of such coating enables substantial improvement of system stability and protects the tunnel from bursts of cold air to prevent its icing [3, 4].

The use of heat-exchange tunnels as protective modules should include their reliable lining, especially for tunnels in dispersive frozen rocks, characteristic of permafrost zone. Strength of such rocks to a large extent depends on temperature regime and drastically drops when the rocks start to thaw. Exploitation of protective structures always implies positive temperatures of inside air, which will cause active thawing of surrounding rocks. With this in mind, special fire-resistant multifunctional thermal coating (based on cement binders) has been designed and implemented for a more efficient use of double-purpose tunnels. This coating can be put on the tunnel walls by means of either dry or wet shotcreting. Experimental research, carried out in Norilsk and Yakutia mines, has shown that for the periods of tunnel use for protection purposes such coating can create a comfortable and safe environment for the whole period of emergency exploitation. Besides, under normal conditions the coating does not deteriorate characteristics of heat-exchange tunnels, as it prevents rocks in the active zone from drying out.

Drying out of the rocks in the active zone leads to a decrease in their thermal conductivity, which in its turn deteriorates energy characteristics of heat-exchange tunnels. That means that in order to get the same energy effect the chain of heat-exchange tunnel has to be lengthened. Application of thermal coating solves this issue. According to calculations, an increase in thermal conductivity of the lining, which is provided by the coating, and consequent reduction of heat exchange intensity are abundantly compensated by conservation of thermophysical rock properties in the active zone.

To secure rock stability of heat-exchange tunnels in case of possible mine fires, when the ventilation stream is reversed and air temperatures in some sections of the tunnel may exceed 200 °C,

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specific coating has been designed, which alters its thermal resistivity with rising temperature. Coatings of two types have been developed. The first one uses intumescent paint, which can change its thermal resistivity by a factor of 5-7. Lamination of such paints between layers of thermal coating of the lining allows to secure stability of frozen rocks and to rule out rockslides in the tunnel. The drawback of this construction is that it is non-reusable, i.e. after the fire the tunnel lining needs complete reconstruction. The second type of the coating is free from this disadvantage, as it allows changes of thermal conductivity in both directions – to the higher or to the lower side – depending on the heat current. Selection of one or another coating has to be based on results of techno-economic analysis [1, 6, 7, 13].

A procedural base has been created in order to assess and select optimal ventilation modes, ways of connecting tunnels into a single network, number and geometrical parameters of double-purpose tunnels and other characteristics, the combination of which permits to obtain maximal energy and economic effect from using heat-exchange modules in underground facilities. In particular, it has been identified that the most reasonable way to integrate heat-exchanging tunnels into a single network is their series connection. From the viewpoint of energy, the most efficient systems belong to recuperative type with a «dividing wall», not «tube in a tube» type, as it had been believed earlier. For regenerative systems of heat regime regulation, all other parameters being equal, there is an optimal amount of air, which is practical to supply to the tunnel. Developed economic-mathematical models allow to select any optimal parameters of double-purpose heat-exchange modules, including parameters of multi-functional thermal coating [1, 2, 10, 12, 14-16].

Conclusions. Analysis of existing regulatory documents on construction of underground facilities has shown that they need to be improved. The main trend lies in development of regulatory documents on design and construction of special double-purpose heat-exchange modules for new enterprises and in inclusion of certain mined-out tunnels into technical plans for operating mines. Results of numerous investigations confirm appropriateness, practicability and economic efficiency of this approach to solving the problem of constructing protective facilities in permafrost zones throughout Russia.

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Author **Aleksandr F. Galkin,** *Doctor of Engineering Sciences*, *Professor*, *afgalkin@yandex.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

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