PROBLEMS OF COOLING SEALED FIRE AREAS IN UNDERGROUND COAL MINES

VYBRANÉ TECHNOLOGIE OCHLAZOVÁNÍ PROSTOROVĚ UZAVŘENÝCH POŽÁŘIŠŤ V HLUBINNÝCH UHELNÝCH DOLECH

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Abstract

In current mining practice, the most often used methods of cooling spatially sealed fire areas are: natural cooling, cooling by nitrogen, cooling by water and inert foam and cooling by combustion product recirculation. The technology of cooling with nitrogen represents two variants - the use of liquid nitrogen or nitrogen gas in the area of closed mine workings. From a technical and safety points of view the application of liquid nitrogen is today considered unsatisfactory, while the use of nitrogen gas seams to be highly safe technology for cooling explosion-proof sealed fire areas. Another possibility for cooling fire areas in deep coal mines is so-called natural cooling, where economical costs are indeed zero, but comparing to cooling processes induced by the application of cooling technologies a longer time period necessary for the natural refrigeration of fire areas causes financial losses.

Abstrakt

V současné hornické praxi patří mezi nejpoužívanější způsoby ochlazování prostorově uzavřených požářišť přirozené ochlazování, ochlazování dusíkem, ochlazování vodou a inertní pěnou a ochlazování recirkulací požárních zplodin. Technologie ochlazování pomocí dusíku představuje dvě varianty – použití kapalného dusíku nebo plynného dusíku v prostoru uzavřených důlních děl. Z technicko-bezpečnostního hlediska je aplikace kapalného dusíku již dnes považována za nevyhovující, naproti tomu aplikace plynného dusíku se jeví jako vysoce bezpečná technologie ochlazování výbuchuvzdorně prostorově uzavřeného požářiště. Další z možností ochlazování požářišť v hlubinných uhelných dolech představuje tzv. přirozené ochlazování, kdy jsou sice ekonomické náklady nulové, ovšem ve srovnání s ochlazovacími procesy vyvolanými aplikací chladících technologií však delší doba potřebná k přirozené refrigeraci požářiště způsobuje finanční ztráty.

Key words: liquid nitrogen, nitrogen gas, cooling, spatially sealed fire area

1 INTRODUCTION

A spatially sealed fire area in a deep coal mine is a system of explosion-proof sealed mine workings, in a part of which an exogenous or endogenous mine fire occurred that failed to be extinguished by a direct extinguishing intervention (accessible mine fires), or by the application of a set of technical measures (inaccessible mine fires), aiming at its efficient damping. So in terms of its refrigeration such a fire area represents a closed thermodynamic system, which is separated from its surroundings by an interface allowing the exchange of energy as heat, but not the exchange of mass (mine air). In this case, the interface is formed by the adjacent rock mass and currently used closing plaster dams or water seals. Mine fires must, as other types of fires, meet three main conditions of the process of combustion - a fuel (combustible) must be present, oxygen (as an oxidizing agent) and heat (initiation energy) that support and maintain combustion.

In case of extinguishing or effective damping an inaccessible endogenous mine fire in a longwall gob area it is technically impossible to ensure the removal of burning coal mass - i.e. the fuel of the factual combustion reaction. Due to the inaccessibility of a certain type of endogenous fires it is also impossible to realize the direct cooling of burning fuel with extinguishing agents, unless angular ratios enable flooding the fuel location by water or fly ash sludge. The only removable component of the so-called combustion triangle in an ongoing inaccessible endogenous fire in a longwall gob area is thus oxygen contained in the mine atmosphere. The technical means which prevents access of oxygen to burning fuel of the fire in question is the spatial explosion-proof closure of the system of mine workings where the fire is in progress. Such a closure is used in operational practice provided the measures to reduce the oxygen concentration in air masses flowing to the fire outbreak were not effective, e.g. inertisation with nitrogen gas.

2 TECHNOLOGY OF COOLING WITH NITROGEN

Cooling of spatially sealed fire areas with nitrogen can basically be realized in two ways:

- spraying liquid nitrogen into the area of closed mine workings,
- discharging nitrogen gas into the area of closed mine workings.

2.1 Cooling with liquid nitrogen

The spraying of liquid nitrogen into the area of sealed mine workings is not currently used under the conditions of Czech deep coal mining. In Polish mining, the method was used since a half of 70s years of the last century until the recent past, when the AUG-2 equipment was developed for injecting liquid nitrogen under pressure through dams sealing the fire area. The equipment consisted of 12 pieces of thermally insulated transport containers for a unit volume of 1 m^3 of liquid nitrogen, the device for passing liquid nitrogen from a tank into the transfer containers and the device for injecting liquid nitrogen behind the dam sealing the fire area.

The efficiency of the described system of cooling with liquid nitrogen is however too low, because the latent heat of vaporization of nitrogen is only 199,3 $kJ.kg^{-1}$ which is more than eleven times lower value than the latent heat of vaporization of water reaching the value of 2.257 $kJ.kg^{-1}$. The overall summary of the data on physical features of nitrogen may be found at http://homen.vsb.cz/~ada70/Nitrogen/cz/n2.htm.

Another reason of low efficiency of the technology for cooling spatially sealed fire areas in deep mines is the method of application of liquid nitrogen by the pressure injection through the dams isolating the fire. In this application, liquid nitrogen is sprayed into the area just behind the dam, not into the critical zone of a longwall gob area where the occurrence of the outbreak of mine fire may be expected, which could be just due to the change of liquid nitrogen into a gas state efficiently cooled. This leads to cooling the immediate surrounding of the place of spraying liquid nitrogen and thereby to an increase in the temperature gradient in the long mine working closed by the respective dam. This results in an increase in natural convective heat flux in the atmosphere of the particular mine working which, however, takes place only within the closed thermodynamic system of the explosion-proof spatially sealed fire area (heat is not carried off outside the system).

The change in state of liquid nitrogen to gaseous nitrogen leads, of course, to inertisation of the mine atmosphere, i.e. to a decrease in concentration of oxidizer (atmospheric oxygen) in the area of the enclosed fire area.

2.2 Cooling with nitrogen gas

Gaseous nitrogen used to cool the spatially sealed fire area in an underground coal mine is now, under conditions of the European and global mining industry, produced solely on the surface of mine (vaporiser of liquid nitrogen, membrane gaseous nitrogen generators, PSA nitrogen gas generators - molecular sieves, cryogenic nitrogen gas generators) and then transported to the points of destination through pipe (hose) lines of a required dimension.

The production and distribution system of nitrogen gas so predetermines the temperature of the inert gas in the point of its discharge into the mine atmosphere corresponds approximately to the temperature of this atmosphere. Cooling the body of coal mass combusted in a mine fire takes place during the fire termination process and after its termination by conducting the heat between the coal mass and surrounding rocks (conduction) and then by the heat flux between the coal mass and the surrounding mine atmosphere (convection).

The nitrogen gas being discharged into the explosion-proof sealed fire area is, in terms of cooling the body of coal mass combusted during the mine fire, of a great importance just as an external factor causing the movement of air masses in the fire area (the critical zone of the longwall gob area). The natural flow of heat between the coal mass and the mine atmosphere then takes a constrained nature (forced convection) by discharging nitrogen gas into the mine atmosphere. However, it is never just a pure form of heat flux, because both at the interface between the cooled body of coal mass and nitrogen inertised by air masses, and in these air masses themselves it is always accompanied by heat conduction (conduction).

To determine the convective heat flux Q_{konv} *(W)* in cooling coal mass the following Newton's equation applies:

$$Q_{konv} = \alpha.(T_{uh} - T_{vz,n}^{v}).S_{uh,ts}\,, \qquad (1)$$

where:

α - convection heat transfer coefficient [$W.m^{-2}.K^{-1}$] ,

T_{uh} - temperature of coal mass [^{o}C, K],

$T_{vz,n}^{v}$ - normal temperature of moist air masses (gaseous nitrogen) flowing to the outbreak of fire [^{o}C,K],

$S_{uh,ts}$ - heat transfer surface of coal mass [m^2].

The above equation shows that the increase in value of convective heat flux and thus the intensity of cooling is possible mainly by increasing the heat transfer coefficient of moist air masses (gaseous nitrogen) flowing to the outbreak of fire. If the air masses are in terms of the physico-chemical aspects considered a single fluid or a group of fluids of related properties, it is possible to increase the value of the coefficient in question by increasing the fluid rate.

The empirically determined value of heat transfer coefficient depends on the type of flow and flow conditions in the place of occurrence of the cooled body of coal mass. The bases of empiricism are criteria equations determined under precisely defined conditions for each model areas of convective heat transfer. From these equations it is then possible to calculate the value of the dimensionless Nusselt number that characterizes, according to the equation (2), the ratio between the heat transfer and the temperature field in a so-called thermal boundary layer defined on the surface of the cooled body of coal mass by the film theory of heat transfer (Fig. 1).

$$Nu \equiv \frac{\alpha.L_{uh}}{\lambda_{vz}^{v}} \equiv \frac{L_{uh}}{\Delta}\,, \qquad (2)$$

and thence

$$\alpha \equiv \frac{Nu.\lambda_{vz}^{v}}{L_{uh}}\,, \qquad (3)$$

where:

L_{uh} - characteristic dimension of the body of coal mass [m],

λ_{vz}^{v} - coefficient of thermal conductivity of moist air masses (gaseous nitrogen) flowing to the outbreak of fire [$W.m^{-1}.K^{-1}$],

Δ - thickness of the thermal boundary layer on the surface of the cooled body of coal mass [m].

The thickness of the static thermal boundary layer on the surface of the cooled body of coal mass decreases in proportion to the intensity of moist air masses (gaseous nitrogen) to the outbreak of fire. The intensity of cooling the fuel of an extinguished endogenous mine fire is the greater, the smaller the thickness of the thermal boundary layer on its surface.

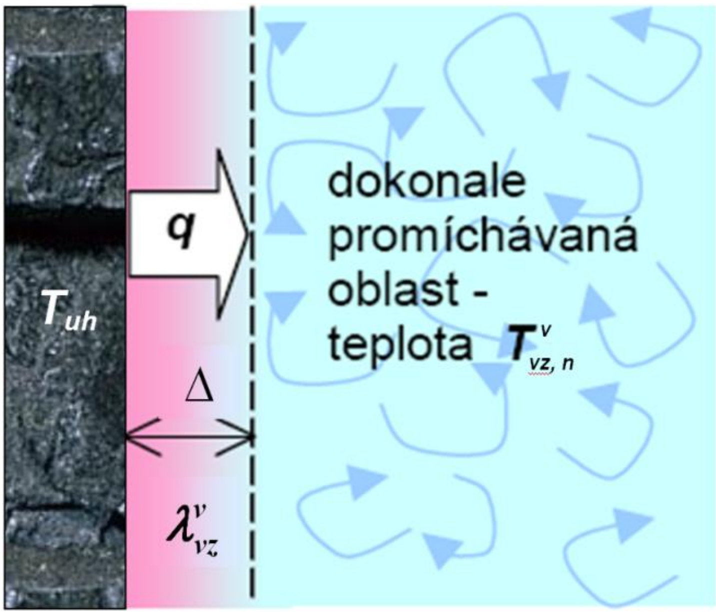

Fig. 1 Schematic representation of the film theory of heat transfer on the surface of the cooled coal body - forced convection **(**Perfectly mixed area - temperature T**)**

In practice, the heat transfer coefficient calculated via the relation (4) rarely coincides with the values obtained by experimental measurements. It achieves 3,5 ÷ 12,0 $W.m^{-2}.K^{-1}$ in a quiet atmosphere and in a flowing atmosphere it reaches the values of 12,0 ÷ 580,0 $W.m^{-2}.K^{-1}$ (Vaverka, 2006).

Gaseous nitrogen plays an important role in cooling the body of coal mass combusted in a mine fire also in terms of the desirable minimization of time required to transfer the combustion process from the propagation phase to the termination phase in the period immediately after sealing the fire area. This phase transition is accompanied by a gradual reduction in the combustion reaction rate and thus the amount of heat developed by the mine fire into the closed fire area.

In case of using nitrogen gas to cool the explosion-proof spatially closed fire area in an underground coal mine it is true that all the cooling processes take place only within the closed thermodynamic system of the fire area (heat is not removed outside the system).

An important fact which must be borne in mind when using nitrogen gas to cool a spatially sealed fire area in underground coal mines is a demonstrable increase in oxireactivity of coal following its exposure to inert environment under an increased temperature. The increase in oxireactivity has been demonstrated by the method of pulse calorimetry (PC) in the laboratories of the Chemistry Department, Faculty of Science, Technical University of Ostrava, when both coal samples were measured, which were previously oxidized for five hours with air oxygen at the temperature of 200°C, or 250°C and coal samples, which were previously exposed for five hours to the inert environment at the temperature of 200°C, or 250°C.

The measurement results of the samples of coal from the seam No. 504 - "40", face area 340 502, Darkov Mine 2 in OKR by the PC method are shown in a summary graph (Fig. 2), which illustrates the influence of the pre-treatment of coal sample on the development of its oxidative heat. The comparative "base" for the evaluation of changes in coal oxireactivity after each pre-treatment was the value of thermal effect observed during the oxidation of the original, untreated coal sample.

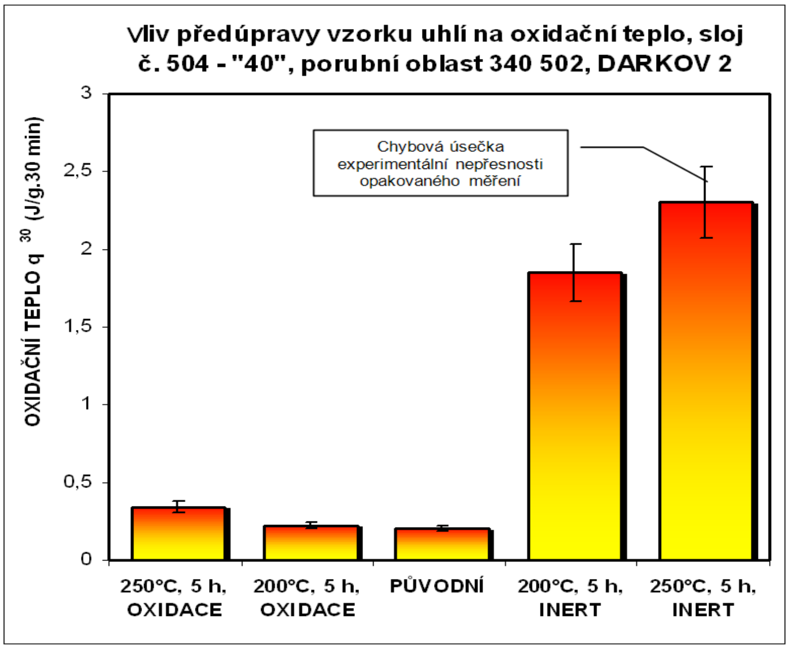

Fig. 2 Graph of the influence of pre-treatment of a sample on its oxidative heat

Influence of pre-treatment of a coal sample on oxidative heat, seam No. 504 - "40", face area 340 502, DARKOV 2
OXIDATIVE HEAT q30 (J/g.30 min)
Experimental error of repeated measurements
OXIDATION OXIDATION ORIGINAL INERT INERT

3 NATURAL COOLING TECHNOLOGIES

The natural cooling of spatially closed fire areas is considered to be such a cooling system, when in the fire area no active intervention is conducted, consisting in the application of fire extinguishing agents, inerting medium or technologies intended for the refrigeration through the use of the closing dams of isolated atmosphere or geological environment. Another attribute of this type of cooling is a way of interrupting the combustion of coal mass in a mine fire, which is caused solely by reducing the concentration of oxidizing agent in the fire area, which occurs due to oxidation reactions taking place after the spatial closure of the system of mine workings affected by the mine fire.

The actual process of natural cooling of the body of coal mass, being combusted in an inaccessible endogenous mine fire in the longwall gob area, takes place due to heat conduction between the body in question and the surrounding caved rocks, and heat transfer by free (natural) convection as well. The course of such a cooling of coal depends on the temperature at which its combustion is interrupted. The achieved temperature corresponds to the amount of released heat, namely depending on the proportion of active elements contained in the combustibles contained in the coal mass. Other factors influencing the course of refrigeration of the body of coal mass at the given type of mine fire is the shape and weight of the coal body, the thermal conductivity of ambient rocks surrounding the coal body and the filter characteristics of the longwall gob area.

The advantage of the natural cooling of a spatially sealed fire area is the possibility of assessing the extent of extinguishing the mine fire and the clear risk of its imminent recovery by means of number indicators, which reflects gradual changes in the composition of mine air mass in the fire area depending on its cooling. It concerns, for example, the dimensionless Litton indicator (Litton, 1986), which when reaching the value of $LiR<1$ indicates the refrigeration of coal mass and surrounding rocks to a temperature corresponding to the primary temperature of rocks in the depth of bedding:

$$LiR = \frac{\frac{1}{3} \cdot CO}{\left[100 - 4{,}774 . O_2 - \left(CH_4 + C_2H_6\right)\right]^{3/2} . O_2^{1/2}}, \quad (4)$$

where:
CO - volume concentration of carbon monoxide [ppm],
O_2 - volume concentration of oxygen [%],
CH_4 - volume concentration of methane[%],
C_2H_6 - volume concentration of ethane[%].

4 EVALUATION

From the technical and safety points of view the **application of liquid nitrogen** to cooling an explosion-proof spatially sealed fire area is inappropriate. The need of container transport of liquid nitrogen to the evaporating facility located underground of a deep mine limits the amount of sprayed liquid to a large extent. The small volume of the sprayed liquid together with the above physical properties of liquid nitrogen and its application technology so causes low efficiency of both the refrigeration and inertisation of the sealed fire area. The technology of evaporation of nitrogen gas in a mine brings with also the risks of operator burns by the vaporiser, when the thermodynamic process of the conversion of liquid into steam takes place at a temperature of -195.8^{o}C.

Unlike liquid nitrogen the **application of nitrogen gas** is, from the technical and safety points of view, now considered highly secure technology of cooling an explosion-proof spatially sealed fire area. The prerequisite of the high security is, however, a well situated and hence a sufficiently tight pipe line designed to transport gaseous nitrogen from the surface of the mine down to the place of its discharge in the fire area. At high volume of transported quantities of inert gas a leak of the gas pipeline going through active mine workings can affect the health and lives of mine workers due to a significant reduction in volume concentration of oxygen in the mine atmosphere of the active workings by leaking inert gas.

A special variant of the use of gaseous nitrogen in cooling outbreaks of inaccessible endogenous fires in longwall gob areas is its **replenishment into the sealed fire area, while relieving the over-pressure of air mass emerging by this adding in the fire area** (OKD HBZS, a.s., 2003). This adding of inert gas into the fire area is a way of its cooling (the axiom of cooling efficiency is the addition of such a volume of inert gas or a mixture, which corresponds to three times the volume of mine workings of the fire area), at which the thermodynamic system opens, when between the fire area and surrounding active workings an exchange of not only energy (heat), but also mass (air mass) occurs. Opening the thermodynamic system of the explosion-proof spatially sealed fire area considerably increases the efficiency of its cooling, provided the drains of nitrogen gas are installed deep enough in the longwall gob area. However, this is associated with considerable risks, as air masses being relieved from the fire area may exhibit characteristics of explosive mixtures, especially after their mixing with the air masses flowing in the mine workings immediately adjacent to the fire area. All work associated with the relieving the over-pressure of air masses arising in the fire area as a result of adding nitrogen gas into its enclosed area must therefore be conducted under the planned intervention mode of mining rescuers.

Cooling spatially sealed fire areas using the technology of **natural cooling** allows determining, relatively accurately, its theoretical course using stoichiometric and thermodynamic calculations. However, these calculations are not implemented in today's Czech underground coal mining, although they are the default parameter in determining the appropriate type of cooling of fire areas using artificial cooling technology.

5 CONCLUSIONS

For the realization of spatial explosion-proof closure of the system of mine workings affected and by a mine fire legislative requirements are imposed on tightness of dam closure - Section 190(5), CBU Decree No. 22/1989 Coll., on occupational safety and health at work and operational safety in mining activities and subterranean mining of non-reserved minerals, as amended (the Mining Authority, 1989). In case of fulfilling the diction of the regulation and elimination of other possible drafts of mine air into the sealed fire area a reduction in the concentration of oxidizing agent (atmospheric oxygen) occurs in the fire area due to ongoing oxidation reactions. As a result of the drop the combustion process of the inaccessible endogenous fire is interrupted and the fuel combustion is transferred from the propagation phase (flame or flameless combustion) into the termination phase (afterburning). The mechanism of combustion termination is represented by a system of physico-chemical processes in the breakout of mine fire and its surroundings, causing further reduction in oxygen concentrations in the closed fire area.

The termination of the combustion process in a mine fire attained by a decrease in the concentration of oxidizing agent reduces the combustion reaction rate and thus the amount of heat developed by the mine fire. In addressing the issues of cooling spatially sealed fire area in underground mines is therefore crucially important to minimize the time expired since the closure of the fire area to the interruption of the coal mass combustion due to the decreased concentration of oxidizing agent.

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RESUMÉ

Veškeré skutečnosti a závěry týkající se využívání plynného dusíku coby vysoce bezpečné technologie při refrigeraci ohnisek endogenních důlních požárů v uzavřených požářištích je také možné vztáhnout na jakýkoliv jiný inertní plyn vyráběný na povrchu dolu, jenž je transportován k místu vypouštění do atmosféry požářiště potrubním či hadicovým systémem.

Technologie přirozeného ochlazování prostorově uzavřených požářišť v současné praxi hlubinného dobývání uhlí v České republice není z ekonomických důvodů využívána. Z ekonomického hlediska jsou sice náklady spojené s tímto relativně bezpečným typem ochlazování téměř nulové (kromě nákladů spojených se stavbou výbuchuvzdorných uzavíracích hrází), ve srovnání s ochlazovacími procesy vyvolanými aplikací chladících technologií však delší doba potřebná k přirozené refrigeraci požářiště způsobuje finanční ztráty z titulu neproduktivního vázání strojních dobývacích technologií v důlních dílech uzavřených z důvodu důlního požáru, ale především blokováním dalších uhelných zásob, nacházejících se v bezprostřední blízkosti uzavřeného porubu nejenom sousedního, ale i v podloží.