Microclimate normalization in working areas in oil mines

YuA Klyuykin* and MA Semin
Mining Institute, Ural Branch, Russian Academy of Sciences, Perm, Russia
E-mail: aeroyuri@gmail.com

Abstract. The paper discusses microclimate normalization methods applicable in oil mines, including air flow velocity variation, air sprinkling or cooling; installation of local blowing or drawing ventilation systems; arrangement of closed oil-bearing fluid harvesting system; heat-insulation lining; and integrated activities.

1. Introduction
Since 1972 Yarega viscous oil project uses thermal recovery to produce oil from reservoirs earlier treated using the Ukhta technique or systems of high-angle wells [1]. Parameters of microclimate in drilling galleries in oil mines in Yarega field sensibly increase the standards set by Industrial Safety Code [2] and Public Health Regulations [3] due to injection of great volumes of saturated steam in the reservoir [4]. This problem was in spotlight of many studies [1, 5, 6], and various mining methods were proposed for specific sites of Yarega field, including optimization of microclimate. Despite the implemented research and development, the problem remains urgent so far [7].

Using the developed model of heat exchange and mass exchange processes in a drilling gallery in the course of thermal recovery of oil via a system of surface and underground wells [8], efficiency of various approaches to microclimate normalization in operating areas of oil mines is analyzed. The microclimate in drilling galleries of oil mines is largely conditioned by the assumed mine design [8]. This paper presents the calculation data for the distance of 300 m between a drilling gallery and steam injection wells as the most severe microclimate conditions in sloping panels. Qualitatively, the conclusions drawn are valid for the other parameters of thermal oil mining using systems of surface and underground wells.

Normalization of thermal conditions begins with the ventilation efficiency tests in mines [9].

2. Air flow velocity
The increase in air flow velocity accelerates heat exchange between rock mass and heat sources, on the other hand, and, on the other hand, results in enhanced air flow for the heat energy to be spread in. The air flow rate linearly depends on the air flow velocity, and the heat transfer coefficient has a power of 4/5 according to Shcherban’s formula [10]. As against heat exchange with rock mass having high natural temperature, oil mines lack formation of a “heat leveling jacket” the process of heat removal from rock mass with air flow runs concurrently with heat propagation from wells toward the interior of the sloping panel [8]. Figure 1 shows the curves of air temperature in the drilling gallery and the air flow velocities of 0.5, 2 and 6 m/s. The increase in the air flow by 4 times in the given conditions leads to the decrease in the air temperature at a distance of 100 m from the drilling gallery entrance from 34.5 to 31.2 °C, which is reflective of low efficiency of this microclimate normalization approach. As
seen in Figure 1, in sloping panels longer than 200 m, the effect of the air flow velocity increase is very weak.

![Graph showing air temperature distribution](image)

**Figure 1.** Calculated air temperature distribution in drilling gallery at different air flow velocities: a—0.5, b—2, c—6 m/s.

For another thing, the increase in the air flow velocity results in the decreasing humidity of air. At the dry-bulb thermometer readings under 36 °C, the increase in the air flow velocity improves freezing of a miner’s body, which reduces ‘perceptible temperature’ [11]. At the air temperature above 36 °C, the phenomenon is opposite—a miner’s body experiences increased heating, which generally limits the application area of this approach. Furthermore, with increasing air flow velocity, air temperature lowers at the entrance to the sloping panel due to weaker air heating in the main air fee opening in the oil mine. Quantitatively, the decrease in the air temperature essentially depends on the distance between the sloping panel and the air feed shafts or boreholes.

In currently operating oil mines, the use of this approach is limited due to the long distance between the sloping panels and the air feed or ventilation openings.

3. **Air sprinkling**

Oil mines widely use sprinkling systems (fog generators) which utilize water from the central water supply and discharge water via mine drainage. Efficiency of this approach essentially depends on the temperature and relative humidity of air at the sprinkling system inlet, while the temperature and relative humidity vary within wide ranges in different sites in oil mines and in different seasons. In remote sloping panels, subjected to the least seasonal variations in temperature, relative humidity of feed air varies depending on weathering conditions on ground surface and on operating regime of air conditioning system. In cold seasons, air at sloping panel inlet has a low humidity (30–40%), while its humidity in hot seasons can reach 80% at the sloping panel inlets. The efficiency of air sprinkling as an approach to microclimate control in different sites of oil mines is analyzed using a sloping panel model. The modeling results are depicted by curve 2 in Figure 2.

Air sprinkling application is analyzed in a drilling gallery longer than 100 m in case of the mine air temperature of +36 °C, which is the upper limit as per the Industrial Safety Coal for Underground Mining of Oil Reservoirs. Relative air humidity in such drilling galleries weakly depends on fluctuations of relative humidity of air from ground surface and is assumed as constant in our calculations.
Figure 2. Calculated air temperature distribution in drilling gallery: 1—without any measures undertaken; 2—air sprinkling 3—closed oil-bearing fluid harvesting system; 4—heat insulation lining; 5—air cooling.

In the drilling gallery under analysis, air reaches the temperature of +36 °C at a distance of 110 m; in this section, a sprinkling system is modeled. Given efficient operation of the sprinkling systems, which means adiabatic cooling of air from +36 °C to +25 °C, the microclimate is normalized in the follow-up section of 80 m in the drilling gallery. Later on, along the air flow efficiency of the sprinkling system lowers as the moisture content of air tends to its limiting value, which reduces efficiency of adiabatic cooling. The sprinkling systems which are currently operated in oil mines are much less efficient, due to deficient design [12] and owing to low water feed.

4. Closed oil-bearing fluid harvesting
At the present time, many various systems are being developed for oil-bearing fluid harvesting in underground excavations of a sloping panel. The idea is to reduce intensity of heat exchange between air and oil-bearing fluid. The heat exchange processes between air and oil-bearing fluid is more intense than with rock mass owing to evaporation of hot water having a temperature of 70–90 °C, flowing together with oil in a water drain. Oil recovery can be accompanied with team rashes though the producing wells, which also increases the heat content of air in the operating zone. The use of a closed oil-bearing fluid harvesting system can reduce moisture feed as hot oil and water is harvested in an intermediate reservoir and is then removed from the mine via pipelines, or through the elimination of steam rashes from producing well. Moreover, the heat exchange interface between air and oil-bearing fluid diminishes. Additional reduction in heat input is achievable with coating of the harvesting system by heat insulation. The efficiency of the closed oil-bearing fluid harvesting system is evaluated using the developed model, and the modeling results are depicted by curve 3 in Figure 2. Heat insulation coating of the closed oil-bearing fluid harvesting system reduces heat input from the oil-bearing fluid but has no essential influence on air flow heating in case the other high-temperature sources are present in the drilling gallery. The expedience of heat insulation coating of the closed oil-bearing fluid harvesting system is assessed below in the analysis of integrated activities.

5. Heat insulation lining
Heat insulation lining aimed to normalize thermal conditions in mines is described by many researchers [13, 14] but is yet underused due to high rate and output of heading and stoping
operations. Low efficiency of this approach is mainly explained by reduced intensity of rock mass thawing because of heat insulation, and by the impossibility of using rock mass as an ‘accumulator of cold’ in cold seasons.

Heat transfer processes run differently in sloping panes—thawing is weak, and heat front propagates from sidewalls (from injection wells) toward the panel center (production openings). The maximal temperature in rock mass can grow to 180 °C. In such conditions, it is impossible to create a chilled zone at the sidewall, and, consequently, no sufficient natural thermal insulation of production opening from heat flow from steam injection wells is possible. Furthermore, production openings in sloping panels are operated for 15–20 years, and heading is only carried out at the stage of preparing a panel for operation, for this reason, the volume of a production area is smaller than the volume of the rest rock mass. The microclimate parameters in openings of a sloping panel in case of heat insulation coatings and linings are determined from the developed heat transfer model. The calculation results are depicted by line 4 in Figure 2.

It follows from the plot that heat insulation without any other activities undertaken has minor effect (or even opposite in case of long lengths).

6. Air cooling

The idea is to cool air at the inlet to the working zone. Air cooling inside the working zone, with heating equipment arrangement in the gallery is eliminated as the equipment of the required capacity to be arranged in the gallery needs essentially larger cross-section of the openings, which is inexpedient given the other refrigeration supply flow charts available.

Air cooling allows enhancing heat recovery potential of ventilating current. Intensity of rock mass–air heat exchange processes grows proportionally to the increasing temperature head. Without the ‘heat leveling jacket’ in rock mass, such measure leads to cooling in the initial section of the drilling gallery. As seen in Figure 2 (line 5), in the variant without air cooling, the temperature limit permissible for temporary stay (+36 °C) is achieved at a distance of 120 m from the gallery entry. In case of air cooling, such temperature is observed at a distance of 190 m.

The calculations show that this approach is of low efficacy in case of long path of air flow without other measures undertaken.

7. Blowing and drawing systems

Local blowing system installed in a drilling gallery makes it possible to enlarge the zone of permissible temperatures as compared with the initial variant but requires laying of heat-insulated air lines and features low efficiency in case of long drilling galleries.

Installation of a drawing system in a drilling gallery allows reduction in moisture feed in mine air from steam inrushes, which decreases relative humidity of air and its sensible temperature. On the other hand, given intense heat inflow in mine air and high air temperature, relative humidity is far from its limit values and is not a key parameter to contribute to unfavorable microclimate.

8. Integrated activities

The proposed integrated activities include a closed oil-bearing fluid harvesting system, heat insulation lining and air cooling at the inlet of a drilling gallery. The modeling results of the integrated activities are demonstrated in Figure 3.

A seen in Figure 3, the integrated activities including closed oil-bearing fluid harvesting +air cooling make it possible to normalize microclimate in drilling galleries to 400 m long (line 2) and event to 600 m long in case of closed oil-bearing fluid harvesting +heat insulation lining+air cooling (line 3).

The described modeling results demonstrate different efficiency of microclimate normalization methods. In order to determine the sound operating conditions of microclimate normalization systems, we analyzed the influence of thermal mining technology parameters on microclimate in drilling galleries of oil mines.
Figure 3. Calculated air temperature distribution in drilling gallery in case of integrated activities undertaken toward microclimate normalization: 1—without any measures undertaken; 2—closed oil-bearing fluid harvesting system+air cooling; 3—closed oil-bearing fluid harvesting system+heat insulation lining+air cooling.

According to the equation of advective heat transfer in mine air [8, 15], the maximal air temperature in an underground excavation is affected by such technological parameters as: averaged temperature of heated surface in the excavation; air temperature at the inlet of the excavation; cross section area of the excavation; air flow rate in the excavation:

\[
\rho_a \cdot c_a \cdot Q_a \frac{dT_a}{dx} = \alpha_s P_s (T_s - T_a) + \alpha_{oil} P_{oil} l (T_{oil} - T_a),
\]

(1)

\[
\alpha_s = \frac{3.4 \cdot V^{0.8}}{d^{0.2}},
\]

(2)

\[
\alpha_{oil} = \frac{9.4 \cdot V^{0.8}}{d^{0.2}},
\]

(3)

where \(\rho_a\) is the air density, kg/m\(^3\); \(c_a\) is the air heat capacity, J/kg°C; \(Q_a\) is the air flow rate, m\(^3\)/s; \(\alpha_s\) is the rock mass–air heat transfer coefficient, W/m\(^2\)/°C; \(\alpha_{oil}\) is the oil-bearing fluid–air heat transfer coefficient, W/m\(^2\)/°C; \(P_s\) is the rock mass heat transfer perimeter, m; \(P_{oil}\) is the oil-bearing fluid–air heat transfer perimeter, m; \(l\) is the excavation length, m; \(T_s, T_a, T_{oil}\) are the temperatures of sandstone, air and oil-bearing fluid, respectively, °C; \(d\) is the equivalent diameter of the excavation, m; \(v\) is the air flow velocity, m/s.

We introduce the criterion for the influence of thermal oil mining technology on mine microclimate:

\[
K = \frac{X \cdot \frac{\partial T_a}{\partial X}}{26 - T_0 \cdot \frac{\partial T_a}{\partial X}},
\]

(4)

\[
X = \{T_m, T_0, S, Q_a\},
\]

(5)
where $T_m$ is the average temperature of heated surface in an underground excavation, °C; $T_0$ is the air temperature at the inlet of the excavation, °C; $S$ is the cross section area of the excavation, m².

Physically, the criterion is the ratio of the relative increment in the air temperature at the end of the drilling gallery to the relative increment in the technology parameter $X$ represented by any of the four parameters listed above.

Figure 4 shows the calculated $K$ versus the drilling gallery length for different technology parameters $T_m$, $T_0$, $S$ and $Q_a$.

![Figure 4. Criterion K versus length of drilling gallery in oil mine.](image)

It is seen in Figure 4 that in shorter drilling galleries, the highest effect on the temperature increment is exerted by the initial air temperature. In longer drilling galleries, the increment in the temperature is mostly influenced by the average rock mass temperature. This means that in shorter drilling galleries, the efficient temperature control is possible through adjustment of the temperature of air which is fed in the gallery.

9. Conclusions
The research allows some conclusions to be drawn, namely:
— it is expedient to control microclimate in short galleries by feeding cold air in them;
— maintenance of the top temperature and minimum air flow velocity as per the Industrial Safety Code [2] makes it possible to reduce heat supply in mine air;
— application of heat insulation lining is only effective in combination with a closed oil-bearing fluid harvesting and removal system.

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