International Journal of Heat and Mass Transfer 86 (2015) 288–293

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Stability of natural ventilation mode after main fan stoppage

B.P. Kazakov, A.V. Shalimov, M.A. Semin *

Mining Institute, Perm, Russia

ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form 27 February 2015
Accepted 2 March 2015
Available online 20 March 2015

Keywords:
Natural draft
Convection
Pressure loss
Stability
Heat exchange

ABSTRACT

Results of seasonal experimental investigations of natural draft in the potash mines after main fan stoppage are presented and analyzed. Underground mines with equal top elevations are considered. Three modes of natural ventilation depending on the season are determined: flow-through, local and convective ventilation modes. The mathematical model of unsteady heat exchange between mine air, shaft support and rock mass is proposed. This model allows prediction of natural draft intensity for flow-through ventilation mode. Also using system of linear convection equations we formulate natural ventilation stability criterion in case of convective natural ventilation mode for mine shafts after main fan stoppage. Formulated criterion based on Rayleigh number allows prediction of convective ventilation mode formation in shafts.

1. Introduction

In underground mines with different top elevations of downcast and upcast shafts and air temperature differing from outside an additional air moving force appears due to different hydrostatic pressures in shafts. This air moving force is called natural draft [1–3]. Considering that air temperatures and densities in upcast and downcast shafts can be different, natural draft occurs also in mines with shafts of equal top elevations. For example, cold outside air entering downcast shaft become warm not instantly and outlet air in the upcast shaft has temperature, which is approximately equal to warmer rock mass temperature. As a result, the column of cold air in downcast shaft is heavier than the column of warm air in the upcast shaft. Therefore, after main fan stoppage air movement does not stop completely, but decreases to finite value corresponding to convective natural ventilation. In this case, the moving force of natural mine ventilation is the heat of rock mass. According to [2], natural ventilation will occur whenever heat transfer occurs in the subsurface. Estimative calculations show that differing weights of downcast and upcast shaft air columns provides air flows is one order less than in case of normal ventilation mode.

Natural ventilation has been observed ever since the beginning of underground mining [4]. G. Agricola describes this thermodynamical phenomenon and determined two seasonal regimes of natural ventilation: spring-summer season when air flows into the deeper shafts and finds its way out of the shallower shafts; and autumn–winter season, when air enters the upper tunnel or shaft and comes out at the deeper ones. Many engineers and researchers in mine ventilation carried out only qualitative evaluations of natural ventilation pressure and energy influencing on air distribution in case of fires and in normal mine ventilation mode [1–4]. Accordingly to [4] theoretical analysis of natural ventilation can be rather complicated, especially using the thermodynamic approach, and will not be attempted.

In this paper we investigate heat transfer influence on the natural draft intensity and modes of natural ventilation depending on season. Underground mines with equal shaft top elevations are considered. In this case, the primary factor of natural draft appearance is rock mass heat flow, and barometric pressure influence is negligible.

2. Experimental measurements of natural draft

For the purpose of obtaining consistent results about natural draft intensity after main fan stoppage, we accomplish a set of seasonal experimental investigations of natural draft in shafts and insets of potash mine RU-3 (JSC "Belaruskali"). Mine RU-3 has exhaust system of ventilation. The main fan pressure difference in normal ventilation mode is 5000 Pa. Experimentally measured natural ventilation pressure is about 500 Pa. It is much less than in normal ventilation mode with active fan. Therefore, when main fan become shutdown, high rarefaction of the air in upcast shaft leads to reversal of air movement and outside air intake. According to experimental data, transient regime of air movement reversal in upcast shaft continues 10–15 min. After that a steady-state regime of air movement establishes in the mine. In general, transient regime duration depends on mined-out space volume

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.004
0017-9310/

Nomenclature

$\mathbf{A}$	temperature gradient, °C/m
A	absolute value of temperature gradient, °C/m
c_v^a	air volume-specific heat capacity, J/(m^3 °C);
c_{eff}^a	air volume-specific effective heat capacity, J/(m^3 C);
c_{v1}	concrete volume-specific heat capacity, J/(m^3 °C);
c_{v2}	rock volume-specific heat capacity, J/(m^3 °C);
D	mine airway (shaft) diameter
g	acceleration of gravity, = 9.8 m/s^2
Gr_t	turbulent Grashof number
h	shaft depth, m
h_l	thickness of layer, m
i	unit imaginary number
j	mine level number
$\mathbf{j}_{c-a}$	heat flux in the "air—concrete" interface
$\mathbf{j}_{r-c}$	heat flux in the "concrete—rock mass" interface
J_a	Bessel function of order a
k	dimensionless wavenumber
n	mine levels count in depth interval $(0,z)$
N_a	Neumann function of order a
p	complex parameter
P	static pressure, Pa
P_0	barometric pressure, Pa
$\bar{P}$	Reynolds-averaged value of pressure, Pa
P'	dimensionless pressure
P'_0	dimensionless pressure corresponding to unperturbed solution
$\delta P'$	small perturbation for dimensionless pressure
Pr_t	turbulent Prandtl number
q_{wall}	heat flux from wall (shaft support) to mine air, W/m^2
Q	air flow, m^3/s
r_0	shaft radius, m
R	dimensionless radius of interface between layers
R'	universal gas constant, J/mol/°C
Ra_t	turbulent Rayleigh number
$\mathrm{Ra}_t^{(cr)}$	critical turbulent Rayleigh number
Re_t	turbulent Reynolds number
t	time, s
t'	dimensionless time
T	air temperature, °C
T_1	concrete shaft support temperature, °C
T_2	rock mass temperature, °C
T_{out}	outside (reference value) temperature, °C
T'_{out}	outside (reference value) dimensionless temperature
$T_{out}^{(0)}$	mean annual outside air temperature, °C
T_∞	virgin rock temperature depending on depth and reciprocal gradient, °C
$\bar{T}$	Reynolds-averaged value of air temperature, °C
T'	dimensionless temperature
T'_0	dimensionless temperature corresponding to unperturbed solution
$\delta T'$	small perturbation for temperature
$\mathbf{V}$	air velocity vector, m/s
$\mathbf{V}'$	dimensionless air velocity vector
$\mathbf{V}'_0$	dimensionless air velocity vector corresponding to unperturbed solution
$\delta\mathbf{V}'$	small perturbation vector for velocity, m/s
$\bar{\mathbf{V}}$	Reynolds-averaged value of air velocity, m/s
V_0	mean air velocity, m/s
V	mine shaft axial air velocity, m/s
V'_0	dimensionless air velocity axial component
x	shaft horizontal coordinate, m
x'	dimensionless shaft horizontal coordinate
z	shaft vertical coordinate, m
z'	dimensionless shaft vertical coordinate
z_j	vertical coordinate of jth level, m
α	heat-transfer coefficient, J/(m s °C)
β	air thermal-expansion coefficient, 1/°C
η	effective air viscosity, Pa s
θ	reciprocal gradient, m/°C
λ	dimensionless wave length
μ	air molecular mass, kg/mol
ν_t	turbulent eddy viscosity, m^2/s
ρ_0	air density at normal conditions, kg/m^3
$\bar{\rho}_a$	mean air density in mine airway, kg/m^3
$\bar{\rho}$	Reynolds-averaged value of air density, kg/m^3
$\bar{\rho}_{dwn}$	mean density in downcast shaft
$\bar{\rho}_{up}$	mean density in upcast shaft
τ_a	image of the Laplace transform
τ_0	dimensionless temperature term depending only on radial coordinate
χ_1	heat diffusivity of concrete support, m^2/s
χ_2	heat diffusivity of rock mass, m^2/s
χ_t	turbulent air heat diffusivity, m^2/s
ψ	stream function

and shafts depth. For deeper and larger underground mines transient regime will continue for a longer time. Three seasonal experimental investigations of natural draft in mine RU-3 after main fan stoppage in different times of year and different outside air temperatures allowed determination of three different steady-state natural ventilation modes.

The results of springtime experimental investigations (May, outside air temperature +11 °C) have shown that main fan shutdown leads to the air movement reversal. After 15 min downward air movement in the upcast shaft changes its direction to primary, upward direction. As expected from theoretical analysis, after main fan shutdown short-duration air movement reversal occurs in the upcast shaft due to high rarefaction of the air produced by the main surface exhaust fan. But the heavier air column in downcast shaft prevents it and after several minutes recovers previous air movement direction with smaller intensity.

As follows from the results of wintertime experimental investigations (December, inlet air temperature after passing through the unit-heater is equal +2 °C), air motion in upcast and downcast shafts after main fan shutdown is more complex than normal ventilation mode with active main fan. In this case, natural ventilation is represented as superposition of flow-through ventilation "downcast shaft — mine airways — upcast shaft" and convective stratificated air motion, when cold air drops down and warm air flows up.

We have accomplished numerical simulation of air flow in simplified RU-3 mine ventilation network using SolidWorks software in order to analyze convective stratification precesses detected experimentally. Mine RU-3 has three downcast shafts, one upcast shaft and two levels: "−420" and "−620 m". Diameters of downcast and upcast shafts are 7 and 8 m correspondingly. Shaft cross timbers are not considered in the computational model. Analysis of air path lines shows the transient character of large convective eddies in shafts (Fig. 1). Convective eddies length varies in a wide range. Natural draft of entire mine decays after main fan shutdown. But between relatively warm lower level "−620 m" and relatively cold higher level "−420 m" local air circulation appears due to natural draft. Herewith air flow in higher level "−420 m"