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The determination of parameters concerned with heat flow into underground excavations

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THE DETERMINATION OF PARAMETERS CONCERNED WITH HEAT FLOW INTO UNDERGROUND EXCAVATIONS

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March 1968.

SYNOPSIS

In Part I of this dissertation Starfield's two mathematical models which represent an advancing stope subject to linear heat flow and an airway subject to radial heat flow are used in a series of computer experiments with a view to determining trends which will be useful in ventilation planning.

Firstly, the significance of the heat transfer coefficient H and the mass transfer coefficient E as used in a typical stope calculation, is examined. It is found that while the heat pick-up is insensitive to large changes in H, the choice of E is critical.

Wetting down cycles in a stope are next considered and it is shown that controlled wetting down is equivalent to a substantial saving in refrigeration. Deeper level mines are also treated and it is seen that as the virgin rock temperature (VRT) increases so the wetting down technique becomes more and more important.

Finally, the advantage to be gained by insulating an airway as opposed to keeping it wet is calculated. The results show that only extremely high VRT's will justify the expense of insulating.

Part II is devoted to examining the problem of two dimensional heat flow into an advancing stope.

The finite difference approximation proposed by Saul'ev is used to solve the two dimensional diffusion equation for the idealised representation of an underground stope which is taken as a rectangular opening in an infinite plate.

I hereby declare that this dissertation is my own work and that it has not been submitted for a degree in any other University.

M. J. Gould.

M.J.Gould.
April 1968

The choice of boundary conditions is discussed and an error analysis is carried out on the results obtained. Saul'ev's method is found to be extremely fast and reasonably accurate.

Various characteristics of the recurring state are discussed and the effect of wetness in a stope on the temperature distribution in the rock surrounding the stope is examined.

Finally, using Saul'ev's finite difference network together with heat and mass transfer and psychrometry, a complete two dimensional model of an advancing stope, which may be used to calculate wet and dry bulb temperature increases, is formulated.

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CHAPTER 1

Introduction

Ventilation planning in mines is dependent, amongst other things, on a knowledge of heat flow into tunnels and stopes. As mines become deeper the virgin rock temperature (VRT) increases and the necessity for planning ahead becomes more and more acute. Knowledge of heat flow into mines may be obtained in two ways. It may be gained either from empirical studies or from analytical considerations.

In order to obtain laws governing heat flow from experimental observations, it is necessary to process many thousands of observations and adopt a statistical approach. Usually these observations will have been taken over a wide range of conditions, making it extremely difficult to completely separate and account for all the variables involved. Any laws deduced empirically will only be valid within the range of conditions covered, which while useful for current planning do not permit extrapolation to situations which may be encountered in the future.

Underground excavations may be represented by idealised mathematical models. In these models it is desirable to simulate as closely as possible the actual events which occur underground. It is quite obvious that exact simulation will never be possible, but provided that the most significant parameters are included, meaningful results should be obtainable. Once a model has been formulated, extrapolation to any envisaged set of conditions is possible.

We thus have on the one hand an empirical approach, which

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while not confronted with any problems of simulation, does not give a detailed picture of the significance of individual variables or permit extrapolation to different conditions. On the other hand we have a mathematical model in which each variable is clearly defined and on which any conditions may be imposed, but which does not always exactly represent the underground situation. It would thus appear that neither theory nor empiricism alone will suffice and that a combination of the two is required in solving heat flow problems.

Empirical results may constantly be bettered by improving experimental techniques and by collecting data in a way such that in the resulting statistical analysis, variables are isolated as far as possible. An analytical model may be improved by using better simulations of natural phenomena as they become available, and by the addition of further information defining the physical configuration as understanding of the subject increases. Experimental results play a major role in increasing this understanding as does the theory in guiding experimental techniques. Empiricism and theory are thus mutually complementary.

Stopes and tunnels form two distinct problems and the progress towards complete solutions of each must be dealt with separately.

The tunnel is the easier of the two problems as far as the formulation of a mathematical model is concerned. By assuming that the heat flow into the tunnel is radial and by ignoring heat flow parallel to the direction of the tunnel a reasonably good simulation may be obtained.

More than twenty-five years ago Goch and Patterson[1] produced tables for heat flow into a tunnel for an infinite value of the surface heat transfer coefficient H. Several attempts to solve the problem of calculating air temperatures in wet or dry airways have been made[2][3][4][5], but each involved severe approximations or assumptions. The problem of a dry tunnel was solved by van Heerden[6] and independently by Jordan[7], where the effect of the temperature history of the tunnel was included. Starfield[8] obtained quasi-analytic expressions for the flux into a tunnel by a finite strip method and later produced a model for calculating wet and dry bulb temperature increases in an airway[9]. Jordan[10] also formulated a method for calculating temperature distributions in a force-ventilated development end.

Much data relating to airways is available. Two of the most comprehensive surveys were done by Biccard-Jeppe[11] and Lambrechts[12]. From these observations, empirical laws which agreed well with the theory over a limited range, were obtained. Starfield and Dickson[13] showed that by including features such as drains in airway models which were subjected to several different conditions of VRT, wet bulb and dry bulb temperature etc., a scatter similar to that obtained in practice could be generated by calculation.

The stope presents a more complicated problem. It is essentially a rectangular box subjected to two dimensional heat flow. In contrast to the tunnel, which is a long term problem, the stope continually advances, thus making short term effects most significant. A good illustration of this difference is the effect of the dry bulb temperature on heat pick up in stopes and airways. In a stope it may be ignored whereas after a certain time it plays a major role in tunnel problems[14].

The theoretical solution of the stope problem had its origin in a paper by Paire[15], where a stope which advanced by distinct steps (jumps) was first examined. Wiles[16] produced formulae for the continuously moving stope and Concer[17] formulated solutions for smoothly advancing stopes having both circular and elliptical cross-sections. Starfield[8] obtained quasi-analytic expressions for the heat flow into a stope by separating the face and the hangingwall (or footwall) and summing the linear heat flux contributions from these parts. This theory was later extended[18] to include the computation of wet and dry bulb air temperatures in advancing stopes.

Biccard-Jeppe[11] and Lambrechts[19][20] have analysed experimental stope data and again the empirical laws formulated have agreed well with theoretical results in the range covered by the data. Due to the tremendous number of variables inherent in the stope problem it is unlikely that a general model capable of producing absolute results will be produced. However, if some sort of stope temperature history were available it might well be possible to "calibrate" the model for each particular set of circumstances, and hence produce accurate results for future planning.

In Part I of this thesis, use is made of Starfield's mathematical models of a stope[13] and airway[9], in order to examine ventilation procedures occurring underground, in an attempt to obtain trends which would be useful in practical ventilation planning.

The following is an outline of the general model designed by Starfield.

The solution of the complete problem involves the three distinct subjects of psychrometry, heat and mass transfer, and heat conduction in rock. The equations pertaining to each subject will be dealt with in turn.

(a) Psychrometry

Two of the input parameters for the models are the wet and dry bulb temperatures of the ventilating air. Since the theory can conveniently be developed in terms of the absolute humidity w and the dry bulb temperature θ_D, it is necessary to relate the absolute humidity to the wet bulb temperature θ_w. The absolute humidity of the air w may be written

$$w = p/(\mu + \nu\theta_D) \qquad (1.1)$$

where p is the partial pressure of the water vapour in the air and μ and ν are constants depending on the system of units chosen.

The vapour pressure may be written in terms of the wet bulb temperature θ_w as follows :

$$p = p_s(\theta_w) - e\,p_o(\theta_D - \theta_w) \qquad (1.2)$$

where p_o is the atmospheric pressure, e is a psychrometric constant and $p_s(\theta_w)$ is the saturated vapour pressure of the air at the wet bulb temperature. $p_s(\theta_w)$ may be found from steam tables but for computing purposes it is simpler to use a parabola (found from steam tables by a least squares fit) to describe the variation of pressure with temperature viz.

$$p_s(\theta) = a\theta^2 + b\theta + c \qquad (1.3)$$

where a, b and c again depend on the units being used.

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