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A PHYSICAL SCALE MODEL OF FLOWS IN THE WASTE OF A RETREAT LONGWALL COALFACE

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ABSTRACT

A physical model has been developed to simulate the flows and mixing of gases in the waste of a longwall retreat coalface. The model is used in conjunction with computational modelling, and the distributions of permeability and gas emission in the model waste follow those in computer simulations (Pokryszka et al 1996). The physical model represents at 1/70th scale a 200 m long, 3 m high coalface with a waste extending up to 280 m to the face start line. The model is tilted to the same seam slopes as the real face, e.g. 22° ascensional ventilation along the face and 7° slope to the dip. The purpose is to investigate the flow of three components: ventilation seepage flow through the waste; methane; and nitrogen injected to quell spontaneous combustion. A heavier-than-air surrogate gas (SF_6) is used in place of methane, and therefore the model is inverted so that gas layers form along the "roof". The main forces driving the flows in the waste (pressure gradients due to ventilation and the density difference of gas layers) are kept in proportion by appropriate scaling of the permeability. Calibration and validation used data from a coalface at a mine in the Lorraine coalfield. The model is now in operational use.

INTRODUCTION

Background Both physical and computer models are dependent on data from the real mine for calibration and validation. The two types of modelling also assist each other. For example, measurements of ventilation flows in the roadways and face are evidence of the seepage flow through the waste and these data are interpreted by the computer model to produce estimates of the permeability of the waste; these estimates serve, in the present calibration of the physical model, as the specification for the distribution of permeability. Conversely, physical models have traditionally been used to test and develop computer models, e.g., Sorbie et al (1990). Once consistency between the two types of model has been demonstrated (or differences satisfactorily explained), then greater confidence can be placed in results from modelling changes in mining or ventilation conditions. The computer simulations may be more readily suited to varying some parameters such as face length. Conversely, there may be situations where the results of the physical model appear more realistic.

The mines in the Lorraine coalfield have faces with steep slopes, significant gas emission from the waste, and are prone to spontaneous combustion; hence the importance of effective control of the circulation of gases (air, methane, and nitrogen used to quell combustion) within the waste. As part of a programme of studies intended to provide information which will aid ventilation engineers to make optimal use of the resources at their disposal, an aerodynamically scaled model has been developed, calibrated and validated in conjunction with a computer model used at INERIS to simulate the flows through the waste (Pokryszka, 1996).

This paper describes the aerodynamic scaling, the structure of the physical model, results of tests to calibrate the model to the conditions on a particular French coalface (DORA 1 SUD), and initial tests using the model to examine the consequences of changes in the techniques used for control of gas or spontaneous combustion. The validation included measurements of transit times across the waste for comparison of the model with the real waste underground, thereby indicating whether similar distributions of velocities apply across the model and real wastes.

Objectives The objectives were to design, construct, calibrate, validate a physical model representing the entire zone of the waste, with aerodynamic scaling of the forces included in the computer simulations (ie., pressure gradients due to ventilation and gas density differences, and the resistance of the face and waste). The model was intended to be small enough so that important features (e.g., seam slopes) could be changed to represent different situations. This is possible with a 1/70th scale model, as described below, although it unavoidably involves sacrificing the completeness of the aerodynamic scaling of the flows on the face (Jones and Lowrie, 1995).

SCALING RELATIONSHIPS

Physical Processes Controlling the Flow and Dispersion

The flow and mixing of gases within the waste are controlled by:

- inertial dispersion - a function of the Reynolds number ($R_e=ud_g/v_a$) and occurs at R_e > about 2;
- dispersion by molecular diffusion - a function of the Peclet number ($P_e=ud_g/D$);
- pressure gradients - produced by the main ventilation and by differences in the density of the gases (due to both temperature and composition).

The Reynolds number and Peclet number are functions of the velocity of the seepage airflow through the waste (u), the nominal grain diameter (d_g), and respectively, the kinematic viscosity v_a of air and the coefficient of diffusion of the emitted gas (D).

The structure of the waste affects the relative importance of these processes; in principle, the model waste could represent a real waste where there are either fissures between large blocks of rock or a relatively homogenous bed of crushed granular material. In the first instance, the latter was chosen because it aids straightforward comparison with the computer models which treat the waste as a permeable material.

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Similitude of Flows for the Seventieth Scale Model

Since the internal structure of the real waste cannot be specified exactly, only indirect estimates were available for the nominal diameter of grain or fissure; hence the Peclet and Reynolds numbers also could only be order-of-magnitude estimates. Consequently, the main conditions for attaining similar flow in the model were that:

- the pressure gradients due to ventilation or gas density should be scaled by the same factor;
- the relative locations in the waste where inertial and diffusive mixing dominate should be similar; and
- the effect of molecular dispersion should not become disproportionately large in the reduced scale model.

Scaling factors fulfilling these requirements were derived (Jones and Lowrie, 1995) and are summarised in Table 1. This scaling includes the effects of density due to gas composition (e.g. methane vs air), but not temperature differences; as was the case for the computer model (Tauziéde et al, 1993).

Table 1. Summary of the scaling factors for the 1/70th scale model with SF_6 used as a surrogate for methane

PROPERTY	SCALING
Reynolds number ud_g/v_a	constant
Peclet number ud_g/D	3 times larger
nominal grain size d_g	× 0.48
velocity u	× 2.1
permeability K	× 0.23
geometry, face length L and face height h	× 1/70
transit time L/u	× 0.0068
Peclet number uL/D	10 times smaller
flow uL^2	× 4.3 × 10^{-4}

The scaling of the flows between full scale and model by x 4.3 x 10^{-4} (as in Table 1) means that a flow of 10 m^3s^{-1} in the full scale becomes 4.3 litre per second, or 260 litres min^{-1} in the model. A typical district ventilation flow of 30 m^3s^{-1} becomes 774 litres min^{-1}.

With these scaling factors for the geometry, permeability and velocity, the Reynolds number (defined in terms of the nominal grain diameter) is kept constant. (The permeability is dependent on the grain size, Dullien (1975)). In principle, this constant Reynolds number should preserve the contribution made by inertial mixing to the dispersion at any given location in the waste. The above specification also maintains the pressure gradients, due to the difference in density (either between methane and air or between SF_6 and air) and due to the ventilation respectively, in correct proportion. The transit time through the model is scaled down with both the change in velocity (x 2.1) and the reduction in geometrical scale, i.e., by 6.8 x 10^{-3}. Thus, for example, a transit time for flow though the waste of 10 hours in the full scale becomes approximately 4 minutes in the model. The effect of molecular diffusion, although not kept fully in proportion to this transit time, remains relatively insignificant during transit times as low as this. In the waste, the product ud_g is kept constant in preserving the Reynolds number for the ventilation flow through the waste. Therefore, the Peclet number ud_g/D (relevant to comparing the significance of molecular diffusion to the inertial mixing) changes in proportion to D which becomes the value for the surrogate gas (SF_6). This means that the Peclet number (based on the nominal grain diameter) is larger in the model waste than in the full scale waste by a factor of about 3. So the relative locations in the waste where the mixing of gases becomes dominated by either inertial or diffusive processes should be similar for the model and the full scale.

The Peclet number based on the grain size is informative about the relative locations of inertial and diffusive mixing. However, a Peclet number can also be calculated from the dimensions (i.e. length L or height h) of the coalface (which are scaled down by a factor of 1/70th) as a basis for comparing the rate of transport by the flow with that by molecular diffusion. This gives a Peclet number uL/D which is approximately ten times smaller in the model than in the full scale. So the effect of the seventy fold reduction in geometric scale (which would tend to increase the significance of molecular diffusion) has been ameliorated by the increase in velocity and the use of the surrogate gas (with a lower diffusion coefficient). Consequently, mixing by molecular diffusion is still relatively slow in the small scale model.

Given the various uncertainties involved in estimating the conditions in the real waste, there appears to be sufficient resemblance between the flows in the full scale and in the model.

MODELLING THE FLOW OF THREE GASES

Densities of surrogate gases With SF_6 as a surrogate gas for methane, the density difference and the consequent pressure gradients are scaled by x 9.3. A surrogate gas can also be used in place of the nitrogen in order to produce a proportionate increase in density difference. For example, the difference (0.04 kg m^{-3}) between the densities of air (1.29 kg m^{-3}) and nitrogen (1.25 kg m^{-3}) could be scaled up approximately by x 9.3 (and inverted) with the selection of argon (1.70 kg m^{-3}). However, it has been reported by INERIS that the nitrogen at the point of injection is typically 10°C cooler than the ambient air temperature. This temperature difference is sufficient to reduce the density difference between air and nitrogen to zero, near the point of injection at least! In this situation, the model could be used with one and then the other in order to investigate the effect of this order of difference in density.

Measurement of Gas Concentrations

The experimental procedures developed for determining the concentrations of 3 components (ventilation air, injected nitrogen/argon, and the emitted SF_6) used infra red absorption to measure the concentrations of the two injected/emitted components. However, neither nitrogen (N_2) nor argon (Ar) are detectable with the infra red gas analyzer; consequently, a tracer gas mixed with the nitrogen/argon was used as a marker of the gas concentration. Ethane (C_2H_6) was chosen as the tracer because:

- its molecular weight of 36, and therefore its coefficient of molecular diffusion, are of the same order as those for N_2 (molecular weight 28) or Ar (molecular weight 40);
- it is measurable at an infra red wavelength which does not interfere with the measurement of SF_6.

At a concentration of approximately 3% in nitrogen or argon,

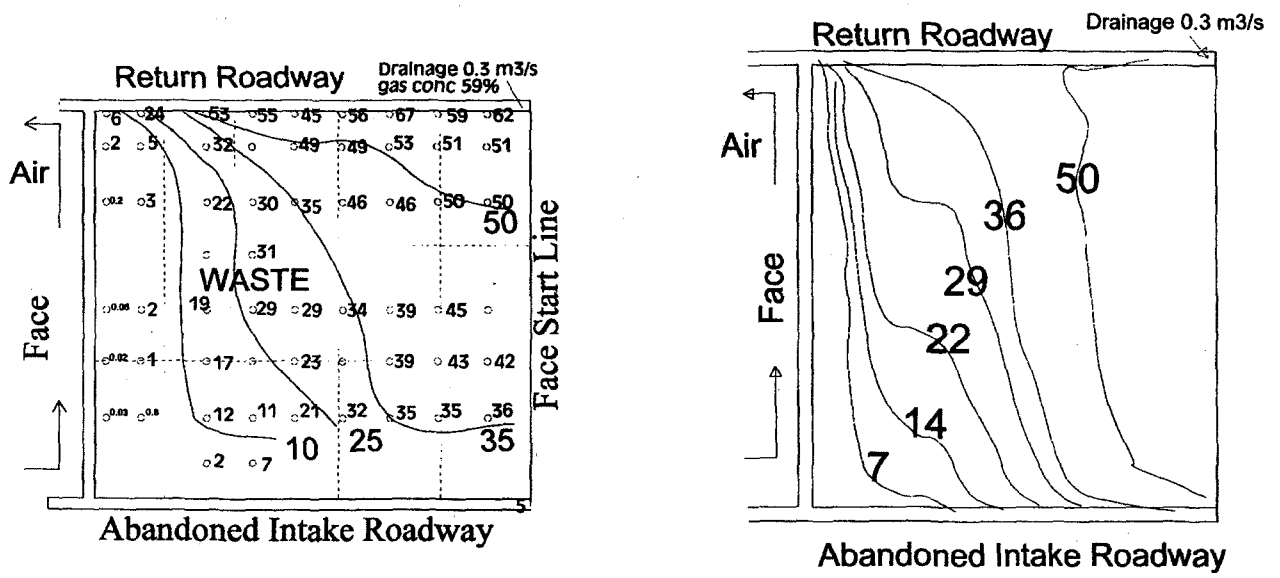

Figure 1: 1a Concentrations Measured in the Physical Model; 1b Concentrations in the CFD simulation.

the level of tracer is high enough for the gas analyzer to yield the measurements of interest but also low enough to ensure that the ethane does not create any risk of explosions (or the constraints associated with working with flammable gases).

DESIGN AND CONSTRUCTION OF THE MODEL

The model comprised a rectangular box structure with an open channel representing the face and the (4 m x 3 m) zone representing the waste filled with granular material of appropriate permeability, and with gas injection lines.

The 1/70th scale model required a tilting support table similar to that built for a 1/30th scale model (Jones and Lowrie, 1993). The tilting system consisted of two large hydraulic pistons which could raise one or the other end of a lower frame to produce angles of up to 35°; this lower frame held four smaller pistons acting in pairs to produce a transverse slope for the upper frame holding the model.

PREPARATION OF THE 1/70TH SCALE MODEL TO REPRESENT DORA 1 SUD

Main Characteristics of the face to be simulated

The characteristics of the face to be simulated were defined by measurements made at DORA 1 SUD; this specification included: (i) face on a slope of 22° and mining at 7° to the dip, and with ascensional ventilation; (ii) drainage (of 0.306 m^3s^{-1}) from a chamber on the intersection of face start line and return roadway; (iii) ventilation flow of 31.5 m^3s^{-1}; (iii) gas emission into the waste of 0.68 m^3s^{-1}; (iv) face at approximately 220 m from the face start line; (v) face-length treated as approximately 200 m (actually 240 m); and (vi) a pressure gradient along the face estimated from data from a similar face.

Consistency with the Computer Simulation

Preparation of the physical model to represent the distributions of permeability and gas emission for DORA 1 SUD as estimated from the computer simulation involved:

- approximating the continuous distribution of permeability (of the computer simulation) by zones of selected materials of fixed (different) permeabilities;
- obtaining the range of permeabilities by preparation and measurement (of the permeability) of a range of suitable materials;
- approximating the continuous distribution of gas emission by point sources from the smallest practicable orifices in pipelines in the base of the waste;
- spacing the orifices in the injection pipes to produce approximately the same variation with distance from the face;
- placing the injection pipes parallel to the roadways, and at intervals calculated to give the specified distribution of emission with distance from the roadways;
- supplying gas (SF_6) injection flows to 17 zones of the waste, with each zone monitored independently by rotameters;
- injecting gas along the coal face, simulating emission from the uncut coal seam.

EXPERIMENTAL MEASUREMENTS

Experimental measurements on the model comprised:

- ventilation flow, total and on the face, by pitot static tube and dilution of tracer gas;
- pressure differences across the waste and face, with a micromanometer attached to an array of needle probes;
- injection flows, with calibrated flow meters;
- gas samples, collected from the waste using an array of 50 needle probes;
- transit times for the flow across the waste, with helium as a tracer gas (Pokryszka and Tauziède, 1995);
- after calibration and validation, gas concentrations illustrating the model's use in simulating nitrogen injection at two alternative sites and three flows.

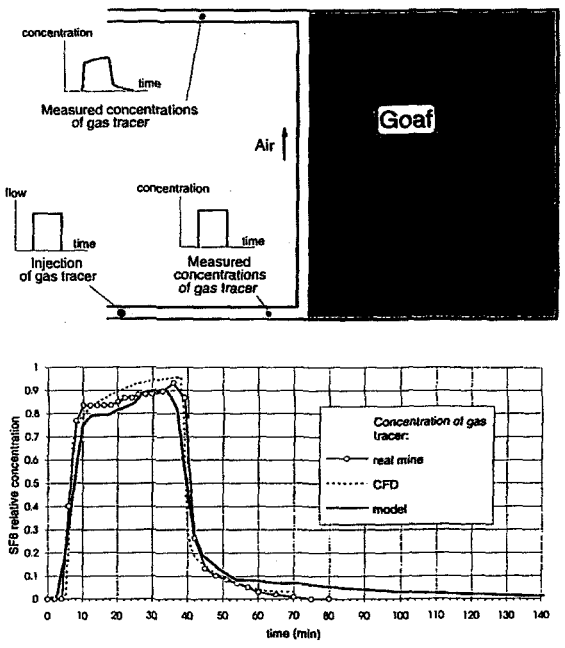

Figure 2. Deformation of a rectangular pulse of tracer by the ensemble of the face and waste.

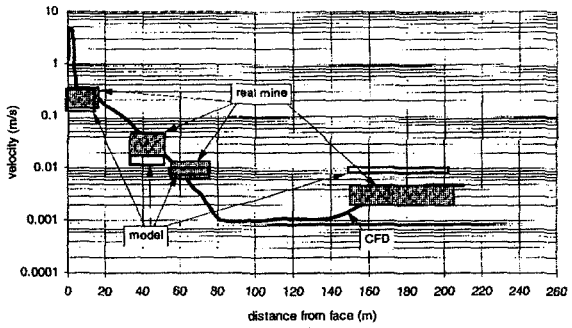

Figure 3. Order of magnitude of velocity across the waste as a function of distance from the face, as estimated from transit time measurements in the real mine, in the model, and by CFD simulation.

RESULTS

Flows and Pressure Gradients

The model was operated at the target flows for the ventilation, gas emission, and drainage. The pressure gradient along the face was consistent with the estimated approximate target.

Concentration Distributions

With the model operating at the specified flows, the concentrations were measured at the array of sampling points in three test runs, giving repeat samples at some of the sample points. Consistency appeared reasonably good between runs; therefore, the concentrations in Figure 1a are averages (where available). Figure 1a show the data for each sampling point and the curves indicate the main trends. Figure 1b illustrates the comparable trends calculated from the computer simulation of the same face. The computer simulations are readily adjusted to the real face length (of 240 m), whereas the physical model was equivalent to 200 m. Nevertheless, the main trends in the concentrations can still be compared between Figure 1a and Figure 1b. Importantly, the general trends appear sensibly consistent.

Characteristics of Velocity Distributions

Transit Times The transit time measurements were used to characterise the distribution of velocities around the face and waste. Depending on where the tracer pulse was injected and where the passing pulse detected, the signals either characterised the distribution of velocities for the entire ensemble of face and waste, or gave a direct estimate of velocity across the waste at a given distance from the face. Figure 2 shows the deformation of a rectangular pulse of tracer due to the range of different transit times involved in the passage of a pulse of tracer across the ensemble of face and waste. The data points indicate the measurements taken underground (with observation points at finite intervals as samples were taken and subsequently analyzed); the curve of continuous readings taken from the experiment in the model follow a very similar shape; and the CFD simulation also gives a similar predicted response.

Velocity Distribution for Flow in the Waste The transit times measured with injection and sampling points respectively in the abandoned intake and abandoned return roadways, and each at the same distance from the face, were used to estimate velocities across the waste at given distance from the face. The values estimated from measurements underground, from measurements on the model, and from CFD simulations, are shown in Figure 3. The two sets of experimental data show similar dependence on distance from the face. The CFD simulation shows the dependence as a continuous function with velocity diminishing with distance from the face , eventually reaching a minimum level at about 80 m from the face where the waste is expected to be fully compacted. Near the face start line, the compaction of the waste is less complete, and the velocity above the minimum level. This form of the dependence for the CFD simulation was supported by comparisons with other experimental data from the real face at a later stage in its working when the waste had extended further, and from other faces investigated.

Example of Application of the Model Once the above results had supported the consistency of the model with the full scale, a series of simulations (Jones et al, 1995) were undertaken to assess how the effectiveness of nitrogen injection would depend on site and rate of injection. This included injection at two alternative points in the intake abandoned roadway: (equivalent at full scale to) 25 m or 90 m from the face; and each at three flow rates (0.3, 0.6 and 1.2 m^3s^{-1}). The results showed that the increase from the lowest flow rate produced a large increase in the area of the waste where the nitrogen injection reduced the air (and hence oxygen) concentrations to below the level needed to support combustion. However, further increase in nitrogen flow had relatively little effect on the concentration profiles. The concentration profiles fitted to the data (for concentrations at the array of sampling points) from the tests at the lower flows (0.3 and 0.6 m^3s^{-1}) are shown in Figure 4. The form of the dependence estimated from the CFD simulations is also very similar (Pokryszka et al, in press).

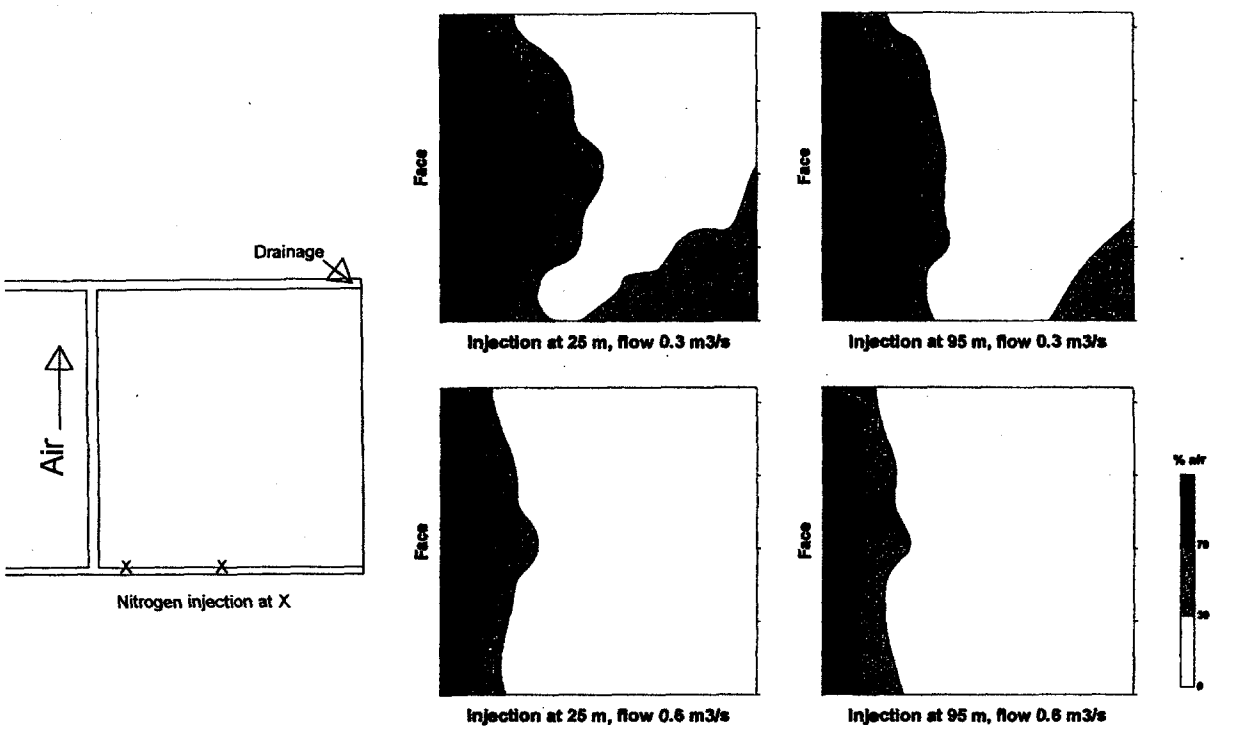

Figure 4. Map of the concentrations of air in the waste by fitting contours to the data from experiments with nitrogen injection in the seventieth scale model.

DISCUSSION

Calibration and Validation

The main points for comment concern the physical effects which have been taken into account in the scaling, the information on which the 1/70th scale physical model is based, its consistency with both the real mine and the computer simulation, and the scope for its application.

The flows have been scaled for the effects of the ventilation pressure, pressure due to the density difference of gas layers associated with differences in gas composition, the inertial and molecular dispersion in the waste, the permeability of the waste, and the resistance of the face.

The information from a computer simulation (Pokryszka et al, 1996; Tauziède et al, 1993) provided the best available definition of the distribution across the real waste of both gas emission and permeability and the model was prepared to match these specifications. The resultant pressure gradient across the model was shown to be consistent with pressure gradients estimated from underground data (from ERNA 3 NORD and DORA 1 SUD).

The proportion of flow entering the model waste was similar to that in the full scale (approximately 85% of the ventilation on the face at its mid-point).

The data for the gas concentrations in the model showed satisfactory repeatability between repeat tests.

Comparison of the concentrations in the waste between computer and physical model is affected by the way the computer model treats the seam as being two dimensional whereas the physical model has a finite depth, so that data from the computer are always average concentrations whereas data from the physical model are mid-seam concentrations. Nevertheless, the form of the concentration distributions in the waste were qualitatively similar for the physical model and the computer simulation (Pokryszka'et al 1996, Tauziède et al, 1994).

Probably the main limitation of the 70th scale model is that the flows on the 1/70th scale model face were not scaled for the effects of gas layering, and the model face was a simple open duct with the resistance to give the right balance of flows between face and waste. The exchange of gas between model waste and model face produced a relatively slower increase in concentration towards the return end of the face. However, such interchanges would be more suitable for modelling at the 1/30th scale: calibration and validation a thirtieth scale model is in progress.

In summary, the operation of the model has shown that with permeabilities spanning a thousand fold range (10^{-8} to 10^{-5} m^2) and gas emission flux varying over a 7 fold range, the concentrations obtained in the model were of similar magnitude to those in the full scale and the transit times for flows through the waste were shown to be consistent with the scaling of the transit times for the full scale waste.

The Example of Application

The nitrogen injection simulations show some marked differences between injection rates and injection sites. For example, it appears that injection of a low (0.3 m^3s^{-1}) nitrogen flow at 25 m from the (full scale) face will probably be inefficient as the concentration of air is reduced only in a relatively small zone. With injection at 95 m from the face, the low injection rate produced a larger area of high nitrogen concentration (and low air concentration) in the low permeability core of the waste. With injection at 0.6 m^3s^{-1}, the area of low air concentrations became larger, and the critical

zone of rapid change occurred near the periphery of the lowest permeability zone (equivalent to about 70 m from the full scale face). Further increase in nitrogen flow caused relatively little change in the zone of inertisation.

CONCLUSIONS

The main conclusions are:

- an aerodynamically scaled physical model of the flows in the waste has been successfully designed, calibrated and validated in comparison with data from a real coalface and with consistency with a computer simulation of the same face;
- simulations in the model have indicated how the effectiveness of nitrogen injection depends on the site of injection and the flow used; and, again, the predicted trends showed consistency with those predicted from the computer simulations;
- the model is suitable for use in further simulations;
- the results of these initial simulations illustrate the use of the model in providing information to help engineers make optimal use of available resources.

THE FUTURE

The model described above was designed and constructed at the Institute of Occupational Medicine (IOM), following a related programme of work for the European Coal and Steel Community (ECSC) and British Coal which had produced the design and construction of a similar model representing the flows on the face in more detail, including the effect of gas density on dispersion of gas (Jones, 1994; Jones and Lowrie 1994a, 1994b). This earlier model is designed for use as a twentieth or thirtieth scale representation of a coalface and waste.

After the measurements described above, the seventieth scale model has been transferred to Charbonnages de France and is now utilized for simulations. For example, recent simulations have further examined the dependence of the effectiveness of nitrogen injection on the site of injection; these confirmed that, for the conditions at DORA 1 SUD as investigated above, injection at 25 m from the face is less effective than at approximately 100 m, and have indicated that injection at 50 m is as efficacious as at 100 m. The gas concentrations in the 1/70th scale model are now sampled from 64 sampling points with an automatic sequencing system, and the concentrations are measured directly on line.

The thirtieth scale model remains at the IOM and has recently been calibrated to operate as a physical analogue of computer simulations.

Further investigations using both these physical models and the linking element of the CFD simulations are in progress and will be reported in due course. The available results of the CFD simulations are also currently being reported, e.g. (Pokryszka et al, in press).

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