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CFD SIMULATION OF UNDERGROUND COAL DUST EXPLOSIONS AND ACTIVE EXPLOSION BARRIERS

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ABSTRACT

Computational fluid dynamics (CFD) is being applied to the study of coal dust explosions and their suppression in underground coal mines. As part of an ACARP funded project to develop a practical active explosion barrier, CFD is being used to simulate the explosion dynamics in simple mine roadways before examining the design requirements for an active explosion barrier. Results of these simulations will be used to develop the specifications for a prototype active explosion barrier with a reduced requirement for large scale testing.

Results to-date are very encouraging with validation of the model behaviour against a range of explosion conditions in the Simtars Siwek 20 litre chamber and the CSIR's 200 m explosion tunnel in South Africa. This paper presents the results of a number of simulations with comparison against data obtained from the 200 m tunnel and preliminary modeling of an active barrier.

This modeling provides an opportunity to examine explosion dynamics at a level not seen before.

INTRODUCTION

Coal dust explosions have always and will continue to represent the most significant hazard in an underground mine. Much effort has been expended in developing methods of prevention and suppression and these generally centre on the use of passive processes, such as adding stone dust to accumulations of coal dust to prevent its ignition. Traditional methods of investigating underground explosions have generally been limited to observations of staged explosions in facilities such as Bruceton (USA), Buxton (Britain), Barbara (Poland), Tremonia (Germany) and Lake Lynne (USA) experimental mines or the Kloppersbos (South Africa) explosion tunnel.

Many of these facilities are now closed and, despite the undoubted value of the knowledge gained from their operation, there is still much to learn regarding the nature of coal dust explosions and their suppression.

One aspect of research pursued by SkillPro at the Kloppersbos facility in South Africa was that of the demonstration and development of an active explosion barrier. With support from ACARP, Projects C8010 [1] and 9008 [2] did produce a successful result in showing the operation of a system to extinguish a coal dust explosion with an electronically initiated system of suppression dispersal ahead of the explosion flame. For various reasons it was not possible not to progress the demonstration. There was however a significant desire in Australia to continue the research effort in this area. It was therefore proposed to develop Computational Fluid Dynamics methods for modeling of coal and methane explosions in underground coal mines and ultimately the performance of active explosion barriers in an effort to minimize the large scale testing required for these systems. ACARP has again supported the work described here and BMT WBM has collaborated with SkillPro in the development and analysis of the modeling and its outcomes.

METHODOLOGY

Any numerical modeling effort is only as good as the accuracy of the predictions it is able to make. For the purpose of this project, a substantial selection of test results for explosions carried out in the 20 litre Siwek spherical chamber at Simtars and CSIR Kloppersbos explosion tunnel in South Africa was available for validation purposes. In earlier ACARP funded projects (C8011 [3] and C9011 [4]), SkillPro had investigated the minimum inerting requirements of a range of Australian coals using the small scale 20 litre chamber and the 200 m long explosion tunnel. It was decided to make use of this data to validate the CFD model developed by firstly modeling the Siwek chamber dispersal and explosion and then to repeat the process with the data from the Kloppersbos tunnel. It was considered essential to obtain reasonable agreement with the modeled and actual explosion characteristics with these methods of testing before proceeding to modeling of active explosion suppression systems.

The Kloppersbos Explosion Tunnel

As the modeling of the Siwek chamber was an intermediate step in the model development, the 20 litre chamber will not be described in this paper, but it is desirable for the reader to understand the nature of the Kloppersbos facility. Consisting of a steel pipe 200 m long and 2.5 m diameter, the explosion tunnel is mounted on concrete blocks on the surface (Figure 1). Originally developed by Cook [5], the tunnel has been used to examine the minimum inerting requirements of coals from South Africa and Australia, the suppression of coal dust explosions by the CSIR bagged barriers and active explosion systems. The tunnel is equipped with a series of pressure and flame transducers at regular intervals along its length to allow analysis of the explosion characteristics.

(a) Aerial view (b) Tunnel exit

Figure 1: Kloppersbos explosion tunnel, Pretoria, South Africa

Explosions are staged by igniting a small zone of methane/air mixture at the closed end of the tunnel (Figure 2). This lifts up and provides the ignition source for various combinations of coal and coal/stone dust mixtures distributed inside the tunnel. The configuration commonly used to test inerting requirements is the "double strong" explosion in which 35 kg of pulverised coal is loaded on six shelves (three on each side of the tunnel) between 20 m and 50 m from the closed end. This is repeated for a second set of shelves running from 64 m to 94 m from the closed end. To examine the minimum inerting requirement of a coal, a mixture of progressively higher incombustible content is loaded onto the second set of shelves until there is no flame propagation through this zone.

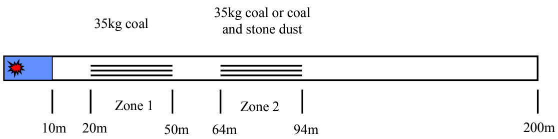


Figure 2: Kloppersbos tunnel layout – double strong coal dust explosion (not to scale)

Another type of explosion is the "seminar" explosion in which the same quantity of coal is placed on the floor of the tunnel. This explosion is used on industry training days and always produces a spectacular result (Figure 3).

Figure 3: Results of a "seminar" coal dust explosion at Kloppersbos

The most recent efforts in this project have been aimed at validating the modeling outcomes against the results of a wide range of "double strong" explosion results gathered during ACARP Project C9011 [4] and then proceeding to examining the performance of a water based active barrier in a "double strong" explosion.

MODEL DETAILS

The CFD model is detailed and complex. The full description of the theory and mathematics is beyond the scope of this paper. In this section we present a brief summary of the content of the model without going into mathematical details

Compressible flow solver

At the heart of the CFD model is a transient compressible flow solver evolving total gas density, temperature, pressure and velocity all as a function of time. The k-epsilon Reynolds Averaged Stress turbulence model is employed. The OpenFOAM CFD libraries were utilised, as access to the source code was essential for this work.

Gas chemistry

Kinetic gas phase chemistry and coal char surface reactions with oxygen deliver the energy required for the ignition and propagation of a coal dust explosion. The majority of the gas phase chemistry is related to the combustion of CH_4 and H_2 with oxygen to produce CO_2 and H_2O. This process is modeled by tracking mass fractions of N_2, O_2, CH_4, H_2, CO_2, and H_2O of the total gas density on a cell-by- cell basis, and employing the simplified single step irreversible reactions:

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$$
$$2H_2 + O_2 \Rightarrow 2H_2O$$

Single rate Arrhenius equations are used to describe the molar conversion rates for these two reactions, with the equation coefficients tuned to yield the correct laminar flame speeds for these reactions at stoichiometric fuel-air ratios and standard temperature and pressure.

More advanced chemistry models are possible but are not realizable given computational constraints. The above simplified models yielded good pressure-time comparisons against test data for the combustion of CH_4 and H_2 within a 20 litre Siwek spherical test chamber.

Coal dust

The evolution of position and velocity of particles of coal dust is calculated by integrating the velocity and acceleration of the particles. The acceleration of the particles is computed using the relative velocity between the particles and the gas, and a drag model which transitions from Stokes law at low Reynolds numbers to constant drag coefficient at high Reynolds numbers.

The evolution of the temperature of the particles is calculated using the Ranz-Marshall heat transfer model and the difference in temperature between the particles and the local gas around them. Heat input/loss from the particles due to radiation effects (see below) is also accounted for.

Both the momentum and thermal coupling between the particles and the gas is bi-directional. Total momentum and enthalpy of both particles and gas is conserved.

The devolatilisation of the coal particles is modeled with a single kinetic rate equation of Arrhenius form. All volatile species are assumed to evolve at the same rate. This is known not to be the case in reality, but this reduction in complexity is not considered to be detrimental to the model.

The surface oxidation of the char particles is modeled with a single kinetic rate equation [6]:

$$C + O2 \Rightarrow CO2$$

The rate of reaction is proportional to the square root of partial pressure of O2 at the particle surface (i.e. the reaction is of order 0.5), which is factored down from that in the far field according to the diffusion law and also the emission of volatiles from the particle. Importantly, the energy yield of the reaction in the first instance heats the particle and not the far field gas. The temperature of the particle is then controlled by the conduction and radiation heat transfer processes.

As the coal particles are only microns in size, it is not possible to track the evolution of every individual particle of coal, as there are billions of particles. Instead, the evolution of a computationally more tractable number of "parcels" is modelled, where each parcel represents a collection of individual particles. The exchange of momentum, heat, and gas species with the gas phase is scaled according to the number of particles within a parcel.

To model the physical process of entrainment of the coal dust from the floor of a tunnel or roadway into the gas flow within the CFD simulation would normally require a very fine mesh near the coal laden surface in order to resolve the flow boundary layer. This represents a significant computational expense that may be avoided through the use of an entrainment model. Such a model was developed for these simulations, in which the addition of new dust particles into the (coarse) layer of cells adjacent to the wall is governed by the flow velocity and the dust loading already present in the cells. It appears to yield an intuitive result in the animations, and has not presented a stumbling block with regard to model calibration against available test data.

Radiation field

The transfer of energy ahead of the flame front by means of radiation plays an important role in a dust explosion. Radiative heat transfer is accounted for using the "P1" model in which the radiation intensity is assumed to be isotropic, and its distribution is diagnostically solved at each time step according to the volumetric absorptivity and emissivity of the dust cloud and gas phase combined.

Water spray

The evolution of droplets of water injected in the vicinity of the flame front is solved in much the same way as for the coal particles. Again the parcel approach to modeling particles is employed, but the devolatilisation and surface reaction models are replaced by an evaporation phase change model. Again total mass, momentum, and energy for both water droplets and gas are conserved.

The evaporation model used is based on that of Bird et. al. [7]. Of particular importance is the effect known as "Stefan flow" in which the evolution of gaseous vapour from the particle surface acts to shield the particle from the thermal conduction processes heating the particle. Hence the temperature of a droplet of liquid injected into a hot gas flow asymptotes to the boiling point of the liquid as it progressively shields itself from the hot gas. Neglecting this effect can cause the cooling effect of the liquid spray to be overestimated by a factor of 4 or more

CFD mesh

The CFD model uses a three dimensional (3D) hexahedral mesh of the tunnel with a cylindrical expansion volume at the end of the tunnel to provide a realistic representation of the pseudo wave-transmissive pressure and velocity boundary condition that exists at the end of the tunnel. Figure 4 shows the cross-section of the main tunnel mesh, which is duplicated at 0.125 m intervals for the length of the tunnel, totalling over 300,000 cells including the expansion volume. A plane of symmetry on the centreline of the tunnel was utilized.

The cells highlighted in blue in Figure 4 are voided to create the shelves on which the coal dust and stone dust is placed for the "strong" explosions. The shelves in the test facility are constructed of wire mesh, hence they will provide some resistance to the flow in the longitudinal direction, but offer little resistance in the vertical direction. This aspect was represented in the CFD mesh by "perforating" the shelves with a 50/50 duty cycle for cells voided / cells present.

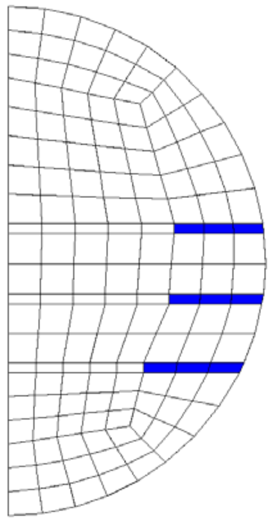


Figure 4: Tunnel mesh cross-section

Computational considerations

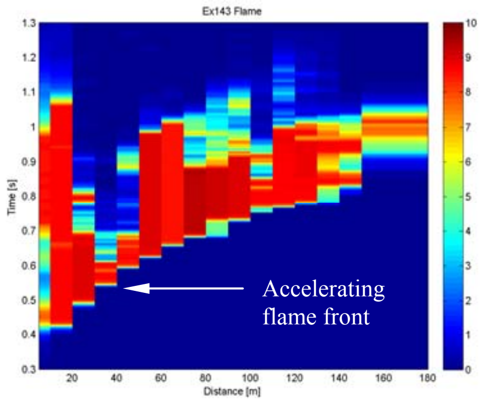
The CFD mesh is not large by way of CFD models, but the fine dust particles require a small time step to follow the fast time scales at which the heat transfer and combustion processes occur. The large number of time steps combined with a moderate size CFD mesh, chemistry calculations, and tracking hundreds of thousands of dust parcels, has necessitated the running of the model on a large multiprocessor computer.

RESULTS

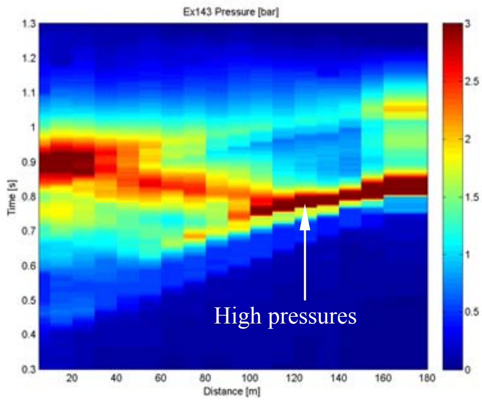
Calibration

Prior to modelling the Kloppersbos tunnel, a significant amount of effort was directed to modeling coal dust combustion within a 20 litre Siwek spherical chamber. Having obtained reasonable calibration with test data the work progressed to modeling the Kloppersbos tunnel.

Figure 5 shows flame sensor and pressure transducer data during a typical "double strong" test in which coal dust is loaded onto the shelves in both fuel zones. The salient features to note are the accelerating flame front (curvature in the distance-time domain) and the high pressures beyond the second fuel zone. Also note that the flame sensor data is presented in volts as sampled by the instrumentation system as there is no known calibration to either gas temperature or radiation intensity. From the photocell datasheet and the circuit geometry we estimate that 5 V output corresponds to the range of about 1500-1600 K black body temperature within the tunnel, but this has not been confirmed.



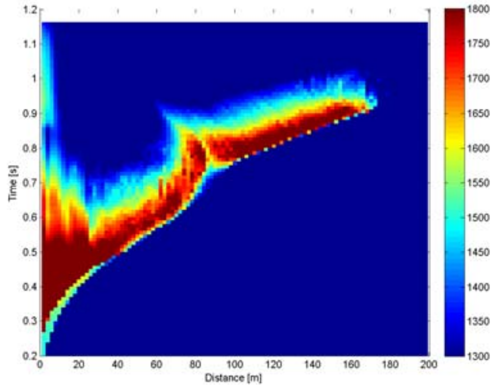
(a) Flame sensors [V]



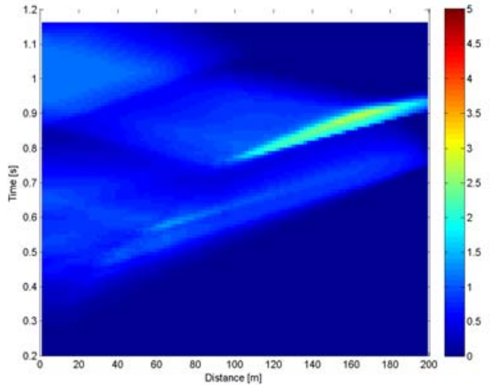
(b) Pressure [bar

Figure 5: Typical test “double strong” results

Figure 6 shows the results of the CFD model in the same format, except now the temperature is in Kelvin direct from the model. The salient features of accelerating flame front (in the early stages of development) and pressure pulse beyond the second fuel zone are present. Further improvement in calibration may perhaps be obtained with improved dust entrainment models, better coal combustion models, more detailed chemistry, and so on. However, the authors are of the opinion that the CFD model is of sufficient accuracy to allow investigations into active barrier concepts, bearing in mind that any promising concept will be significantly tested against real explosions during its development.



(a) Gas temperature [K]

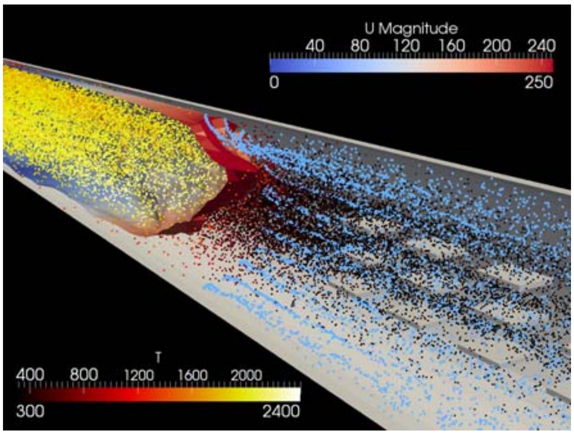


(b) Pressure [bar]

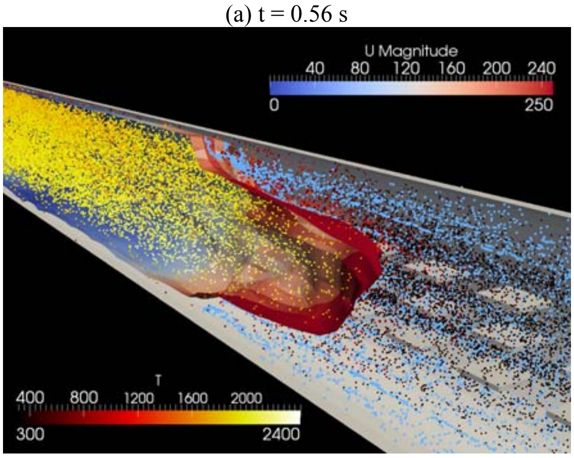
Figure 6: Simulated “double strong” results

Active barriers

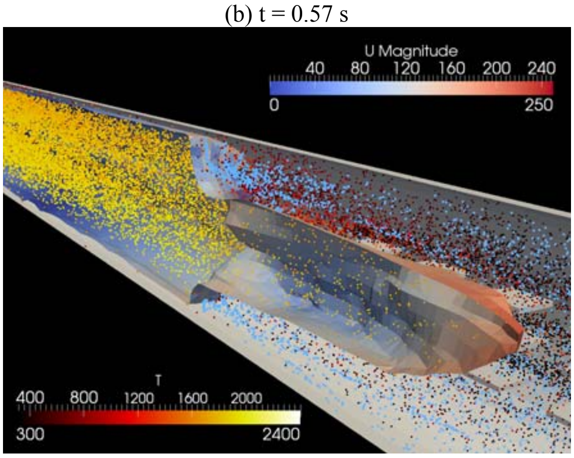
The first active barrier concept modeled was that of a ring of water injectors located at 60 m down the tunnel, just before the second set of shelves. Figure 7 illustrates the results of the CFD simulation from t = 0.56-0.59 s, just as the flame front passes through the injector ring. The coal dust is coloured with the black body radiation spectrum in Kelvin (lower left scale), and the water droplets are blue. The iso-surface is a temperature contour marking the approximate position of the flame front, coloured according to gas velocity in m/s (upper right scale). The dynamics of the flow are striking, particularly the motion of the water sprays as they cool the passing flame front.



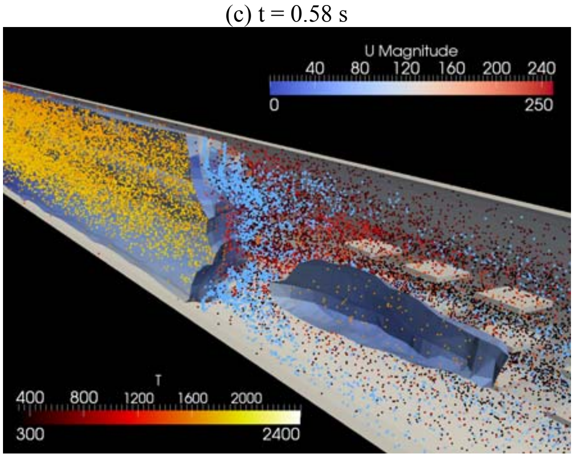
(a) t = 0.56 s



(b) t = 0.57 s



(c) t = 0.58 s



(d) t = 0.59 s

Figure 7: Initial active barrier concept

Figure 8 shows temperature contours as a function of distance and time for this single ring active barrier geometry, with mono-disperse droplets at 20 µm and 200 l/s volume flow rate into the tunnel. The temperature data was sampled on a line near top of the tunnel funning from 0-200 m. As can be seen the ring suppresses combustion in its local vicinity, but a bubble of hot products passes through allowing the flame to extend into the second fuel zone from which the explosion is re-established.

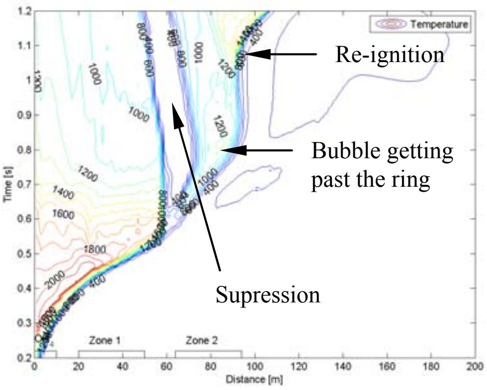


Figure 8: Single ring, 20 µm droplets, 200 l/s flow rate

The obvious route to improving the performance of the barrier is to increase the volume flow rate. But before resorting to brute force, we wished to investigate the effect of spray geometry on the performance of the barrier. Figure 9 shows the results for a triple ring active barrier geometry, with mono-disperse droplets at 100 µm and 200 l/s total volume flow rate into the tunnel. In this model the rings were spaced 10 m apart and only occupied the upper two thirds of the tunnel to better represent what may be more practical for use in a real roadway. The explosion is successfully prevented from propagating beyond the second fuel zone, and this for the same total flow rate and larger droplet size than the single ring design.

The effectiveness of the barrier is strongly dependent on the droplet size in the spray. Theory predicts that for a given volume flow rate, the total evaporation rate is inversely proportional to droplet diameter squared. Hence if the droplet size can be halved the barrier need only inject water at a quarter of the rate to be equally effective.

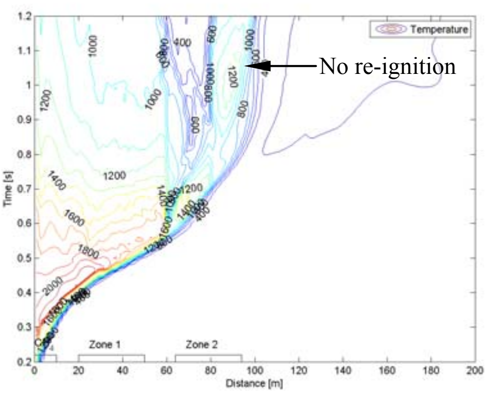


Figure 9: Triple ring, 100 µm droplets, 200 l/s flow rate

FUTURE DIRECTIONS

The results presented here are somewhat preliminary, but offer a promising picture as to what might be achievable in terms of a re-locatable explosion barrier that will allow normal mine traffic to pass unhindered, yet prevent both incipient and mature dust explosions from propagating past the barrier.

Future work will involve the design and construction of a prototype system for evaluation in the Kloppersbos test facility. The test data gathered will enable further calibration of the CFD model, which then in turn may be used to progress the designs for systems suitable for real roadways.

CONCLUSION

In summary SkillPro and BMT WBM have jointly developed a highly advanced capability in simulating the dynamics of coal dust explosions. Further, the software is able to predict the impact of injected explosion inhibitors on the propagation of the explosion, and therefore assess the effectiveness of active explosion barriers.

The software has been validated to the extent possible with test data from a dedicated coal dust explosion test facility, and has been used to investigate possible prototype barrier designs for use in this facility.

It appears that a violent coal dust explosion may be prevented from propagation with the injection of a fine water spray in quantities of less than 20 litres per square meter of tunnel area, provided reasonable requirements for droplet size, nozzle velocity, and water flow rate are met.

ACKNOWLEDGMENTS

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REFERENCES

HUMPHREYS, D. R., (2001), "Demonstration of Active Explosion Barrier Technology", *ACARP Project Report 8010*

HUMPHREYS, D. R., (2003), "Demonstration of Active Explosion Barrier Technology", *ACARP Project Report 9008*

HUMPHREYS, D. R., (2000), "Stone Dust Requirements and Options", *ACARP Project Report 8011*

HUMPHREYS, D. R., (2000), "Stone Dust Requirements and Options", *ACARP Project Report 9009*

COOK, P. M., (1993) "The Inhibition of Coal Dust Explosions in a Large Scale Explosion Gallery", *CSIR (South Africa) Report ENER 93001*

MURPHY J. J., SHADDIX, C. R., (2006), "Combustion of coal chars in oxygen enriched environments", *J. Combustion and Flame*, **144,** 710-729.

BIRD R. B., STEWART, W. E., LIGHTFOOT, E. N., (2007), "Transport Phenomena", *John Wiley & Sons*.

