

# **The Preliminary Analysis of the Pressure Wave Transmission/Reflection Characteristics of Explosion Doors Using One-Dimensional Finite Isentropic Wave Theory**

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fa Üafna Kapılarının Basınç Dalgası Reime/fansıtma  
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## **ABSTRACT**

In a previous paper the outlines of a new approach for the arresting of underground tunnel explosions were presented. Research work is continuing on the development of the technique and an explosion door is modelled as a simple orifice in a circular duct. This paper presents the results of a theoretical study of the likely amplitudes of the transmitted/reflected pressure waves which would govern the explosion door pressure loading.

## **ÖZET**

Önceki bir makalede yeraltı ocak patlamalarının ilerlemesinin durdurulması ile ilgili yeni bir yaklaşım açıklanmıştı. Bu yöntemin geliştirilmesi ile ilgili çalışmalar devam etmektedir. Patlama kapısı dairesel bir boru içindeki basit bir delik olarak modellenmektedir. Bu makale patlama kapılarındaki basınç yüklerini belirleyen, iletilen/yansıtılan basınç dalgalarının muhtemel genliklerinin teorik olarak belirlenmesi ile ilgili sonuçları vermektedir.

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## 1. INTRODUCTION

Mining operations unavoidably and continually generate methane and coal dust in underground coal mines. Mechanization and concentration of production has exacerbated the possibility of a coal dust explosion and although coal dust has the ability to explode by itself, almost all coal dust explosions are initiated by a methane explosion. The methane explosion creates shock waves that raise the coal and other rock dusts into the air and these are exploded by the flame or heat generated by the methane explosion. Therefore, a self generating coal dust explosion is initiated. This can continue as long as enough fuel exists ahead of the explosion and if there is no barrier system to stop it. The results of such an explosion are devastating. Even if mine personnel survive the blast force and heat, the flame uses up available oxygen and death can be caused by suffocation or carbon monoxide poisoning. Although the number of explosions have been greatly reduced by proper planning of ventilation and improved safety measures, the percentage of fatalities due to explosions has unfortunately increased. Arresting of an explosion is currently only possible using barriers. Generally, barriers disperse a large amount of inert materials into the path of the flame to deprive the flame of fuel and cool it down. As a result the explosion flame is extinguished.

Explosion barriers are of two types; passive and active (triggered) Passive barriers are activated by the movement of air ahead of the explosion front. The barriers are simply tripped or broken by the blast and the inert material is released into the path of the flame. A common type of stone dust barrier consists of a number of planks of wood suspended from the tunnel roof and piled with stone dust. As the pressure wave passes it upsets the planks and the dust is dispersed. Active barriers detect the on-coming explosion and using a sensor which triggers some mechanism, cause a rapid discharge of inert material into the path of the flame n.2,3].

## 2. ACTIVE FLAME PROOF DOOR SYSTEM

This system proposed in a previous paper<sup>14</sup> is a new approach for arresting the propagating explosion flame by means of a flame proof door made of individual perforated steel sandwich packages. The idea, although new in this area, has been used in LPG systems to prevent back firing and in safety lamps to cool down the lamp flame in a gaseous media.

of at least two flame proof doors (spaced an appropriate distance apart) to ensure the arrest of the flame. Figures 1 and 2 illustrate front and side elevations of the door assembly.

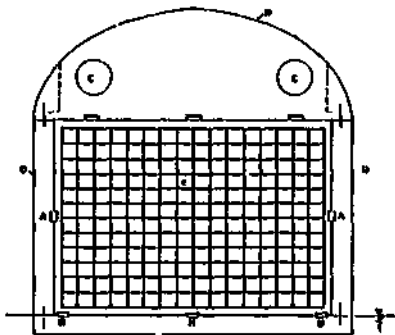
## **2.2 Theory of the Door Operation**

In this technique, the on-coming explosion is detected by a pressure sensitive device with a pre-determined rise in static pressure. The sensor then triggers a mechanism which causes the doors to be closed in a specially constructed concrete barrier zone. The doors are of a special construction and consist of perforated steel plates having holes small enough to stop the explosion flame while allowing the blast Wave to pass through, otherwise the doors and their frames would be destroyed. The system has been designed in such a way that it does not interfere with any tunnelling activity or equipment, including overhead rail conveyance. The other advantages of such a system are that it is relatively less complicated than triggered barriers, is easy to manufacture and requires little maintenance after installation.

## **3. THEORETICAL AND LABORATORY INVESTIGATION**

It will be necessary to define the construction of the doors according to a number of parameters. These include; tunnel cross-sectional area; how much blast force the doors will have to withstand; thickness of the perforated steel packages; hole dimensions of the perforated steel packages and other considerations. All of the design factors will be used to compose a computer design model which can be used to select an optimum design for a given situation.

In the research outlined in this paper the explosion door is modelled as a simple orifice in a circular duct. The explosion produces both a pressure front and flame front. As the blast wave travels along the tunnel it may undergo transition to a shock wave. When the blast (or shock wave) reaches the door, the nature of the door construction allows some of the pressure wave to pass through. However, some of the wave will be reflected and this reflection will cause a rise in static pressure. This pressure could be sufficient to damage or destroy the door. The response of the model to incident explosion pressure pulses of realistic amplitudes is investigated for a range of ratios of duct area to orifice area. This is therefore a means of investigating the likely pressures the explosion door

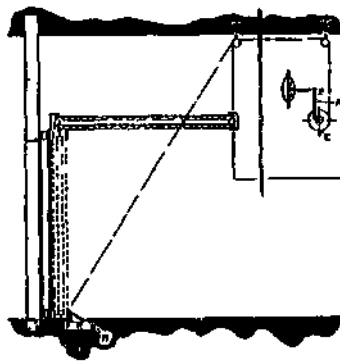


- A & B - locking mechanism
- C - services (pipes etc.)
- D - door frame
- E - individual flame-proof sandwich components

Figure 1 Front Elevation of the Explosive Door

### 2.1 The Door Unit

This unit consists of a flame proof door (the door case (frame) and the locking mechanism). The door is built up of perforated steel packages which stop the passage of



- A - Door activation device (sensor)
- B - Locking mechanism
- C - Pulley and wire for door release

Figure 2 Side Elevation of the Explosive Door

the flame. The packages are fitted in a door frame which is made of maximum dynamic pressure. The door is closed against a door frame which is made of reinforced concrete, steel or other suitable material. The door is built up of perforated steel packages which stop the passage of flame. After closing, the door is secured by a locking mechanism. The complete barrier system is comprised of

may have to withstand in relation to the obstruction it causes to the passage of the blast wave. The largest hole size possible for the perforated plates will be best so as to cause less of a pressure drop as the blast passes through the door but there is a danger that the flame wave (which closely follows the blast wave) will not be stopped.

### 3.1 Theoretical Analysis

The analysis of the flows resulting from the impingement of the initial pressure wave emanating from a dust or gas generated explosion in a one-dimensional duct upon a semi-opaque door is a task of considerable complexity.

An approximate analysis may be attempted if a simplified model is adopted in conjunction with certain assumptions regarding the nature of the flow. Accordingly, it is henceforth assumed that:

- i) the door and the duct in its immediate vicinity is idealised as a convergent-divergent nozzle of almost zero length and this configuration corresponds closely to an orifice plate of small axial extent,
- ii) no account is taken of the detailed geometry of the door,
- iii) the fluid is treated as air throughout,
- iv) transition of the initial pressure pulse to a shock wave does not occur, and
- v) as a consequence of the previous assumption the flow is adequately described by the differential equations of mass and momentum conservation which govern the unsteady isentropic motion of a compressible fluid in one spatial dimension, viz

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial x} + u \frac{\partial \rho}{\partial x} = 0 \quad \dots [1]$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{a^2}{\rho} \frac{\partial \rho}{\partial x} = 0 \quad \dots [2]$$

Where  $\rho$ ,  $u$  and  $a$ , are the fluid density, fluid particle velocity and local acoustic speed, respectively.

From Equations [1] and [2] and using the result  $a^2 = \frac{\partial p}{\partial \rho}$  it may be shown that the variation of pressure,  $p$  with fluid particle velocity is given by:-

$$\frac{\partial p}{\partial u} = \pm \rho a \quad [3]$$

Where the + and - signs refer to rightward and leftward propagating waves, respectively.

Equation [3] may be integrated between the limits corresponding to the undisturbed fluid conditions 'o' and any point on the wavefront to yield the fluid particle velocity for a wave of finite amplitude, i.e.,

$$u = \pm \frac{2 a_0}{\gamma - 1} \left[ \left( \frac{p}{p_0} \right)^{\gamma-1/2\gamma} - 1 \right] \quad [4]$$

where  $\gamma$  is the isentropic index.

Figure 3 shows a simple schematic of the physical problem of the underground tunnel and explosion door. In this case the underground tunnel is modelled by a simple tube and the explosion door by an orifice. In the analysis the tube/orifice combination is replaced by an isentropic convergent/divergent transition.

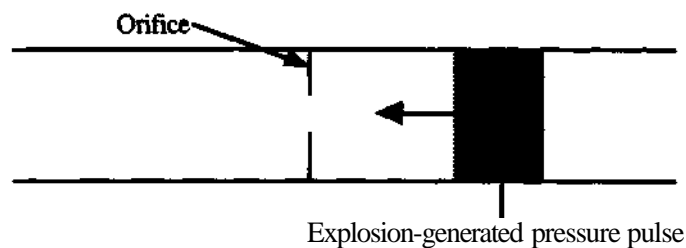


Figure 3. Schematic Representation of the Model

When the pressure pulse impinges upon the transition then processes of transmission (T) and reflection (R) will occur. For these processes the equations of energy and mass conservation are assumed to apply hence

$$\frac{\gamma}{\gamma-1} \frac{p_T}{\rho_T} + \frac{u_T^2}{2} = \frac{\gamma}{\gamma-1} \frac{p_R}{\rho_R} + \frac{u_R^2}{2} \quad [5]$$

and  $\rho_T u_T A_T = \rho_R u_R A_R$  [6]

It should be noted that the velocities (u) in the above pair of Equations [5] and [6] are absolute velocities and A denotes the cross-sectional area.

Denoting the absolute pressure of the incident pulse as p', then after algebraic manipulation of Equations [4], [5] and [6] there results

$$2 \left( \frac{p'}{p_0} \right)^{\gamma-1/2\gamma} = 1 + \frac{1}{\phi^{\gamma-1/2\gamma} (1-\chi^{1/2})} + \frac{\chi^{1/2}}{1-\chi^{1/2}} \cdot \phi^{1/\gamma} \cdot \left( \frac{A_T}{A_R} \right) \quad [7]$$

where  $\phi = \frac{p_T}{p_R}$  and  $\chi = \frac{1 - \phi^{\gamma-1/\gamma}}{\frac{2}{\gamma-1} \phi^{\gamma-1/\gamma} [1 - \phi^{2/\gamma} \cdot (\frac{A_T}{A_R})^2]}$

Additionally, it can be shown that  $\frac{p_T}{p_0} = \left( \frac{1}{1-\chi^{1/2}} \right)^{2\gamma\gamma-1}$  [8]

Equation [7] is highly non-linear in 4> but, where solutions exist may be solved by a simple incrementing technique.

In order to determine the amplitude ratio  $\frac{p_R}{p_0}$  of the reflected wave, Equation [7] is solved with  $\frac{p'}{p_0}$  set equal to the amplitude ratio of the explosion-generated pressure pulse. This generates values of  $\frac{p_R}{p_0}$  and  $\frac{p_T}{p_0}$ .

Equation [7] is again solved with  $\frac{p'}{p_0}$  set equal to the value of  $\frac{p_T}{p_0}$  obtained from the first part of the solution and thus the magnitude of the transmitted pulse  $\frac{p_T}{p_0}$  is determined.

During the numerical investigation of Equation [7] for the second part of the solution it was found that for certain combinations of  $\frac{A_T}{A_R}$  and  $\frac{p'}{p_0}$  (equal to  $\frac{p_T}{p_0}$  from the first part of the solution) closure of the equation was not possible.

It was thus concluded that, for these combinations of geometry and pressure amplitude, isentropic flow could not exist in the transition from the orifice to the duct downstream of the orifice. Now, the flow emanating from the orifice will be in the form of an expanding free jet with the accompanying shearing on the boundary rendering the flow irreversible and hence the breakdown in the equations in the second part of the solution is by no means surprising. Further, in the actual flow situation on the upstream side of the orifice the impingement of the incident pulse upon the upstream face will result in a situation somewhat like that encountered at the closed end of the duct.

For the condition of closed-end impingement it may be shown that the pressure,  $\bar{p}_R$  in the plane of the closed end is given by:-

$$\bar{p}_R = p_0 \left[ 2 \left( \frac{p'}{p_0} \right)^{\gamma-1/2\gamma} - 1 \right]^{2\gamma/\gamma-1} \dots[9]$$

In view of the complexity of the actual situation and the absence of 'isentropic solutions' under certain circumstances in the downstream flow it is proposed to model the pressures on the upstream and downstream faces of the orifice as 'area-weighted' linear combinations of the pressures predicted from the isentropic transition and closed-end reflection processes respectively.



Thus the upstream pressure,  $p_u$  is given by.-

$$p_u = \left(1 - \frac{A_T}{A_R}\right) \overline{p_R} + \frac{A_T}{A_R} \cdot p_R,$$

whilst the downstream pressure,  $p_o$  is given by :-

$$p_D = \left(1 - \frac{A_T}{A_R}\right) p_o + \frac{A_T}{A_R} \cdot p_T,$$

Using this procedure the downstream pressure is always less than that predicted for the flows where isentropic solutions exist and this is consistent with the dissipative nature of the downstream flow.

The non-dimensional pressure difference across the door is given by,

$$\frac{\Delta p}{p_o} = \frac{p_u - p_D}{p_o} \quad \dots[10]$$

The magnitudes of  $\frac{\Delta p}{p_o}$  given by Equation [10] are shown plotted against area ratio,  $A_r$  in

Figure 4. The curves clearly show for a given incident pressure amplitude ratio,  $\frac{p'}{p_o}$  that the non-dimensional pressure rise is independent of area ratio for area ratios greater than approximately ten - for all of the incident amplitude ratios investigated which are thought to be characteristic of the pressure amplitudes generated in actual mine explosions. Additionally, the amplitude ratio (area-weighted) of the transmitted wave is shown plotted in Figure 5 against area ratio for the same selection of incident waves. The graph clearly shows that substantial attenuation of the incident pulse is obtained for area ratios greater than ten.

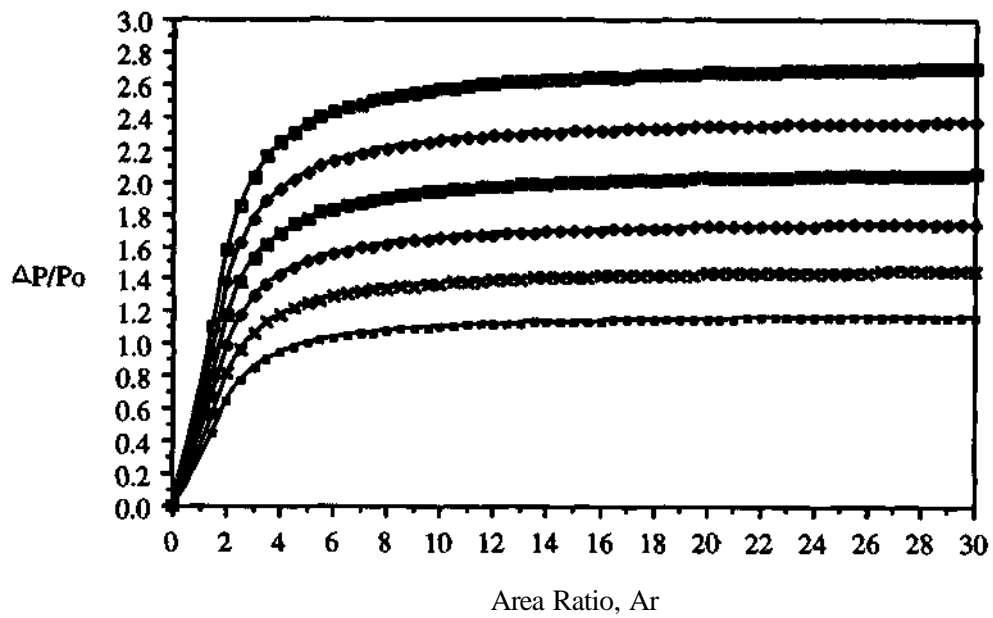


Figure 4. Variation of Non-dimensional Pressure Difference with Area Ratio.

- Amplitude ratio 2.0
- Amplitude ratio 1.9
- Amplitude ratio 1.8
- Amplitude ratio 1.7
- × Amplitude ratio 1.6
- Amplitude ratio 1.5

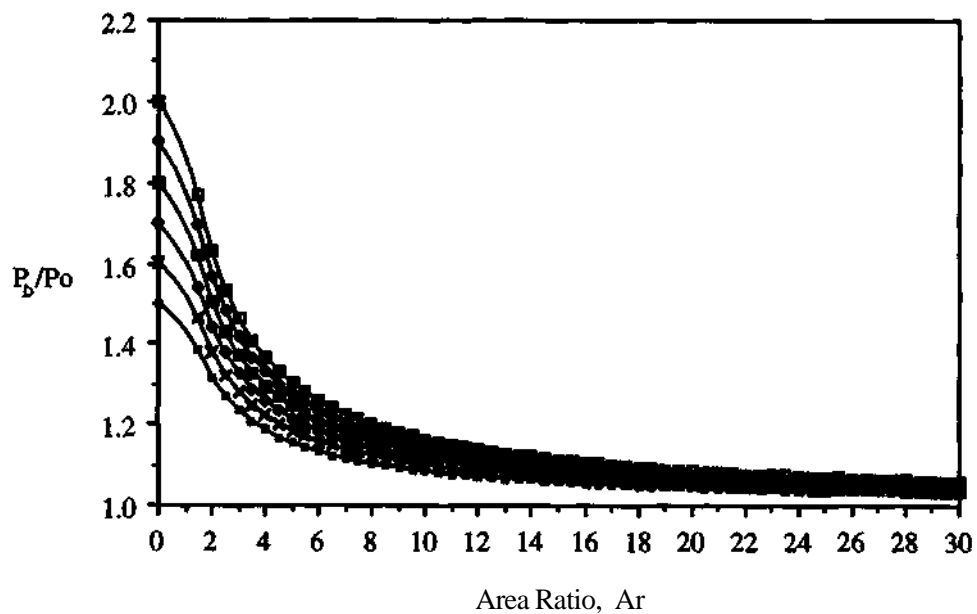


Figure 5. Variation of Area-weighted Transmitted Pressure Ratio with Area Ratio.

#### 4. DISCUSSION

This paper has presented the results of a theoretical investigation of the pressure wave transmission/reflection characteristics for a new system of an active door **barrier to stop** underground explosions. Essentially, it is necessary to gain an understanding of the typical pressures, both across the door due to attenuation of the blast wave, and downstream of the door so that they can be designed to withstand such pressures. The response of the model to incident blast pressure pulses has been investigated for a range of duct area to orifice area i.e. as a representation of how greatly the door attenuates the blast wave. The analysis at this stage has taken no account of the frictional effects that would occur in the real flow of the blast wave through the door. A more realistic simulation may be performed by means of computational fluid dynamics but such a simulation would almost certainly require an input of data which could only be obtained by experiment.

Further, as yet unpublished experimental work undertaken in the Department of Mechanical Engineering at Dundee Institute of Technology with a shock-tube has shown that the theory presented in this paper on the pressure wave transmission/reflection characteristics of explosion proof doors, predicts, for orifices consisting of single and multiple holes, amplitudes of the transmitted waves which are in very close agreement with experimental data. Whilst the incident waves in these experiments were rarefactive there is no reason to believe that the theory will be substantially less successful in its predictions when the incident pressure pulse is compressive. Thus, Figures 4 and 5 may be used in the preliminary design of explosion doors to

- i) predict the pressure loading on the orifice (hence the explosion door), and
- ii) using Equation [9] with  $p'$  set equal to  $p_0$  predict the pressure loading on any closed door downstream of the orifice since the pressure downstream of this closed door will be the undisturbed pressure,  $p_0$ .

#### 5. ACKNOWLEDGEMENTS

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