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Experimental air curtain solution for refuge alternatives in underground mines

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ABSTRACT

To provide an optimal aerodynamic sealing solution for an alternative refuge in underground mine, a commercial air knife was selected as the air curtain device (ACD) for its lower compressed air use and uniform airflow. A series of simulated chamber model experiments were then performed to evaluate the sealing efficiency of different ACD configurations and the influence of interruption by transiting personnel on ACD performance. By considering the overall sealing efficiency, stability and air consumption, a double-sided ACD equipped with a baffle on the side exposed to harmful gases inside the entrance of the protected door is proposed as the most suitable configuration. This requires compressed air to be supplied at a pressure of 0.10–0.20 MPa to generate an air barrier, which means that a standard compressed air cylinder (40 L, 15 MPa) can provide suitable sealing conditions for a period of about 3.5 min.

1. Introduction

Refuge alternatives can provide a safe, confined place for miners who are trapped underground when a mine emergency occurs, thereby isolating them from hazardous environments and sustaining their lives for a period of at least 96 h (Margolis et al., 2011; MSHA, 2008). This level of isolation requires adequate aerodynamic sealing measures, such as airlocks or air curtains, to protect the interior living space from the external contaminated atmosphere when miners move through the entrance to the refuge alternative.

Air curtain devices (ACD) can isolate a protected area from its surrounding environment by producing one or more high-momentum parallel air streams between the two. Considered flexible and unencumbered, ACDs have proven to be a suitable alternative to conventional physical barriers that cannot be used in certain scenarios due to practical or other reasons (Foster et al., 2003). Today, ACDs are used widely in refrigeration, architecture, tunnels, etc. to prevent the impingement of undesirable heat, smoke, contaminants, etc. into protected areas.

The sealing efficiency of an ACD, which is essentially the ratio of momentum between the initial jet stream and the airflow in the cross direction that the curtain needs to neutralize, is influenced by the following factors: (1) air stream parameters (thickness, velocity, temperature, etc.); (2) ACD configuration (installation position, jet orientation, existence of a recirculation system, number of jets, etc.); and (3) ambient parameters (temperature, pressure, etc.) (Gonçalves et al., 2012). As the practical performance of an ACD varies with application (Giráldez et al., 2013), there has been considerable experimentation and simulation-based research into the mechanism and effectiveness of different ACD configurations (Ciocănea and Dragomirescu, 2013; Foster et al., 2003; Gonçalves et al., 2012; Hayes and Stoecker, 1969; Hetsroni and Hall, 1964; Luo et al., 2013; Navaz et al., 2002; Severino et al., 2013; Shih et al., 2011).

With regards to fire safety, several studies have suggested that ACDs with a return grill for air recirculation should provide better sealing efficiency (Hu et al., 2008; Shih et al., 2011). However, if these were to be used in underground refuge alternatives, they would be vulnerable to the possibility of power interruption during a mine emergency such as an explosion (Brake and Bates, 2001). In other words, ACDs that rely on fan units or other electric equipment have a degree of inherent unreliability that makes it difficult to recommend their use underground. A recently introduced type of ACD that uses compressed air to form an air barrier through uniformly perforated stainless pipes or air knives has been widely used in China; however, there has been little research into verifying or optimizing its effectiveness.

With the ultimate aim of developing an aerodynamic sealing solution for large refuge alternatives, this paper studies a commercial air knife for its lower compressed air use and uniform airflow. A series of simulated chamber model experiments were performed to evaluate the sealing efficiency of different ACD configurations, as well as the

Abbreviations: ACD, air curtain device; DO, discrete ordinates; HRR, heat release rate; RNG, renormalization group; VHS, volumetric heat source

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Nomenclature

Q_a	standard volumetric flow rate (293.15 K, 101,325 Pa) at experimental conditions ($m^3 h^{-1}$)
Q_s	rotameter reading ($m^3 h^{-1}$)
p_a	experimental pressure (Pa)
p_s	standard pressure (101,325 Pa)
T_a	experimental temperature (K)
T_s	standard temperature (293.15 K)
ρ_a	gas density at experimental conditions ($kg\ m^{-3}$)
ρ_s	standard air density (1.205 $kg\ m^{-3}$)
Q_0	flow rate of carbon dioxide passing through the entrance profile without an ACD ($l\ min^{-1}$)
Q_1	flow rate of CO_2 passing through the entrance profile when an ACD is operating ($l\ min^{-1}$)
c_0	average volume fraction of carbon dioxide inside the chamber without an ACD (vol.%)
c_1	average volume fraction of carbon dioxide inside the chamber when an ACD is operating (vol.%)
V_{in}	inner volume of the simulated chamber (5.59 m^3)
Q_{CO_2}	standard flow rate of CO_2 (293.15 K, 101,325 Pa), 23.88 $l\ min^{-1}$ in the test
ϕ	common dependent variable
ρ	density
u	velocity vector
Γ	diffusion coefficient
S_ϕ	remaining term

influence of interruptions caused by the transit of personnel through the ACD on its performance. Three criteria were selected for evaluating the optimal ACD configuration: (1) sealing efficiency; (2) stability (effect of interruption due to personnel entering); and (3) air consumption (a high air consumption may require an enormous amount of compressed air, thus leading to storage and maintenance problems in underground mines). An overall consideration of these criteria is used to identify a reasonable ACD configuration for underground refuge alternatives.

2. Establishment of experimental setup

2.1. Simulation of airflow pattern at refuge alternative entrance during fire scenario

In most realistic emergency scenarios in underground mines, it is difficult to precisely describe the airflow at the entrance of a refuge, as this may vary depending on the scale and nature of the emergency, climatic conditions in the mine, and other factors. Here, a small cable fire emergency scenario was simulated through FLUENT, as smoke and harmful gases are considered important factors contributing to the deaths of miners trapped underground after such an accident (MSHA, 2008). The general governing equations involved were (Fluent User's Guide, 2006):

$$\frac{\partial}{\partial t}(\rho\phi) + div(\rho u\phi) = div(\Gamma grad\phi) + S_\phi \tag{1}$$

where ϕ is the common dependent variable, ρ is density, u is a velocity vector, Γ is the diffusion coefficient, and S_ϕ is a remaining term. Detailed equations with respect to fire simulation have been described elsewhere (Wang et al., 2009), and so are not be expressed here.

The prototype for this study was a refuge alternative in an underground gold mine located in Shandong Province, China (see Fig. 1). This refuge alternative included four air-tight doors, with an inner space divided into three parts: a transition zone at each end, and a living zone in the middle. Next, a calculation model was established that consisted of a roadway (2700 mm W × 2700 mm H × 40,000 mm L), transition zone (2700 mm W × 2700 mm H × 10,000 mm L) and entrance (1500 mm W × 1800 mm H × 2000 mm L). The doors of the living zone are kept closed in their normal state, and when an

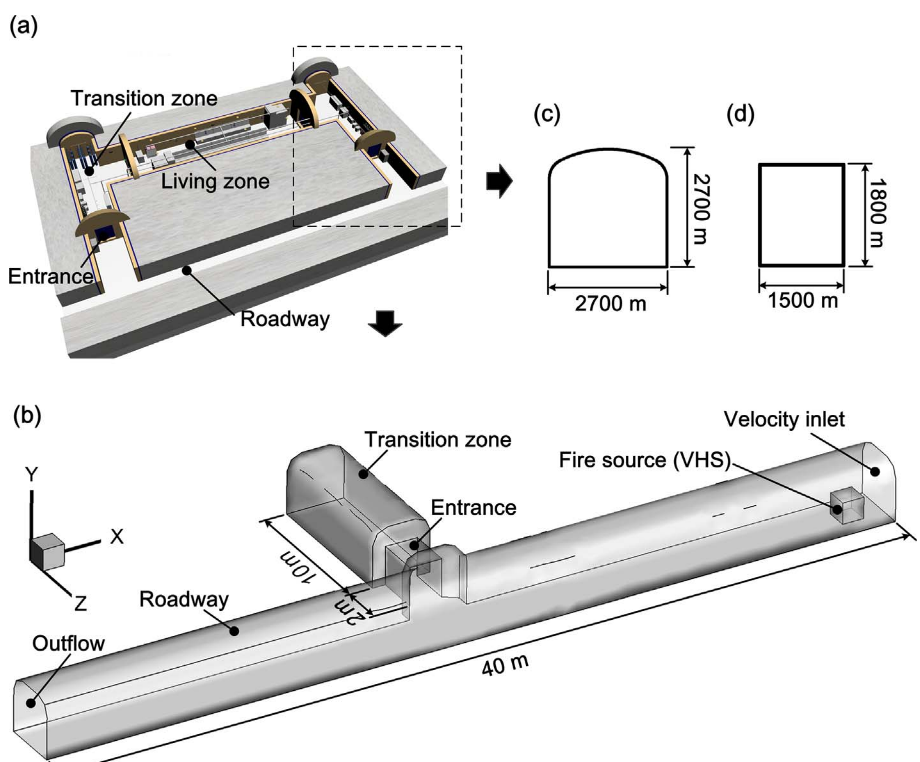

Fig. 1. Alternative refuge and its CFD model: (a) schematic of alternative refuge; (b) CFD model of entrance; (c) section of tunnel; (d) section of entrance.