Computational Fluid Dynamics Study on Hot Spot Location in Longwall Gob

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Abstract

Spontaneous combustion is one of the main sources of fires in underground coal mines. Most of these fires are initiated in the caved area (gob). This process starts with the formation of hot spots, which may develop into the self-heating of coal. A study involving experimental measurements and computational fluid dynamics (CFD) simulations was carried out to identify the location of these spots. Four CFD gob models of three different permeability zones were formulated and solved. Three utilized a bleeder ventilation system and the fourth a bleederless system. The simulation results showed that in a model ventilated by a bleeder system, the hot spot was located in the consolidated zone near the return side of the gob. Once the process was initiated, it propagated along the tailgate side as the gob progressed. The leakage flow through the gob played an important role in determining the size and location of the hot spot. In the model ventilated by a bleederless system, the hot spot was located by the face line. This was mainly caused by air leakage from the headgate. The study concludes with a set of ventilation schemes and recommendation to reduce the development of hot spots.

Introduction

Spontaneous combustion in underground coal mines has become a serious problem, particularly in the caved area (gob). Recent statistics have shown that approximately 17% of a total of 87 underground coal mine fires in the United States are attributed to spontaneous combustion (De Rosa, 2004). Spontaneous combustion results from a self-heating process in exothermic conditions. The accumulated heat, if not removed, is conducive to the rapid increase of temperature and may result in mine fires or explosions.

It is well accepted that the interaction between oxygen and coal substances is the main cause for spontaneous combustion, while other factors such as pyrite, moisture and bacteria play secondary roles in the self-heating of coal. Therefore, only coal oxidation is considered in this study.

Coal oxidation occurs as coal comes in contact with air. This process involves complex phenomena in terms of heat transfer, chemical surface absorption and energy balance related to inherent properties of coal (Wang et al., 2003).

For simulation purpose, the overall reactions can be simplified as suggested by Mitchell (1990)

$$C + O_2 \rightarrow CO_2 + \text{heat} \qquad [65^\circ \text{ to } 94^\circ C] \qquad (1)$$

$$CO_2 + C \rightarrow 2CO + \text{heat} \qquad [100^\circ \text{ to } 150^\circ C] \qquad (2)$$

Stoichiometric Reactions (1) and (2) show that 2.66 grams of oxygen are required to oxidize 1.0 gram of carbon. Once the temperature exceeds 100°C (212°F), the reaction has little chance of stopping.

The crucial step in reducing spontaneous combustion risk is locating the ignition point of spontaneous combustion (hot spot). This information is useful in the effort of developing a preventive method effectively. In this study, this was conducted based on the best gathered information, including ventilation surveys conducted in an existing longwall mine located in the western United States; laboratory experiments performed on a physical gob model; and CFD models used to investigate the flow behavior in the gob, the oxidation of coal and heat transfer phenomena.

The hot spot location is determined as a function of oxygen concentration and gob temperature. The critical values are the following: 5% (by volume) for oxygen and 100°C (212° F) for gob temperature.

Characteristics of gob material and models

Permeability concept. Permeability is one of the key parameters in any study dealing with porous medium. This is determined by particle size and the ratio of void volume to the total volume (porosity) of porous medium. This relationship is known as the Carman-Kozeny equation (Scheidegger, 1957) and is given mathematically as

$$k^* = \frac{d_m^2}{180}\frac{n^3}{(1-n)^2} \qquad (3)$$

FIGURE 1

Ventilation model used for permeability tests.

where

k^* is the theoretical specific permeability (m^2),
d_m is the mean particle size (m) and
n is the porosity.

However, permeability tests with various particle sizes were carried out at the University of Utah's ventilation model (Fig. 1) to verify this relationship. These tests indicated a necessity to modify this theoretical relationship. A factor of 0.898 was obtained to make up the difference between theoretical permeability and the experimental one. The modified version of Eq. (3) is

$$k_{\text{mod}} = \frac{d_m^2}{200.44}\frac{n^3}{(1-n)^2} \tag{4}$$

This equation is used to determine permeability of the simulated mine gob throughout the study.

Mine gob material. The gob is represented by zones filled with material of given size distribution. For physical measurements and CFD simulations, the materials used were crushed rock and coal. Due to compaction, three different characteristics of gob material were used in the model: unconsolidated, semiconsolidated and consolidated.

In the real condition, the largest coal-rock particles are more likely to be located in the area behind the shields. This material is freshly broken and unconsolidated. The size of these broken particles is based on a study carried out by analyzing images taken from the area behind the shields in three coal mines in the United States (Pappas and Mark, 1993). The results have shown that the mean size of materials behind the shields is about 1.22 m (4 ft). The permeability associated with this size was then obtained from Eq. (4) and permeability tests, and this value was 4.68 x10^{-7} m^2. For semiconsolidated and consolidated zones, due to the lack of experimental data, these were determined through CFD simulations. These simulations were designed by assigning a permeability of 3.15 x 10^{-8} m^2 for consolidated zone and 7.98 x 10^{-9} m^2 to the other zone. The airflow pattern in the gob assigned with a given permeability was expected to follow the experimental distribution (Brunner, 1985). The mean particle sizes for the semi-consolidated and consolidated zones were 0.02 and 0.006 m, respectively, smaller than those of the unconsolidated zone. Figure 2 shows the three-dimensional view of permeability changes in the gob.

Gob model. Four CFD gob models (Models A through D) were constructed. Models A, B and C utilized a bleeder ventilation system, and Model D utilized a bleederless ventilation system. With length varying from 912 to 2,445 m (2,992 to 8,022 ft), each gob model was divided into three zones (Fig. 3). A typical longwall entry, 6 m (20 ft) wide and 3 m (10 ft) high, was used for all airways, except the face and bleeder entries. The width of the face entry was 3 m (10 ft), while that of the gob perimeter is 2 m (6.6 ft). The wall roughness for these entries was set at 0.1 m (0.33 ft).

In Model A, the gob length was one-third of the panel length. This stage may be reached after 3 to 4 months of operation. In Model B, the gob took up one-half of panel length. This stage may be reached after 6 to 7 months of operation. Model C simulated the panel condition near the end of the production schedule. These three models were intended to address the dynamic aspect of the mining sequence. Model D was used to investigate the effect of the bleederless ventilation system onto the hot spot development. This model replicated Model A, but the panel was ventilated by a bleederless system.

The coal presence in gob was simulated by several particle injection points. In the model, these points were evenly distributed. Each point is 1 m (3.3 ft) in diameter. There were three points along the width of the gob, and several along its length. It was assumed that 10% to 28% of the volume of the gob area is occupied by the leftover coal.

Hot spot location — simulation exercises

Input parameters. These parameters are used to spec-

FIGURE 2

Specific permeability distribution in gob.

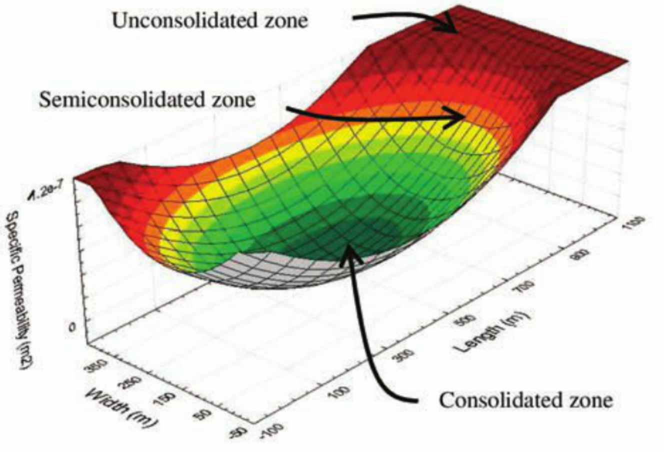


FIGURE 3

Schematic for CFD.

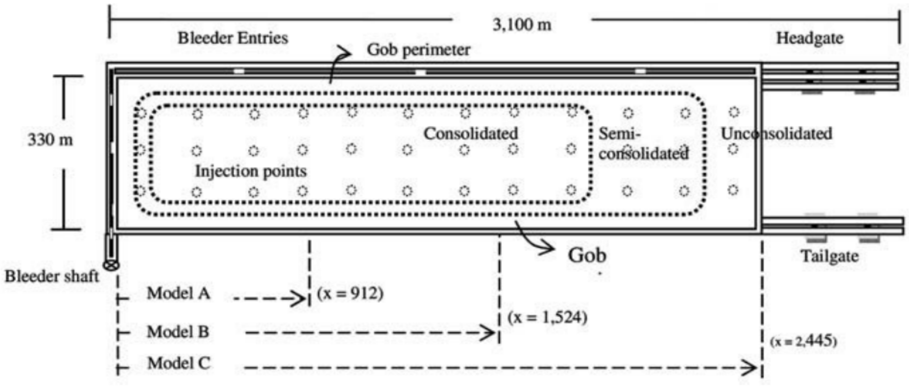


Table 1

Input parameters used for a two-phase model.

Parameter	Value
Ventilation	
Pressure inlet (Pa):	
Main entry	250
Belt entry	-250
Escape entry	250
Pressure outlet (Pa):	
Return at tailgate	-100
Bleeder fan	-2,500
Airflow condition at face:	
Min air quantity (m^3/s)	14.16
Min mean air velocity (m/s)	0.3
Doors:	
Face permeability (m^2)	4.67e-07
Pres-jump coefficient (1/m)	1,800
Curtains/regulators:	
Face permeability (m^2)	2.47e-05
Pres-jump coefficient (1/m)	96.8
Operation temperature (K)	293
Coal particles	
Properties:	
Moisture (%)	10.00
Volatile matter (%)	35.43
Fixed carbon (%)	45.92
Ash (%)	12.33
Density (kg/m^3)	1,324
Injection ports:	
Particle diameter (cm)	0.5
Injection rate (kg/s)	2.4
Gob	
Specific permeability (m^2):	
Unconsolidated	4.68×10^{-7}
Semiconsolidated	3.15×10^{-8}
Consolidated	7.98×10^{-9}
Gob materials:	
Density (kg/m^3)	2,800

ify the boundary conditions for CFD models. The parameters were divided into two groups: ventilation and self-heating. The ventilation parameters are used to determine the airflow behavior in the gob and the self-heating parameters to determine the location of potential fire sources (hot spots). These parameters are for a gob model ventilated by a bleeder system and include: pressure inlet for intake entries, pressure outlet for return entries and bleeder fan, porous jump for regulators and stoppings and porous medium for gob permeability zones.

Ventilation parameters: At the headgate side, the inlet pressure (main and escape) was set at 250 Pa (0.036 psi). The belt entry was used as a return with an inlet pressure of -250 Pa (-0.36 psi). At the face, the air was split, with about 30% directed to the face and the remainder to the gob and bleeder entries. At the tailgate side, the outlet pressure was set at -100 Pa (-0.015 psi). The gob was represented by porous media and a ventilation control by a parameter called porous jump. Three permeability zones, as described below, were used to characterize the gob. Their permeability reflected three degrees of gob consolidation.

To simulate the ventilation air in the gob, four regulators and six doors were used. Further, the calculated air velocity at the face was compared against the minimum requirements (30 CFR Part 75 Section 325-326). The average air velocity was at least 0.3 m/s (0.67 mph). When the gob model was ventilated by a bleederless system, the following two changes were made to the model with bleeder system: the bleeder fan removed and the bleeder entries inside the face were blocked.

Self-heating parameters: In this study, the flow mixture consists of two phases: a primary phase (ventilation air) and a secondary phase (coal particles). The coal samples used in the analyses were obtained from a mine in the western United States. Table 1 shows the input parameters for a two-phase model ventilated by a bleeder system.

In the Fluent software (Fluent Inc., 2003), the primary phase was represented by atmospheric air with a density of 1.12 kg/m^3 and an initial temperature of 20°C (68°F). Phase 2 was represented by high-volatile coal particles that were added to the system. The chemical reaction (oxidation) between both phases resulted in a mixture that consisted of combustion products, i.e., carbon dioxide (CO_2), carbon monoxide (CO) and water vapor (H_2O_g). Reactions (1) and (2) are also defined in Fluent. These are specified as self-heating parameters.

The primary phase, atmospheric air, is composed of 21% O_2 and 79% N_2. Other constituents, such as argon (0.93%) and carbon dioxide (0.038%), are neglected in this study. The properties, such as density, thermal conductivity and viscosity, of each gas are imported from the Fluent database that contains properties of about 6,000 other materials (www.fluent.com). These properties can be customized, if necessary, based on the ventilation survey data. Other parameters, including released heat from the coal oxidation, Arrhenius rate, latent heat and carbon-oxygen burnout ratio, were obtained from reliable sources (Smith and Lazzara, 1987; Wang et al., 2003).

Simulation results.

Model A: Gob length = 912 m: In Model A, the oxygen concentration ranges from 11% to 21%. The lowest concentration is found near the bleeder shaft. Figure 4 shows the area where the coal temperature increases from 365 to 400° K. Based on the isotherm contours, the area with potential heat buildup is located in the consolidated zone. A careful inspection showed that the hot spot is located at the back of the gob on the tailgate side near the bleeder shaft (shaded area in Fig. 5). In this area, the gob temperature reached 385° K (112°C), i.e., 12° K above the critical temperature.

Model B: Gob length = 1,524 m: In Model B, the permeability zones are elongated as the gob length increases. The gob perimeter also has higher resistance than that of Model A due to roof failure. This results in airflow reduction to the gob, thus reducing its oxygen concentration. The oxygen concentration in gob ranges from 5% to 21%. The lowest oxygen concentration is found along the tailgate side.

Figure 6 illustrates the temperature contours for Model B. An inspection of this graph shows the heat buildup in the gob near the tailgate end. Locations with temperatures greater than 373° K are found in semiconsolidated and consolidated zones. In the semiconsolidated area, the ventilation air carries part of the heat away, and the remainder is absorbed by the coal, which ultimately increased its self-heating temperature. In the consolidated area, this ventilation effect of ventilation air is not shown. This is due to its low permeability.

Figure 7 shows the area where the gob temperature ranges from 365 to 400° K. The area with greater potential heat buildup is located along the tailgate side (shaded area). This starts from the back of the gob near the bleeder shaft to the mid-gob area. This can be considered as an extension of the hot spot in Model A. The gob temperature in this area reaches 386 K (113°C), i.e., 13° K above the critical temperature. In addition, another hot spot location is identified near the face-tailgate junction. This location may be regarded as the beginning of a new hot spot that has potential to grow as the mine progresses.

FIGURE 4

Temperature contours for Model A.

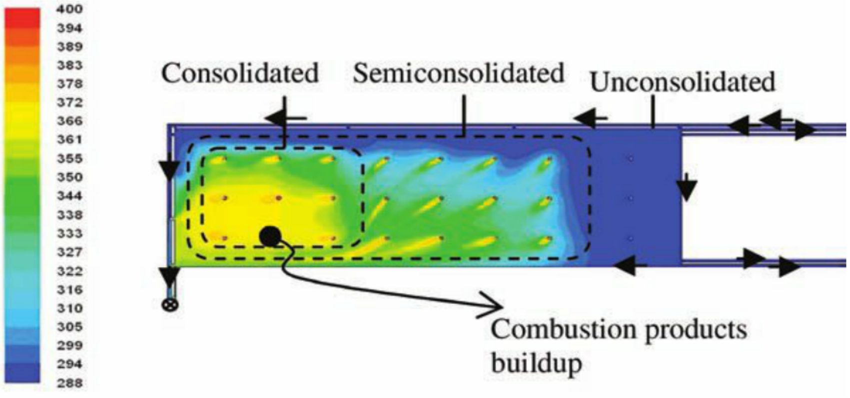


FIGURE 5

Potential hot spot location for Model A.

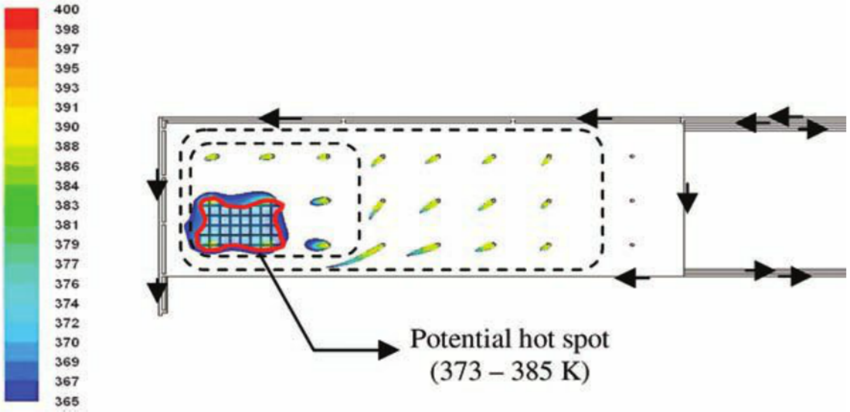
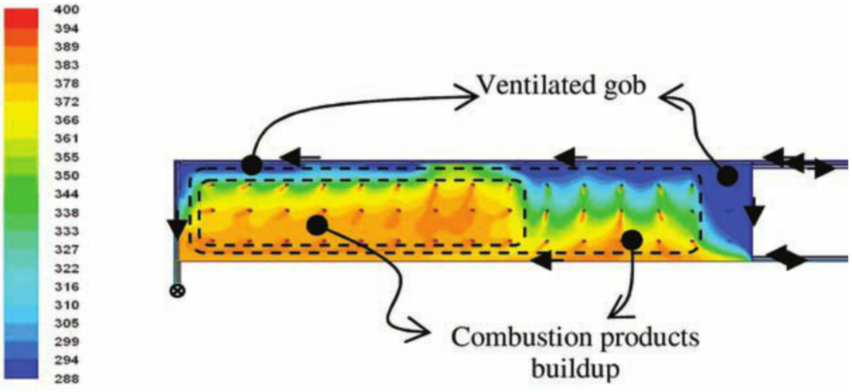


FIGURE 6

Temperature contours for Model B.



Model C: Gob length = 2, 445 m: Model C simulates the condition at which mining approaches the panel end. In contrast to Models A and B, one tailgate entry is utilized as an auxiliary intake to dilute the mine gases and eliminate the heat buildup near the tailgate corner. The oxygen concentration ranges from 3% to 21% throughout the gob. Due to continuous oxidation, the lowest oxygen concentration is found along the tailgate side of the consolidated area. The combustion products also reduce oxygen concentrations on this area.

Figure 8 shows the temperature contours in the gob. The highest temperature is found in the consolidated

FIGURE 7

Potential hot spot location for Model B.

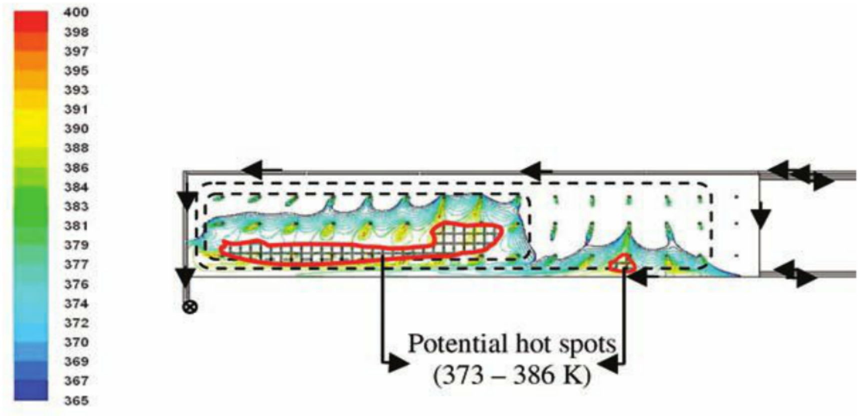


FIGURE 8

Temperature contours for Model C.

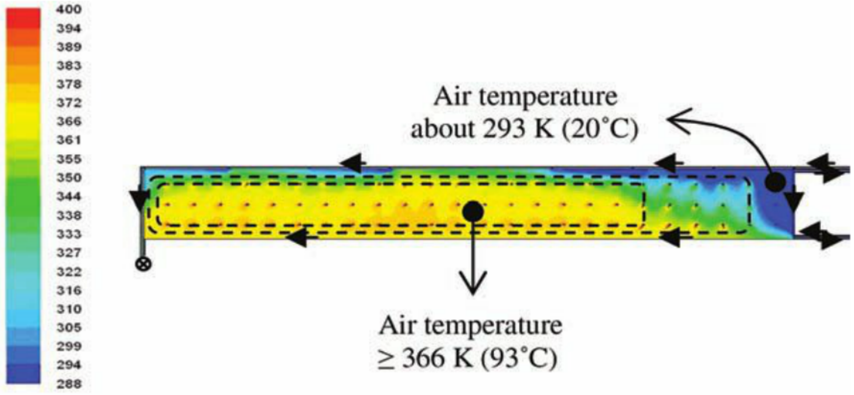
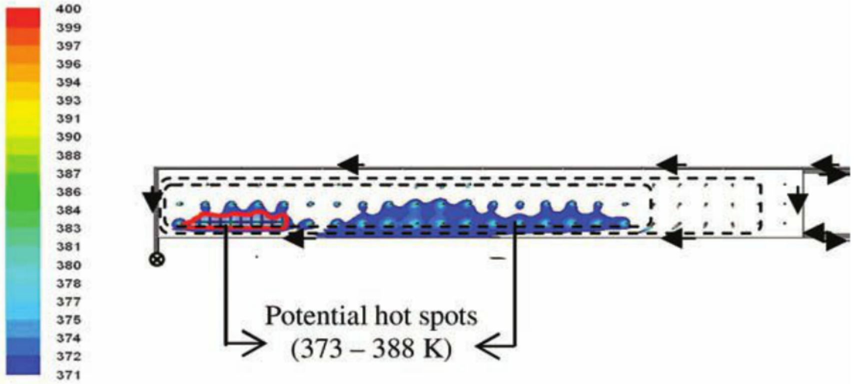


FIGURE 9

Potential hot spot locations for Model C.



zone. The ventilation air entering the gob through stoppings and headgate junction removes most of the combustion products, thus eliminating the heat buildup in the gob perimeter.

Figure 9 shows the temperature contour lines for the 371 to 400° K range. The areas with a potential hot spot are located on the tailgate side of the consolidated area. The hot spot in this zone is longer than those of Models A and B. This zone has higher resistance to airflow, thus providing a favorable condition for the build-up of combustion products. This figure also shows two hot spot areas: one located near the back corner of the gob and another, a larger area, in the mid-area. The irregular thermal patterns shown on the headgate side are caused by the leakage flow through stoppings. The gob temperature in both areas reached 388° K, i.e., 15° K greater than the critical temperature.

Bleederless ventilation system: Model D: Model D replicates Model A, but it utilizes a bleederless ventilation system. The gob is about 912 m (3,000 ft) long. The input parameters are the same as those of Model A, except the entries behind the face line are sealed completely. However, in practice, a substantial amount of air is lost in the form of leakage through stoppings and seals.

With the bleederless system, the ventilation air follows a "U" pattern from headgate to tailgate. Seals are used to direct the air to the face from headgate. The oxygen concentration found in this model ranges from 0% to 21%. The lowest concentration is found in the center area and covers all three zones. Areas with higher oxygen concentrations are located near the gob perimeter. Figure 10 shows the temperature contours in the gob. The area with higher temperatures is located in semi-consolidated and unconsolidated zones (Fig. 11).

The area with a potential hot spot is found along the face line behind the shields (shaded area). The area starts at the headgate, extends to the inner section, and ends at the tailgate junction in Zone 1. It may also extend to Zone 2, depending on its permeability. The gob temperature in this area reached 398° K (125°C), i.e., 25° K above the critical temperature.

Summary and conclusion

In the models utilizing a bleeder ventilation system (Models A, B and C), the hot spot always starts in the consolidated area near the bleeder shaft. As the panel becomes longer, the hot spot becomes elongated along the tailgate side. The increased size of the hot spot is due to the increased temperature of the gob. The risk for the hot spot development increases with the gob length.

When the gob length was equal or greater than 50% of the panel length, two hot spots were observed: one near the bleeder shaft and the other near the face. These hot spots were the effect of leakage flow from the headgate crosscuts. This effect of flushing the heat buildup

FIGURE 10

Temperature contours for Model D.

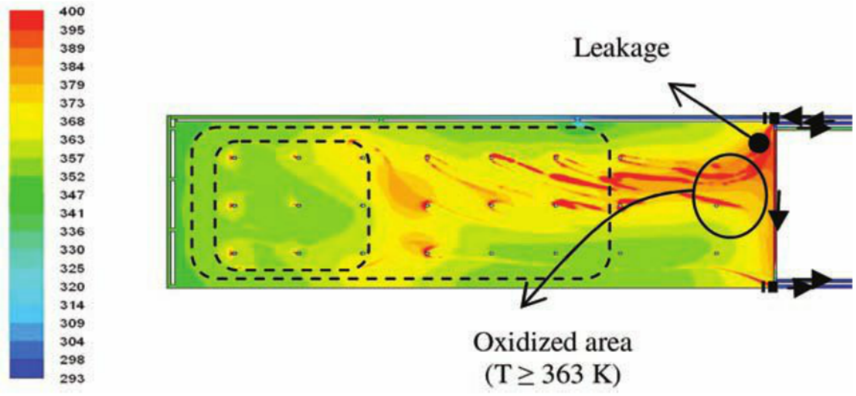
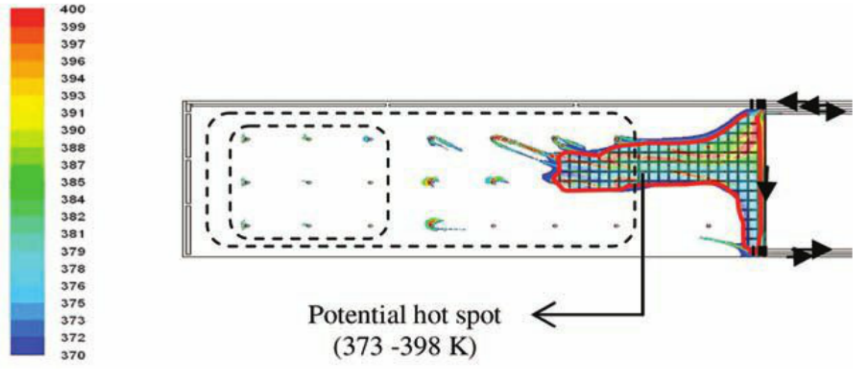


FIGURE 11

Potential hot spot location for Model D.



into the gob should be maximized.

When a bleederless ventilation system is used (Model D), the consolidated area is practically kept free of oxygen; then, the hot spot can only be developed in the unconsolidated area along the face line where the oxygen is still present due to leakage flow. The hot spot area extends for about 200 m (660 ft) from the face line. Within this area, the gob temperature reaches 125°C (257°F) (the highest of all the models), representing a greater potential risk for fire initiation. To reduce this risk in panels ventilated by a bleederless system, the leakage air quantity should be minimized. ■

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