NUMERICAL SIMULATION OF HIGH EXPANSION FOAM IN PIPES AND MINE OPENINGS

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

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ACADEMIC ABSTRACT

High expansion foam (Hi-Ex) is a firefighting technology that has been widely used for fire suppression in underground locations. Hi-ex foam can be applied remotely through boreholes from the surface reducing firefighter exposure to fires. Despite the experimental studies that have been carried out there are still some uncertainties about foam behavior in underground locations. For this reason, the main objective of this thesis was to estimate Hi-Ex foam flow behavior in different underground configurations using computational fluid dynamics (CFD) simulations. An experimental apparatus was built to study the foam rheology in order to determine the rheological model parameters to simulate foam as a continuous Non-Newtonian fluid. Furthermore, numerical and experimental results of Hi-Ex foam flowing in a pipe were compared with the objective of validating numerical results.

Results of this study show that Hi-Ex foam with an expansion ratio between 1:250 and 1:1280 behaves as a shear thinning fluid represented by the power law model. Numerical simulations results were between 0.06% and 14% of experimental results for Reynolds numbers between 200 and 1700. Finally, numerical simulations of Hi-Ex foam in different mine entry slopes were carried out and compared with qualitative results of prior field work.

This work generates some of the necessary numerical parameters for the simulation of Hi-Ex foam flow in mines. Furthermore, results of this work and the methodology used can allow for improved predictions of foam flow in underground mine fires, while improving safety for mine workers.
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High expansion foam (Hi-Ex) is a firefighting technology that has been widely used for fire suppression in underground locations. Hi-Ex foam can be applied remotely through boreholes from the surface reducing firefighter exposure to fires. Despite the experimental studies that have been carried out there are still some uncertainties about foam behavior in underground locations. For this reason, the main objective of this thesis was to predict Hi-Ex foam flow in different underground configurations using computational fluid dynamics (CFD) simulations. An experimental apparatus was built to study the foam rheology in order to determine the rheological model parameters to simulate foam as a continuous Non Newtonian fluid. Furthermore, numerical and experimental results of Hi-Ex foam flowing in a conduit pipe were compared with the objective of validating numerical results.

This work generates some of the necessary numerical parameters for the simulation of Hi-Ex foam flow in mines. Furthermore, results of this work and the methodology used can allow for improved predictions of foam flow in in underground mine fires, while improving safety for mine workers.
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Chapter 1. Introduction

Underground coal fires are a serious occupational safety and environmental problem that cause countless negative impacts to ecosystems and communities, such as greenhouses gas emissions, surface subsidence and infrastructure damage (Prakash, Fielding, & Gens, 2001; Wu & Liu, 2011; Richmond, 2017; Ozment & Trevits, 2018). Some data published in the U.S. Office of Surface Mining Reclamation and Enforcement Abandoned Mine Land Inventory System showed that there were nine underground mine fires burning in nine states in the US in 2013 (Richmond, 2017). However, some specialists conclude that the number of active underground mine fires is actually much greater in the U.S. (Ozment & Trevits, 2018). Additionally, some statistics indicate that in the last 30 years about 600 people have been affected and six fatalities have occurred due to 1,060 mine fires reported in the U.S. (De Rosa, 2004; Smith & Thimons, 2010).

Due to high temperatures close to the fire, most underground coal fires must be addressed remotely. After the initial stages of the fire, temperatures are elevated, large gas accumulation may occur and the possibility of an explosion make the application of direct fire-fighting techniques impossible (Smith et al., 2005). Hi-Ex foam technology has been used as an alternative for fire suppression in underground mines since 1950. This kind of foam can be applied into underground locations remotely through boreholes from the surface (Smith et al., 2005). Also, Hi-Ex foam has been shown to be effective for underground coal fires because it has the ability to flood large enclosed spaces in short times using low amounts of water and foam concentrate (Sthamer, 2012; Martin, 2012). Despite the fact that Hi-Ex foam has been shown to be effective for addressing fires there are still some uncertainties about its behavior in underground locations where different topographies, geometries and obstructions are found (Smith et al., 2005).

Some experiments have been carried out to study the stability, movement and control of Hi-Ex foam in underground locations. For instance, Smith and others conducted a series of full-scale experiments in NIOSH’s Lake Lynn Experimental Mine (LLEM) (Smith et al., 2005), in which foam was produced on the surface and foam flow was evaluated through different slopes and non-linear configurations, through and around obstructions. According to the results, foam flow movement and speed are directly dependent on the slope of mine floor. Another full scale experiment in underground locations was carried out by Chasko and others in which foam was generated from an underground location far away from the fire (Chasko, Conti, Derick, Krump, &
Lazzara, 2003). Results showed that a Hi-Ex foam plug can flow hundreds of feet in mine entries with slopes up to 20%. Although these experiments have helped to understand foam flow behavior in some underground configurations, these experimental studies are limited to the geometry and slopes of mine entries where they are carried out (Smith et al., 2005). Furthermore, conducting full scale experiments in active mines results in interruptions of activities affecting mine productivity, and may be costly.

In the mining literature there is no evidence of attempts to simulate Hi-Ex foam in underground openings. Other fields, such as petroleum drilling engineering have simulated low expansion foam as a non-Newtonian fluid through porous media (Osunde & Kuru, 2008). Prediction of Hi-Ex foam flow behavior through numerical simulations in underground locations would reduce the number of full-scale experiments, contributing to improvements in mine fire response plans and application techniques. Furthermore, the study of foam rheology could help with advances in foam concentrate characteristics and foam generation processes.

In this study Hi-Ex foam was numerically simulated as a continuous non-Newtonian fluid in order to estimate its behavior in conduits and mine entries using computational fluid dynamics (CFD). This work was divided into three parts. First, Hi-Ex foam rheology was investigated with the objective of confirming its non-Newtonian character evidenced in previous studies for low expansion foam (Gardiner, Dlugogorski, & Jameson, 1998; Khan, Schnepper, & Armstrong, 1988; Calvert & Nezhati, 1987). Additionally, a rheological model that best fit with experimental behavior was found. Then, numerical simulations in conduits were carried out using the rheological model and compared with experimental results obtained from the experimental apparatus. Finally, numerical simulations of Hi-Ex foam were made in different mine slopes and relationships between foam velocity, foam advancement and time were found in order to estimate foam behavior.

References


http://sthamer.com/englisch/f33_high_foam.html

Chapter 2 . Rheology of High Expansion Foam

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Abstract

Even with modern detection and firefighting techniques, mine fires continue to be a considerable safety concern. Evacuation from large underground mines is complex and direct firefighting is high risk, even for specially trained mine rescue teams and fire brigades. However, some underground mine fires can be addressed with the remote application of high expansion (Hi-Ex) foam, reducing firefighter exposure to hazards, and allowing for rapid response. The flow of this foam can be numerically or computationally simulated in order to gain a better understanding of its behavior, but rheology parameters are needed as inputs to produce accurate simulations. For this reason, this work studies the rheology of firefighting Hi-Ex foam using a foam generator and pipe viscometer. Results show a strong agreement with the power law model for non-Newtonian fluid viscosity. Rheological parameters for foams with expansion ratios between 250-1280 are represented by the consistency index (k) and the power law index (n). Furthermore, experimental results show that Hi-Ex foam behaves as a shear thinning fluid with a power law index of around 0.4 and viscosities in the range of 0.15 Pa-s to 0.042 Pa-s for shear rates between 44 s\(^{-1}\) and 187.3 s\(^{-1}\). The rheological model represents the constitutive equation of Hi-Ex foam that, along with the field equations, are used in order to obtain the foam governing equation for numerically solving its flow.

Keywords: High Expansion Foam, Foam Rheology, Power law, Non-Newtonian fluids

1. Introduction

High expansion (Hi-Ex) foam is a firefighting technology that has been used for fire suppression in large enclosed spaces, such as underground mines. Hi-Ex foams possess the ability to flood confined indoor spaces in short times due to their high expansion ratios greater than 200 (Sthamer, 2012; Martin, 2012; NFPA, 2014). In most underground mine scenarios, fires have to be addressed remotely to reduce miner and firefighter exposure to the hazards. Thus, Hi-Ex foams are applied remotely by means of conduit pipes or boreholes into the mine openings from the surface (Smith et al., 2005). Foam flow in conduit pipes or along the mine entries can be numerically or
computationally simulated in order to predict and gain a better understanding of its behavior, but rheological parameters are needed as inputs to produce accurate results.

Previous rheology studies for firefighting foam have shown that low expansion foams behave as shear thinning fluids represented by the power law or Herschel Bulkley model (Gardiner et al., 1998, Khan et al., 1988; Wenzel, Brungraber, & Stelson, 1970; de Kransinski & Fan, 1984; Thondavadi & Lemlich, 1985). In other words, foam viscosity is proven to be inversely proportional to the shear rate. In the same way, results of a study by Wenzel and others showed that medium and Hi-Ex foams with expansion ratios less than 250 also behave as shear thinning fluids (Wenzel et al., 1970). The results were fitted to the Herschel Bulkley model for shear rates between 200 and 250. Rheological model parameters obtained in some of the previous studies mentioned above are summarized in Table 2-1.

**Table 2-1 Summary of previous foam rheology studies**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Expansion ratio, E</th>
<th>Shear rates (s⁻¹)</th>
<th>Consistency index k (Pa sⁿ)</th>
<th>Power law index, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>(de Kransinski &amp; Fan, 1984)</td>
<td>10-17</td>
<td>0.05-500</td>
<td>18.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(Thondavadi &amp; Lemlich, 1985)</td>
<td>8.3-100</td>
<td>0.2-6.2</td>
<td>1.43</td>
<td>0.61</td>
</tr>
<tr>
<td>(Wenzel et al., 1970)</td>
<td>38-250</td>
<td>0.2-18</td>
<td>1.73-6.8</td>
<td>0.13-0.69</td>
</tr>
</tbody>
</table>

There is no evidence of studies for Hi-Ex foam with expansion ratios greater than 250 in the literature. Although foam with this expansion ratio could have the same shear thinning behavior evidenced in previous studies, rheological parameters are necessary in order to determine the constitutive equations for this kind of foam. Also, an accurate prediction of the Hi-Ex foam flow using computational fluid dynamics (CFD) is directly dependent on the rheological model parameters. Thus, in this work we studied the rheology of Hi-Ex foam with expansion ratios between 250 and 1280 using a foam generator composed of a blower fan with a variable frequency drive (VFD) that can deliver different foam flow rates. The rheological behavior of Hi-Ex foam was studied under shear rates between 29 to 190 s⁻¹. Finally, the constitutive equations along with the rheological parameters of Hi-Ex foam are shown.
2. Methodology

2.1. Experimental Apparatus

As can be seen in Figure 2-1 the experimental apparatus is composed of a small scale foam generator and pipe viscometer. The foam generator was built based on NFPA 11 Standards (NFPA, 2012) and previous foam generator patents (Harding, Zhang, Liu, Chen, & Mannan, 2016; Fleming & Sheinson, 201; Jamison, 1966; O’Regan, Lundberg, & Mussoni, 1970). Foam is produced when the air is pushed by the blower fan going through a #60 screen (100 mesh cells per inch) that is previously wet by a spray nozzle delivering a solid cone pattern. The distance between the nozzle and screen is set so that the spray pattern can cover the screen to avoid large air gaps and to maintain homogeneous bubble size during foam production. The foam generator also contains a water pump, flowmeter and variable frequency drive (VFD) attached to the blower fan in order to control the foam expansion ratios. Different foam solution flowrates can be delivered through the nozzle depending on the change of pressure produced on the flowmeter. Foam solution flowrates delivered by the nozzle are shown in Table 2-2. Figure 2-2 shows air flowrates delivered by the blower fan by different frequencies. The foam expansion ratio is calculated using the known air and foam solution flowrate as shown Equation 2-1.

\[ E = \frac{(7.48Q_a) + Q_f}{Q_f} \]  

Equation 2-1

Where \( Q_a \) is the air flowrate (cfm) and \( Q_f \) is the foam solution flowrate (gpm).

<table>
<thead>
<tr>
<th>Nozzle pressure (psi)</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>20</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate capacity (gpm)</td>
<td>2.9</td>
<td>3.4</td>
<td>4.0</td>
<td>5.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>
The foam concentrate used in this experiment is called Chemguard X-tra High Expansion Foam, which was diluted with water to a 2% solution by volume. Two percent solution indicates that foam solution is a mixture of 2 parts liquid foam concentrate and 98 parts of water.

The pipe viscometer, also called a Poiseuille rheometer was built to allow for collection of parameters related to Hi-Ex foam rheology. This part of the apparatus is based on the experimental apparatuses built by Gardiner and others (Gardiner et al., 1998) and Enzendorfer and others (Enzendorfer et al., 1995). The pipe viscometer was composed of a 4 inch (0.1016 m) PVC pipe, 10 ft (3.048 m) in length and two pressure transducers to record the pressure drop over 2 ft (0.6096 m) and 8 ft (2.4384 m) pipe sections. The pressure transducers used in this experiment can measure pressures between 0-1.5 psi (0-6894.76 Pa) and are connected to a programmable logic controller (PLC) through a 4-20MA current loop. Effects due to the entrance are eliminated by setting the first transducer 2 ft (0.6096 m) away from the pipe inlet and exit.

Figure 2-1 Experimental Apparatus
2.2. Data Analysis

The apparent Newtonian shear stress at the wall for a flow in a pipe is given by Equation 2-2.

\[
\tau_w = \frac{D \Delta P}{4L}
\]  

Equation 2-2

Where \( \tau_w \) is the wall shear stress [Pa], \( \Delta P \) is the pressure drop [Pa] between pressure transducers spaced a distance \( L \) [m] apart each from other and \( D \) [m] is the internal diameter of the pipe. The Newtonian shear rate at the wall for a flow in a pipe is given by

\[
\gamma_w = \frac{32Q}{\pi D^3}
\]  

Equation 2-3

Where \( \gamma_w \) is the wall shear rate \([s^{-1}]\), \( Q \) is the foam flowrate \([m^3/s]\) and \( D [m] \) is the internal diameter of the pipe.

2.3. Wall slip and yield stress

Wall slip is the phenomenon when foam flows on a thin liquid layer at the pipe walls of thickness order between 1 – 30 \( \mu m \) (Thondavadi & Lemlich, 1985; Calvert, 1986; Calvert & Nezhati, 1987). The liquid layer at the pipe walls comes from the liquid drainage from the foam (Gardiner, Dlugogorski, & Jameson, 1999). The wall slip phenomenon produces errors in foam flowrates as we can see in Equation 2-4. The observed flow rates will be higher than true foam flow rates (Gardiner et al., 1998).
\[(Q)_{observed} = (Q)_{true} + Q_{slip} \quad \text{Equation 2-4}\]

This wall slip should be accounted for in the data analysis because experimental results could be geometry dependent. It is important to mention that thin layer thickness depends on pipe roughness, diameter, foam shear rate, surfactant concentration, bubble size distribution and expansion ratio (Gardiner et al., 1999). According to the Oldroyd-Jastrzebski method, the slip velocity is defined by Equation 2-5 (Jastrzebski, 1967):

\[u_{slip} = \frac{\beta_c \tau_w}{D} \quad \text{Equation 2-5}\]

Where \(\beta_c\) is the slip coefficient \([m^3s/kg]\) that varies only with wall stress, \(\tau_w\) is the wall shear stress \([Pa]\) and \(D\) is the inner diameter of the pipe \([m]\).

Thondavadi and others and Calvert and others reported that the slip velocity is greater for thicker layers and the slip layer thickness tends to increase as the expansion ratio falls (Thondavadi & Lemlich, 1985; Calvert & Nezhati, 1987). Additionally, Gardiner and others stated that expansion ratio is the most important variable in determining wall slip behavior because the more liquid is in the foam the more liquid is available to form a slip layer (Gardiner et al., 1999). Considering these conclusions and acknowledging that in this study only foams with expansion ratios greater than 250 were used, high flow velocities and small residence times were observed, it is assumed that the formation of a slip layer is negligible, and thus, slip velocity is near zero. However, this assumption can affect slightly the results for foam residence times close to 3 seconds (shear rates between 20-40 s\(^{-1}\)) since the induction time for Hi-Ex foam is roughly this time (Conroy, Taylor, Farley, Fleming, & Ananth, 2013).

3. Results

Tests were carried out at room temperature between 18-20 Celsius degrees. As mentioned before, air and foam solution flowrates delivered by the blower fan and the water pump were changed independently using the variable frequency drive (VFD) and the flowmeter in order to achieve different foam expansion ratios. Two groups based on expansion ratio were studied. Group number 1 was composed of foam with expansion ratios between 250 and 600. Group number 2 was composed of foam with expansion ratios between 600 and 1279. Table 2-3 shows different expansion ratios used in this study and the air and foam solution flowrates in which these expansion ratios were achieved. It is important to mention that the highest expansion ratios were obtained for
foam solution flowrates lower than 3 gpm using air flowrates of 257 cfm, 312 cfm and 348 cfm. On the other hand, expansion ratio between 250 and 600 were obtained with foam solution flowrates greater than 3.5 gpm. This fact indicates that expansion ratios decrease when the liquid flowrate is increased, as shown in Figure 2-3.

![Figure 2-3 Expansion ratio vs. foam solution for all expansion foam trials. Legend shows air flowrates](image)

Pressure drop and foam flowrate were determined for all expansion foam trials. Then, using Equation 2-2 and Equation 2-3 the flow curves were obtained. The results for group 1 and group 2 are shown in Figure 2-4 and Figure 2-5, respectively. The flow curves lines were fitted to the power law model represented by Equation 2-6 since good agreement was found. The good fit between the experimental data and the power law is evidenced in the R-squared values equal 0.92 and 0.96 for groups 1 and 2, respectively.

\[ \tau_w = k \gamma_w^n \]  
Equation 2-6

Where \( \tau_w \) is the wall shear stress [Pa], \( \gamma_w \) is the Newtonian shear rate [s\(^{-1}\)], \( k \) is the consistency index (Pa \( \cdot \) s\(^n\)) and \( n \) is the power law index.

\( k \) and \( n \) parameters are shown in the Table 2-4. Constitutive equations for groups 1 and 2 are shown in Equation 2-7 and Equation 2-8, respectively.
Table 2-3 Groups of Foam Expansion Ratios used in this study

<table>
<thead>
<tr>
<th></th>
<th>Group #1 (250-600)</th>
<th></th>
<th>Group #2 (&gt;600)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air Flowrate (cfm)</td>
<td>Solution flowrate (gpm)</td>
<td>Expansion Ratio</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>7</td>
<td>276</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>5</td>
<td>386</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>4.5</td>
<td>429</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>4</td>
<td>482</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>3.5</td>
<td>551</td>
</tr>
<tr>
<td></td>
<td>312</td>
<td>7</td>
<td>334</td>
</tr>
<tr>
<td></td>
<td>312</td>
<td>5</td>
<td>467</td>
</tr>
<tr>
<td></td>
<td>312</td>
<td>4.5</td>
<td>519</td>
</tr>
<tr>
<td></td>
<td>312</td>
<td>4</td>
<td>584</td>
</tr>
<tr>
<td></td>
<td>348</td>
<td>5</td>
<td>522</td>
</tr>
<tr>
<td></td>
<td>348</td>
<td>4.5</td>
<td>580</td>
</tr>
</tbody>
</table>

\[
\tau_w = 2.3562\gamma_w^{0.4044} \quad \text{Equation 2-7}
\]

\[
\tau_w = 2.5492\gamma_w^{0.4091} \quad \text{Equation 2-8}
\]
The rheological parameters show that for both groups (i.e., expansion ratios greater than 250), foam behaves as a shear thinning fluid ($n<1$). Furthermore, it can be observed that there is not a significant difference between the rheological parameters for group 1 and 2.
Table 2-4 Rheological parameters for group 1 and 2

<table>
<thead>
<tr>
<th>Expansion Ratio</th>
<th>Consistency Index k</th>
<th>Power Law Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>250-600</td>
<td>2.3562</td>
<td>0.4044</td>
</tr>
<tr>
<td>600-1279</td>
<td>2.5492</td>
<td>0.4091</td>
</tr>
</tbody>
</table>

The viscosity of foam can be calculated through the slope of the line for any point in a plot of shear stress vs shear rate, according to the Equation 2-9. It is important to highlight that for non-Newtonian fluids the viscosity depends on the shear rate applied to the fluid. The results indicate that for Hi-Ex foam the viscosity decreases when the shear rate increases. Clearly, this behavior confirms the shear thinning character of Hi-Ex foam.

\[ \mu = n k \gamma_w^{n-1} \]  
\text{Equation 2-9}

Where \( \mu \) is the foam viscosity [Pa-s], \( \gamma_w \) is the wall shear rate [s\(^{-1}\)], \( k \) is the consistency index (Pa – s\(^n\)) and \( n \) is the power law index.

Using Equation 2-9 to calculate the viscosities for group 1, it is observed that they are between 0.0421 Pa-s and 0.1 Pa-s for shear rates equal 187.3 s\(^{-1}\) and 44 s\(^{-1}\), respectively. For group 2 the viscosities observed are between 0.0501 Pa-s for a shear stress equals 170 s\(^{-1}\) and 0.15 Pa-s for a shear stress equals 29.8 s\(^{-1}\).

4. Conclusions

This paper has studied the rheological parameters for Hi-Ex foam with expansion ratios between 250 and 1280 for shear rates between 20 s\(^{-1}\) and 190 s\(^{-1}\) in order to measure the input parameters for numerical simulations of Hi-Ex foam flow. This study was carried out in an experimental apparatus composed of small scale foam generator and a pipe viscometer. The slip correction was not taken into account in this study because foam with expansion ratios greater than 250 was used (not enough liquid is available to form a slip layer), and short residence times were evidenced. The data for the two groups shows a good agreement with the power law model. Group 1 exhibited a power law index equal to 0.4044 and a consistency index equal to 2.3562 Pa – s\(^n\). The minimum and maximum viscosity for this group were 0.0421 and 0.1 Pa-s for shear rates between 187.3 s\(^{-1}\)
and 44 s\(^{-1}\). For the second group foam exhibits a power law index equal to 0.4091 and a consistency index of 2.5492. The minimum and maximum viscosity for this group were 0.0501 Pa-s and 0.15 Pa-s for shear rate between 170 s\(^{-1}\) and 29.8 s\(^{-1}\). According to the results Hi-Ex foam shows a shear thinning behavior when it has undergone shear stresses greater than 20 Pa. The general results of this paper are only applicable for the foam produced by our foam generator but can be used as an estimation for rheological parameters required in numerical simulations. Finally, Further investigation could be focused in foam flows with residence times greater than the foam induction time in order to study the slippage phenomenon of Hi-Ex foam for low shear rates.

5. Acknowledgment

Manuel Barros Daza is lead the author of this chapter and responsible for most of the original writing. He conceived and wrote the paper with editorial input from Kray Luxbacher and Brian Lattimer. Much of the work in this chapter was published in:


6. References


gas-enhanced foam for suppressing coal mine fires.


High expansion (Hi-Ex) foam has been used widely for fire suppression in underground mines because they have the ability to flood large enclosed spaces using a low amount of water and foam concentrate. Hi-Ex foam is conducted through pipes or boreholes over long distances to reach a fire. Because of their somewhat limited applications, no obvious attempts have been made to numerically simulate Hi-Ex foam features due to the complex behavior of multiphase flow. This paper proposes to simulate Hi-Ex foam flow in a pipe with constant circular cross section as a continuous and non-Newtonian fluid using computational fluid dynamics (CFD) as has been done previously for low expansion foam. Pressure drops calculated from the numerical model were compared with an experimental data set obtained in the laboratory in order to validate this approach for Hi-Ex foam. Numerical results are shown to be between 0.06% and 14.66% of the experimental data set with a Reynolds number between 200 and 1734. The highest difference between the experimental and numerical pressure drops were found for Reynolds Numbers lower than 200. Finally, it is concluded that the approach of modelling foam as a continuous and non-Newtonian fluid is satisfactory for Reynolds numbers greater than 200 when the slippage phenomenon is not taken into account for experimental results. This preliminary work will allow for reasonable accuracy when modelling movement of Hi-Ex foam in mine firefighting applications.

Keywords: high expansion foam, numerical simulation, non-Newtonian fluid, flow in a pipe.

1. Introduction

Foam firefighting technology is mainly used to address fires in large enclosed spaces such as underground locations. For underground fires, Hi-Ex foam is applied remotely or far away from the fire due to the hazard conditions nearby to the fire. Normally, foam is applied through boreholes or conducted via-pipes over long distances (Smith et al., 2005). Large pressure drops during Hi-Ex foam flow in pipes can be present due to frictional loss and shock losses (Galindo Rosales &
Rubio Hernandez, 1999). The prediction of velocity and pressure drop can facilitate better design in regards foam generation, optimum pipe diameter and foam application techniques (Chhabra & Richardson, 1999).

One of the most common parameters to characterize fire-fighting foam is called the expansion ratio. This term is defined as the ratio of the volume of foam and the volume of liquid used to produce that volume of foam (Wenzel et al., 1970). Hi-Ex foams possess an expansion ratio greater than 200 giving them to have the ability to fill large enclosed spaces quickly. In contrast, low expansion foams have an expansion ratio less than 20 being able to reach long distances and cover large areas when they are thrown through fire hoses (Martin, 2012).

Most of the previous studies in this area have been concerned with numerical simulation of low expansion foam since this kind of foam tends to be more versatile for different fire scenarios, particularly surface firefighting applications. In these previous studies, low expansion foam has been simulated as a non-Newtonian and continuous fluid, instead of as a multiphase fluid. This approach has been demonstrated to have adequate accuracy and is much simpler than the application of multiphase flow models as seen in the work developed by Osunde and Kuru. In this study, low expansion foam was considered to be a homogeneous non-Newtonian fluid whose rheology was represented by the power law in order to develop a two phase fluid flow model composed of foam, a cuttings bed and suspended solids solved using the Crowe’s method (Osunde & Kuru, 2008). Another study where low expansion foam was simulated as non-Newtonian fluid was done by Gao and others (Gao, Zhang, Xia, Song, & Wang, 2016). In this research, a new rheological model was proposed and imported to the commercial software Ansys Fluent-15.0. The proposed model combines the Herschel-Bulkley model for non-Newtonian fluid, a structural damage coefficient and a foam index to relate the change of rheological behavior of foam with foam drainage.

As was mentioned before, in order to carry out numerical simulations of firefighting foams under the approach of a non-Newtonian fluid, rheological studies have been done to characterize firefighting foams behavior when they have undergone stress. Most of the results of these studies have concluded that firefighting foams behave as shear thinning fluids represented by the power law model or Herschel Bulkley model (Gardiner et al., 1998; Wenzel et al., 1970; Wearie, 2017; Barros Daza, Luxbacher, & Lattimer, 2018). For instance, Gardiner and others concluded that
compressed-air low expansion foams behave as shear thinning fluids represented by the power law model with an index (n) of 0.29 and consistency index (K) of 2.63 \( Pa \ s^n \) (Gardiner et al., 1998). Wenzel and others using a vaned cone and plate viscometer for foam with expansion ratios between 1:200 and 1:250, demonstrating that foam shows a pseudoplastic or shear thinning behavior and good agreement with the Herschel Bulkley Model. The power law index obtained in this study was between 0.68 and 0.45 (Wenzel et al., 1970).

The most recent study of rheology of Hi-Ex foam was carried out by Barros and others (Barros Daza et al., 2018), studying the rheology of foam with expansion ratio between 250 and 1280 using a foam generator blower type and a pipe viscometer composed of 4 inches PVC tube. The results of this study are summarized in Table 3-2 and were used as the input parameters in this study for solving numerically the Hi-Ex foam flow in a circular pipe. The numerical results were compared with the experimental results obtained in the laboratory in order to validate the numerical results under the approach of treating Hi-Ex foam as a continuous and non-Newtonian fluid.

2. Model development

In this study, a model of steady flow Hi-Ex foam in circular pipe of constant radius is solved. The model is based on the constitutive equation of Hi-Ex foam and Navier Stokes equations. Foam flow is assumed as laminar, incompressible and fully developed. Furthermore, foam is considered continuous, non-Newtonian and time independent fluid with viscosity given by the power law. Foam drainage was not considered due to low amount of liquid in Hi-Ex foams and short residence time of foam in the pipe.

2.1. Geometry and Mesh

The simulation of Hi-Ex foam flow was carried out in a pipe 3.048 m (10 ft.) in length and diameter equals 0.1016 m (4 in). Since the flow is axisymmetric (Galindo Rosales & Rubio Hernandez, 1999) the volume domain can be reduced to a 2-D domain with a width of 0.1016 m and a length of 3.048 m. The geometry was meshed by quadrilaterals in a structured grid. Mesh parameters are shown in Table 3-1, and the mesh effectiveness was validated comparing analytical and numerical results for a Newtonian fluid. It is important to mention that this geometry comes from the dimensions of the experimental apparatus used in the laboratory.
Table 3-1 Mesh Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>106201</td>
</tr>
<tr>
<td>Elements</td>
<td>104400</td>
</tr>
<tr>
<td>Min Aspect Ratio</td>
<td>1.0334</td>
</tr>
<tr>
<td>Max Aspect Ratio</td>
<td>1.0418</td>
</tr>
</tbody>
</table>

2.2. Governing equation

For the derivation of the governing equation for Hi-Ex foam flow in the geometry mentioned previously, a modification of Stokes equation was used. This approach was previously used for numerical simulation of general non-Newtonian fluid flows in pipes (Galindo Rosales & Rubio Hernandez, 1999).

For Hi-Ex foam the viscosity depends on the shear rate as is shown in Equation 3-1.

\[ \tau' = \mu(\dot{\gamma}) \tilde{\dot{\gamma}} \]  

Equation 3-1

Where \( \tau' \) is the stress tensor of viscous stresses, \( \dot{\gamma} \) is the deformation rate tensor, \( \mu \) is the viscosity that depends on the shear rate \( \dot{\gamma} \).

Equation 3-1 is a particular case to represent Equation 3-2 for isotropic fluid.

\[ \bar{\tau} = -\nabla p + 2\mu(\dot{\gamma}) \left( \frac{1}{2} (\Delta \tilde{v} + \Delta \tilde{v}^T) - \frac{1}{3} \Delta \tilde{v} \right) \]  

Equation 3-2

Where \( \tilde{v} \) is the velocity vector of the fluid.

The derivation of the model for Hi-Ex foam flow is based on the continuity and momentum equations. It is important to highlight that isothermal conditions are assumed, thus, the energy equation is decoupled from the conservation of mass and momentum.

Equation 3-3 and Equation 3-4 are the generalized continuity and momentum equations, respectively

\[ \frac{\delta \rho}{\delta t} + \nabla \cdot (\rho \tilde{v}) = 0 \]  

Equation 3-3

\[ \frac{\delta \rho \tilde{v}}{\delta t} + \nabla \cdot (\rho \tilde{v} \tilde{v}) = \nabla \cdot \bar{\tau} + \rho \bar{f}_m \]  

Equation 3-4
As was mentioned before foam in this model is considered incompressible ($\rho = cte$) since foam drainage was not considered (not mass losses during the foam flow). Besides, body forces as gravity are not taken into account for this flow, thus, the equation of continuity and momentum reduce to equations Equation 3-5 and Equation 3-6.

$$\nabla \cdot \vec{v} = 0$$  \hspace{1cm} \text{Equation 3-5}

$$\rho \left( \frac{\delta \vec{v}}{\delta t} + \vec{v} \cdot \nabla (\vec{v}) \right) = \nabla \cdot \vec{r}$$  \hspace{1cm} \text{Equation 3-6}

Assuming laminar steady state, fully developed flow and replacing Equation 3-2 and Equation 3-5 into Equation 3-6, Equation 3-7 is obtained.

$$-\nabla p + \nabla \cdot \left( 2\mu(\dot{\gamma}) \left[ \frac{1}{2}(\Delta \ddot{v} + \Delta \ddot{v}^T) \right] \right) = 0$$  \hspace{1cm} \text{Equation 3-7}

The unidirectional and steady flow in x direction as shown in Figure 3-1 allow for simplification of Equation 3-7 into Equation 3-8. The model of Hi-Ex foam flowing through a circular cross section can be represented by Equation 3-8. As was mentioned before, foam viscosity is function of shear rate resulting in a differential equation which is complex to solve analytically. For this reason, Equation 3-8 was solved through numerical techniques to obtain solutions using the commercial CFD software Ansys Fluent.

$$\frac{dp}{dx} = \frac{d}{dy} \left( \mu(\dot{\gamma}) \frac{du}{dy} \right)$$  \hspace{1cm} \text{Equation 3-8}

![Figure 3-1 side view of the 2D pipe with diameter D and length L and the coordinate system](image-url)
1.1. Boundary conditions

For the inlet boundary condition located at the left face of the geometry (Figure 3-1) different inlet x-velocities were used considering y-velocity equals zero for any case. These velocities were the same ones obtained in the laboratory during the experiment and are outlined in Table 3-3.

For outlet boundary condition the static pressure was set zero assuming that it is open to the atmosphere. Backflow direction was specified normal to boundary method. For wall boundary a non-slip boundary condition was used.

1.2. Rheological parameters of High expansion foam

Foam was divided into two different groups. Group 1 contains foam with expansion ratios between 250 and 600 and group 2 is foam with expansion ratio between 600 and 1280. In order to solve Equation 3-8, it is necessary to have the constitutive equation and the rheological parameters of Hi-Ex foam to determine the foam viscosity for any shear rate, \( \mu(\dot{\gamma}) \). The constitutive equation for groups 1 and 2 are shown in Equation 3-9 and Equation 3-10, respectively. Table 3-2 shows rheological parameters for both groups according to the work done by Barros and others (Barros Daza et al., 2018).

\[
\tau_w = 2.36 \gamma_w^{0.4044} \quad \text{Equation 3-9}
\]

\[
\tau_w = 2.55 \gamma_w^{0.4091} \quad \text{Equation 3-10}
\]

Viscosity can be expressed directly as function of shear rate as seen in Equation 3-11 and Equation 3-12.

\[
\mu = \frac{0.95}{\gamma_w^{0.6}} \quad \text{for} \quad 40s^{-1} < \gamma_w < 168s^{-1} \quad \text{Equation 3-11}
\]

\[
\mu = \frac{0.97}{\gamma_w^{0.59}} \quad \text{for} \quad 50s^{-1} < \gamma_w < 170s^{-1} \quad \text{Equation 3-12}
\]

Substituting Equation 3-11 and Equation 3-12 into Equation 3-8, the governing equations for group 1 and 2 can be expressed as the following, respectively:
\[
\frac{dp}{dx} = \frac{d}{dy}\left(0.95 \frac{du}{dy}\right) \\
\frac{dp}{dx} = \frac{d}{dy}\left(0.97 \frac{du}{dy}\right)
\]

Equation 3-13  
Equation 3-14

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency Index, k (Pa (\text{s}^n))</td>
<td>2.36</td>
<td>2.55</td>
</tr>
<tr>
<td>Power Law Index, n</td>
<td>0.4044</td>
<td>0.4091</td>
</tr>
<tr>
<td>Minimum Viscosity Limit (kg/m-s)</td>
<td>0.045</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum Viscosity Limit (kg/m-s)</td>
<td>0.1</td>
<td>0.15</td>
</tr>
</tbody>
</table>

2. Experimental Apparatus

Experimental data sets were obtained using a 4 inch PVC pipe with 3.048 m (10 ft) in length. Two pressure transducers were attached to the pipe 1.83 m (6 ft) apart from each other in order to measure the pressure drop of Hi-Ex foam for different velocities. The pressure transducers were located 0.6 m (2 ft) and 2.43 m (8 ft) away from the pipe inlet as it can be seen in Figure 3-2. They measured pressures between 0 and 10,300 Pa (0-1.5 psi) and were connected to a programmable logic controller (PLC) using a 4-20 mA current loop. Pressure drops were displayed on a screen installed in the PLC.

Foam was generated using a small scale foam generator based on NFPA 11 standards and some previous foam generator patents (Harding et al., 2016, Fleming & Sheinson, 2012, Jamison, 1966,O’Regan et al., 1970). This foam generator was able to produce foam with expansion ratios between 1:250 and 1:1280 and deliver foam flow rates between 0.006 \(\frac{m^3}{s}\) and 0.011 \(\frac{m^3}{s}\). Foam velocity and expansion ratios were controlled by varying foam solution flowrates and airflow. For controlling airflow, a variable frequency drive (VFD) was attached to the blower fan in order to modify the fan speed. Also, a flowmeter was used to control foam solution flowrate. The sketch of the foam generator is showed in Figure 3-3.

Foam velocities were calculated using a collector at the pipe outlet with known volume and a timer in order to determine the foam flowrate. Then, using the diameter of the pipe, the velocity was
calculated.

![Diagram of experimental apparatus](image)

Figure 3-2 side view of experimental apparatus used to record Hi-Ex foam pressure drop

![Diagram of Hi-Ex foam generator](image)

Figure 3-3 Hi-Ex foam generator

Although in previous experimental studies with low expansion foam done by Gardiner and others (Gardiner et al., 1998) and Wenzel and others (Wenzel et al., 1970) a method for slip correction was used, in this study, Hi Ex foam slippage phenomenon was neglected for two reasons. First, Hi-Ex foam possesses low amounts of foam solution available to form a slip layer (Gardiner et al., 1999). The second reason is the short residence time of the foam in the pipe; the foam does not have enough time to drain and form the wall layer (Gardiner et al., 1998). It is possible that for low foam velocities (longer residence times) the slippage phenomenon must be taken into account during the experimental tests since the residence time of foam in the pipe is close to the foam induction time (2.7-3 seconds) (Conroy, Taylor, Farley, Fleming, & Ananth, 2013) but this consideration is discussed later in this paper.

3. Results and Discussions
The commercial software Ansys Fluent 14.5 was used to solve Equation 3-13 and Equation 3-14
using the finite volume method. Different inlet velocities were set and pressure drops between two points located 0.60 m (2 ft) and 2.43 m (8 ft) away from the inlet were calculated and compared with pressure drop obtained experimentally at the same points $P_1$ and $P_2$ (see Figure 3-2). Inlet velocities between 0.73 m/s and 2.13 m/s were developed for group 1 and between 0.730 m/s and 2.07 m/s for group 2. These velocities, were imposed as boundary conditions for the numerical simulations were measured during the experimental test using the foam generator. The relationship between pressure drop and foam velocity obtained from solving the Equation 3-13 and Equation 3-14 for both groups are shown in Figure 3-4. Also, In Figure 3-4 can be seen the relationship between pressure drop and foam velocity obtained experimentally in the laboratory.

![Figure 3-4 Relationship between pressure drop and velocity obtained experimentally](image)

In order to validate the numerical solution of the proposed model in Equation 3-13 and Equation 3-14, percentage error was calculated according to Equation 3-15. The main idea was to evaluate how different were the experimental and numerical values and to find a possible relationship between error percentage, Reynolds number, and viscosity.

$$ E = \left| \frac{\Delta p_{Exp} - \Delta p_{Num}}{\Delta p_{Exp}} \right| \times 100 $$

Equation 3-15
Reynolds numbers for both groups were calculated for each test using Equation 3-16, proposed by Edwards and others for a power law fluid (Edwards, Jadallah, & Smith, 1985).

Table 3-3 shows the Reynolds number for each test velocity. It is evident that at higher velocities, Reynolds number increases as a consequence of an increasing of the inertial forces. All Reynolds numbers lower than 2,000 indicate laminar flow which was assumed during the experimental procedure to determine the governing equations for both groups.

A plot between Reynolds number and error percentage can be seen in Figure 3-5. Although a trendline was not plotted, in this graphic is clear that at higher Reynolds numbers than 200, the error is lower than 15%. The highest errors obtained were 23% and 33.65% for Reynolds numbers lower than 200. Although not fully investigated, one possible reason for these high error percentages for Reynolds numbers lower than 200 are inaccurate velocity readings due to foam slippage at the wall surface. Small Reynolds numbers indicate long foam residence times in the pipe allowing the foam more time to be drained, thus the wall slip layer can generate higher observed foam velocities than true foam velocities (Gardiner et al., 1998).

\[
Re = \left( \frac{4n}{3n + 1} \right)^n \frac{\rho D^n V^{2-n}}{\mu 8^{n-1}} \quad \text{Equation 3-16}
\]

Where, \( Re \) is the Reynolds number, \( n \) is the power law index, \( D \) is the diameter of the pipe, \( V \) is
the foam velocity, \( \mu_o \) is the dynamic viscosity of the fluid and \( \rho \) is the density of the fluid.

*Figure 3-5 Relationship between Percentage Error and Reynolds Number*

In the same way, error percentage was plotted versus foam viscosity as shown in Figure 3-6, showing that for higher viscosities, error percentage trends to be greater. For shear thinning fluids, high viscosities are evidenced for low Reynolds numbers. Thus, Figure 3-6 agrees with Figure 3-5 where the highest errors were obtained for viscosities greater than 0.08 Pa-s that occur when the Reynolds number is lower 200.

*Figure 3-6 Relationship between percentage error and viscosity*
4. Conclusions

Numerical simulation of Hi-Ex foam flow as a shear thinning fluid in circular pipe of constant radius was performed and compared with experimental data. An apparatus composed of a small scale blower type foam generator and pipe viscometer were used to perform tests with different foam velocities. Pressure transducers were attached to the pipe viscometer in order to get the pressure drop of Hi-Ex foam flow. Experimental foam flow pressure drops were compared with results of the numerical model. The model was numerically solved using the commercial CFD software Ansys Fluent 14.5, assuming Hi-Ex foam as a continuous, non-Newtonian fluid with viscosity given by the power law. This approach had been used previously for low expansion foam and demonstrated in other foam studies.

Numerical results are between 3.47% and 8.83% of the experimental data set for group 1 and Reynolds numbers between 200 and 1078. For group 2, numerical results were between 0.06% and 14.66% of the experimental data for Reynolds numbers between 600 and 1734. The highest difference between experimental and numerical pressure drops were evident for Reynolds number lower than 200 for both groups. For group 1, the highest error percentages of 33.65% and 23% were found for Reynolds numbers equal to 181 and 192, respectively. A similar case occurred for group 2 where numerical results were 18.44% and 21.89% of experimental pressure drop for Reynolds numbers equal to 143 and 162, respectively. These high error percentages for small Reynolds numbers can be attributed to the slippage phenomenon. As a consequence of this phenomenon, higher velocity readings than true velocities for Reynolds numbers lower than 200 can be observed during the experimental test since foam has more time to be drained and form a slip layer (foam residence times close to the foam induction time). This conclusion agrees with previous low expansion foam studies (Gardiner et al., 1998) where it was concluded that when foam moves faster through a conduit pipe there is less time for foam solution to drain from at the boundary, avoiding the formation of a complete slip wall layer.

The numerical model was capable of predicting Hi-Ex foam flow behavior satisfactorily for Reynolds numbers between 200 and 1700, allowing for reasonable accuracy when modeling movement of Hi-Ex foam in mine firefighting applications. Finally, further investigation could be focused on the slippage phenomenon for foam flows with low velocities (foam residence times
greater than the foam induction time) and low wall shear rates.

5. Acknowledgments

Manuel Barros Daza is lead the author of this chapter and responsible for most of the original writing. He conceived and wrote the paper with editorial input from Kray Luxbacher and Brian Lattimer.

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31(June 1997), 61–75.


Chapter 4. Numerical Simulation of High Expansion Foam into Mine Openings

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\textsuperscript{a}Virginia Tech, Blacksburg, Virginia, USA

Abstract

High expansion (Hi-Ex) foam has been used as firefighting technology to suppress underground coal fires due to its ability to flood large enclosed spaces in short times and be applied remotely through boreholes from the surface. Previous studies have shown the high dependency of foam flow behavior with the slope of the mine floor. For this reason, this paper investigated the relationships between three mine entry slopes (0\%, 9.52\% down dip and 5\% up dip), foam advancement, and foam velocity in order to estimate the foam flow behavior in these three mine configurations using computational fluid dynamics (CFD). Hi-Ex foam was simulated as a continuous non-Newtonian fluid. Additionally, foam behavior in some scenarios were compared with qualitative results of a full scale experiment carried out by NIOSH in the Lake Lynn Experimental Mine (LLEM), with the objective of evaluating the approach of modeling foam as a non-Newtonian fluid in mine openings. Logarithmic relationships between advancement and time were found for the foam moving up dip, down dip and on a flat mine entry. Also, exponential relationships between velocity and advancement were found for foam flowing on down an incline and along a flat entry, demonstrating that in these scenarios foam can reach distances longer than 15 meters (49 ft) easily. For foam flowing up dip a linear relationship was fitted between foam velocity and advancement demonstrating that foam cannot reach distances greater than 6.6 m (21.6 ft) when it is moving up dip. The results and approach used in this paper can be helpful as first approximation to estimate the behavior of foam flow in different mine entry slopes contributing to improvements in mine emergency plans during fire scenarios, enhancing response time and fire extinguishment when Hi-Ex foam is used.

Keywords: high expansion foam, foam flow, numerical simulation, non-Newtonian fluid, mine fires
1. Introduction

Underground coal fires are one of the major mining safety concerns that can threaten on the health and safety of people working in underground mines (Prakash et al., 2001). Also, underground coal fires can burn large areas of the coal seam causing voids that can collapse, generating the considerable surface subsidence, and affecting overlying infrastructure (Bell, Bullock, Hälbich, & Lindsay, 2001; Richmond, 2017; Ozment & Trevits, 2018). Another consequence of underground coal fires, is the emission of greenhouse gases such as carbon dioxide ($CO_2$) and carbon monoxide ($CO$) that can propagate through fractures to the surface, affecting vegetation and communities on the surface proximate to the fire (Zhang, Kroonenberg, & de Boer, 2004). Finally, coal reserves are also affected by underground coal fires where millions of tons are burned or deemed no longer minable (Zhang et al., 2004; Stracher & Taylor, 2004; Wu & Liu, 2011).

Some data published by the Office of Surface Mining, Reclamation and Enforcement Abandoned Mine Land Inventory System showed that there were nine underground mine fires burning in nine states in 2013 (Richmond, 2017). Although some specialists conclude that this number is underestimated and more underground fires could be active (Ozment & Trevits, 2018). Among these underground fires, the most famous is located in Centralia, PA, and has been active for around 60 years (Nolter & Vice, 2004; Department of Environmental Protection PA, 2017). Also, data indicate that these fires are a problem globally; 37 million tons of coal were consumed and 1.453 billion of tons have been blocked by underground coal fires in the Jharia coalfield, India (Stracher & Taylor, 2004). Similarly, in New South Wales, Australia the oldest active fire in the world is located, having started about 6,000 years ago, and affecting a total area of 6.5 square kilometers (Wu & Liu, 2011).

Underground coal fires can occur in active or abandoned underground coal mines. In abandoned mines fires can be started in places where the coal seam is exposed on the surface (Wu & Liu, 2011). Forest fires, people burning trash or lighting can be sources of fire ignition. Once the fire is produced can grow and consume the remaining coal pillars. The oxygen that is indispensable for coal combustion is available due fractures and unsealed mine shafts (Nolter & Vice, 2004; Richmond, 2017; Ozment & Trevits, 2018). Additionally, coal is a combustible material that can react with oxygen in many different scenarios producing heat. This heat produces a self-heating that in some cases can reach the coal ignition temperature yielding to a flame (Akgün & Arisoy,
Due to high temperatures and dangers close to the fire, most underground coal fires need to be addressed remotely whether in inactive areas or active mines. After the initial stages of the fire, temperatures are elevated, large gas accumulation are present and potentially explosive atmospheres do not allow the application of direct fire-fighting techniques (Smith et al., 2005). Hi-Ex foam has been used since 1950 for fire suppression in underground locations (Hartmann, Nagy, Barnes, & Murphy, 1958). This agent has shown to be effective for fire suppression because it has the ability to flood large enclosed spaces in a short time and using a low amount of water and foam concentrate (Martin, 2012). Hi-Ex foam has three different mechanisms to put fires out in enclosed spaces. The three mechanisms are fuel isolation, fuel cooling and oxygen dilution (Martin, 2012). Fuel isolation is generated because Hi-Ex foam acts as barrier between the fuel and oxygen, starring the fire. As a consequence of the contact between foam and fuel at high temperatures, fuel transfers heat to the foam resulting in fuel cooling. Additionally, due to the heat transfer foam bubbles break down releasing foam solution that turns into water vapor, diluting the oxygen concentration available for the combustion reaction (Fleming & Sheinson, 2012, Smith et al., 2005). Finally, due to the surfactants in foam concentrate water surface tension is reduced allowing foam solution to penetrate into some solid fuels with hydrophobic surfaces, such as coal (Martin, 2012).

Hi-Ex foam can be applied remotely into underground locations through boreholes when it is generated on the surface (Smith et al., 2005). A full scale experiment was carried out in the NIOSH’s Lake Lynn Experimental Mine (LLEM) in which foam was applied from the surface into different mine configurations as can be seen in Figure 4-1. Basically, in this full-scale experiment the foam flow was evaluated through different slopes and non-linear configurations, through and around obstructions. According to the results, it was evidenced that foam flow movement and speed are directly dependent on the slope of mine floor (Smith et al., 2005).
In spite of the fact that Hi-Ex foam has been used widely for more than 70 years and some experiments show that foam is a useful firefighting technology, it is still challenging to predict its behavior in underground locations where different mine slopes are found (Smith et al., 2005). Conducting full scale experiments in active mines results in interruptions of some activities, affecting mine productivity. Therefore, this paper aims to investigate the relationships between mine entry slope, foam advancement and foam velocity in order to estimate the foam flow behavior for three different mine slopes. Hi-Ex foam was numerically modeled as a non-Newtonian fluid using rheological parameters previously obtained by Barros (Barros Daza et al., 2018). Numerical results were compared with qualitative results of the full scale experiment mentioned before carried out by NIOSH in LLEM with the objective of evaluating the simulation of Hi-Ex foam as a non-Newtonian fluid in mine openings. The commercial CFD software, Ansys Fluent, was used to run the numerical simulation of Hi-Ex foam.

2. **Geometry**

In this study, three different mine scenarios were considered for investigating the Hi-Ex foam behavior in different mine entries slopes. For scenario 1, foam flow was studied in a flat mine entry with 0% gradient slope. The geometries of scenario 2 and 3 proposed in this study were based on the full-scale experiment carried out by Smith and others (Smith et al., 2005) in the LLEM in order to compare foam behavior in both studies. 2-D geometries were used with the objective of reducing the calculation time. The heights of the mine openings were 2.0 m (6 ft) and the diameter of injection points were 0.25 m (9.8 in) for all scenarios. In the following section detailed information about the geometry for the three scenarios is displayed.
2.1. Scenario 1

Scenario 1 represents a flat mine entry (0% gradient) 12.5 m (41 ft) long, with an injection point located 2.25 m (7.38 ft) from the left wall. The right wall was located 10.25 m (33.6 ft) away from the injection point as shown in Figure 4-2.

![Figure 4-2 Geometry for scenario 1 (side view with 0% gradient)]

2.2. Scenario 2

The scenario 2 represents when the location elevation of the fire is below the foam application point. The mine entry has a slope equal to 9.52% where foam is moving down dip along 10 m (32.8 ft) in length from the application point as shown in Figure 4-3. The left wall was located 0.9 m (2.95 ft) from the injection point.

![Figure 4-3 Geometry for scenario 3 (side view with 4.5% gradient)]
2.3. Scenario 3

In scenario 3, foam flow was studied flowing up dip on a 5% gradient slope. The injection point was located 0.875 m (2.87 ft) away from the left wall and 11.136 m (36.5 ft) from the right wall as shown in Figure 4-4.

![Figure 4-4 Geometry for scenario 3 (side view for 5% gradient)](image)

3. Mesh, initial and boundary conditions

The 2D geometries were meshed by triangles in a structured grid. Mesh parameters are shown in Table 4-1 for the three scenarios. The inlets were located at the application points. The volume flowrate was set at 0.05 m³/s for all scenarios. For outlet boundary conditions the static pressure was set as outflow in the right wall. For wall boundaries, a non-slip boundary condition was assumed. Furthermore, in this study isothermal conditions were assumed (T=20 Celsius degree). No temperature variations were taken into account during the foam flow through the mine entries. Furthermore, wall roughness of mine entries, effects of foam drainage and ventilation were omitted during the foam flow simulations. As a consequence of the omission of the foam drainage, foam density is constant over time (incompressible fluid) since mass losses were not considered. This consideration can be made due to the low liquid content in Hi-Ex foam. Gravity was set equal to 9.81 m/s² and a turbulent flow was assumed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>33250</td>
<td>33673</td>
<td>33665</td>
</tr>
<tr>
<td>Elements</td>
<td>46036</td>
<td>46512</td>
<td>46498</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>1.559</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

As was mentioned above, Hi-Ex foam was simulated as a non-Newtonian flow using the
rheological parameters obtained by Barros and others (Barros Daza et al., 2018) for foam with expansion ratios between 250 and 600 as shown in Table 4-2

Table 4-2 Rheological parameters for Hi-Ex foam with expansion ratio between 250 and 600

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency Index, ( k (Pa \cdot s^n) )</td>
<td>2.36</td>
</tr>
<tr>
<td>Power Law Index, ( n )</td>
<td>0.4044</td>
</tr>
<tr>
<td>Minimum Viscosity Limit (kg/m-s)</td>
<td>0.045</td>
</tr>
<tr>
<td>Maximum Viscosity Limit (kg/m-s)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

4. Results

In all scenarios, the volume fraction of Hi-Ex foam was investigated in order to determine the relationship between foam advancement and velocity as well as the relationship between foam advancement and time for three different mine entry slopes. Contours plots of Hi-Ex foam volume fraction were located in xy planes for each scenario and presented for different time steps. Time was initialized \((t = 0)\) at the moment that foam comes through the inlet in the application point. Distances calculated for foam advancement were referenced from the application point line as shown in Figure 4-2, Figure 4-3 and Figure 4-4.

Initially, it is observed that after foam is injected through the inlet and touches the floor, the flow spreads out, flowing in both directions away from the application point line (i.e. towards left and right walls) for all scenarios as is shown in Figure 4-5.
In the scenario 1 (flat mine entry) the foam volume fraction in different time steps (1, 3 and 6.5 seconds) is shown in Figure 4-6. Clearly, it can be seen that foam reached the left wall, and, at the same time, flows towards the right side wall. As it flows to the right, the foam velocity decreases, showing an exponential relationship with foam advancement (see the blue line in Figure 4-7). This exponential relationship is represented by Equation 4-1. Additionally, it is observed that the relationship between foam advancement and time follows a logarithmic pattern (see the blue line in Figure 4-8), characterized by Equation 4-2. Also, it is seen that close to the application point, foam starts filling the mine entry uniformly as shown in Figure 4-6 at 6.5 seconds.

\[ V = 3.85e^{-0.18D} \]  

Equation 4-1
Where \( V \left( \frac{m}{s} \right) \) is the foam plug velocity in and \( D \) (m) is the foam advancement.

\[
D = 4.8 \ln(t) - 0.6
\]  

Equation 4-2

Where \( t \) is the time elapsed.

From Equation 4-1 and using the extrapolation method, it was calculated that 35 m (112 ft) away from the application point the foam flow velocity is 0.01 \( \frac{m}{s} \) when it is flowing in the flat mine entry, and the time elapsed to reach this distance is around 27.7 min, according to the relationship between distance and time showed in Equation 4-2. In Table 4-3 can be seen the time elapsed of foam flow to reach different distances away from the application point for scenario 1.

In the scenario 2 where foam is moving down dip on 10\% gradient slope, foam plug velocity decreases along the mine entry but in a slower rate than scenario 1 as shown in Figure 4-7. The exponential relationship between foam velocity and advancement for scenario 2 is represented by Equation 4-3. Additionally, for foam moving down it is also observed a logarithmic relationship.
between foam advancement and time as can be seen in Figure 4-8. This logarithmic pattern is represented by Equation 4-4 for different time steps can be seen in Figure 4-9. Applying the extrapolation method for Equation 4-3 and Equation 4-4, foam flow moving down on a mine entry with 10% slope can reach up to 30 meters (96 ft) with a velocity of $0.11 \frac{m}{s}$ in around 4.8 min. In Table 4-4 can be seen the time elapsed of foam flow to reach different distances away from the application point for scenario 2.

$$V = 3.94e^{-0.12D} \quad \text{Equation 4-3}$$

$$D = 5.26 \ln(t) + 0.24 \quad \text{Equation 4-4}$$

![Graph](image)

*Figure 4-7 Relationship between foam velocity and foam advancement for different mine entry slopes*

For the scenario 3 (foam moving up), it was evidenced that the foam velocity is about zero when it reaches 6.6 m (21.6 ft) away from the application line. This result shows that when foam is pushed up it is not able to advance easily along the mine entry. Instead of advancing, foam starts accumulating down dip from the injection point as it is shown in Figure 4-10. Equation 4-5 represents the linear relationship between velocity and foam advancement for the first 7 m (23 ft). Finally, it is observed that the relationship between foam advancement over the time follows a logarithmic pattern (see Figure 4-8), characterized by Equation 4-6.
\[ V = -0.5D + 3.3 \]  
Equation 4-5

\[ D = 2.9 \ln(t) + 0.8 \]  
Equation 4-6

Figure 4-8 Relationship between foam advancement and time for different mine entry slopes

Figure 4-9 Side view of foam flow in the mine entry in scenario 2 A)\( t=3 \) s B)\( t=4 \) s
Figure 4-10 Side view of foam flow in the mine entry in scenario 2 at 5s

Table 4-3 Time elapsed of foam flow to reach different distances away from the application point for scenario 1

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Distance (ft)</th>
<th>Time (min)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>35.2</td>
<td>0.2</td>
<td>0.55</td>
</tr>
<tr>
<td>12</td>
<td>38.4</td>
<td>0.2</td>
<td>0.46</td>
</tr>
<tr>
<td>13</td>
<td>41.6</td>
<td>0.3</td>
<td>0.39</td>
</tr>
<tr>
<td>14</td>
<td>44.8</td>
<td>0.3</td>
<td>0.32</td>
</tr>
<tr>
<td>15</td>
<td>48.0</td>
<td>0.4</td>
<td>0.27</td>
</tr>
<tr>
<td>16</td>
<td>51.2</td>
<td>0.5</td>
<td>0.23</td>
</tr>
<tr>
<td>17</td>
<td>54.4</td>
<td>0.7</td>
<td>0.19</td>
</tr>
<tr>
<td>18</td>
<td>57.6</td>
<td>0.8</td>
<td>0.16</td>
</tr>
<tr>
<td>19</td>
<td>60.8</td>
<td>1.0</td>
<td>0.13</td>
</tr>
<tr>
<td>20</td>
<td>64.0</td>
<td>1.2</td>
<td>0.11</td>
</tr>
<tr>
<td>25</td>
<td>80.0</td>
<td>3.5</td>
<td>0.05</td>
</tr>
<tr>
<td>30</td>
<td>96.0</td>
<td>9.8</td>
<td>0.02</td>
</tr>
<tr>
<td>35</td>
<td>112.0</td>
<td>27.7</td>
<td>0.01</td>
</tr>
<tr>
<td>40</td>
<td>128.0</td>
<td>78.6</td>
<td>0.003</td>
</tr>
<tr>
<td>50</td>
<td>160.0</td>
<td>631.0</td>
<td>0.001</td>
</tr>
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</table>
Table 4-4 Time elapsed of foam flow to reach different distances away from the application point for scenario 2

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Distance (ft)</th>
<th>Time (min)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>35.2</td>
<td>0.1</td>
<td>1.05</td>
</tr>
<tr>
<td>12</td>
<td>38.4</td>
<td>0.2</td>
<td>0.93</td>
</tr>
<tr>
<td>13</td>
<td>41.6</td>
<td>0.2</td>
<td>0.83</td>
</tr>
<tr>
<td>14</td>
<td>44.8</td>
<td>0.2</td>
<td>0.73</td>
</tr>
<tr>
<td>15</td>
<td>48.0</td>
<td>0.3</td>
<td>0.65</td>
</tr>
<tr>
<td>16</td>
<td>51.2</td>
<td>0.3</td>
<td>0.58</td>
</tr>
<tr>
<td>17</td>
<td>54.4</td>
<td>0.4</td>
<td>0.51</td>
</tr>
<tr>
<td>18</td>
<td>57.6</td>
<td>0.5</td>
<td>0.45</td>
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<tr>
<td>19</td>
<td>60.8</td>
<td>0.6</td>
<td>0.40</td>
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<td>64.0</td>
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<tr>
<td>25</td>
<td>80.0</td>
<td>1.8</td>
<td>0.20</td>
</tr>
<tr>
<td>30</td>
<td>96.0</td>
<td>4.8</td>
<td>0.11</td>
</tr>
<tr>
<td>35</td>
<td>112.0</td>
<td>12.4</td>
<td>0.06</td>
</tr>
<tr>
<td>40</td>
<td>128.0</td>
<td>32.0</td>
<td>0.03</td>
</tr>
<tr>
<td>50</td>
<td>160.0</td>
<td>214.0</td>
<td>0.01</td>
</tr>
</tbody>
</table>

5. Discussion

Results for foam flowing in a flat mine entry showed that its velocity is at about zero, 30 meters away from the application point. This indicates that further than this distance foam flow would take a long time to reach the fire. Also, it was evident that foam close to the application point starts filling the mine entry uniformly so that at this scenario an obstruction or seal close to the application point is necessary. For this scenario, the foam application point should be no more than 30 m (98.4 ft) away from the fire in order that foam can reach the fire quickly.

Foam behavior from the numerical simulations for scenario 2 and 3 has similarities to the foam behavior described in the full-scale experiment done by Smith and others (Smith et al., 2005). For scenario 3, it was observed that when foam is moving up dip (application point below to the fire elevation), it was not able to advance more than 6.6 m (21.65 ft). Instead of advancing, foam started filling the mine entry void from floor to roof, as can be seen in Figure 4-10. This behavior was
also seen in the full-scale experiment in which for this scenario, it was concluded that the injection point should be located as close to the fire as possible and an obstruction or seal located down dip from the application point is vital to get the foam to flow up and fill the mine entry. On the other hand, foam flow moving down dip can flow easily a distance up to 30 meters (96 ft) in 4.8 min. Even though, as was also mentioned in the conclusions in the work of Smith and others (Smith et al., 2005), an obstruction will be critical down dip of the fire to allow the foam fill the entire mine entry.

It is important to highlight that numerical relationships obtained in this study could overestimate the real foam flow values because wall roughness and foam drainage were disregarded and isothermal conditions were assumed during the simulations. Furthermore, for longer distances than the ones treated in this study, an extrapolation process is required, causing some level of uncertainty. However, the results and the approach used in this study can be helpful as first approximation to ascertain values of advancement and velocity for foam flow on different mine entry slopes.

6. Conclusions

Numerical simulations of high expansion (Hi-Ex) foam in three mine scenarios were carried out in order to investigate the relationships between foam advancement and velocity on different mine entry slopes. During the simulation, Hi-Ex foam was treated as a non-Newtonian shear thinning fluid represented by the power law. The foam flowrate applied from the injection point was equal to \(0.05 \frac{m^3}{s}\). In the first scenario, foam flow behavior was observed in a flat mine entry (0% gradient) evidencing an exponential relationship between foam velocity and foam advancement and a logarithmic relationship between foam advancement and time. Also, applying the extrapolation method to the relationships found, it was possible to determine that in a flat mine entry the foam application point must located no more than 30 m (98.42 ft) away from the fire since further than this distance foam velocity is about zero. Furthermore, it was evidenced that when foam flows in a flat mine entry close to the injection point, foam starts filling the mine entry uniformly evidenced that an obstruction or seal is necessary in order to enclose the foam.

Foam flow moving up dip and down dip shows similarities to the behavior described in the results
of the full scale experiment. Foam moving up on the 5% mine slope only was able to reach the first 6.6 m (21.65 ft) while at the same time foam started to fill the mine entry close to the seal of the left wall. Thus, in this scenario the injection point must be as close as possible to the fire and obstruction has to be located down dip from the injection point. This latter conclusion was also seen in the full-scale experiment done by Smith and others (Smith et al., 2005).

On the other hand, for foam moving down a 10% slope an exponential relationship between foam advancement and time was found, evidencing that foam can easily flow a distance up to 30 meters (100 ft). However, as was also concluded in the work by Smith (Smith et al., 2005), it is important that an obstruction or seal down dip from the fire is constructed in order for foam can fill the mine entry.

Finally, bubble breakages due to foam drainage and wall roughness were not taken into account during the numerical simulations. Thus, numerical relationships obtained in this study could overestimate real values of Hi-Ex foam flow. However, this approach can be helpful as first approximation to ascertain the behavior of foam flow in different mine entry slopes, particularly when planning application of foam during a fire. Furthermore, numerical simulations such those described here can contribute to improvements in design of mine emergency plans during fire scenarios, improving response time and fire extinguishment time. More fire scenarios can be evaluated using the approach exposed in this paper in order to determine more relationships for different mine slopes. Finally, further investigations could be focused on quantifying the effect of bubble breakage, wall roughness and high temperatures on foam flow on different mine slopes.

7. Acknowledgements

Manuel Barros Daza is lead the author of this chapter and responsible for most of the original writing. He conceived and wrote the paper with editorial input from Kray Luxbacher and Brian Lattimer.

8. References


Chapter 5 . Conclusion and future work

Numerical simulations of high expansion (Hi-Ex) foam in pipe and mine openings were carried out with the objective of validating numerical results under the assumption of Hi-Ex foam as a continuous non-Newtonian fluid, and estimating the behavior of Hi-Ex foam flow in mine openings through relationships between foam flow characteristics and mine entries slopes. In order to carry out the numerical simulations using computational fluid dynamics (CFD), a rheology study of foam was designed and carried out to obtain the rheological model and parameters that best represent the Hi-Ex foam flow behavior. The rheology study was carried out using an experimental apparatus composed of a small scale blower type foam generator that was able to produce Hi-Ex foam with expansion ratios between 250 and 1280. The apparatus was also composed of a pipe viscometer able to record the pressure drop of foam flow in the pipe. Then, a rheological model and parameters were set as inputs to carry out numerical simulations of foam flow in pipes and different mine opening slopes. Simulations of Hi-Ex foam flow were performed in the same geometry of the pipe viscometer so that pressure drops calculated numerically could be compared with experimental results obtained from the apparatus. Finally, relationships between foam velocity, foam advancement and time were determined for three different mine slopes: 0% gradient, 10% gradient down dip and 5% gradient up dip.

The result of the rheological study shows that Hi-Ex foam behaves as a non-Newtonian fluid with shear thinning behavior that can be represented by the power law. Rheological parameters of this model exhibit a power law index (n) of 0.4 and a consistency index (k) of 2.4 Pa s$^n$. Hi-Ex foam viscosity was between 0.042 Pa s and 0.15 Pa s for shear rates equal to 187.3 s$^{-1}$ and 44 s$^{-1}$, respectively. On the other hand, pressure drops calculated numerically were within the range of between 0.06% and 14.66% of the experimental data set with a Reynolds number between 200 and 1734, demonstrating satisfactory results for this approach. Lastly, logarithmic relationships between foam advancement and time were found for the three scenarios evaluated. Also, a linear relationship between foam velocity and foam advancement was found for foam flowing up in an incline mine entry, and showing that in this scenarios foam cannot reach distances greater than 6.6 m (21.65 ft) easily when a foam flow rate of $0.05 \frac{m^3}{s}$ is applied. For foam flowing down dip and in a flat mine entry an exponential relationship was fitted demonstrating that foam can reach...
distances up 30 m (100 ft) in times lower than 10 min. Numerical relationships obtained in this study could be overestimated, because wall roughness and foam drainage were disregarded and isothermal conditions were assumed during the simulations. However, this approach can be helpful as a first approximation to estimate the behavior of foam flow in different mine entry slopes in order to improve mine emergency plans during fire scenarios using foam, enhancing response time and fire extinguish.

Future work should be focused on studying the slippage phenomenon of Hi-Ex foam for low shear rates and long residence times in pipes with constant circular diameter. Furthermore, future studies also should be concerned with determining the effect of bubble breakage, wall roughness and high temperatures to foam flow characteristics.