



An experimental study of temperatures in cloud from release of flashing liquid CO₂ in 3m long channel

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Abstract

Flashing of the liquid CO₂ is an accidental hazards that may occurs in many industrial sector such as, process industries, carbon capture and storage projects, crude oil extraction process etc. Sometimes the accidental release of liquid CO₂ that causes the health hazards which may costs loss of lives and properties. In order to alleviate the aforementioned probable hazards, the experiment will be highly beneficial. This research activity is conducted through the temperature measurement in the cloud of flashing liquid CO₂ confirming the formation of dry ice and measuring frontal velocity of the cloud as well as its height formed from the vapour CO₂ dispersion. The liquid CO₂ was released in the 3m long channel from the cylinder through two nozzles of diameter 0.5mm and 1.0mm. This leads the formation of dry ice measuring -73°C and -71°C from the nozzle sized 0.5mm and 1.0mm respectively. 0.5mm nozzle and 1.0mm nozzle having mass flow rate of liquid CO₂ as 0.0089 kg/s and 0.029 kg/s, overall frontal velocity of 0.52 m/s and 1.51 m/s thus formed cloud height measuring 0.05m and 0.1m respectively. Frontal velocity of the cloud was found to be highest at distance of 0.5m from nozzle with 1.49 m/s and 5.5 m/s for both nozzles 0.5mm and 1.0mm diameter respectively. Upon the increasing distance from the nozzle, the temperature of the formed cloud was seen to be in increasing order.

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1. Introduction

Accidental release of the pressurized liquid gases has caused numerous accidents all over the world. The release of pressurized gas generates flammable and toxic gases clouds. The hazard of CO₂ is a natural events, in Cameroon, West Africa, sudden release of Carbon Dioxide(CO₂) gas from Lake Nyos caused the deaths of around 1700 people on 21 August 1986 [1].

Carbon Capture and Storage(CCS) are known as globally mitigating technology as it can capture and store large amount of CO₂ and preventing it to reach the atmosphere. In CCS projects, large quantity of CO₂ is compressed to high pressure that can be transported to the storage site. Accidental release of pressurized CO₂ while transporting and storing cause flashing of liquid and a huge amount of gas is escaped which can cause frostbite and asphyxiation [2].

With the increase of the respiration problem, if CO₂ concentration is above 5% approximately it causes other health symptoms, such as headache, palpitation, breathing difficulty, weakness and dizziness. 20% of CO₂ gas is considered to be instantaneously fatal for the human health [3].

Lisbona et al. [4] wrote, "Currently, the source term for a CO₂ release is not well understood because of its complex thermodynamic properties and its tendency to form solid particles under specific pressure

and temperature conditions. This is a key knowledge gap and any subsequent dispersion modelling, particularly when including topography, may be affected by the accuracy of the source term". It is very important to know and predict the behavior of flashing liquid so that an accidental release could be prevented and mitigated. The temperature measurement gives knowledge of understanding two phase dense gas dispersion. This paper presents the result from the experiments to investigate flashing scenarios of liquid CO₂. The major goal of this paper is to ensure and include:

- Released liquid CO₂ includes phase transition into mixture of gas and solid with formation of dry ice.
- Froude Scaling can be used to validate high pressure CO₂ dispersion.

CO₂ is a heavy-gas and under normal pressure and temperature it is a colorless and odorless gas. It is denser than air because of different specific weight of the air and CO₂ which leads to form a gravity current flow [5]. When liquid CO₂ is emptying from a horizontal channel with constant cross-section, it changes its phase to dry ice and vapour [6]. The dry ice is formed and deposited in the horizontal channel base and the vapour mixes with air to form cloud and moves forward with frontal velocity, u_F . The mass of the heavy gas cloud increased due to air entrainment. Figure 1 describes the flow design of the liquid CO₂ flowing in a horizontal channel with constant cross section area.

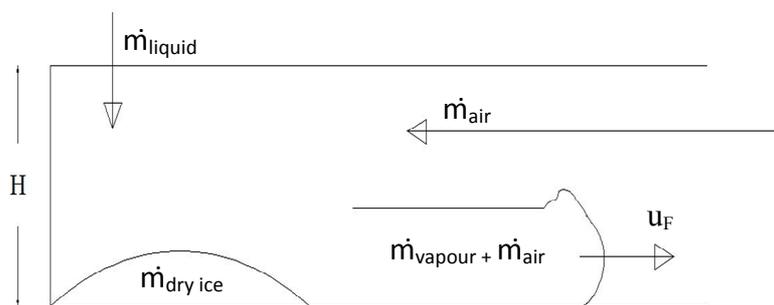


Figure 1. Flow model for liquid CO₂ released in the rectangular channel

The mass balance of the model from Figure 1 can be described as below:

$$\dot{m}_{liquid} + \dot{m}_{air} = \dot{m}_{dryice} + \dot{m}_{vapour} + \dot{m}_{air} \quad (1)$$

where \dot{m}_{liquid} is mass flow rate of liquid CO₂ (kg/s), \dot{m}_{dryice} is mass flow rate of solid CO₂ (kg/s) and \dot{m}_{air} is mass flow rate of air (kg/s).

2. Experiment setup

The experiment setup is shown in Figure 2 and Figure 3. The experiment was conducted on long channel tube comprising of 3m length, 0.1m width and 0.1m height. The system was made up of transparent polycarbonate and steel. The designing of tube was closed on one end and open at the other. The system comprised of five type K thermocouple with different time responding units. The thermocouple T#1 was placed at the side glass wall at height of 0.05m, thermocouple T#2 at distance 0.5m, thermocouple T#3 and T#4 at 1.5m, and thermocouple T#5 at 2.5m from the side wall of the tube. T#1 and T#4 has response time of 0.08 s, T#3 and T#5 with a respond time 1 μ s and T#2 is slow responding thermocouple. The layout of the experimental setup of the channel has been shown in Figure 2.

Liquid CO₂ is released from the top of the channel with the nozzle of 0.5mm and 1.0mm diameter. The nozzle is placed 0.1m from the closed end of the channel.

The experimental setup for measuring temperature in the cloud from flashing of liquid CO₂ is illustrated in Figure 3.

The liquid CO₂ gas cylinder is connected to the pneumatic valve which is further connected to the nozzle. The liquid CO₂ was supplied from the cylinder. The mass flow of liquid CO₂ released was measured by standard 'HBM RSCA 100 kg' load cell device, and the cylinder was suspended in the load cell device. The initial and final weight of the cylinder during the release of liquid CO₂ with respect to time was noted down, which in fact, helps to calculate the mass flow rate of liquid CO₂ from the cylinder.

Signal from the thermocouples and load cell were connected to the 'QuantumX MX410' amplifier via which data were logged. Sampling rate of data was used as 2400 Hz.

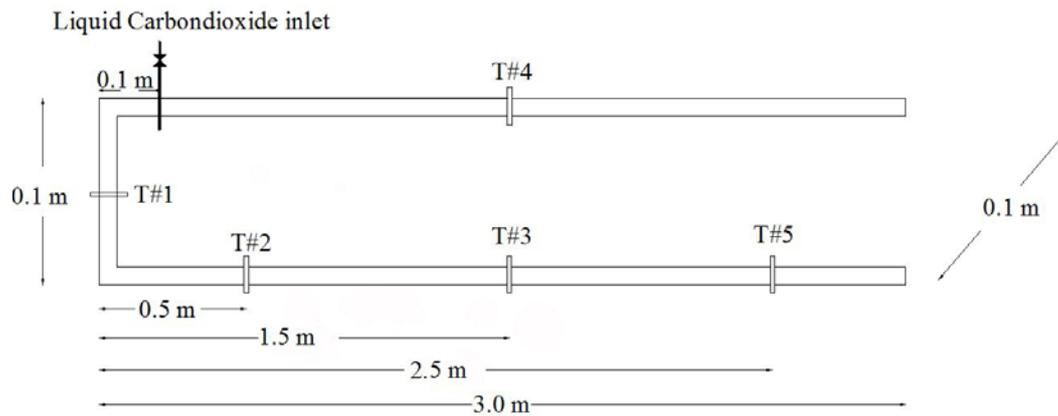


Figure 2. Schematic setup showing temperature measurement location and liquid CO₂ inlet

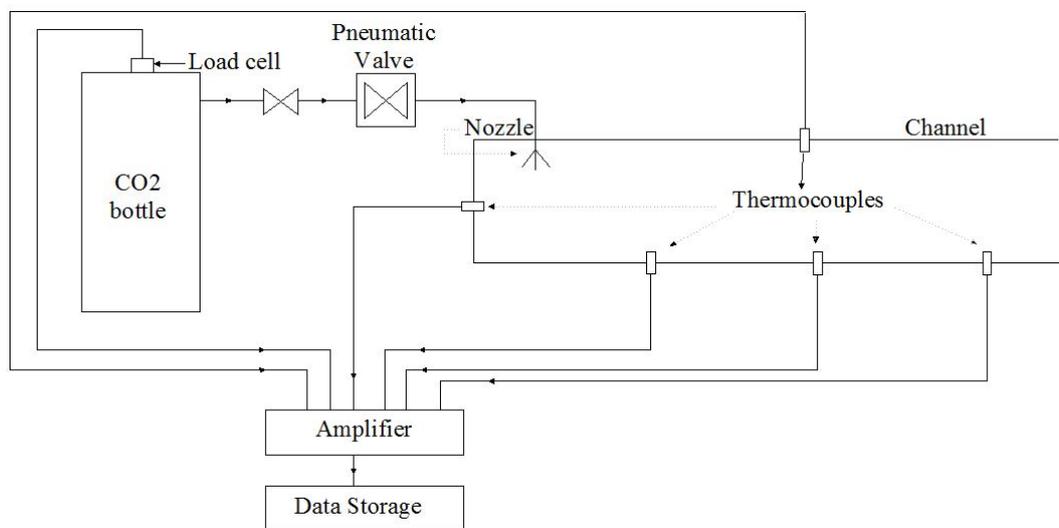


Figure 3. Experimental setup for the liquid CO₂ release system

3. Results and discussion

3.1 Frontal velocity and cloud height

Frontal velocity in this experiment is the velocity of CO₂-air cloud which is defined as, u_F (m/s) and which was found from HD video recording. As liquid CO₂ was released from the 0.5mm nozzle diameter, the overall frontal velocity of the cloud was found to be 0.52 m/s as shown in Figure 4.

Flow from the 1.0mm diameter nozzle gives the overall frontal velocity of 1.51 m/s which is shown in Figure 5.

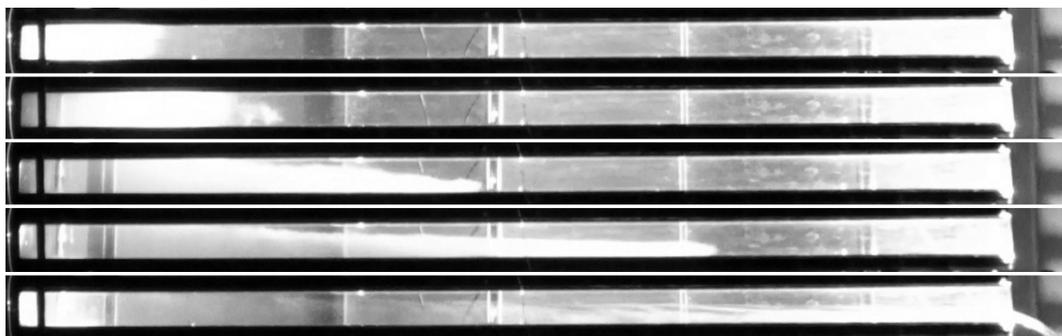


Figure 4. Photo of carbon dioxide propagation with the 0.5 mm nozzle

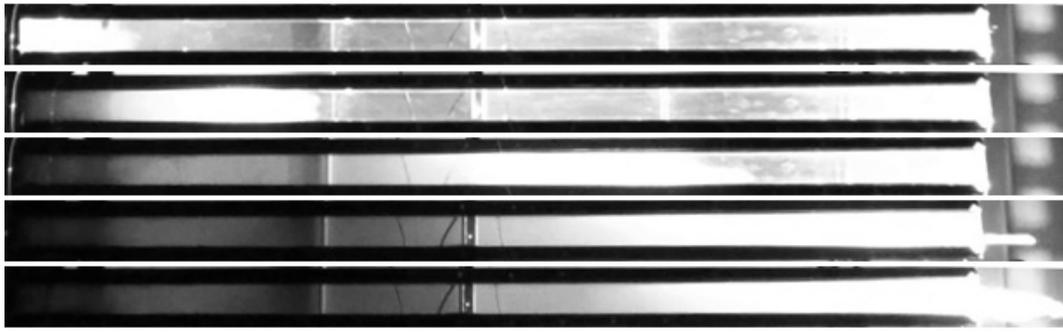


Figure 5. Photo of carbon dioxide propagation with the 1.0 mm nozzle

The experimental results has shown two different regimes of the flow of vapour CO₂ inside the channel. The flow regimes are shown in Figures 4 and 5. Gravity current flow was observed from the release of 0.5mm nozzle, whereas plug flow was observed when release from 1.0mm nozzle diameter. The time taken for CO₂ cloud to reach the various distance in the channel is shown in Figure 6 which gives the information about the initial and later frontal velocity of the cloud. Frontal velocity of the cloud was found to be increased rapidly until the cloud distance of 0.5m as shown in Figure 6.

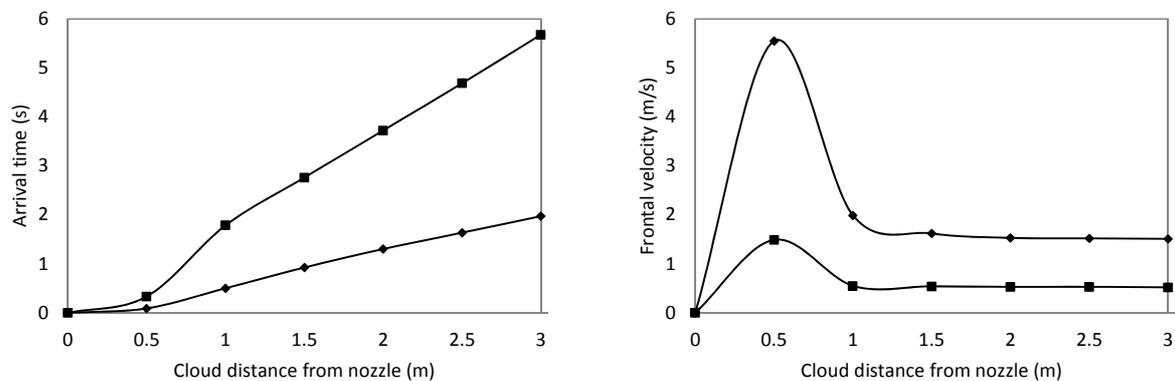


Figure 6. Distance variation with time and frontal velocity, symbols refers to nozzle diameter:
 ◆ 1.0mm nozzle; ■ 0.5mm nozzle

At distance 0.5m from the nozzle, the frontal velocity of cloud when released from 0.5mm and 1.0mm nozzle diameter were found to be 1.49 m/s and 5.5 m/s respectively. Later after 1m of release distance, frontal velocity were approximately constant.

Using the video, the height of the cloud was estimated. As it can be noticed from Figure 5, there is a plug flow in the channel after liquid CO₂ is released from 1.0mm nozzle diameter. The height of the cloud is same as the height of the channel i.e. 0.1m .

Height of the cloud after it is release from 0.5mm nozzle diameter was found to be half of the height of the channel. From the video, it can be concluded that, the height of the cloud was approximately 0.05m as shown in Figure 4.

Nozzle diameter affects the height and frontal velocity of the cloud. Higher the nozzle diameter for the release of liquid CO₂ in the atmosphere, higher will be the cloud height as well as frontal velocity of the cloud.

3.2 Froude scaling

With knowledge of the frontal velocity, Froude scaling with this type of experiments can be performed. Froude number is defined as the ratio between the momentum and gravity force acting in the fluid flow which is given as:

$$Fr = \frac{u}{\sqrt{gh}} \quad (2)$$

where u is a velocity (m/s), g is the acceleration of gravity (m/s^2), h is height of cloud (m).

Experiment from 0.5mm nozzle shows frontal velocity of 0.52 m/s with Froude number of 0.74. Based on the observed Froude number, it suggests to be in a range of Froude scaling which was done in same type of experiment but with hydrogen-air [7]. Gravity current effect was observed from the release of 0.5mm diameter nozzle as seen in Figure 4 and with smaller nozzle than 0.5mm gravity current effects can be studied and used for the Froude scaling.

3.3 Mass flow of liquid CO₂

The mass flow of liquid CO₂ in 1.0mm and 0.5mm diameter nozzles were 0.029 kg/s and 0.0089 kg/s respectively as shown in Figure 7 verifying that the mass flow of liquid CO₂ is dependent on nozzle diameter. Wider the diameter of the nozzle, higher will be the mass flow of liquid CO₂.

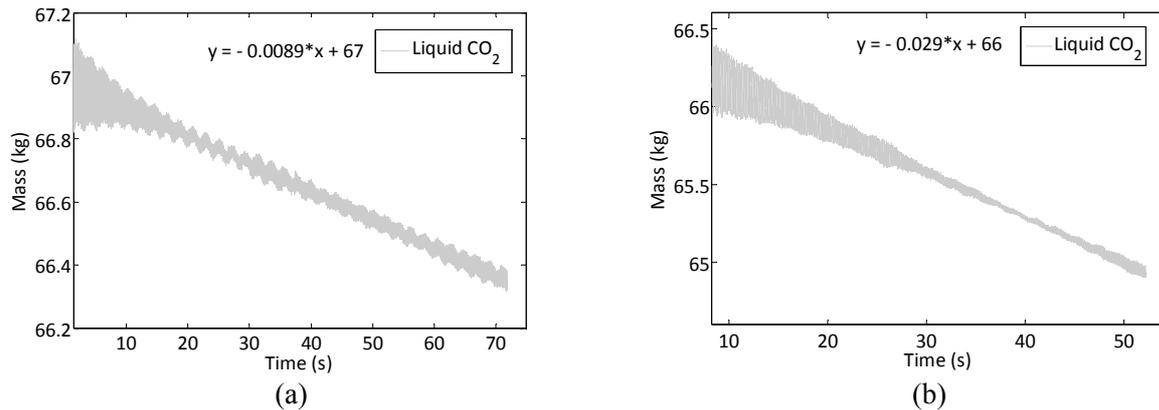


Figure 7. Mass flow of liquid CO₂ from (a) 0.5mm nozzle, (b) 1.0mm nozzle

3.4 Temperature measurements

In this experiment, the temperature of the cloud after flashing of liquid CO₂ was considered. The temperature reading of CO₂ (solid and vapour) when released from 0.5mm diameter nozzle as shown in Figure 8 below. Initially, all the thermocouple were at room temperature. With the release of liquid CO₂, the significant reduction in temperature was noticed. Whereas, air temperature by T#3 into the channel, remained almost constant throughout the flow.

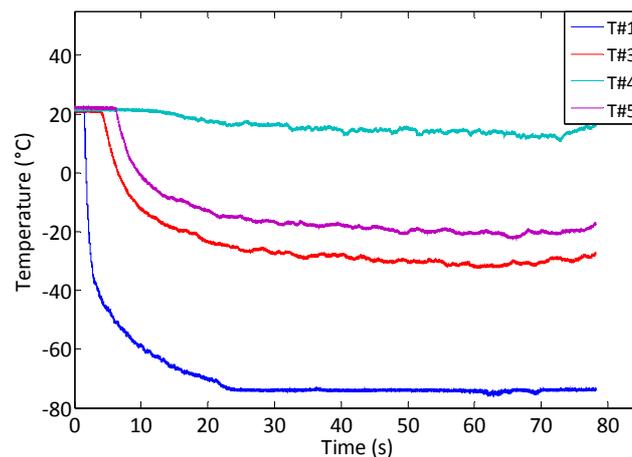


Figure 8. Temperature of CO₂ (solid and vapour) when released from 0.5mm diameter nozzle

T#1 suggests the formation of the dry ice whose temperature is about -73°C at 1 bar which is almost accurate as we find in literatures that a dry ice temperature at 1 bar is -78.4°C or 194.75 K [8].

Released of liquid CO₂ in the atmosphere from cylinder of high pressure changes its phase to solid and vapour. The temperature of the CO₂ cloud and dry ice is constant after it get stabilized at specific point

over time as shown by thermocouple T#1, T#3 and T#5 from both Figure 8 and Figure 9. The temperature reading of CO₂(solid and vapour), when released from 1.0mm diameter nozzle, is shown in Figure 9.

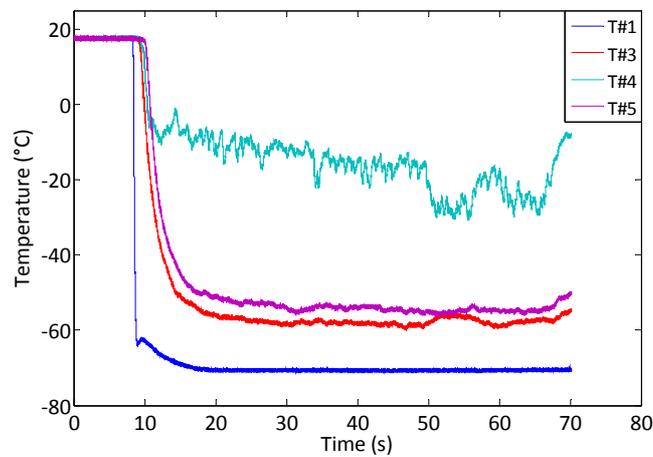


Figure 9. Temperature of CO₂ (solid and vapour) when released from 1.0 mm diameter nozzle

The air temperature(T#4) is not constant which is due to heat transfer from cloud CO₂ to air, and it is a plug flow as shown in Figure 5. Dry ice is formed in T#1 and T#2 which are at minimum temperature of -71°C and -63.5°C. Slow thermocouple T#2 takes relatively long time to reach the stabilized temperature and its graph is not shown in both Figure 8 and Figure 9. The image of the formation of dry ice on the tip of thermocouple T#1 and T#2 and on channel base can be seen in the Figure 10. Dry ice stays in the channel for the long time and vaporize into gas in atmospheric pressure.



Figure 10. Picture of formation of dry ice

Temperature of CO₂ cloud increases with increasing distance of release from the nozzle. The reason behind this is due to the heat transfer into the system from the surrounding. Figure 11 shows that there is a continuous increase in temperature of the cloud as cloud hits the thermocouples down the channel. The stabilized temperature data were used to find out the relation between the opening area of release and temperature at various distance.

However, from both nozzles we can find the difference in the temperature at different distance. When the nozzle diameter is increased to twice(from 0.5mm to 1.0mm) then there is a decrement of CO₂ cloud temperature by approximately -32°C and -37°C at T#3 and T#5 distance respectively.

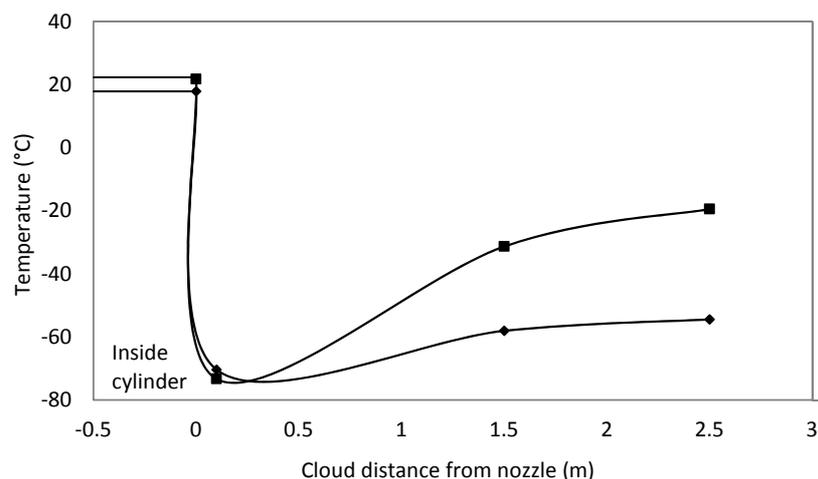


Figure 11. Stabilized temperature of CO₂ cloud at different distance, symbols refers to nozzle diameter: ◆, 1.0mm nozzle; ■, 0.5mm nozzle

4. Conclusion

The temperature measurement of cloud of the flashing liquid CO₂ was investigated by conducting experiments in a 3m long square cross section channel. The liquid CO₂ was released from two different nozzles of diameter 0.5mm and 1.0mm. Release of liquid CO₂ from 0.5mm and 1.0mm nozzle diameter gives the constant frontal velocity of 0.52 m/s and 1.51 m/s respectively over 3m long channel. Sudden release from the nozzle has higher frontal velocity of 1.49 m/s and 5.5 m/s for both nozzles of 0.5mm and 1.0mm diameter respectively. The cloud was found to be 0.05m and 0.1m when liquid CO₂ was released from 0.5mm and 1.0mm diameter nozzle respectively. The mass flow of liquid CO₂ in 0.5mm and 1.0mm diameter nozzle was found to be 0.0089 kg/s and 0.029 kg/s respectively. Using of small diameter nozzles to perform Froude scaling was suggested. The nozzle diameter suggests that wider the nozzle diameter higher will be the frontal velocity, cloud height and mass flow rate of liquid CO₂.

Dry ice and vapour CO₂ was formed from flashing of pressurized CO₂. Dry ice stays for the long time that influence the dispersion. Temperature of cloud was found to be increasing with increase of the distance from the nozzle. The temperature of the cloud and dry ice is found to be constant at specific point and over time which also helped understanding the behavior of slow and fast responding thermocouple.

Further work is to study the heat transfer into the system. The heat transfer is important parameter in determining the temperatures and how it affects to vaporize dry ice into CO₂ gas. Further work will help to develop Froude scaling and models that can predict the concentration and dispersion phenomena of accidental release of liquid CO₂.

Acknowledgements

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