The real-time analysis of oxygen concentrations in an enclosed space during the evaporation of a liquid nitrogen
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There are several potential hazards associated with the use of cryogenic liquids, including explosions due to sudden increases in volume upon evaporation, asphyxiation from decreases in local oxygen concentrations and tissue damage resulting from skin contact. In particular, the leakage of liquid nitrogen in an enclosed space can cause a rapid drop in oxygen concentration and can possibly lead to asphyxiation. The present study used a specially-designed sealed booth to monitor the oxygen concentration at a number of locations following a liquid nitrogen spill at floor level or the introduction of liquid nitrogen from a feed line inside the booth. The oxygen concentration following these incidents was found to vary with the amount of nitrogen spilled and the height above the floor of the feed line. In additional trials involving the introduction of nitrogen gas using a pipe line inserted into the booth, the oxygen concentration was uniform regardless of the height from the floor. The distribution of oxygen concentrations as liquid nitrogen evaporated in the booth was attributed to the high density of the resulting low temperature nitrogen gas. These results show the difference between liquid nitrogen and nitrogen gas leaks and provide helpful safety guidelines.

Keywords: Liquid nitrogen, oxygen concentration, accident

1. Introduction

Liquid cryogens are substances that are normally gases at room temperature but are maintained in liquid form at very low temperatures. These cryogens are used to cool components of instruments such as the superconducting magnets in nuclear magnetic resonance spectrometers and magnetic resonance imaging devices, as well as to measure low temperature physical properties or to preserve various types of specimens. Because liquid cryogens are often found in various facilities, accidents related to their use are common. As an example, the very low temperatures associated with these substances can cause tissue damage when the appropriate gloves are not used or used improperly. The significant volume of nitrogen gas generated via the evaporation of liquid nitrogen at room temperature can also represent a hazard by reducing local oxygen concentrations. An oxygen concentration of 18 vol.% is normally considered to be the lower safe limit for humans, below which symptoms such as headache and/or nausea can appear. Further reductions in the oxygen concentration to less than approximately 8 vol.% can cause loss of consciousness and death within several minutes. Loss of consciousness can result even after only one or two breaths in an oxygen deficient atmosphere, leading to fatal results. Although asphyxiation accidents resulting from the improper use of liquid cryogens are less frequent compared to frostbite incidents, the former are much more serious and so must be prevented by taking the proper measures.

In the present work, real-time analyses of oxygen concentrations were performed in an enclosed booth as liquid nitrogen was introduced in two different manners. The results demonstrate that the potential for asphyxiation accidents resulting from exposure to liquid cryogens is significantly different from that related to simple gas leaks.

2. Experiments

Figure 1 presents a photographic image of the booth used to simulate the risk of asphyxiation by exposure to a liquid cryogen. The size of the booth was 1 m by 1 m by 2.5 m and the ceiling was a simple plastic sheet laid on top of the frame so that the booth was slowly ventilated through the ceiling. A mannequin (1.7 m tall) was set in the booth and three oxygen gas analyzers (ICHINEN JIKO Ltd., JKO-25) were attached to a pole next to the mannequin. These analyzers were placed at heights of 0.1, 0.5 and 1.5 m, which corresponded to the height of the ankle, knee and mouth of the mannequin. These analyzers were placed at heights of 0.1, 0.5 and 1.5 m, which corresponded to the height of the ankle, knee and mouth of the mannequin.

Three types of experiments were performed. In the spill experiments, liquid nitrogen was intentionally spilled from a dewar flask by knocking the dewar flask over on the floor inside the booth. The amount of spilled liquid nitrogen was 1, 2, and 4 L. In the leak experiments, liquid nitrogen was continuously supplied to the interior of the booth via a pipe, with 5 L of liquid nitrogen automatically
introduced over a span of 10 min. The height at which the pipe was positioned was 0.5, 0.9 and 2.0 m. Since the supply rate of liquid nitrogen was slow, the air in the booth was not stirred and mixed. The third type were the gas leak experiments, in which nitrogen gas was introduced into the booth from a gas cylinder for 10 min at a height of 0.5 m. The amount of nitrogen gas allowed to escape into the booth was approximately 1400 L, equivalent to about 2 L of the liquid coolant.

3. Results and discussion

Figures 2(a) – (c) plots the oxygen concentrations at heights of 0.1, 0.5 and 1.5 m after the liquid nitrogen was spilled. Because the dewar flask was knocked onto the floor, the oxygen concentration at the ankle position decreased first, with subsequent decreases in the oxygen concentrations at the knee and mouth positions, regardless of the amount of liquid nitrogen. With increases in the amount spilled, the oxygen concentration at the knee position eventually equaled that at the ankle position, and a quantity of 4 L provided oxygen concentrations at the knee and ankle positions with almost identical time-dependent behaviors. The oxygen concentration at the mouth position,

Fig. 1 A photographic image of the experimental set-up showing the specially made booth (on the right) containing three oxygen sensors and a mannequin. Oxygen concentrations were monitored by a personal computer via a data logger and a visual display also showed the oxygen concentrations.

Fig. 2 Variations in the oxygen concentration over time after spilling (a) 1, (b) 2 and (c) 4 L of liquid nitrogen from a dewar flask in the booth.

Fig. 3 Variations in the oxygen concentration over time after introducing liquid nitrogen into the booth from a nozzle at a height of (a) 0.5, (b) 0.9 and (c) 2.0 m.
in contrast, remained higher than the concentrations at the other positions irrespective of the spilled amount. These differences provide useful information concerning the risks of such spills. Irrespective of the amount spilled, more than 30 s was required to reduce the oxygen concentration to 18% at the mouth position, while a potentially fatal concentration of less than 6% appeared at the ankle position within close to 10 s. These results indicate that lowering the head by bending down, such as to pick up a spilled container, can increase the hazard.

Figures 3 (a) – (c) plot the time-dependent oxygen concentrations determined during the leak experiments in which the cryogen was supplied at heights of 0.5, 0.9 and 2.0 m. Compared to the spill experiments, the oxygen concentrations are seen to have decreased more gradually in all cases because the liquid nitrogen was continuously supplied at 0.5 L/min. The variations in the oxygen concentrations with height exhibit differences between the different supply heights. Specifically, the oxygen concentrations below the supply heights show identical time-dependence while the oxygen concentrations above the supply heights were higher than those below the supply heights. These results demonstrate that the diffusion rate of the nitrogen below the supply height was sufficient to produce a uniform oxygen concentration.

These experimental results were assessed based on examining the physical properties of nitrogen. The results of both the spill and leak experiments can be understood by considering that the density of cold gaseous nitrogen is considerably higher than that of air at room temperature. Although the density of air is slightly higher than that of nitrogen under standard conditions, the volume of nitrogen gas decreased at low temperature, resulting in increased density. Figure 4 plots the density values calculated for nitrogen gas at temperatures in the range of -196 to -50 °C assuming that nitrogen is an ideal gas. In this range of temperatures, the density of nitrogen gas is higher than that of air under standard conditions (1.29 kg/m³), such that these two gases are unlikely to intermingle. Thus, there was a time lag for the oxygen concentration at the mouth position to decrease during the spill experiments. In the leak experiments, the liquid nitrogen (and the cold nitrogen gas generated by evaporation) cooled the air below the supply height so that this air approached the temperature of the nitrogen. Therefore, the gases below the supply height intermingled more readily while the gases above the supply height did not, as was also the case during the spill experiments.

In order to confirm this effect, we also performed gas leak experiments, during which nitrogen gas was introduced into the booth from a gas cylinder. Figure 5 shows the time-dependent oxygen concentrations after the introduction of the nitrogen gas. The oxygen concentrations at the three positions are seen to have decreased linearly following the introduction of the gas and became equal immediately after the gas introduction was stopped (that is, at the 10 min mark). The small differences in the oxygen concentrations between the positions during the introduction of the gas are attributed to the low supply height during these trials (0.5 m). Because the nitrogen and air had similar temperatures during these experiments, the diffusion rate was sufficient to provide a uniform oxygen concentration on this time scale. These data confirm that the different densities of gases having varying temperatures were responsible for the behaviors observed during the spill and leak experiments. Thus, the low temperature of evaporating cryogens is also a critical factor that affects the risk of asphyxiation.

**Conclusion**

This study monitored the time-dependent oxygen concentrations in an enclosed booth following simulated spill and leak accidents involving liquid nitrogen. The spill...
experiments showed that low oxygen concentrations in the lower part of the booth were the primary hazard following a spill, while the leak trials indicated that the height of the leak changed the risk. Comparing these results with those from gas leak experiments established that the varying rates of interdiffusion of air and nitrogen, based on differences in temperature, produce different hazards for liquid cryogens as compared to simple gas leaks.

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