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Experimental and numerical study of ammonia leakage and dispersion in a food factory

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ABSTRACT

With the widespread use of ammonia in the industrial fields, more and more accidents are caused by ammonia leakage and dispersion. To study the dispersion law of ammonia in a food factory, small scale wind tunnel experiments were designed. Different initial conditions such as release flow rate, wind speed, release height and the heights of concentration sensors were considered. Ammonia concentration was measured near release source, obstacles and far from release source, respectively. The law of ammonia dispersion is determined by its physical properties, release source conditions and atmospheric environment. Ammonia concentrated in the axial direction and showed an upward movement near the source as ammonia's density is lower than the air. We obtained the law of ammonia dispersion in a food factory through experiments indicating that the concentration of each measuring point is proportional to the flow rate. With the increase of wind speed, the concentration of ammonia at different points first increased and then decreased. The results showed that the effect of ammonia dispersion was more obvious under the influence of the wind field. The maximum concentration can be reached under the wind speed range of 0.8–1.2 m/s. Changing the height of source and measuring point will make a great difference in the concentration of the measuring point. In the simulation work, RNG k-ε model represents better agreement with the experimental data. Ammonia movement has a strong concentration gradient and the horizontal wind field streamlined ammonia movement.

1. Introduction

Ammonia is widely used in chemical and food industry as a common industrial gas (Cheng et al., 2014), which is mainly used for producing nitric acid, amine, ammonium, etc. Ammonia is also used as a refrigerant because of its thermodynamic properties, which enables it to transfer heat far more efficiently than other refrigerants. It is particularly effective in the range of 0–30 °C to 0 and hence is widely used for food preservation and in the chemical industry. (Gangopadhyay and Das, 2010) Ammonia is colorless, toxic and flammable. The atmospheric boiling point of liquid ammonia is −33.41 °C. The critical temperature is Tc = 132.25 °C and the critical pressure is Pc = 11.333 MPa. The relative density of dry ammonia vapor with respect to air is 0.6. Under standard conditions, the density of ammonia is 0.7713 kg/m^3 at 25 °C. The molecular space and interaction force of ammonia molecules are small. Therefore, ammonia is very easy to spread. Ammonia is toxic and the IDLH-15 min is 50 ppm or 36 mg/m^3. Ammonia vapor is flammable in air atmosphere. The flammability limits are LFL = 14% vol and UFL = 32.5% vol at 25 °C (Europe - Chemsafe) or LFL = 15% vol and UFL = 28% vol at 20 °C (USA – NFPA). Ammonia vapor is difficult to be ignited in air atmosphere because of its high Minimum Ignition Energy (MIE = 680 mJ). Ammonia vapor explosions always occurred in buildings and enclosures. Ammonia is stored in the liquid state under its own vapor pressure in pressure vessels. The vapor pressure is 4.9748 bar ab at + 4 °C and 8.852 bar ab at + 21 °C.

Ammonia gas can create a general discomfort with the concentration between 150 and 200 ppm. At concentration between 400 and 700 ppm, ammonia gas can cause obvious irritation. At 500 ppm, ammonia gas is immediately harmful to health. (Tran. et al., 2014) At a certain ammonia concentration (ammonia/air), ammonia can be explosive with the explosion limit of 15.7%–27.4% (volume fraction) (Griffiths and Megson, 1984; Inanloo and Tansel, 2015). Ammonia is often stored in the liquid form under a certain pressure. The leakage of storage tanks due to various reasons such

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as corrosion, lax sealing, and operational errors may lead to a leaking accident. Ammonia has a strong stimulating effect on eyes and respiration system. In the case of leakage and dispersion of ammonia, it is likely to cause the poisoning of the surrounding population and result in serious environmental pollution. (Gangopadhyay and Das, 2010) Over the past few decades, a number of serious leakage accidents occurred across the world. In 2010, an ammonia leakage accident occurred in a frozen plant in Alabama, United States, resulting in at least 120 people poisoning. In 2013, a large ammonia leakage and explosion accident occurred in a food company in Jilin, China, resulting in a total of 120 people killed and more than 60 people poisoning. When the fire spread to the ammonia plant, the high temperature caused the fracture of ammonia pipeline, resulting in the leakage of a large amount of ammonia. In 2013, gaseous ammonia leakage also occurred in a food company in Shandong, China, with 7 people killed. The leakage and dispersion of ammonia can be classified into continuous and instantaneous leakage. Continuous leakage usually occurs in gaseous form while the instantaneous leakage in the form of gas-liquid two-phase leakage. Gaseous ammonia leakage usually occurs in consequence of the damage aging of the pipeline junction and liquid ammonia leakage occurs in the condition of sudden failure of pressure vessel. These kinds of liquid ammonia leakage accidents also occurred in India, Ukraine and other countries, resulting in casualties and large numbers of people evacuating. The study of ammonia gas dispersion has been of great importance, as the serious consequences caused by the malignant accident and the impact on the environment and society is far more than the accident itself.

Numerous ammonia gas leakage and dispersion accidents have been studied, mainly focusing on the toxic gas leakage and dispersion model. Current research mainly focuses on the theoretical and numerical simulation studies. There's a paucity of experimental studies on either large scale field experiment or small scale wind tunnel experiment. Large scale field experiment can accurately simulate the real situation of an accident. Some large scale experiments were carried out in 1980s such as the Thorney Island Experiments (1984) (Rodean et al., 1984) and the China Lake Experiments (1987) (McQuaid, 1987; Brighton and Prince, 1987). The leakage and dispersion of several different hazardous gases were studied under different circumstances (Hanna et al., 2012; Santos et al., 2005; Morgan., 1987). Different forms of release source and environmental factors were considered (Bouet et al., 2005), and the ammonia concentration at different positions of wind field was obtained. Meanwhile, many numerical simulation studies were conducted to be compared to the field experiments and, in return, were validated by experimental data. (M.R. Theobald et al., 2015) Although large scale experiments are closer to real accident, weather conditions could not be controlled, making it difficult to study wind speed, wind direction, temperature and other meteorological parameters. In addition, large scale field experiments are expensive and difficult to repeat. In this case, it is not easy to find the variation of different variables. Compared to the large scale field experiments, small scale wind tunnel experiments can be easier to control different weather conditions (Ohba et al., 2004). Several studies have been carried out to evaluate ammonia movement with different methods. The most important of them are dynamic flux chambers or wind tunnels and micrometeorological techniques. (Scotto di Perta et al., 2016) However, there are certain risks in laboratory experiments, as ammonia is highly toxic. On the other hand, many wind tunnels cannot meet the requirements of research, according to the size of the food factory. Therefore, most of the studies concentrated in numerical simulation. (Galeev et al., 2013a,b; Labovský and Jelemenský, 2010; Tauseef et al., 2011; Gousseau et al., 2011.

Numerical simulation research is widely used due to its wide application range, good economy and high accuracy. With the development of computer technology and the theory of fluid mechanics, the importance of calculation fluid dynamics (CFD) method has been realized in this field and several CFD software has been developed, such as: FLUENT, FLACS, CFX et al. Numerical simulation based on experimental verification is the most important way of studying natural gas dispersion at present. Many CFD simulated works using different turbulence models such as k-ε model, k-ω model have been conducted to reproduce the gas dispersion. Previously, the standard k-ε model and RNG model were mostly used (Li et al., 2006). However there has not been a consistent conclusion that which one is more applicable in the field of gas dispersion (Yoshie et al., 2011). In the previous study, the turbulence models were evaluated by comparing the numerical results with experimental data at representative points inside a scale model. The results showed that the RNG model is recommended for predicting air velocities, airflow patterns and ammonia concentrations in an indoor climate (Tong et al., 2013).

Regardless of experimental and simulation studies, ammonia dispersion combined with engineering background of the food factory using ammonia as refrigerant are few. This gas dispersion of food factory is different from the open space due to the impact from the physical layout of obstacles. Ammonia leakage and dispersion were involved in the complex momentum transfer process. Although large-scale leak and dispersion experiments of ammonia have been carried out to study the two-phase cloud evolution process of liquid ammonia. The lack of experimental data of ammonia under different atmospheric conditions of the passive dispersion made it difficult to accurately describe the cloud dispersion behavior and the consequences of the accident (Bouet et al., 2005). Thus, the experimental study of ammonia dispersion in a particular environment is of significant importance theoretically and practically. The dispersion of ammonia gas is mainly influenced by its own source conditions and atmospheric environment (Flesch et al., 2005). The height of the release source, the distance between the source and the obstacles and the release flow rate determine the initial conditions of ammonia leakage. Atmospheric environment such as wind speed, wind direction, temperature et al. has a great effect on the dispersion of ammonia. The ammonia dispersion rate can be greatly improved under the action of wind field, and the study of the characteristics of the release source and the atmospheric conditions is key for the comprehensive study of the dispersion of ammonia gas.

2. Theory

2.1. Dispersion model

The laws of gas dispersion have been studied theoretically. Up to now a variety of gas dispersion models have been developed. The classical gas dispersion model is Gaussian model, including the Gaussian plume model and puff model. The Gaussian plume model is considered as a valuable tool in predictions of the atmospheric transport of fungal spores and plant pollen in risk assessments (Spijkerboer et al., 2002). Gaussian plume model assumes that the distribution of medium concentration in the horizontal and vertical directions is followed by Gaussian distribution. Concentration is calculated by formula:

$$C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} e^{-\frac{y^2}{2\sigma_z^2}} \left[e^{-\frac{(z-H_e)^2}{2\sigma_z^2}} + e^{-\frac{(z+H_e)^2}{2\sigma_z^2}} \right] \quad (1)$$

where C(x, y, z) is concentration (kg/s), x is downwind distance(m),