The study on the results of hydrogen pipeline leakage accident of different factors

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Abstract. Pipeline is frequently used in long-distance hydrogen transport, while pipes can be disturbed in some conditions, prone to leakage accident, causing severe combustion or explosion. This paper analyzed the influences of different factors on the consequences of hydrogen pipeline leakage through the simulation software ALOHA. The results show that wind speed, ground roughness, tube pressure and gap area have a great impact on the consequences of the accident; wind speed and ground roughness have negative correlation to danger distance; tube pressure and gap area have positive correlation to danger distance. These results are due to the release amount and release rate influenced by the four factors.

1. Introduction

Hydrogen, as one of the most important chemical materials, has been widely used in industrial production. But the explosion limit of hydrogen is wide, and the minimum ignition energy is only 0.019 mJ with the volume concentration of 30%. When leakage occurs, collision, tiny static electricity or weak spark will be able to ignite it, causing flash fire, detonation or explosion accident [1-3].

The studies on hydrogen leakage have been conducted and many methods were proved effective. Numerical simulation is usually established to analyze the consequences of gas pipeline leakage accident. ALOHA software is used to simulate accident consequences. Besides, a lot of experiments have been carried out. Hydrogen and air premixed flame in a container was studied by Huahua Xiao, Zhanli Mao [4]. Dynamic thickening flame was used to study propane and hydrogen premixed flames by Huahua Xiao, Zhanli Mao [5]. A hydrogen leakage accident in simple closed space was analyzed by Michael R. Swain, Patrick Filose [6]. Numerical simulation of hydrogen was carried out by Hector A. Olvera and Ahsan R. Choudhury [7] in stably stratified atmosphere.

ALOHA software was used in this paper and variables such as wind speed, the inner tube pressure, and the gap size were selected as the factors to simulate the consequences of hydrogen pipeline leakage accidents [8]. Through the diffusion model, the vapor cloud explosion model and the sustained combustion model, the impacts of each variable on accident consequences were analyzed for obtaining the reasonable and effective reference in actual accidents and conducting fire risk assessment [9, 10].
2. Simulation Process

2.1. Types of Hydrogen Pipeline Leakage Accident
Hydrogen at room temperature is colorless, odorless gas. When the pipeline ruptures, hydrogen gas will rapidly diffuse outside, flow with air, and gradually rise. If hydrogen does not encounter an ignition source, but form a cloud of steam, and then a fire source ignites the vapor cloud in the explosion limit, it may cause a flash fire or explosion. If the hydrogen gas encounters an ignition source during early leakage, it is possible to form a stable combustion region.

2.1.1. Hydrogen Diffusion Only. When hydrogen pipeline is damaged, hydrogen continues to spread into atmosphere. The hydrogen diffusion region is formed within a period of time, which is a hazardous area where explosion might occur. The hydrogen concentration is in its explosive limit 4.1% ~ 74.2%, in the event of sufficient ignition energy, explosion will occur.

2.1.2. Sustained Combustion. Hydrogen is ignited by the ignition source in the early diffusion. Although the hydrogen still spreads out, surrounding environment only forms a stable combustion zone because of the continuing consumption of hydrogen and oxygen in the air. If pipeline is not damaged further, combustion will be maintained at a relatively stable level. It is unlikely to explode.

2.1.3. The VCE (Vapor Cloud Explosion). After hydrogen pipeline is damaged, hydrogen in the atmosphere diffuses to a certain extent, and stays in the range of its explosive concentration limit. In the event of an ignition source the whole piece vapor cloud will be ignited, and then vapor cloud explosion occurs. Vapor cloud explosion products a variety of effects, such as shock waves, thermal radiation, which could cause serious damage in a large area.

2.2. Initial Conditions of Simulation
Suppose leakage occurred at a certain section of "Baling-Changling" hydrogen transfer line with a total length of 42 km. The accident site was 300 m high, and was 113°07′E, 29°23′N. It was at 12:13 on April 1, 2016. The accident occurred in the flat region, and there was stable wind speed as well. Other basic data is shown in Table 1.

Table 1. Basic data of simulation condition.

|                          |          |
|--------------------------|----------|
| Length of Pipeline/m     | 1000     |
| Wind Speed/(m/s)         | 2        |
| Ambient Temperature/℃    | 25       |
| Humidity/%               | 50       |
| Ground Roughness/cm      | 0.1      |
| Pipe Diameter/cm         | 50       |
| Tube Temperature/℃       | 25       |
| Tube Pressure/atm        | 20       |
| Gap Area/cm²             | 10       |

3. Simulation Results and Discussion
As described above, three kinds of parlous situations may occur in the hydrogen leakage accident. What causes serious casualties and losses is the overpressure in vapor cloud explosion. And whether a man or a building is safe in a VCE depends on overpressure distance. Besides, the diffusion distance and combustion distance are also the standards to measure the degree of safety in a VCE. A set of scenarios were designed respectively to observe how the hazardous distances were changed with the increasing of wind speed, ground roughness, gap area and tube pressure\(^{[11]}\). In the last comparison among these results was conducted.
3.1. The Influences on Diffusion Distance

3.1.1. Effect of Wind Speed. The maximum distances were respectively recorded from the source of the leakage to corresponding 40000 ppm (Lower Explosive Limit, LEL), 24000 ppm (60% LEL) and 4000 ppm (10% LEL) concentration area within 40 minutes. The simulation results show that wind speed has a significant impact on the diffusion distance. The higher wind speed leads to a shorter diffusion distance at three concentrations of hydrogen. And more details can be indicated in Fig. 1.

![Figure 1. Relationship between wind speed and diffusion distance.](image)

As can be seen, the relation between two parameters is not linear. At the low wind speed (<4 m/s), as wind speed increases, the diffusion distance decreases rapidly; at the high wind speed (>4 m/s), as wind speed increases, the diffusion distance decreases slowly. On the one hand, wind quickens the diffusion of hydrogen; on the other hand, it reduces the hydrogen concentration windward. When the wind speed is 2 m/s, hydrogen diffusion range within 40 min is described by a sector with the release source point as a central point. Because of the effect of wind for long time, the maximum distance of LEL is downwind 200 m from release point. Within the range of LEL, an ignition source will lead to VCE. When the wind speed changes, the shape of leakage area is the same.

3.1.2. Effect of Ground Roughness. Ground roughness refers to the height where the average wind speed is 0 m/s, which is used to indicate the rough degree of ground. Table 2 lists a group of representative values of the ground roughness.

| Ground Cover                          | Roughness $Z_\theta$(cm) |
|---------------------------------------|-------------------------|
| Water Surface                         | 0.1                     |
| Sparsely Populated Grasslands and Fields | 10                     |
| Pasture and Field with Dwelling House | 20                     |
| Fields with Many Houses and Shrubs    | 40                     |
| House Area in Suburb                  | 60                     |
| Urban and Forest                      | 100–500                 |

Ground roughness value was taken from Table 2 respectively. $Z_\theta$ for urban and forest was 200 cm. The maximum distances from the source of the leakage to the regions with the concentration of 40000 ppm, 24000 ppm and 4000 ppm within 40 minutes were recorded, and results are indicated in Fig. 2.
Figure 2. Relationship between ground roughness and diffusion distance.

It can be observed there is a steep decrease when the roughness increases approximately from 20 cm to 40 cm. However, it seems that there is no effect on the diffusion distance when the roughness is below 20 cm or above 40 cm. To a certain extent, the influence of ground roughness is limited.

3.1.3. Effect of Tube Pressure. Hydrogen pipeline pressure is usually 1 ~ 3 MPa. Other basic data unchanged, hydrogen pressure was taken from 10 atm to 30 atm, and maximum distances from the leakage source with the concentration of 40000 ppm, 24000 ppm and 4000 ppm within 40 minutes were recorded. The relation between tube pressure and diffusion distance is indicated as follows.

Figure 3. Relationship between tube pressure and diffusion distance.

Fig. 3 shows that diffusion distance is almost linear with tube pressure. By calculating the slopes of the three curves are 6.9, 8.85 and 21.2. K value is a representative under the accident condition indicated by the basic data, but its versatility needs to be discussed. And for a certain value of the pressure, the greater the K is, the greater the risk distance increases.

3.1.4. Effect of Gap Area. In the basic data, the tube diameter is 50 cm, and the corresponding cross-sectional area is 1963 cm$^2$. Other basic data unchanged, cross-sectional area was taken from 10 cm$^2$ to
1963 cm$^2$ respectively, and maximum distances were recorded from the source of the leakage to the regions with the concentration of 40000 ppm, 24000 ppm and 4000 ppm within 40 minutes. During the simulation, when the gap area was greater than 350 cm$^2$, the diffusion distance was no longer changed. So gap area in Fig. 4 is only shown to 350 cm$^2$.

![Figure 4. Relationship between gap area and diffusion distance.](image)

As can be seen from Fig. 4, when the leakage gap area is less than 150 cm$^2$ (less than 7.6% pipe cross-sectional area), with the gap area increasing, the diffusion distance increases rapidly and then levels off. When the area is greater than 150 cm$^2$, the diffusion distance does not increase any longer.

3.2. The Influences on Combustion Distance

3.2.1. Effect of Wind Speed. The model was changed into a combustion model, and the wind speed was taken from 2 m/s to 10 m/s. The maximum distances from leakage source to the corresponding combustion region were recorded. Simulation results indicate that the wind speed does not affect the maximum distance from the source of the leakage to the combustion area. For the leakage accident where hydrogen burns at the beginning, to some extent the degree of danger is limited.

3.2.2. Effect of Ground Roughness. Ground roughness value was taken from Table 2 respectively. The main influence of rough ground is to make released gas move slowly in the flow due to concentration gradient. But there is usually not so much effect, especially in some complex conditions. Simulation results show that the ground roughness does not affect the corresponding maximum distance in combustion area. We can deduce from 3.2.1 and 3.2.2 that the environmental factors don’t have any effect on the combustion distance. That is because the gas consumption has a greater impact on distance than the diffusion. The release source factors significantly affect the combustion distance.

3.2.3. Effect of Tube Pressure. Tube pressure value was taken from 10 atm to 30 atm respectively in the simulation. Then the maximum distances from leakage source to the corresponding combustion region of 10.0 kW/m$^2$, 5.0 kW/m$^2$ and 2.0 kW/m$^2$ were recorded.
Figure 5. Relationship between tube pressure and combustion distance.

Fig. 5 shows that with the increase of pressure, the combustion distance also goes up, but later its growth trend levels off. The effect of the tube pressure on the combustion distance is limited. Finally, even if the inner tube pressure increases a lot, the combustion distance will tend to an upper limit.

3.2.4. Effect of Gap Area. Gap area value was taken from 10 cm$^2$ to 1960 cm$^2$ respectively. Similar to the result above, the growth of gap area has a negative influence on the accident result. And no matter how large it is, the influence is effective.

Figure 6. Relationship between gap area and combustion distance.

Fig. 6 shows that with the increase of gap area the combustion distance continuously increases. The growth trend is smooth and predictable according to the existing data. And so, it is very necessary to cut off the gas source with all methods when leakage occurs for fear that the scope of risk is expanded.
3.3. The Influences on Overpressure Distance

3.3.1. Effect of Wind Speed. Select the VCE overpressure hazard threshold value, the simulation results show that when the wind speed is 2 m/s, the maximum distance downwind area is 337 m and the maximum distance upwind is 103 m. The maximum distance crosswind is 211 m. Other basic data unchanged, when wind speed ranged from 2 m/s to 10 m/s, record maximum distance downwind in these areas. The results are indicated in Fig. 7.

![Figure 7](image)

**Figure 7.** Relationship between wind speed and overpressure distance.

Fig. 7 shows that as the wind speed increases, overpressure distance of the VCE decreases rapidly. And its value is much larger than the maximum distance of combustion area.

3.3.2. Effect of Ground Roughness. Ground roughness value unchanged, the simulation model was set to vapor cloud explosion model. Record the maximum distances from source of the leakage to the overpressure region of 8.0 psi, 3.5 psi and 1.0 psi, and the results are indicated as follows.

![Figure 8](image)

**Figure 8.** Relationship between ground roughness and overpressure distance.
As can be seen from Fig. 8, when ground roughness $Z_0$ is more than 20 cm, the overpressure distance for VCE product a mutation that is about a quarter to one-third of the original value. Thus, in the flat and open area, warning distance should be increased a third of the original alert distance.

3.3.3. Effect of Tube Pressure. When the tube pressure changes, release rate of gas will significantly be affected. Besides, the initial momentum of flammable gas depends on the pressure inside. Once the tube pressure increase, the gas will flow faster and further. The detailed results are shown in Fig. 9.

![Figure 9](image_url)

**Figure 9.** Relationship between tube pressure and overpressure distance.

Compare Fig. 3 with Fig. 9. It can be seen that the curve of diffusion distance and tube pressure is consistent in trend with the curve of overpressure distance and tube pressure. With the increase of pipe length, the overpressure distance increases linearly. And the approximate slope values are 8.65, 4.55 and 5.4, little difference between the three, which means the impact of tube pressure on the three overpressure distance curves is close, but is much less than the $K$ values of Fig. 3. It means the impact of tube pressure on overpressure distance is much smaller than the impact on diffusion distance.

3.3.4. Effect of Gap Area. The same initial simulation environment using explosion model was chosen and then the maximum distances from leakage source to the corresponding overpressure range of 8.0 psi, 3.5 psi and 1.0 psi were recorded. The results are as follows.

![Figure 10](image_url)

**Figure 10.** Relationship between gap area and overpressure distance.
As can be seen from Fig. 10, when the leakage gap area is less than 150 cm² (less than 7.6% pipe cross-sectional area), with the gap area increasing, the overpressure distance increases rapidly and then levels off. When the area is greater than 150 cm², the overpressure distance does not increase. So there may be two kinds of condition about release source gap area. Whichever condition we stay in, the most important thing is to plug the leak and cut off gas source as soon as possible.

A comparison was conducted after the change trend of diffusion distance, combustion distance and overpressure distance had been calculated. The environment factors have a beneficial influence on the leakage accident consequences, and the release source factors can increase the risk of accident.

4. Conclusion
In this article, the affecting degree about danger distance of different variables in hydrogen leakage accident can be obtained. Conclusions are as follows: (1) Wind speed, ground roughness, and tube pressure and leakage gap area have a great influence on the diffusion distance. And of them the most influential factor is the wind speed; (2) Wind speed, tube pressure and leakage gap area have a great influence on the overpressure distance. And the most influential factor is the gap area; (3) Gap area has a significant impact on the combustion distance. But the impact of other variables on the combustion distance is very little or no; (4) the diffusion distance and overpressure distance reduce as the wind speed and ground roughness increase. Wind speed and ground roughness do not affect combustion distance.

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