Study on the numerical simulation of the Vacuum Cavity explosion venting

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Abstract

In order to study the mechanism of the Vacuum Cavity explosion venting technology in the gas pipe, An L type simulation model referred to the experimental pipe is established in this paper, in which the Vacuum Cavity explosion venting is simulated by means of Fluent software. The change law of the pressure field, temperature field and velocity vector is obtained in the numerical simulation. After the data analysis, the conclusion is that, the propagation of the shock wave in the pipe accords with the fluid water-hammer phenomenon. The gas components which enter into the Cavity impact and neutralize each other before they vanish eventually and suspend the reaction chain of the combustion. The broken timing of weak panel of the cavity and the change of Cavity volume are the important factors that affect the Vacuum Cavity explosion venting.© 2014 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

Keywords: Vacuum Cavity; explosion venting; numerical simulation

1. Introduction

Vacuum Cavity explosion venting is a new prevention and control technology against gas pipeline explosion. By vacuumizing the cavity prefixed in an experimental pipeline, the flames produced by gas explosion are extinguished under the suction and suffocation effect of the Vacuum Cavity and the destructive power of the shock waves are substantially reduced. The scientific experiments have been carried out by Jiang Shuguang and Wu Zhengyan to prove above conclusions\textsuperscript{[1-4]}. And the experimental result at the same condition as the numerical

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simulation is repeatedly obtained, showing that the gas explosion power is reduced by Vacuum Cavity\textsuperscript{[5]}. However the parameter change process details are not clearly revealed in the previous experiments. So the venting process of the methane-air mixture explosion is simulated numerically by means of Fluent software in this paper. This research is a beneficial exploration in the field and provides a theoretical basis for further studies.

2. Physical and mathematical models of Vacuum Cavity explosion venting

2.1. Physical model of Vacuum Cavity explosion venting

An L-shaped simulated pipeline physical model is set up based on related theories of gas explosion and vacuum cavity explosion venting. The vacuum cavity is fixed on the top end of a 80mm × 80mm straight pipeline which is 12 meters long, as is shown in Figure 1. The vacuum cavity is a cylindrical one with a diameter of 300mm and 500mm in length. The cavity is 3 meters away from the ignition source, and the rest of the pipe behind the fire is 9 meters long. The weak panel between the cavity and the pipeline is considered as a flat surface. In the simulation, the ignition area starts from the closed end of the pipe, and the exit of the pipeline is fully open.

![Fig.1. Physical model of the Vacuum Cavity explosion venting.](image)

2.2. Mathematical model of Vacuum Cavity explosion venting

As gas explosion and its propagation in the pipeline is a complex and transient process, the following rules are observed in the simulation: (1) the premixed gases in the pipe before ignition is static, in room temperature at normal pressure. (2) In the simulation, the chemical reaction happens only between methane and oxygen. The reaction is one-step irreversible and the concrete process is ignored in the simulation. (3) The surface of the pipe is adiabatic and the heat exchange between the closed space and the outside world doesn’t occur. (4) The specific heat capacity of the premixed gases is a temperature function, changing with the variation of temperature. (5) The fluid-solid coupling effect of the pipe surface and the premixed gases is ignored, and the space boundary is considered rigid.

The explosion venting process is also the methane-air mixture explosion process, which is in accordance with the fundamental control laws of multi-dimensional fluid flow --- the conservation laws of mass, momentum, energy and species.

Given the limited technological conditions and the calculation speed of computers, the large eddy simulation method is adopted in numerical simulation of the explosion venting. The simulation of whole-scale vortex motion is given up in the thesis. Instead, the turbulent movements larger than grid scale are calculated through N-S equation directly while the impact of small-scale vortex on the large-scale movement is simulated through models.

3. Numerical simulation of Vacuum Cavity explosion venting

Continuity equation and the conservation equations of energy, momentum and species are referred to in the simulation. Unsteady recessive algorithms for pressure-based 3D solver are developed in the simulation, and an LES turbulence model is adopted to construct the viscosity model. A Smagorinsky-Lilly based sub-grid scale model is established with a 1ms long iteration step, and 20 iterations in each step. During the simulation, the whole explosion
process is considered as diabetic. The 0.04mm hemisphere fire source is in the center of the closed end and the initial temperature is 2500K. It is supposed that the pipeline is filled with methane-air mixed gas, of which the mass concentration of methane and oxygen is 5.5% and 22% respectively and the rest are inert gases. Two aspiration cycles are observed to check the explosion venting effect of the vacuum cavity.

3.1. Variations of pressure field

As is shown in Fig. 2, the front end of the shock waves in the pipe reaches the weak panel and breaks it at 63ms, and the vacuum cavity begins to take effect. As the pressure in the pipe is higher than that in the cavity, the gas is absorbed by the cavity. From 64ms to 70ms, the pressure in the cavity keeps rising while the pressure in the pipe decreases gradually until it becomes negative at the closed end of the pipe. In the pipe, the pressure at the closed end rises gradually from 70ms, and reaches a second peak value at 77ms. And then, the pressure decrease process starts again and a new valley value appears at 81ms. From 82ms on, a new cycle of pressure rise begins. In the cavity, however, the peak value of the pressure appears at 70ms, and at 75ms it drops to a negative valley value and again rises to another peak value at 81ms. From 82ms to 86ms, a new process of pressure reduction completes.

![Fig. 2. Variations of pressure field.](image)

3.2. Variations of temperature field

As is shown in Figure 3, at 63ms, the flame front is between the pipe corner and the fire source, which suggests that the shock waves move faster than the flame front. According to Figure 2, the vacuum cavity begins to take effect at this moment and the flame flow field is pumped by the cavity from 63ms and 66ms. Then the flames begin to fold, stretch and fracture (71ms-74ms) until the temperature in the pipe decreases accordingly. During the simulation, as the temperature at the closed end is 2500K, the mixed gases will be reignited. But as the weak panel has broken, the pumping effect of the cavity on the new explosion is lessened, the newly generated flames begin to spread towards the exit via pipe corner (75ms-85.9ms).
3.3. Velocity vector variations near the weak panel

As is shown in Fig. 4, during the time period of 63ms-69ms, under the pumping effect, the gas components rush into the cavity through the weak panel at a high speed. In the cavity, the components crash into the pipe walls at a lower speed in a disordered way. As time extends, the disorder continues and the gas density becomes thicker and the components begin to collide and rub with each other and reduce in quantities. The disorder reaches the climax at 69ms when vortexes are formed in the cavity and affect the fluid flow outside the weak panel and change its original shape. This is the first inspiration process of the vacuum cavity. At 70ms, as the average velocity vector of the components reaches its minimum, the disorder in the cavity increases to such an extent that some of the components begin to rush out of the cavity and flow back towards the pipe. From 75ms to 81ms, the gas components keep flowing back to the pipeline, and the disorder is lessened. This is the first expiration process of the vacuum cavity. The second inspiration happens in 75ms to 81ms and the second expiration takes place from 82ms to 86ms and so on.
3.4. Velocity vector variations of the pipe corner

As is shown in Figure 5, during 63ms to 69ms, the gas components in the pipe line move towards vacuum cavity in an orderly manner under pumping effect (63ms-65ms); then their movement speeds up as the velocity vector tilts upward. At 69ms, the speed reach its limit and a vortex appears at the corner. As a zone of negative pressure is formed, some components begin to move reversely. During the 70ms-73ms expiration process, the component movements from the corner to the exit are little affected. At 74ms, the components begin to begin to rush towards the exit under the effect of the shock waves at the closed end. But from 75ms starts another inspiration process and the components moving towards the exit are absorbed by the cavity again. During the subsequent time period, the components between the corner and the exit are moving towards the vacuum cavity. It suggests that the wake panel broken timing is very important. If the movement towards the exit doesn’t occur at 74ms, the second ignition in the pipe won’t happen.

![Velocity vector variations of the pipe corner](image)

Fig.5. Velocity vector variations of the pipe corner.

4. Conclusions

Compared with general pipeline gas explosion, the interference of vacuum cavity greatly hinders the propagation of shock waves and flame speeds. Follows are firstly proved by means of numerical simulation:

1. The propagation of the shock wave in the pipe accords with the fluid water-hammer phenomenon. The explosion venting process is a repetitive activity of inspiration and expiration.

2. The gas components which enter into the cavity impact and neutralize each other before they vanish eventually. When the growing speed of free radicals is slower than its disappearance, the reaction chain is suspended and the combustion stops.

3. When the weak panel breaks under the pumping effect of the vacuum cavity, the flames will fold, stretch and fracture. The broken timing of the weak panel greatly affects the role of vacuum cavity in explosion venting.

4. During the explosion venting process, the time for first inspiration and expiration cycle depends on the volumes of the pipe and cavity. If the cavity is large enough, the flames will be fully absorbed by the cavity in the first inspiration process and after a series of deceleration, cooling and suffocation activities, they will be extinguished eventually. So it can be concluded that the volume of the vacuum cavity has great impact on its explosion venting effect.
References


