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Research Article

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Experimental Study of the Weakening of Methane Explosion Shock Waves by Rotating Blades

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Abstract In order to investigate the weakening effect of the rotating blade on the methane explosion shock wave and the influence of the relevant parameter changes on the weakening effect, by changing the number of rotating blades and methane volume fraction to observe the rotating blade under the action of the methane explosion shock wave intensity and the explosion of the overpressure changes. The results show that: the rotating vane has a weakening effect on the methane explosion shock wave, mainly in the kinetic energy conversion and energy dissipation, and the increase in the number of rotating vanes, is conducive to the weakening of the explosion shock wave, but with the increase in methane volume fraction, the weakening effect is gradually shown as a finite.

Keywords safety engineering; methane; rotating blades; wave dissipation; energy conversion

1. Introduction

Combustible gaseous fuels are widely used in all aspects of industrial production and residential life. Methane is a typical combustible gas widely involved in all kinds of industrial fields, and is an important chemical raw material and power fuel with high calorific value and low price, which is a kind of high-quality energy, but at the same time, it is also one of the main sources of danger leading to the occurrence of gas explosion accidents[1]. Because gas explosion accidents have the characteristics of short reaction time, long combustion time, and rapid rise of high pressure, they often cause major property losses and casualties, and bring great potential hazards to safety production and practitioners. 2023 January 15, Panjin Haoye Chemical Co., Ltd. exploded and caught fire during the process of pressurized sealing of the inlet pipeline of alkylation device washing tank, which resulted in 13 deaths, 35 people The accident caused 13 deaths, 35 injuries, and direct economic losses of about 87.99 million yuan.

In order to prevent gas explosion accidents of combustible gases in the process of industrial production, transportation, storage, transportation and use, gas explosion accidents occur in the related equipment, pipelines and containers involved, to further improve the level of safe production of industrial site operations and the protection ability of key equipment and key areas, and to reduce the losses and hazards caused by gas explosion accidents. Many scholars at home and abroad have conducted a large number of gas explosion shock wave propagation characteristics and wave dissipation technology research.

Wen et al.[2] studied the propagation characteristics of the gas explosion shock wave, while taking into account the location of the source of the explosion, obstacles and distance and other factors, it was concluded that with the increase of obstacles, the peak of the explosion overpressure also becomes larger, but the flame speed will be reduced. Jing et al.[3] carried out a large number of experimental studies on the propagation law of the gas explosion shock wave in the general air zone, studied and analyzed the attenuation law and its influencing factors in the case of corners, bifurcations, and cross-section changes of the shock wave in the roadway and the reliability of the experimental results verified by means of theoretical analysis and numerical simulation, etc. Wang et al.[4] studied the propagation process of gas explosion shock wave inside the building, drew curves for the damage of the explosion shock wave at different locations, and obtained the optimal filling scheme and the equivalent ratio of gas reaction. Yuan et al.[5] investigated the characteristics of the flame and shock wave evolution of methane explosion inside the horizontal confined pipeline equipped with a new type of three-dimensional reticulated porous material. Shao et al.[6] carried out further research on this basis to investigate the explosion suppression characteristics of vacuum cavities by means of experiment, theoretical analysis and numerical simulation. Wu et al.[7] concluded that the use of vacuum cavity pressure and the gas explosion in the pipeline overpressure pressure difference between the role of extinguishing the flame and shock wave attenuation to achieve the effect of explosion suppression. Yan et al.[8] through a combination of experimental studies and numerical simulation method of gas explosion shock wave propagation to the cavity structure due to the cavity of the shock wave reflection, superposition and other combined effect of the shock wave so that it has a good weakening effect on the gas explosion shock wave. Wang et al.[9] found that the quenching capacity of the porous medium with its characterization parameters and flame propagation speed, the openings of the blocking ratio and the pore density of the increase can improve the quenching efficiency of porous media. Duan et al.[10,11] found that the effect of porous media on the explosion mainly depends on the pore size, followed by the thickness, and different obstacle layouts have a significant effect on the flame structure.

Obviously, many scholars have been on the gas explosion shock wave and flame propagation characteristics as well as the interaction between the two in the explosion process has been studied in depth, on this basis, some scholars have explored the gas explosion wave dissipation technology, but mainly focused on the cavity structure dissipation, column shell and empty shell structure dissipation, dissipation of porous media and other aspects of the shock wave energy attenuation, mainly through the release of energy or energy absorption in the form of the shock wave energy attenuation In this paper, the rotating vane is used to attenuate the shock wave energy mainly through energy release or energy absorption, while the research on attenuating the shock wave energy through energy transfer is less. Therefore, this paper adopts the rotating blade to explore through the energy conversion and energy dissipation in the form of a combination of the explosion shock wave energy attenuation, thereby reducing the damage caused by the explosion shock wave.

2. Experimental System

This experiment adopts the system device shown in Fig. 1, which consists of piping system, gas distribution system, ignition system, collection system and weakening system. The piping system consists of two sections of transparent polymethylmethacrylate (Plexiglas) made of horizontal pipes, each section of the pipe size of 1000mm × 100mm × 100mm, the thickness of the plate is 20mm, the total length of the piping platform for the construction of 2000mm. the right end of the pipe is sealed with PVC film. The air vent is located on the upper surface of the right end of the pipe, and the igniter and air inlet are located in the center of the left side of the pipe. The gas distribution system mainly consists of a mass flow control meter, methane cylinders and an air compressor. The ignition system is mainly composed of a high-frequency pulse igniter and a switch. The igniter is placed at the center of the left side of the pipe, with a voltage of 4.5 V and an ignition energy of 0.15 J. After opening the igniter's DC power supply switch, high voltage is generated by high-frequency pulses, and an electric spark is produced after the high voltage penetrates the air. The acquisition system consists of a computer, a data acquisition card, a high-frequency camera, a pressure sensor, a photoelectric tachometer and a shock wave intensity quantization board, in which the image acquisition rate of the camera is 1000 f/s; two pressure sensors are placed at the end of the horizontal pipeline and after the rotating blade; the photoelectric tachometer is placed in front of the rotating blade, and the rotating speed of the blade is measured by an infrared laser; the shock wave intensity quantization board consists of two equal-length tubes, which are placed in front of the rotating blade. Strength quantization plate by two equal length of thin rope fixed at the end of the device fixed cavity, through the test quantization plate flying up the specific height of the quantization to determine the intensity of the explosion shock wave transmitted to this place. Weakening system consists of a deflector cone, rotating blades and device fixed cavity. Conveying cone is to facilitate the impact of air flow to the surrounding blade, to avoid the shock wave on the rotating blade of the center bearing part of the direct impact of the intensity of the device is too large damage. Rotating blades and the deflector cone as a whole fixed in the device cavity, placed in the horizontal pipeline after the explosion vent, and the center of the device and the center of the horizontal pipeline to maintain the same level.

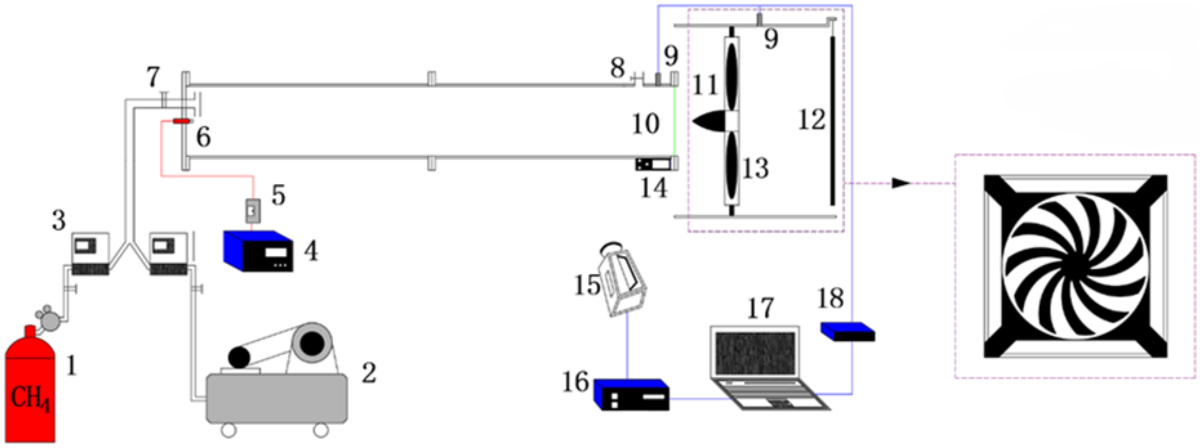


Figure 1: Diagram of the experimental system.

1-methane cylinder 2-air compressor 3-mass flow control meter 4-voltage regulator 5-igniter switch 6-igniter 7-inflator switch 8-exhaust switch 9-pressure transducer 10-PVC membrane 11-conductor cone 12-shockwave intensity quantization plate 13-rotating blade 14-photoelectric tachometer 15-high-frequency video camera 16-controller of video camera 17-computer 18-USB-1208FS type acquisition card

3. Experimental Process

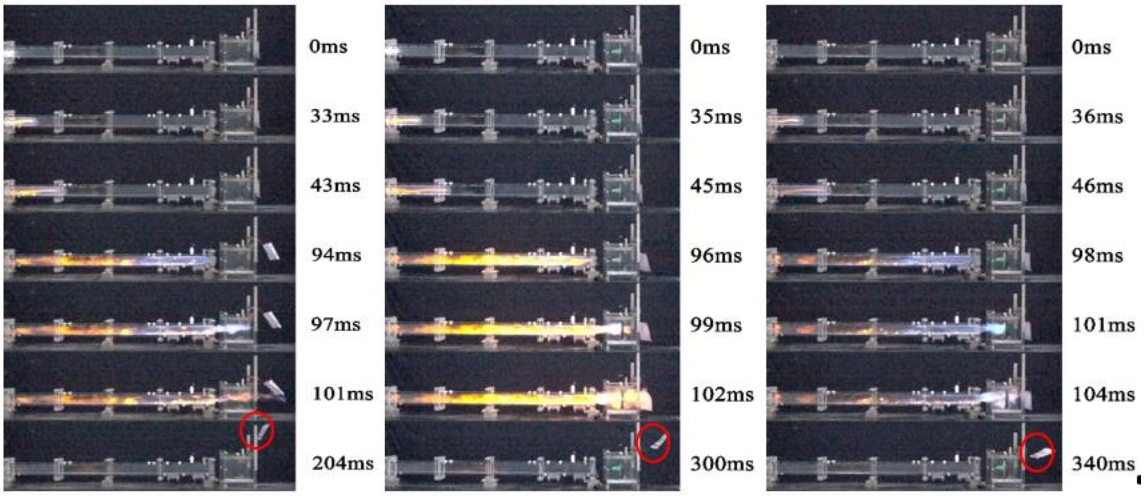
Before each test, the airtightness of the pipeline and gas distribution system and the working status of other systems are checked, and the gas distribution is started after passing the check. By setting the control parameters of the mass flow meter for air and methane respectively, the air and methane are pre-mixed uniformly in the tee tube and then passed into the plexiglass pipeline, and in order to make the concentration of the gas meet the requirements, the gas exchange method is used to inflate the gas with 5 times of the volume of the pipeline. In order to ensure the safety, the gas discharged from the pipeline when inflating by gas exchange method was discharged to the outdoor with a conduit, and the room was kept ventilated. The room was kept ventilated and left to stand for 5 min after inflation to minimize the effect of initial turbulence on the test process. At the same time, it was ensured that the rotating blades and the shock wave intensity quantification plate were in a stationary state, and the acquisition system was in normal working condition. The main variables of the test were the volume fraction of methane in the gas mixture and the number of leaves of the rotating blade, and the specific working condition design is shown in Table 1. After the test, the data were recorded and the pipeline and its residual exhaust gas were cleaned in a timely manner, and the integrity and effectiveness of the device was checked for the next test, which was repeated 2-3 times for each group of tests.

Table 1: Experimental working conditions

Working condition number	Methane volume fraction	Number of rotating blades
1	7.5%	11 blades
2	8.5%	11 blades
3	9.5%	11 blades
4	9.5%	7 blades
5	9.5%	Unset blade

4. Experimental Results and Analysis

A. The effect of rotating blades on the propagation of methane explosions



(a) Unset blade (b) 7 blades (c) 11 blades

Figure 2: Images of methane explosion propagation under the action of rotating blades with different number of blades

Fig.2(a) represents the blank group experimental images without rotating blades, the figure is circled in red is the highest position of the shock wave intensity quantization plate. As can be seen from the figure, due to the explosion of the shock wave propagation prior to the propagation of the explosion flame, in 33ms, the end of the horizontal pipeline PVC membrane rupture, followed by the shock wave rushed out of the end of the relief port, while the explosion flame only propagated to the ignition end of the ignition end of the position of about 0.25m. Shock wave rushed out of the end of the relief port, through the device fixed cavity directly on the shock wave strength quantitative plate, under the joint action of the impact force and the tension of the rope, quantitative plate to the fixed point of the rope as the center of the circle, upward circular motion, in 204ms, quantitative plate kinetic energy reduced to 0, quantitative plate to the highest point of the movement, followed by a downward fall. The height of this highest point will be used as quantitative data of the intensity of the shock wave. Figure shows that in the early and middle of the explosion propagation, shockwave intensity quantization plate action is not fast, the action amplitude is also general, while in the late explosion propagation, shockwave intensity quantization plate began to move greatly. This is due to the explosion in the early and mid-term belongs to the slow development stage, when the explosion propagation is mainly laminar-based, relatively slow, the flame front is also mainly manifested in the shape of a finger tip, the shockwave intensity is relatively weak; to the explosion in the late stage, turbulence intensified, the explosion propagation speed accelerated, the shockwave intensity sharply enhanced. In addition, in the explosion flame rushed out of the vent, the sudden large increase in air, conducive to flame combustion and propagation, the explosion propagation will be briefly enhanced again. Therefore, the late explosion of the shock wave intensity is significantly greater than the intensity of the early stage.

Fig. 2 (b) and Fig. 2 (c) represent the methane explosion propagation images when the number of blades of the rotating blade is 7 and 11, respectively. As can be seen from the figure, compared with Fig. 2(a), the shockwave intensity quantization plate in the explosion propagation of the first and middle of the action amplitude is obviously reduced, and Fig. 2(c) than Fig. 2(b) is more obvious. At the same time, the final maximum height of the shock wave intensity quantization plate is significantly lower than Fig. 2 (a), and with the increase in the number of blades, the maximum height of the shock wave intensity quantization plate is also correspondingly reduced; in addition, the intensity of the shock wave quantization plate to move to the maximum height of the time required to gradually become longer. This is due to the role of rotating blades, on the one hand, the kinetic energy of the shock gas flow into the kinetic energy of blade rotation, on the other hand, the explosion shock gas flow in the rotating blades, the centrifugal force under the action will be transformed into the dispersion of the surrounding area, as shown in Fig. 3, so that the impact of the gas flow will no longer be directly impacted on the protective object. At the same time, the shock wave gas flow after the blade dispersion, flow cross-sectional area increases, according to Q = AV can be known, in a certain flow rate, the cross-sectional area of the gas flow increases, then the flow rate decreases, the kinetic energy and the flow rate is proportional to the kinetic energy, so the kinetic energy of the shock gas flow decreases. In summary, the kinetic energy of the shock gas flow through the transfer and dispersion weakened, the direct effect of the shock wave intensity is also correspondingly weakened. Especially in the early and middle stages of the explosion propagation, mainly in the form of laminar flow propagation, the kinetic energy of the shock gas flow is small, after the weakening of the rotating blades, the shock wave intensity of the quantization of the plate's action amplitude becomes smaller. The more the number of blades more dense, the degree of shock dispersion and energy transfer is stronger, the weakening effect on the intensity of the shock wave is also better, the shock wave intensity quantitative plate can reach the maximum height is lower. And the smaller the kinetic energy of the shock airflow, the slower the movement of the shock wave intensity quantization plate, and the longer the time needed to reach the maximum height.

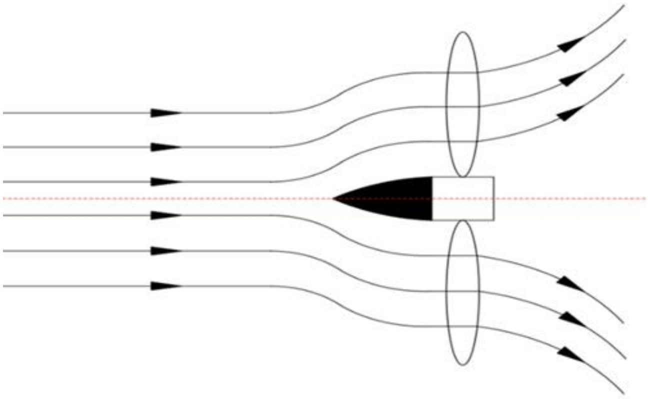
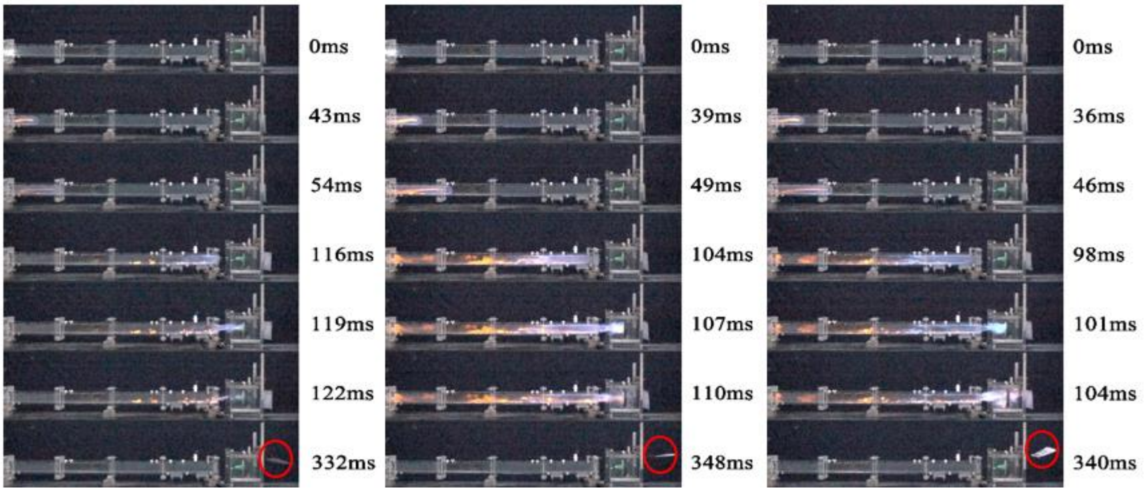


Figure 3: Schematic diagram of impinging air flow under the action of rotating blades



(a)7.5% (b)8.5% (c)9.5%

Figure 4: Images of methane explosion propagation for different volume fractions under the action of rotating blades

Fig. 4(a)-(c) represents the methane explosion propagation images under the action of rotating blades when the methane volume fraction is 7.5%, 8.5% and 9.5%, respectively. As can be seen from the figure, with the increase in the volume fraction of methane in the gas mixture, the explosion flame to the end of the explosion relief port time required for 116ms, 104ms and 98ms, respectively, the time is getting shorter and shorter, but also characterized the degree of explosion development is more and more intense, but in the early and middle stages of the explosion propagation, the back of the shockwave intensity of quantitative plate of the magnitude of the action is basically the same. Similarly, this is due to the explosion propagation in the early and middle stages, the shock gas flow is mainly laminar flow propagation, kinetic energy is small, the rotating blade on its weakening effect is more obvious, resulting in the amplitude of the shock wave intensity quantization plate of the action of the smaller, which in turn shows that the different volume fractions of the methane explosion in the rotating blade under the effect of the amplitude of the action of the quantization plate of the intensity of the shock wave is basically the same. In addition, with the increase in the volume fraction of methane in the gas mixture, the maximum height of the shock wave intensity quantization plate can ultimately be reached is higher, which corresponds to the greater the volume fraction of methane, the more intense the development of the explosion is corresponding to the degree of intensity. Methane explosion limit is 5% -15%, when the methane volume fraction of 9.5%, methane and oxygen equivalent ratio of 1, the most violent explosion.

Table 2: Experimental results data table

Working condition number	**Methane volume fraction**	**Number of rotating blades**	**t_1(ms)**	**t_2(ms)**	**t_3(ms)**	**t_4(ms)**	**H_{max} (cm)**	**RMP_{max} (r/min)**
1	7.5%	11 blades	43	54	116	332	30	1117.2
2	8.5%	11 blades	39	49	104	355	37	1496.8
3	9.5%	11 blades	36	46	98	340	48	1686.4
4	9.5%	7 blades	35	44	96	300	59	1405.5
5	9.5%	Unset blade	35	43	94	201	75	——

Notes:

(1) t1: PVC membrane rupture time at the end of the pipe; t2: shock wave intensity quantization plate to start the action time; t3: explosion flame rushed out of the end of the pipe time; t4: shock wave intensity quantization plate to reach the highest time;

(2) Hmax: shock wave intensity quantization plate to reach the maximum height (experimental platform at the plane of the H=0); RMPmax: the maximum rotational speed of rotating blade in the process of explosion.

The specific test data under each working condition are summarized in Table 2. As can be seen from the table, with the setting of the rotating blade and the increase in the number of blades, due to the same volume fraction of methane, PVC film rupture time t_1 is basically the same, but in the rotating blade on the weakening effect of the shock wave, the shock wave intensity quantization plate to start the action of the time t_2 has been slightly prolonged, the shock wave intensity quantization plate to reach the highest place of the time t_4 is also gradually prolonged. In addition, the explosion flame rushed out of the end of the pipe time t_3 has also been slightly extended, this is because the rotating blade on the shock gas flow conversion and dispersion effect, to a certain extent, affects the generation of turbulence in the horizontal pipeline, which in turn affects the speed of the explosion propagation. Similarly, as the methane volume fraction increases, the explosion intensity is enhanced, corresponding to an acceleration of all times. The maximum height Hmax reached by the shockwave quantization plate and the maximum rotational speed RMPmax of the rotating blades for each condition are more visually represented in Fig. 5 and Fig. 6.

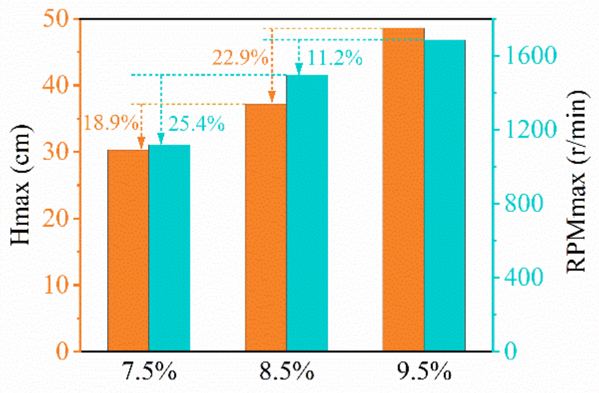


Figure 5: Comparative images of Hmax and RMPmax of methane explosion with different volume fractions under rotating vane action

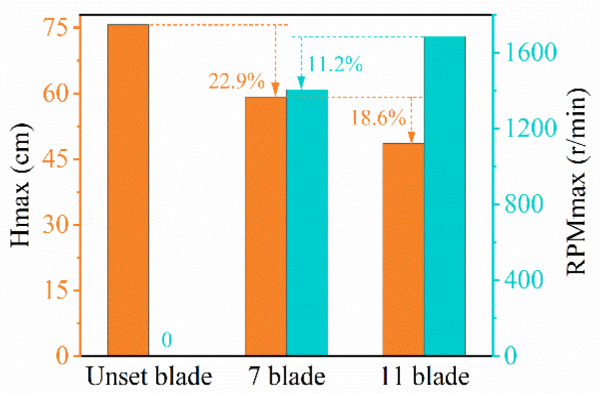


Figure 6: Comparative images of methane explosion Hmax and RMPmax under the action of rotating blades with different number of blades

Fig. 5 shows the rotating blade under the action of different volume fractions of methane explosion test in the Hmax and RMPmax, as can be seen from the figure, with the increase in the volume fraction of methane, the intensity of the explosion is enhanced, the shock wave quantization plate to reach the maximum height of the Hmax and the maximum rotational speed of the rotating blade of the RMPmax are also increasingly large. However, the volume fraction of methane for 8.5% of the working conditions compared to the volume fraction of methane for 9.5% of the working conditions, Hmax decreased by 22.9%, RMPmax decreased by 11.2%; while the volume fraction of methane for 7.5% of the working conditions compared to the volume fraction of methane for 8.5% of the working conditions, Hmax decreased by 18.9%, RMPmax decreased by 25.4%. It can be seen that as the volume fraction of methane increases, although Hmax and RMPmax are increasing overall, but the magnitude of the increase in RMPmax gradually becomes smaller, and the magnitude of the increase in Hmax gradually becomes larger. Therefore, with the enhancement of the intensity of the explosion, the rotational speed of the rotating blade will reach a certain limit, the degree of kinetic energy conversion of the impact of the gas flow and the speed of the gas flow dispersion will reach a certain limit, so the rotating blade on the explosion of the shockwave weakening degree is also limited.

Fig. 6 shows the different blade number of rotating blades under the action of methane explosion test Hmax and RMPmax, as can be seen from the figure, with the set of rotating blades and the number of blades increases, the maximum height of the shock wave quantization plate reached Hmax gradually decreased, the maximum speed of the rotating blades RMPmax gradually increased. Similarly, Hmax decreases by 22.9% for the case with 7 blades compared with the case without rotating blades, and Hmax decreases by 18.6% for the case with 11 blades compared with the case with 7 blades. It can be seen that with the setting of rotating blades and the increase of the number of blades, the decrease of Hmax decreases gradually. Therefore, the increase in the number of blades and the denser blades are conducive to the increase in the rotational speed of the rotating blades, which is more conducive to the increase in the degree of kinetic energy conversion of the impact airflow and the speed of airflow dispersion; however, the increase in the number of blades to a certain amount of the increase in the weakening effect on the shock wave will no longer be so obvious.

B. Effect of rotating blades on methane explosion overpressure

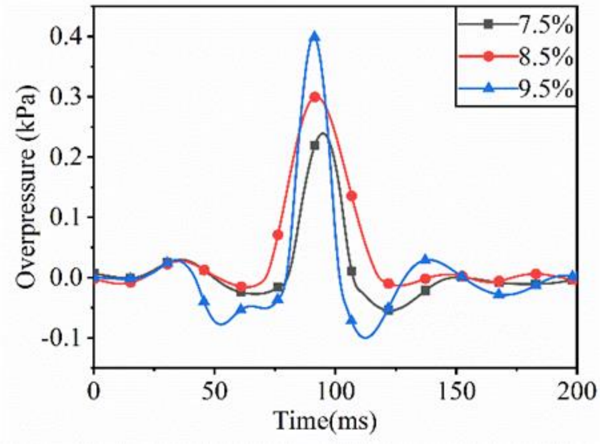


Figure 7: Images of methane explosion overpressure variations with different volume fractions under the action of rotating vanes

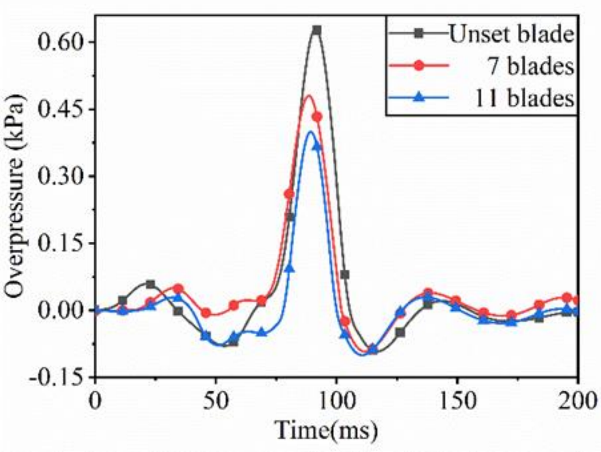


Figure 8: Images of methane explosion overpressure variations under the action of rotating blades with different numbers of blades

Fig. 7 and Fig. 8 show the variation of overpressure at the measurement point after rotating the blade for each operating condition. As can be seen from the figures, the curves in the graphs are mainly characterized by the appearance of a small peak, followed by a larger second peak, and then a small oscillation phase.

Fig. 7 shows the rotating blade action of different volume fractions of methane explosion overpressure changes, as seen in the figure, in different volume fractions of methane explosion overpressure change curve, the first peak of the overpressure peak is basically the same. This is due to the basic consistency of the pressure caused by the broken film, because the explosion of the pre-propagation is relatively slow, and the PVC membrane has a certain pressure-bearing capacity, when more than the PVC membrane pressure limit, PVC membrane rupture, rupture of the instantaneous release of a large number of piled up shock gas flow, which in turn caused a certain overpressure peak, so the strength of the shock gas flow released when the membrane is basically the same, and according to the previous analysis, at this time, the intensity of the shock wave is relatively small, and after the weakening of the rotating blade, only a small overpressure peak is formed. In addition, the figure of the second peak in the overpressure peak is with the increase in the volume fraction of methane and increase, which increases the volume fraction of methane, the explosion intensity is corresponding to the increase.

Fig. 8 represents the variation of methane explosion overpressure under the action of rotating blades with different number of blades. Similarly, as can be seen from the figure, with the setup of rotating blades and the increase in the number of blades, the peaks of overpressure in both the first small wave peak and the second large wave peak become smaller and smaller. According to the previous analysis, this is the result of the improvement of the effect of the rotating blades on the kinetic energy conversion of the shock gas flow and the weakening effect of the gas flow dispersion.

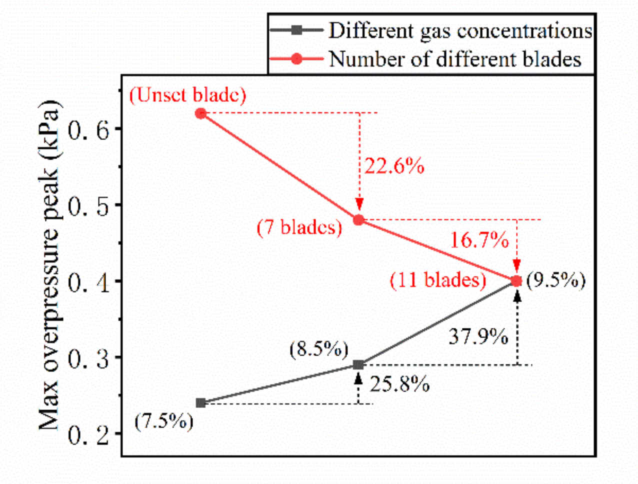


Figure 9: Variation of maximum peak overpressure at each operating condition

Fig. 9 indicates the maximum peak overpressure change under each test condition. The black line in the figure indicates the variation of the peak overpressure of methane explosion under the action of the same rotating blade with different volume fractions, and the red line indicates the variation of the peak overpressure of methane explosion under the action of the rotating blade with different numbers of blades. It is obvious from the figure that the maximum peak overpressure (Pmax) is increased with the increase in the volume fraction of methane, and decreased with the increase in the number of rotating blade settings and blades. However, Pmax increases by 25.8% for the case with 8.5% volume fraction of methane compared to the case with 7.5% volume fraction of methane, and by 37.9% for the case with 9.5% volume fraction of methane compared to the case with 8.5% volume fraction of methane, so it is evident that the magnitude of the increase in Pmax increases with the increase in the volume fraction of methane. In addition, Pmax decreases by 22.6% for the case with 7 blades compared to the case without rotating blades, and decreases by 16.7% for the case with 11 blades compared to the case with 7 blades. It can be seen that with the increase of rotating blade settings and the number of blades, the magnitude of Pmax reduction gradually decreases. This is consistent with the previous analysis of the conclusions obtained, that is, the rotating blade on the explosion shock wave weakening degree is also limited, with the enhancement of the intensity of the explosion or the number of blades to a certain number of times, the rotating blade on the explosion shock wave weakening effect of the increase in the magnitude of the reduction will be reduced.

5 Conclusion

In this paper, the weakening effect of rotating blades on the methane explosion shock wave and the influence of the number of rotating blades and methane volume fraction on the weakening effect are investigated by building a relevant experimental platform. The following conclusions were obtained:

The rotating blades have a weakening effect on the methane explosion shock wave, which is mainly manifested in the energy transfer effect of converting the kinetic energy of the shock gas flow into the kinetic energy of the rotating blades, and the energy dissipation effect of dispersing the shock gas flow to the surrounding area through the centrifugal force.

The increase in the number of rotating blades, blades more dense, kinetic energy conversion and dispersion weakening effect is stronger, more conducive to weakening the strength of the methane explosion shock wave; but when the number of blades increased to a certain number, the weakening effect of the enhancement of the magnitude of the more insignificant.

With the increase of methane volume fraction, the intensity of the explosion shock wave enhancement, but due to the limited rotational speed of the rotating blade itself, the rotating blade on the explosion shock wave weakening effect gradually showed limited.

Acknowledgments

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