

# Effects of vent position and numbers on hydrogen explosion dynamic characteristics

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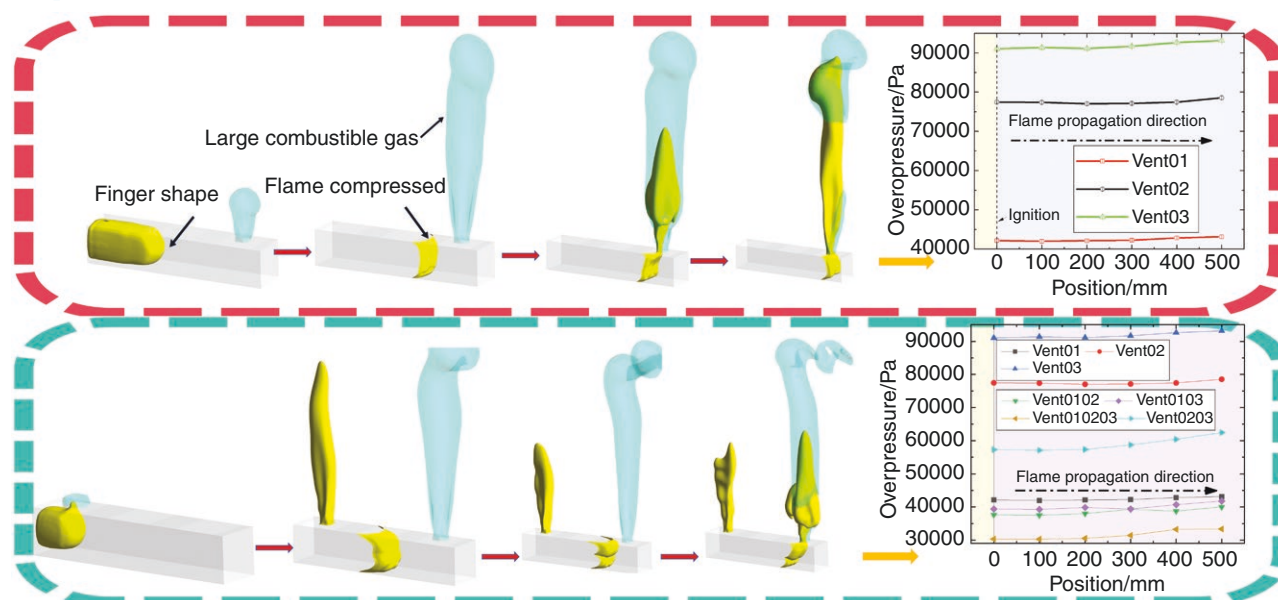
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## Abstract

Hydrogen energy has been widely used in various industrial processes. However, hydrogen explosion can cause significant loss of personnel and property, and explosion venting is an effective method to reduce the explosion damage. The mechanism of hydrogen explosion venting has become an important research topic in hydrogen energy safety engineering. This study employs numerical simulation to explore the impact of vent parameters on the hydrogen-air explosion dynamics. A geometric model considering internal and external explosion is established. Results show that venting efficiency improves as the vent is positioned closer to the ignition or the number of vents increases. The peak internal overpressure increases by 1.2 times as the single vent moves from the ignition to near the end. The external explosion overpressure and dynamic pressure grows with the decrease of internal explosion venting efficiency. The flame front deflects toward the vent and ejects from the duct under the suction effect of the vent. The vortex flow characteristics near the vent cause the flame to deform as it propagates downstream. Vents located closer to the ignition induce the formation of a reverse flow field and lead to reverse propagation of the flame. The formation of symmetrical vortex regions within the flame causes it to compress, resulting in a longer external flame length as the vent is located farther from the ignition. The maximum flame speed increases by 1.1 times as the single vent moves from the ignition to near the end. Multiple flame propagation speed are exhibited under multiple vents conditions.

## Graphical Abstract



**Keywords:** numerical simulation; vent numbers; vent position; explosion dynamic; hydrogen

## 1. Introduction

Hydrogen is acknowledged as a sustainable energy source capable of mitigating challenges associated with greenhouse gas emissions, air pollution, and energy scarcity. However, it is im-

perative to highlight that hydrogen exhibits notable characteristics, including a pronounced leakage capacity, an extensive explosion range, and rapid flame propagation. Hydrogen energy ships have special fuel cabins for storing hydrogen; the high

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pressure during hydrogen explosions on ships can result in significant loss of life and equipment [1]. Explosive venting stands out as a pivotal strategy for preventing explosion-related damage and safeguarding equipment. Reasonable setting of vent parameters can reduce the explosion disaster to the greatest extent. Presently, the coupling effect between flame dynamics, pressure, and flow fields in explosion venting represents a critical topic in explosion research. The study of the mechanism of hydrogen explosion venting is the key to prevent explosions and minimize accidental damage. Consequently, studying the kinetic behavior of hydrogen venting explosions assumes paramount importance in ensuring the safe deployment of hydrogen energy technologies.

Combustion and explosion occur when the combustible hydrogen-air cloud forms in a venting space. Conducting full-scale hydrogen ship experiments are usually difficult due to size limitations and safety concerns, numerical simulations have become the good methods for researchers to study hydrogen explosion dynamics. Some researchers have compared various computational fluid dynamics (CFD) codes and point out the good computational accuracy of Fluent. We have previously studied the hydrogen deflagration and detonation. Sheng *et al.* [2] developed the Charlette-Sheng dynamic turbulent combustion velocity model using large eddy simulation (LES) method, studied the hydrogen detonation behavior under different obstacle shapes, and quantified the degree of turbulent-flame interaction with Karlovitz, observing the transformation of deflagration flame from “folding flame” to “thin reaction zone”. After that, Sheng *et al.* [3] found that flame propagation was mainly affected by two instabilities: Rayleigh–Taylor (R–T) and Kelvin–Helmholtz (K–H). The two kinds of instability are quantitatively modeled, and it is pointed out that they play a significant role in the flame structure evolution and acceleration. In deflagration to detonation research, Sheng *et al.* [4] used Openfoam to model the self-ignition effect of the turbulent premixed model, and studied the deflation-to-detonation process in the field of non-uniform concentration, observing two kinds of initiation of detonation mechanisms. Sheng *et al.* [5] also study the dynamic of hydrogen explosions with different obstacle passage lengths. It was found that the longer obstacle passage offered the flame more time for acceleration, causing higher flame velocity and higher overpressure rise rate. The influences of obstacle spacing on flame accelerating and deflagration-detonation transition in heterogeneous mixtures are discussed based on nine detailed 21-step chemical reaction mechanisms [6]. The results show that the flame propagation speed is inversely proportional to the distance between obstacles, which is because the interference intensity of obstacles to flow in a unit channel length is negatively correlated with the distance between obstacles. High explosion overpressure and strong turbulent flame instability would be generated during hydrogen detonation in a confined space, and flame acceleration and detonation would be induced under the action of obstacles. Therefore, the study of reasonable explosion suppression and release modes is conducive to further promoting the development of hydrogen energy safety engineering. Baraldi *et al.* [7] utilized four CFD codes to predict the hydrogen venting explosion within a 0.95-m<sup>3</sup> vessel under different vent sizes, observing notably accurate predictions with the Fluent. Similarly, Bauwens *et al.* [8] predicted explosion behaviors for different vent sizes and post ignition conditions. However, the Openfoam prediction had suboptimal accuracy for pre-ignition conditions. Zhou *et al.* [9, 10] conducted investigations on the significant influence of vent location and size on pressure venting dynamics. Optimal venting efficacy was achieved when the vent was located near the ignition. Cao *et al.* [11] found that the influence of the vent pipe

length can be ignored for hydrogen explosions as the vent pressure ( $P_{\text{bur}}$ ) is higher than 0.35 MPa. Chao *et al.* [12], Cu *et al.* [13], and Bao *et al.* [14] noted that reducing vent sizes increased the explosion overpressure, the vent pressure had varying effects on overpressure and overpressure rise rate in different locations. Lv *et al.* [15] analyzed the explosion pressure and flame propagation in an open pipe with obstacles and pointed out that the combustion rate increased when the flame passed through the obstacles, resulting in a larger explosion pressure. Rocourt *et al.* [16] studied the impact of vent size in a confined space, noting that ignition at the rear wall produced the highest overpressure. Wan *et al.* [17] and Ajrash *et al.* [18] demonstrated the effectiveness of lateral vents in mitigating the explosion intensity. There may be multiple pressure peaks due to the influence of various factors in internal and external space. Rui *et al.* [19] noted that the first peak overpressure increased with the growth of vent pressure. Ma *et al.* [20] conducted numerical calculations on the explosion venting in 5 L and 64 m<sup>3</sup> vessels. They found that adding hydrogen gas shortened the explosion time. Alexiou *et al.* [21] indicated that in a vessel with a large aspect ratio, the effect of a side vent was evaluated and compared with an end vent. The peak overpressure of the side vent condition with obstacles was higher than that of the end vent condition, which was caused by the rapid combustion of the trapped end gas. The experimental results Yu *et al.* [22] indicated that the flame speed gradually decreased as the flame moved past the side vent due to the side vent. Yu *et al.* [23] and Wan *et al.* [24] discovered that the effectiveness of side vents with varying sizes was influenced by the positions of obstacle and vent. Specifically, when the side vent was positioned in front of the obstacle, it more effectively decelerated flame propagation and released overpressure, with the release effect being less sensitive to the vent size. Li *et al.* [25] demonstrated that introducing a side vent near the ignition significantly reduces the maximum internal overpressure. Crowhurst [26] pointed out that dust explosion pressure relief was better when multiple pressure relief ports when the same total area was used. The above scholars mainly focus on the change of overpressure, but the dynamic pressure cannot be ignored in some vent conditions. Zhang and Ma [27] evaluated the risk of explosions in underground coal mines and highlighted that the dynamic pressure from high-speed gaseous combustion products also caused significant damage. Current studies have mainly focused on the explosion pressure characteristics in internal spaces, with fewer studies on explosion in external spaces. Most studies have analyzed data from a single monitor point and have yet to study in depth the evolution of pressure at various locations in internal and external spaces.

The dynamics of pressure are profoundly influenced by the development of flames in both internal and external spaces, and the propagation of flames during explosion venting is significantly affected by vent parameters. Consequently, it is critical to examine the evolution of flame propagation under various venting explosion conditions. Zhang *et al.* [28] and Cao *et al.* [29] conducted numerical analyses of explosion peak pressure and flame propagation under varying vent pressures, discussing the phenomenon of an under expanded jet near the vent. Meanwhile, Li *et al.* [30] and Zhang *et al.* [31] investigated peak pressure within a slender pipe, considering different concentrations and numbers of vents, thereby observing three distinct stages of flame morphology transition. Zhang *et al.* [32] and Guo *et al.* [33–35] studied the effects of vent pressure, hydrogen concentration, and the use of double vents on explosion pressure characteristics. They observed multiple pressure peaks at the vessel outlet when the vent pressure was low. Employing two vents with the same total vent size

significantly reduced the external flame length. In the presence of an obstacle, the flame exhibited significant distortion upon reaching the obstacle, with flame propagation strongly accelerating towards the end vent. The flame slowed down as it reached the side vent [36]. Chen *et al.* [37] found that compared to an end vent, a side vent caused greater distortion of the flame within the duct, leading to more significant changes in the flame area. Alexiou *et al.* [38, 39] noted that if the side vent was away from ignition, very high flame speed and overpressures were measured. Solberg *et al.* [40] found that an explosion that opened a vent on one wall would cause Taylor instability, so it was recommended to place the vent on the side of as many containers as possible. Previous studies on flame structure evolution in numerical simulations have primarily focused on the internal space, with less attention given to the evolution of flame propagation structure in the external space. Rui *et al.* [41] found that a Mach disk began to emerge when the vent coefficient grew to 12.7 for front ignition and 8.6 for other ignition conditions. Pang *et al.* [42] pointed out that the increasing of vent pressure and vent opening time enhanced the flame speed and decreased the gas cloud volume, thereby reducing the explosion progress. Decreasing vent size will heighten the flame velocity, and promote unburned cloud spreading at a farther distance.

When the flame propagates into the external space, it interfaces with the surrounding combustible gas mixture and generates a secondary explosion. However, there exists a lack of research on secondary external explosion. Pang *et al.* [43] conducted an analysis of the external disaster area caused by a high-speed hydrogen explosion in a 64 m<sup>3</sup> space. They found that dynamic pressure experienced an increase with the duration of venting within a specific range proximate to the vent. Tolia and Venetsanos [44] highlighted that the substantial increase in external pressure occurred only subsequent to the flame's ingress into the turbulent recirculation zone. Li and Hao [45] proposed a CFD modeling approach utilizing FLACS/Fluent to model the internal turbulent flame and calculate shock waves propagation in low turbulence intensity air. The analytical results of Bauwens *et al.* [46] indicated that peak pressures were controlled by the combination of the maximum flame area, combustion speed, and explosion outside the combustion chamber. Their analysis highlighted the gas cloud and flame shape, as well as the explosion kinetics of propane in both internal and external spaces for various vent sizes. Notably, it was elucidated that a smaller vent size could disrupt the vortex bubble, engendering a jet that entrained a substantial volume of external atmosphere. Wang *et al.* [47] discovered that reducing the vent size led to an increasing in internal explosion overpressure and dynamic pressure outside the vent. Proust and Leprette [48] observed the flame and unburned gas being ejected from the internal space, coiling and sucking up to form a mushroom cloud morphology. The maximum peak of external overpressure near the vent may be smaller than that in the downstream region, indicating that the external explosion occurred away from the vent. Wang *et al.* [49] conducted experiments and found that the intensity of Rayleigh-Taylor instability and Helmholtz oscillation increased with larger vent sizes. Pan *et al.* [50] discovered that the flame oscillation propagation decreased as the distance between the vent and the ignition increased. Ajrash *et al.* [18] observed that the vacuum effect pushed the flame back towards the vent, triggering a secondary pressure rise at high methane concentrations. Li *et al.* [51] found that the external peak overpressure decreased as the nitrogen fraction increased. The peak external impulse exhibited an opposing trend in relation to the nitrogen fraction. The maximum

temperature, flame length and flame width initially decreased and subsequently increased with the growth of nitrogen fraction. The analysis of Lu *et al.* [52] showed that as the hydrogen fraction reached 50.0% and 60.0%, the flame contacted with external unburned hydrogen and caused a secondary explosion, which accelerated the flame speed and resulted in a high flame temperature zone with peak temperature of 1165 and 1208 °C. Hu *et al.* [53] observed under the impact of external explosion and wave overlap, the distribution evolution of overpressure hazard areas became unpredictable.

In summary, previous work has primarily focused on studying the pressure characteristics of a single monitoring point and flame morphology evolution in the duct. However, there remains insufficient research on the pressure characteristics of different locations, flame propagation behavior, and the phenomenon of secondary explosions within both the internal and external spaces. The evolution mechanism of pressure, flame, and flow field during explosion needs further study. This paper employs numerical simulation methods to study the hydrogen explosion venting in both internal and external spaces under various vent positions and vent numbers. The research aims to investigate the coupling effect of pressure, flame, flow field, and vent parameters to reveal the dynamic behaviors of the hydrogen venting explosion. This work provides substantial references for the venting structural design of hydrogen energy ships and holds significant implications for human and asset protection.

## 2. Numerical modeling

### 2.1 Governing equations

The hydrogen venting explosion process can be described by the momentum, energy, and mass conservation equations, these equations are also available in the literature [43, 54] as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \quad (2)$$

$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial x_j}(u_j(\rho e + p)) = \frac{\partial}{\partial x_j} \left( k \frac{\partial T}{\partial x_j} - \sum h_m J_m + u_i \tau_{ij} \right) + \dot{Q}_c \quad (3)$$

where  $x$  is the Cartesian coordinate,  $p$  is the static pressure,  $t$  is the time,  $u$  is the velocity,  $\rho$  is the density, and  $i$  and  $j$  is the coordinate directions. Additionally,  $\dot{Q}_c$  represents the chemical reaction source term, and  $h_m$  and  $J_m$  are the specific enthalpy and diffusion flux of component  $m$ .  $\tau_{ij}$  is the viscous stress tensor, as is expressed as the flow formula:  $\delta_{ij}$  is the Kronecker number, and  $\mu_t$  is the turbulent viscosity coefficient.

$$\tau_{ij} = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} \left( \rho k + \mu_t \frac{\partial u_i}{\partial x_i} \right) \quad (4)$$

### 2.2 Turbulent flow and premixed combustion model

In this study, the scale-adaptive turbulence model (SAS) [28, 55] has been employed, as shown in the following.

$$\mu_t = \frac{\rho k}{\omega} 1 / \max \left[ \frac{1}{\alpha^*}, \frac{SF_2}{a_1 \omega} \right] \quad (5)$$

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i k) = G_k - \rho c_k k \omega + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \quad (6)$$

$$\begin{aligned} & \frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i \omega) \\ &= \alpha^{\omega/k} G_k - \rho \beta \omega^2 + Q_{SAS} + \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] \\ &+ (1 - F_1) \frac{2\rho}{\sigma_{\omega,2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \end{aligned} \quad (7)$$

$$Q_{SAS} = \max \left[ \rho \eta_2 k S^2 \left( \frac{L}{L_{vk}} \right)^2 - C \cdot \frac{2\rho k}{\sigma_\phi} \max \left( \frac{1}{\omega} \frac{\partial \omega}{\partial x_i} \frac{\partial \omega}{\partial x_j}, \frac{1}{k^2} \frac{\partial k}{\partial x_i} \frac{\partial k}{\partial x_j} \right), 0 \right] \quad (8)$$

where  $k$  is turbulent kinetic energy and  $\mu$  is molecular viscosity. Coefficient  $\alpha^*$  suppresses turbulent viscosity and makes low Reynolds number corrections. The value of  $\alpha_i$  is 0.31,  $\sigma_\eta$  is 2/3,  $C$  is 2, and  $C_\mu$  is 0.09 m<sup>2</sup>/s.  $G_k$  is the generation of turbulent kinetic energy. The length scale of the simulated turbulence is denoted by  $L$ , and  $S$  represents the strain rate scalar.  $L_{vk}$  is a three-dimensional generalization of the classical boundary-layer definition.  $\sigma_k$ ,  $\sigma_\omega$ , and  $\beta$  are computed as follows:

$$\sigma_k = \frac{1}{F_1/\sigma_{k,1} + (1 - F_1)/\sigma_{k,2}} \quad (9)$$

$$\sigma_\omega = \frac{1}{F_1/\sigma_{\omega,1} + (1 - F_1)/\sigma_{\omega,2}} \quad (10)$$

$$\beta = F_1\beta_1 + (1 - F_1)\beta_2 \quad (11)$$

The combustion is resolved by utilizing the average reaction process variable equation [56]:

$$\frac{\partial}{\partial t} (\rho c) + \nabla \cdot (\rho u_i c) = \nabla \cdot \left( \left( \frac{k}{c_p} + \frac{\mu_t}{Sc_t} \right) \nabla c \right) + \rho Sc \quad (12)$$

where  $c$  is reaction process variable. The turbulent Schmidt number is denoted by  $Sc_t$ , which is equal to 0.7. The reaction process source term is defined by  $S_c$ , and the specific heat capacity of the mixture is represented by  $C_p$ .  $S_c$  is calculated using Eq. (13).

$$\rho Sc = \rho_u u_t |\nabla c| \quad (13)$$

where  $\rho_u$  represents the density of unburnt mixture,  $U_t$  is the turbulent flame velocity, which is calculated by the Zimont model, as the following formula [57].

$$U_t = A(u')^{3/4} U_l^{1/2} \chi_u^{-1/4} l^{-1/4} \quad (14)$$

where  $A = 0.52$  is model constant,  $U'$  is the turbulence intensity,  $U_l$  is the laminar flame propagation velocity,  $\chi_u$  is the thermal conductivity of the unburned hydrogen-air mixture, and  $l$  is the turbulence length scale.

### 2.3 Case settings and boundary conditions

A 3D model of hydrogen venting explosion is established, which includes the internal duct and the external field. The dimensions of the duct are specified as 500 mm × 100 mm × 100 mm; three vents are arranged at different positions of the duct as shown in

Fig. 1. For example, the case of vent01 represents only one vent chosen under this condition, and this vent is set closer to the vent. The case of vent0102 represents two vents chosen under this condition; one vent is located closer to the ignition, and the other is located in the middle of the duct. The external space extends five times the duct diameter in the radial direction and axially to nine times its length. The adiabatic nonslip wall is used, and the boundary of the external space is set as a non-reflective pressure outlet. The duct contains a stoichiometric hydrogen-air mixture, while the external space contains only air. The ignition is initialized with a spherical region of 2 mm radius and ignition is achieved by setting the reaction process variable to  $c = 1$ . The computational domain is discretized using the finite volume method. We use the pressure-implicit with splitting of operators (PISO) algorithm to solve the hydrogen explosion venting in this study. PISO is a pressure-velocity coupling algorithm, which uses neighbor correction to improve the calculation efficiency. Space and time discretization are performed in the second format. Adaptive time steps are used to ensure computational stability with an initial time step of 1E-6 s and a Courant number of 0.8. The residuals of the mass, momentum, turbulent kinetic energy, average mixture fraction, turbulence dissipation rate and process variable equations are all less than 1E-3. Additionally, the energy equation residual is less than 1E-6 in the simulation calculations.

### 2.4 Grid independence and model validation

Numerical calculations are conducted to validate the process of hydrogen explosion, as described by experimental results in the literature [15]. A rectangular obstacle with a 50% obstruction rate is inserted into a 100 mm × 100 mm × 500 mm rectangular duct, located 200 mm away from the ignition. The duct is made of steel plate and organic glass, filled with hydrogen-air mixture at an equivalent ratio. The ignition and pressure monitor are positioned at the bottom of the duct. The mixture is introduced into the duct via an inlet located at the lower steel plate, with the gases subsequently being vented through an outlet valve situated proximal to the duct's top. Four times the duct volume of premixed hydrogen air is passed into the duct and stands for 15 s to achieve good premixed air. Data are collected by pressure sensors and high-speed cameras. We divided the complete hexahedral structured grid in the whole computing domain, and calculated four mesh sizes in the duct of 2, 3, and 4 mm. The results (Fig. 2) show that when the mesh size is less than 4 mm, the effect of the mesh size on the calculation results can be ignored. In order to ensure the calculation accuracy and avoid high computational costs caused by excessive grid cells, the 3 mm grid is selected for simulation. In the external space, the key area where an external explosion will occur is encrypted by grids, and the minimum grid after encryption is 3 mm. The grid is sparsely processed away

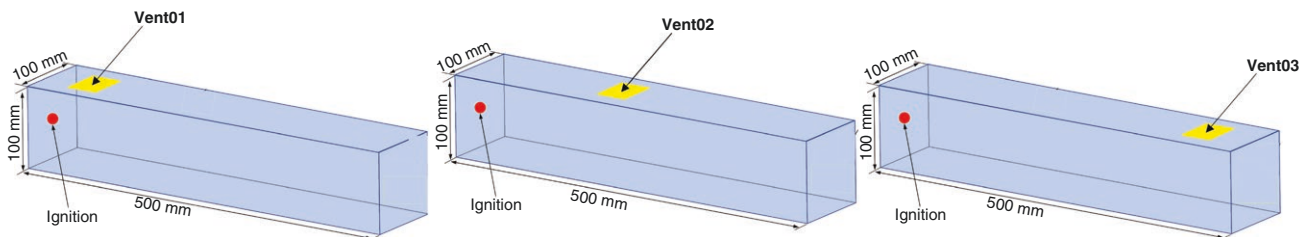


Figure 1. Geometric model.

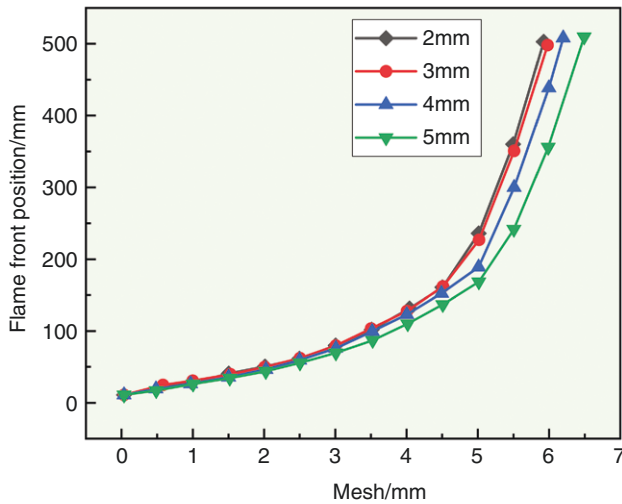


Figure 2. Grid independence validation.

from the external explosion, and the size growth rate of the adjacent two grids does not exceed 1.5. The total number of grids is 13 369 603.

The comparison of flame structure in the numerical simulation and captured by high-speed camera is delineated in Fig. 3. The flame spreads in spherical and finger forms in the early stage. The flame morphology and propagation position at different moments are in good agreement with the experimental results. The flame undergoes deformation after passing through the obstacle, accompanied by a gradual expansion of its surface area. Consequently, there is a notable increase in the combustion rate and overpressure leading evident acceleration of the flame. The simulation result shows that the overpressure and flame speed are in good agreement with the experimental results. Deviation observed may be attributed to the omission of heat transfer considerations at the duct wall.

### 3. Results and discussion

#### 3.1 Explosion pressure characteristics

Figure 4a illustrates the overpressure curves of the ignition monitor under three single vent positions. The overpressure rate following the opening of vent01 is lower compared with the other two conditions, attributed to the pressure relief effect of vent01. When vent03 is positioned at the duct end, the maximum overpressure rise rate exceeds that of the other two cases. Peak overpressure consistently occurs when the combustible gas mixture within the duct remains partially unconsumed, irrespective of the vent's location. The position of the vent influences the peak overpressure, which is related to the change of venting efficiency. Altering the position of a single vent leads to a uniform distribution of explosion overpressure at various locations inside duct, as depicted in Fig. 4b. The disparity in overpressure at distinct locations within the pipeline is small, and the overpressure in the far-field direction of the vent initially increases and then declines. When the vent is situated at a considerable distance from the ignition, the internal explosion overpressure will continue to accumulate, resulting in more significant overpressure at different locations within the duct. In contrast, the proximity of the vent to the ignition allows the explosion to be released in the initial phase, which permits a considerable amount of explosive energy to be released through the side vents [23].

The peak internal explosion overpressure is 43.1, 78.5, and 93.1 kPa when the vent is moved from 75 mm to 250 and 475 mm from the ignition. The vent closer to the ignition significantly reduces the internal pressure, and the quantity of external combustible gases is less, so the external space is less likely to produce a large explosion overpressure. When the vent is situated far from the ignition, more combustible gases are expelled from the duct, resulting in a larger external volume of combustible gases. Consequently, the secondary explosion is more violent [25]. The peak external overpressure increases to 2.37 times as the vent moves from the ignition to a position further away. The external dynamic pressure changes significantly with the change of vent position. The external dynamic pressure is small under vent01 condition, because the internal and external pressure difference is small in this working condition, and the flame's pushing effect on the external air flow is small. The utilization of vent03 increases the internal pressure within the duct, which in turn accelerates the combustion of the gases in the duct to expel from the duct, thereby creating a larger dynamic pressure peak on the external space.

Two vents situated at a greater distance from the ignition result in less effective pressure relief as compared to using two-stage explosion venting, as shown in Fig. 5. In the condition of vent0102, a higher external explosive overpressure occurs at vent02, which is due to the fact that vent01 allows for the release of less combustible gases to the outside, and an external explosion outside vent01 occurs when the internal overpressure is lower. Conversely, when an external explosion occurs outside vent02, there is more external combustible gas and a higher internal overpressure released to the external space. The least effective pressure relief effect is observed when vent0203 is employed, with the peak explosive overpressure in the duct reaching a value that is 1.56 times greater than that observed under vent0102 conditions. The utilization of the vent0203 configuration can result in the generation of a heightened external explosion overpressure due to the concurrent occurrence of two factors: first, the elevated explosion overpressure that is generated within the duct and subsequently released to the external environment; and second, the presence of a greater quantity of the combustible gas mixture situated outside the duct, which is involved in the secondary explosion. In this case, the maximum external explosion overpressure is 1.26 times higher than under the condition of vent0102. The internal overpressure at different locations is found to be lower than that observed under the double and single vent conditions as the number of vents increased to three, resulting in the most effective explosion venting effect. In vent010203 condition, although vent02 can also generate a large external explosion overpressure, the vent01 pressure relief effect reduces the internal overpressure, thereby weakening the internal contribution to external overpressure. In the case of two vents, the external dynamic pressure increases as the vent away from ignition. When the number of vents increases to 3, the efficiency of explosion venting is greater, and the external peak dynamic pressure is smaller. In conclusion, the optimal configuration for single-stage explosion venting is setting the vent as close as possible to the ignition. This configuration allows for the reduction of overpressure and external dynamic pressure. The use of multi-stage explosion venting indicates that the increasing vents numbers strengthens the explosion venting effect. The vent should also be arranged near the ignition as far as possible as the number of vents is certain.

#### 3.2 Dynamic analysis of flame evolution

The flame has already spread downstream the vent by the time the vent opens in the vent01 configuration, as shown in Fig. 6.

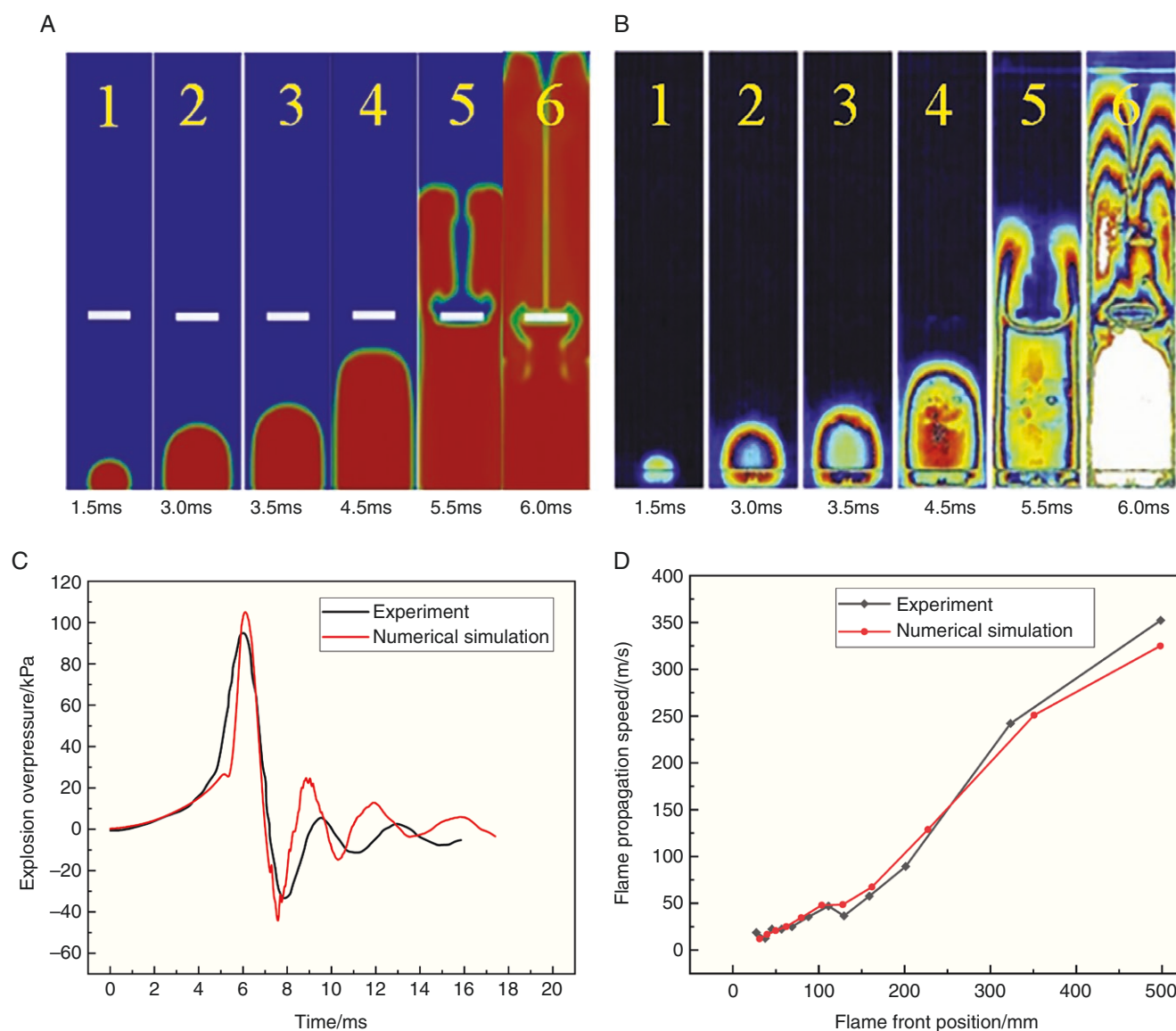


**Figure 3.** Flame shape, explosion overpressure, and flame speed.

Therefore, the flame passes with no significant change in morphology for a period. However, the capacity to transform a spherical flame into a finger-shaped flame is significantly diminished by the fact that the flame has already been sprayed out at the initial stage. The suction effect of the vent results in an asymmetrical flame front in both the axial and transverse directions [24]. The flame is relieved to a more regular finger flame under vent02 condition before it passes through the vent. Upon passing through the open vent, the localized unburned gas near the vent is heated, intensifying the turbulence effect, promoting the mixing of the high-temperature flame with combustible gas [50]. The flame front is deflected to one side of the vent passing the vent, while the flame on the side away from the vent propagates forward under the effect of explosive expansion due to the suction effect caused by the side vents, allowing the airflow near the vent flowing faster than the airflow elsewhere in the duct. When vent03 is situated at the duct end, the explosive expansion and reflected waves of end-wall pressure influence the flame propagation. Consequently, the flame front is subjected to continual compression until the flame is ejected from the duct. In single or

multiple pressure vent configurations, the flame within the duct exhibits a variety of shapes, including finger-like shapes, offset types, and flat plate-like forms. When the vent is close to the ignition, the flame can pass through the vent and into the external space, which reduces the quantity of external hydrogen and external explosion overpressure. When the vent is situated at a distant location, the flame expels more hydrogen gas from the duct, thereby triggering an external explosion. The flame is projected from the pipeline when the external combustible gas mixture is ignited, formation shape of irregular flame clouds. The external flame assumes the form of an elongated jet once the external gas has burned out. As multiple vents located away from ignition end, more hydrogen gas is expelled from the duct. The external hydrogen within the explosion range continues consumed as explosion reaction continues.

The flame front is assumed to represent the process variable 0.5. When a single vent is utilized for explosion venting, the maximum external flame length increases progressively as the distance of the vent from the ignition increases, as shown in Fig. 7. This is because in both the vent01 and vent02 cases, the gas

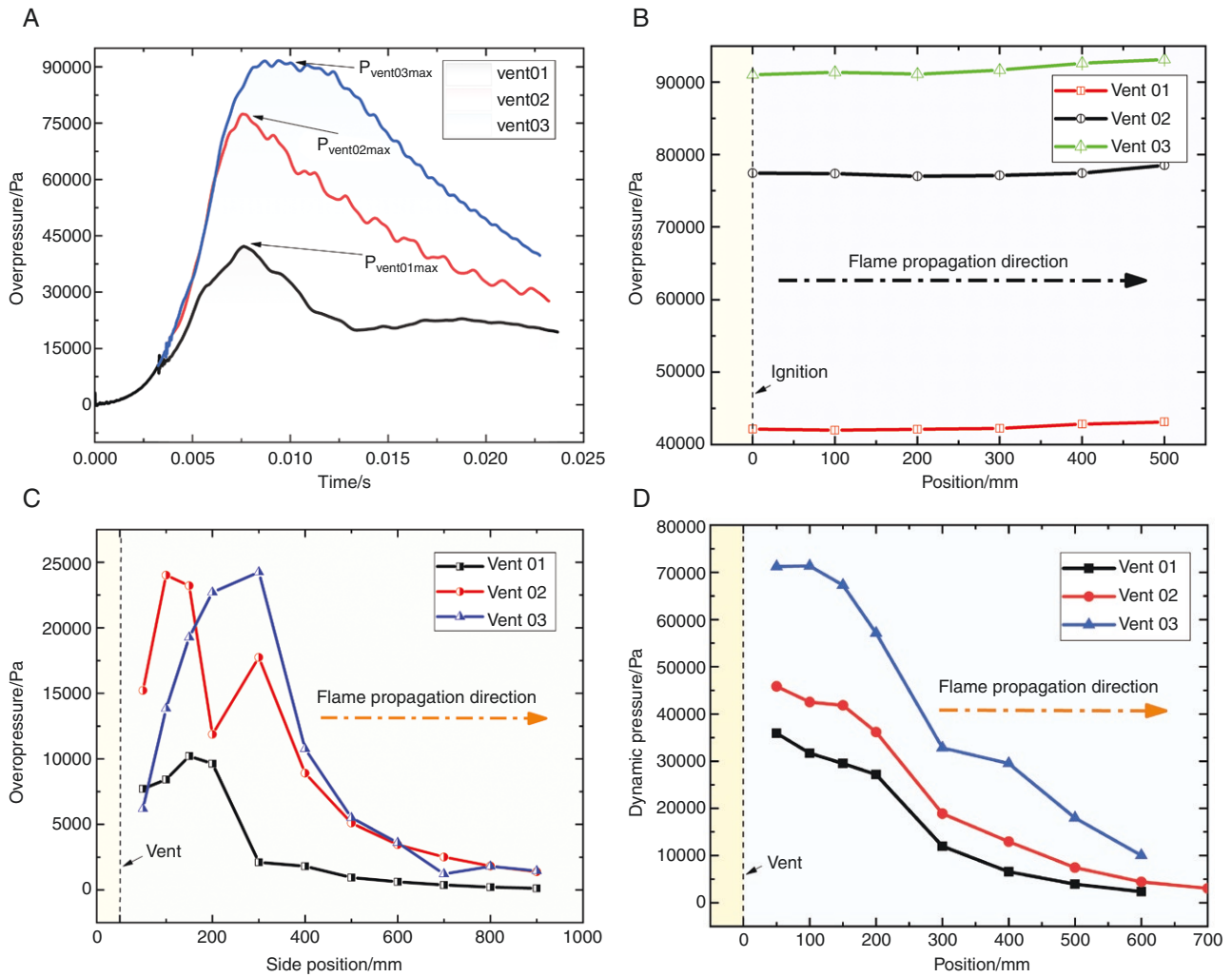


**Figure 4.** Explosion pressure under three single vent conditions.

at the flame front is continuously compressed as the flame advances through the duct beyond the vent, although the pushing effect on the external flame diminishes. In the case of vent03, the vent is situated along the direction of flame propagation for an extended distance, resulting in the external flame traveling a longer distance due to the thrust of the internal fluid [22]. When two vents are used, the farther the two vents are away from the ignition, the greater the external flame length. For example, the flame length at vent03 under vent0103 working condition is greater than that at vent 02 under vent0102 condition, and the flame length at vent01 under vent0103 condition is higher than that at vent01 under vent0102 condition. This is because under the vent0103 condition, vent03 plays a role in promoting the propagation of the internal flame and explosion development for a longer period of time, making the flame release to the external space more actively, rather than stagnating in the duct for a long time. When the number of vents is increased to three, the flame exits the duct through all three vents, thereby reducing the maximum flame length through each vent.

### 3.3 Flow field characteristic in explosion venting

In the condition of a single vent, the position of the vent has similar impact on the distribution of the external flow field. The flame is rolled and sucked into the external atmosphere, forming

a number of vortex zones as it propagates in the external space. As the flame is ejected through more vents, the flame disturbance to the external flow field is similar to other conditions. The flame exhibits a spherical shape before the vent opening, and the streamlines in the duct are parallel to the axis direction. The area near the vent generates large pressure and velocity gradients after the vent opening. This results in the formation of a suction effect on the internal fluid, which causes the combustible gases in the duct to be expelled from the duct. In the case of vent01, the flame has already propagated downstream the vent in a finger-shaped form before the vent opening. Consequently, the vent's suction effect does not significantly affect the flame's form when it passes near the vent. However, as the flame propagates forward, the role of the vent becomes more significant. It is mainly reflected in the appearance of the reverse flow field in the duct section of the combusted region, which is opposite to the flame propagation direction, as shown in 10.6 ms of Fig. 8a. The simultaneous existence of positive and negative flow fields in the burned and unburned areas leads to the appearance of a vortex-like flow field characteristic at the flame front near the vent, as shown in 16 ms of Fig. 8a and 10.1 ms of Fig. 8b, which results in the suppression of flame propagation on the side close to the vent and the promotion of flame propagation on the side far from the vent. Consequently, the flame front is distorted. In

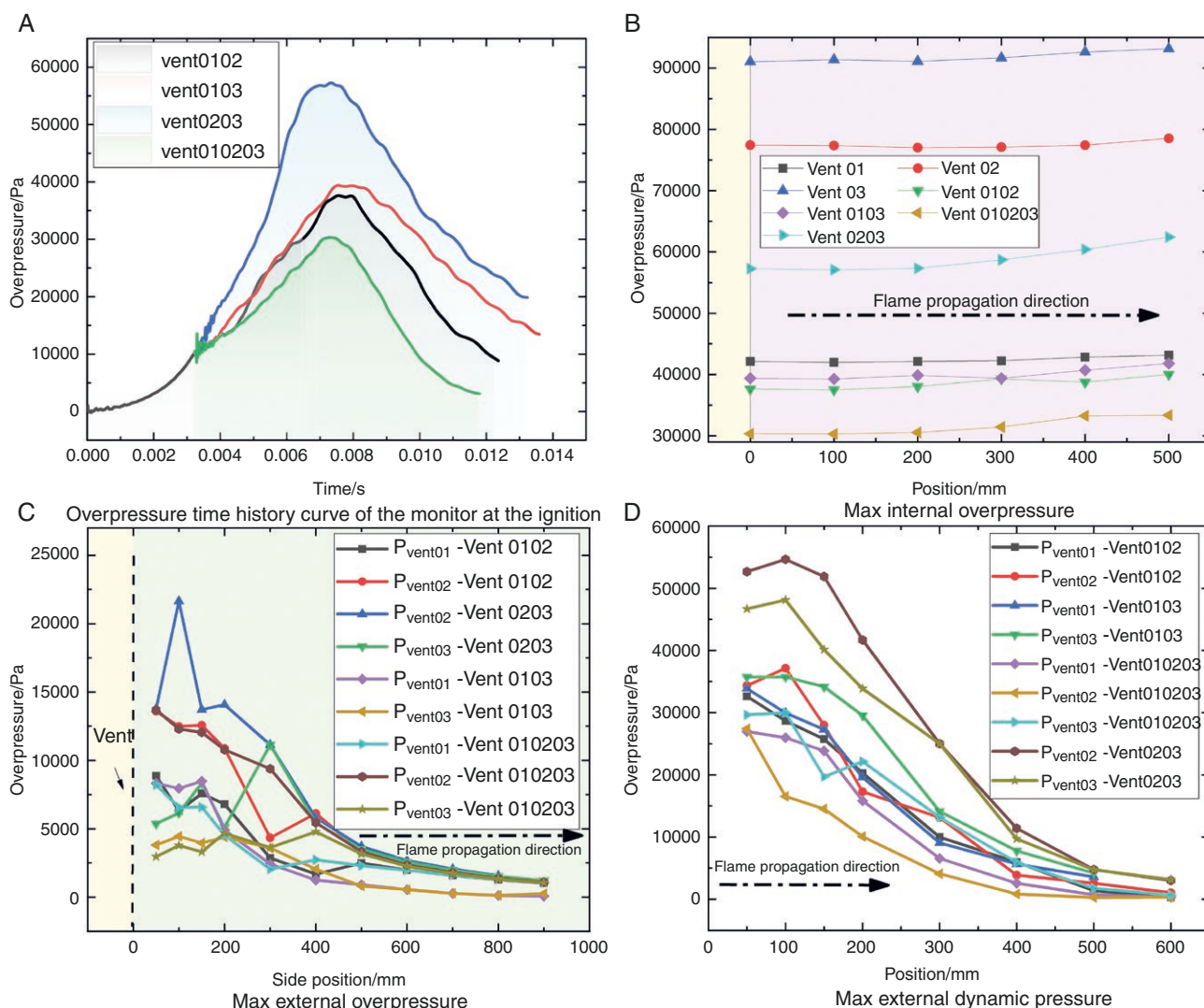


Figure 5. Explosion pressure under four multiple vent conditions.

contrast to the vent01 case, the flame does not pass through the vent immediately as it opens under the condition of vent02. Instead, it maintains its finger shape and propagates forward for a certain distance. The streamlines near the vent point in the direction of the vent, indicating that the area inside the duct near the vent is ejected out of the duct by the suction effect of the vent. As the flame approaches and the vent, the suction effect of the vent exerts a more pronounced influence on the flame morphology, resulting in a shift of the flame front to the side of the vent. This phenomenon is also observed in the vent03 case, as evidenced by 7.1 ms of Fig. 8b and 11.1 ms of Fig. 8c. A constant change in the flow field between forward and reverse directions also occurs obviously under the condition of vent01 and vent02. The flow field distribution within the duct becomes more complex in the vent02 condition than in the vent01 condition as the flame propagates to the middle and back sections of the duct. Distinct sections of the duct may form a multitude of minute vortex areas in both vent01 and vent02 conditions. The flame must propagate a greater distance to pass through the vent in the vent03 configuration. When the flame propagates near the middle of the duct, a symmetrical vortex region is formed at the flame front, as shown in vent03 at 8.6 ms. This phenomenon is

caused by the reflection of the pressure waves from the closed end of the duct. This flow field feature is observed exclusively when the vent is situated at the end of the duct, resulting in the continuous compression of the flame front from a finger shape. Combined with the flow field diagram, flame shape, and explosion pressure analysis, it can be seen that changing vent positions leads to an internal reverse flow field in different positions. Under the vent01 condition, an internal reverse flow field is generated after the flame passes through the vent at the initial explosion stage. However, an internal reverse flow field appears only when the flame spreads to the end duct under the vent03 condition. In addition, the change of flow field distribution caused by the vent position also affects the flame propagation. The flame is distorted and propagated backward under the action of the reverse flow field after it passes through the vent in the vent01 condition, and its propagation position also lags behind that of the vent02 and vent03 conditions. The non-uniformity of the flame structure further leads to the increase of the disorder of the flow field distribution. The reverse flow field has the strongest inhibition effect on flame propagation under vent01 condition, the reverse flow field and backpropagation of the flame slows down the explosion development and reduces the peak overpressure.

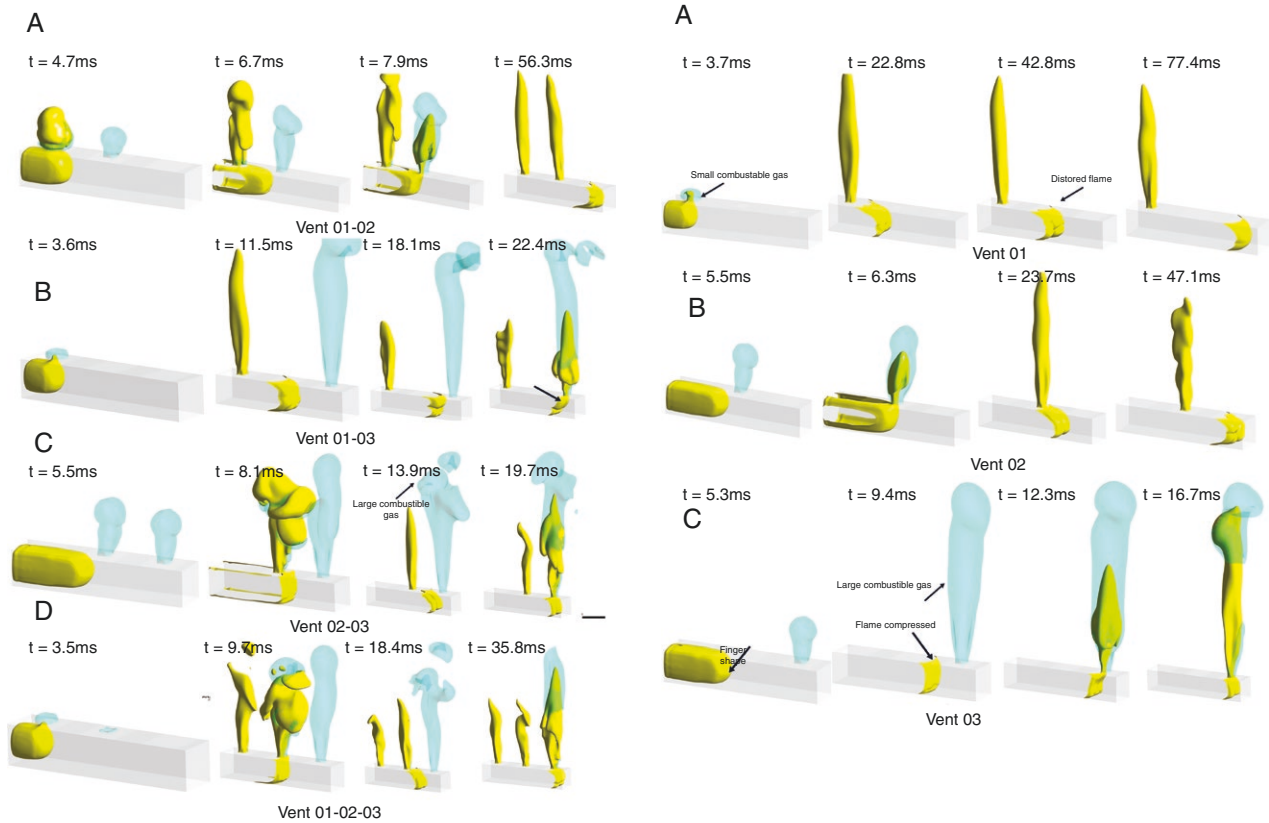


**Figure 6.** Flame shape and combustible gas mixture iso-surface under different vent position (The yellow part is the flame front, and the blue part is the combustible gas.).

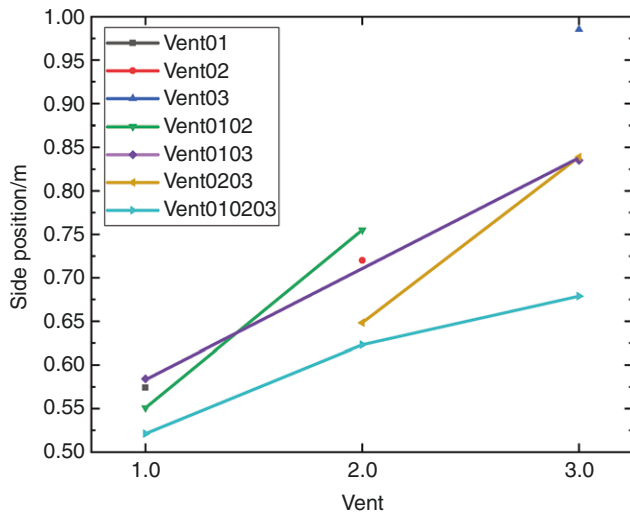


**Figure 7.** Flame length under different vent position and numbers.

The arrangement of vent0102 results in a more turbulent distribution of the flow field in the duct than that observed in the vent01 condition. As the flame passes through vent 01 but not through vent02, vent01 exerts an inhibitory effect on flame propagation, whereas vent02 exerts a promotional effect. As the flame passes through vent02, both vents inhibit flame propagation. In the conditions of vent0102, vent0203, and vent010203, an evident flow field characteristic analogous to the vortex region is generated in the unburned region when the flame is ejected from the vent, impeding the flame propagation in close proximity to

the vent side and promoting the flame propagation in close proximity to the wall side, as shown in 25.8 ms of Fig. 9a, 11.4 ms in Fig. 9b and 11.6 ms of Fig. 9c. The regular flow field distribution is more regular in vent0103 and does not form a complex vortex zone compared with other cases with multiple vents. However, the compression deformation of the flame fronts is the largest in the middle and back sections of the duct in the cases of vent0102 and vent0103. In the case of vent0203, the internal flow field distribution is regular when the flame propagates in the first half of the duct, and the finger flame maintains for the longest time in this case. The internal flow field regions with varying directions generate after the flame passes through the middle of the duct under the combined effects of vent02 and vent03.

The suction effect of the vent will lead to a reverse flow field in the burned area as the vent arranged in vent01, the reverse flow field produces a reverse pull on the flame front, which leads to stagnation and reverse propagation of the flame near the vent. As shown in Fig. 10, the flame speed velocity decreases and appears negative [50]. Although the flame front continues to propagate forward, the inhibition effect of the reverse flow field reduces flame propagation velocity, as illustrated in the velocity diagram. When vent02 is utilized in the middle of the duct, the flame undergoes a longer acceleration period and attains a greater velocity peak when passing through the vent. However, the pressure wave accumulated from the explosion in the duct exerts a force on the flame to propagate forward. Consequently, the inhibition effect of the reflected waves on the flame propagation is less pronounced than that of vent01. When the vent is relocated to vent03, the propagation of the flame to the middle and rear sections is influenced by the formation of

a flame vortex and reflected pressure wave. This phenomenon results in the flattening of the flame front, which subsequently facilitates the propagation of the flame to the middle section at a first velocity peak. The streamlines of the unburned side maintain a directionality towards the vent and play a role in promoting the flame propagation. The flame propagates at the leading edge in all conditions, regardless of the single or multiple vents. When the flame propagates to the rear section, it reaches a second peak velocity under the traction of the vent and pushes the unburned gas out of the duct at a high velocity, which also leads to a more violent external explosion. The peak flame velocity in the vent03 case is approximately 2.1 times that of the vent01 case.

The addition of vent02 weakens vent01's suppression effect compared with vent01. This is evidenced by the flame traveling forward at a faster speed than in the vent01 condition. After the flame passes through vent02, the flame also appears to propagate in the opposite direction, which lasts for approximately 5 ms. The peak propagation velocity is greater than that of vent01, but due to vent01's restriction, it is smaller than that of vent02. In vent0103, the flame does not appear to propagate in the opposite direction. As illustrated in the preceding flow field diagram, the streamlines in the pipe consistently point in the direction of flame propagation after the flame passes through vent01, which is attributed to the promotion effect of vent03. The flame reaches its first peak velocity as it propagates to the middle of the duct under the

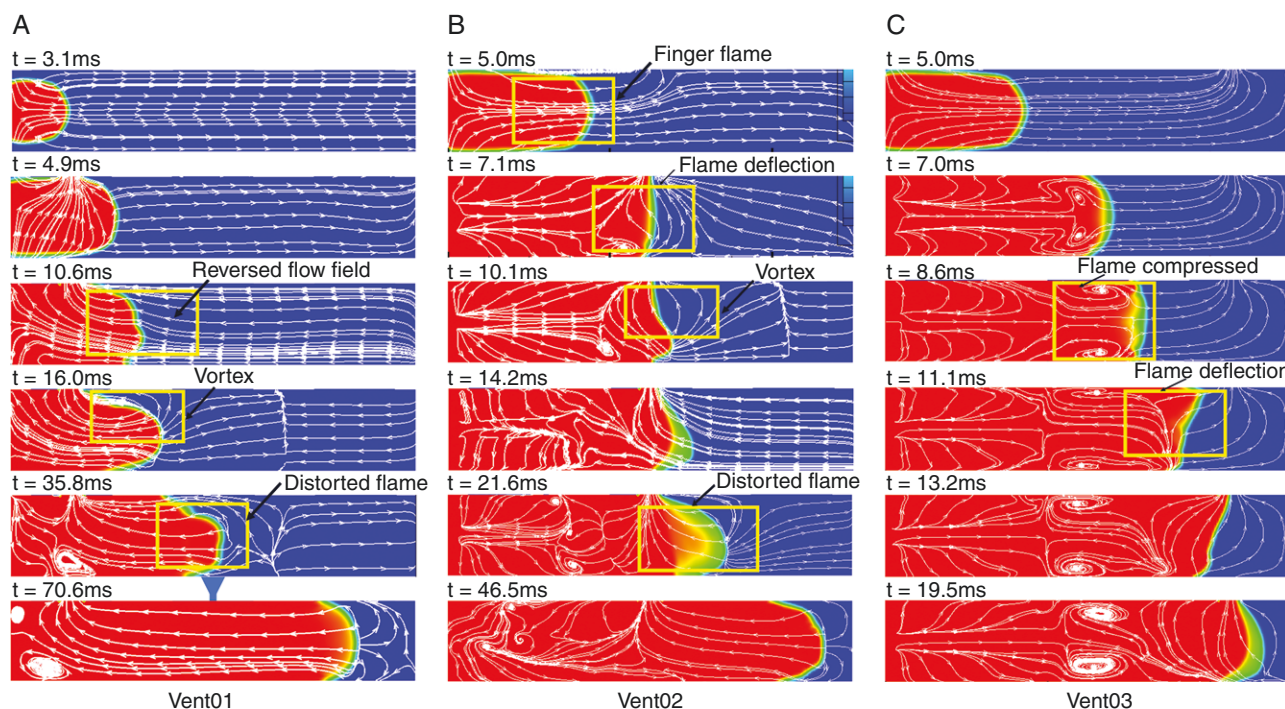


Figure 8. Streamlines diagram at different single vent condition.

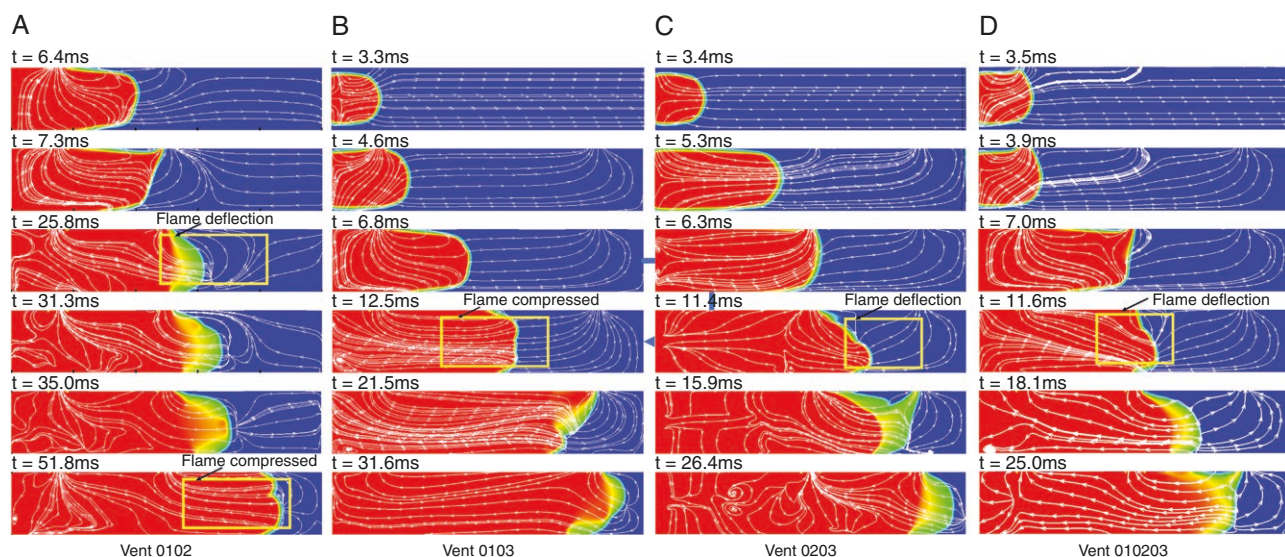


Figure 9. Streamlines diagram at different multiple vent condition.

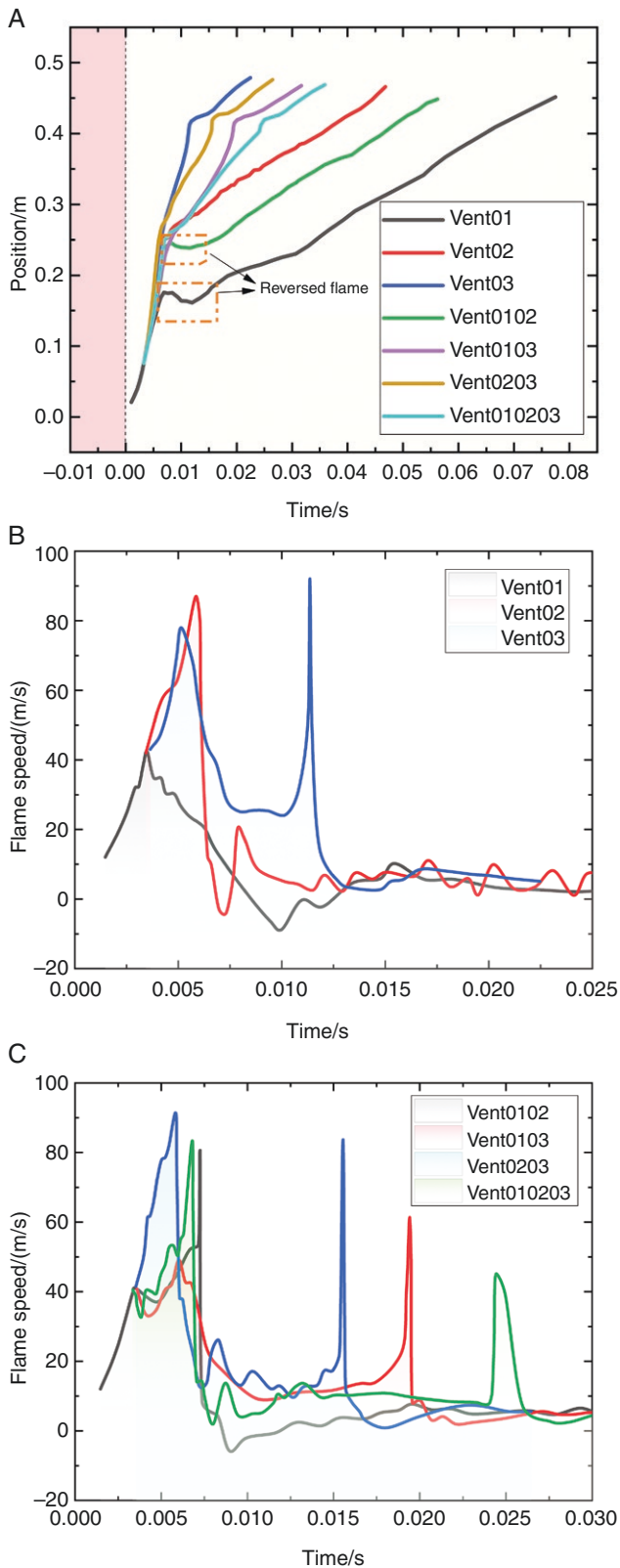


**Figure 10.** Flame position and speed under different vent conditions.

coupling effect of the explosion expansion, pressure venting, and end-wall pressure wave reflection. When the flame propagates to vent03, the flame propagation speed reaches a second peak. Both vent02 and vent03 promote the flame in the vent0203 condition, resulting in a more advanced flame propagation position than in

the other double vent cases. The flame reaches its peak velocity at both vent02 and vent03. The flow field diagram indicates that vent02 exerts an inhibitory effect on flame propagation, resulting in a lag in the flame propagation position after passing through the vent02 compared with the condition of vent03. Both vent0203, vent 0103 and vent010203 conditions can produce a velocity peak at vent03. The peak speed reduces with the increased number of vents and the distance from the ignition. The moment of reaching the peak velocity also gradually lags. In conclusion, in the case of multiple vents, the largest flame propagation velocity is produced under the case of vent0203. The smallest flame speed occurs in the case of vent0103. The peak flame velocity under vent0203 condition is 11.15 times that of vent0103.

The internal turbulence intensity firstly increases from the ignition end and expands as the flame propagates in accordance with the vent01 condition. As the flame propagates forward, the expansion of the burned region increases the turbulence intensity in more regions of the duct. Regions of greater turbulence intensity in the duct are located near the vent and the ignition, as illustrated in 37.8 ms and 51.3 ms of Fig. 11a under vent01 condition. The turbulence intensity expands from the middle of the duct to the two sides of the duct in the vent02 condition. The degree of internal turbulence is greater than that in the case of vent01 when the flame propagates to the end of the duct, as shown in 46.1 ms Fig. 11b under the vent02 condition. In the case of vent03, when the flame propagates to the end, the turbulence intensity is centered around the vent at the end of the pipe and the vortex zone at the front of the flame, as shown in 22.1 ms of Fig. 11c under the vent03 condition. The degree of turbulence in the vent01 case is less than that observed in the other two single vent cases. In comparison to the vent01 configuration, the presence of vent02 in the vent0102 condition primarily increases turbulence intensity within the first half of the duct. In contrast, with the vent0103 configuration, the effect of vent03 is mainly reflected in the higher turbulence intensity near the vent when the flame propagates to the vent03. However, the turbulence intensity in the middle section of the pipe does not change significantly due to the presence of vent03. A comparison of the working conditions of vent0203 and vent03 conditions reveals that the addition of vent02 significantly enhances the turbulence intensity in the middle of the pipe. In the case of single or multiple vents, the streamline and turbulence intensity diagrams analysis reveal that the regions with higher turbulence intensity are concentrated in areas with large pressure and velocity gradients, such as the vents, as well as in regions with complex streamline distributions including the vortex region.

The vent01 working condition results in a larger vortex near the vent, which is attributed to the significant change in pressure and velocity gradient observed in the inner and outer space. The vortex is larger at the flame front and in the region near the duct wall on both sides of the flame. As the combusted area expands and the flow field becomes increasingly disordered, the vortex gradually extends in the direction of flame propagation. The vortex exhibits a notable increase in size from the center of the duct and extends to both sides when the vent is relocated to the center of the duct. The large vortex near the vent enhances the flame's mixing with the combustible gas, thereby accelerating the combustion rate, indicating that the vent's arrangement significantly impacts the development of vortices in the duct. Vortices are observed in the flow field inside the duct in both vent01 and vent02 conditions, and the vortices in these zones are particularly large, as shown in 71.6 and 8.2 ms of Fig. 12a. In contrast to the aforementioned conditions, when the vent is located at vent03, a more

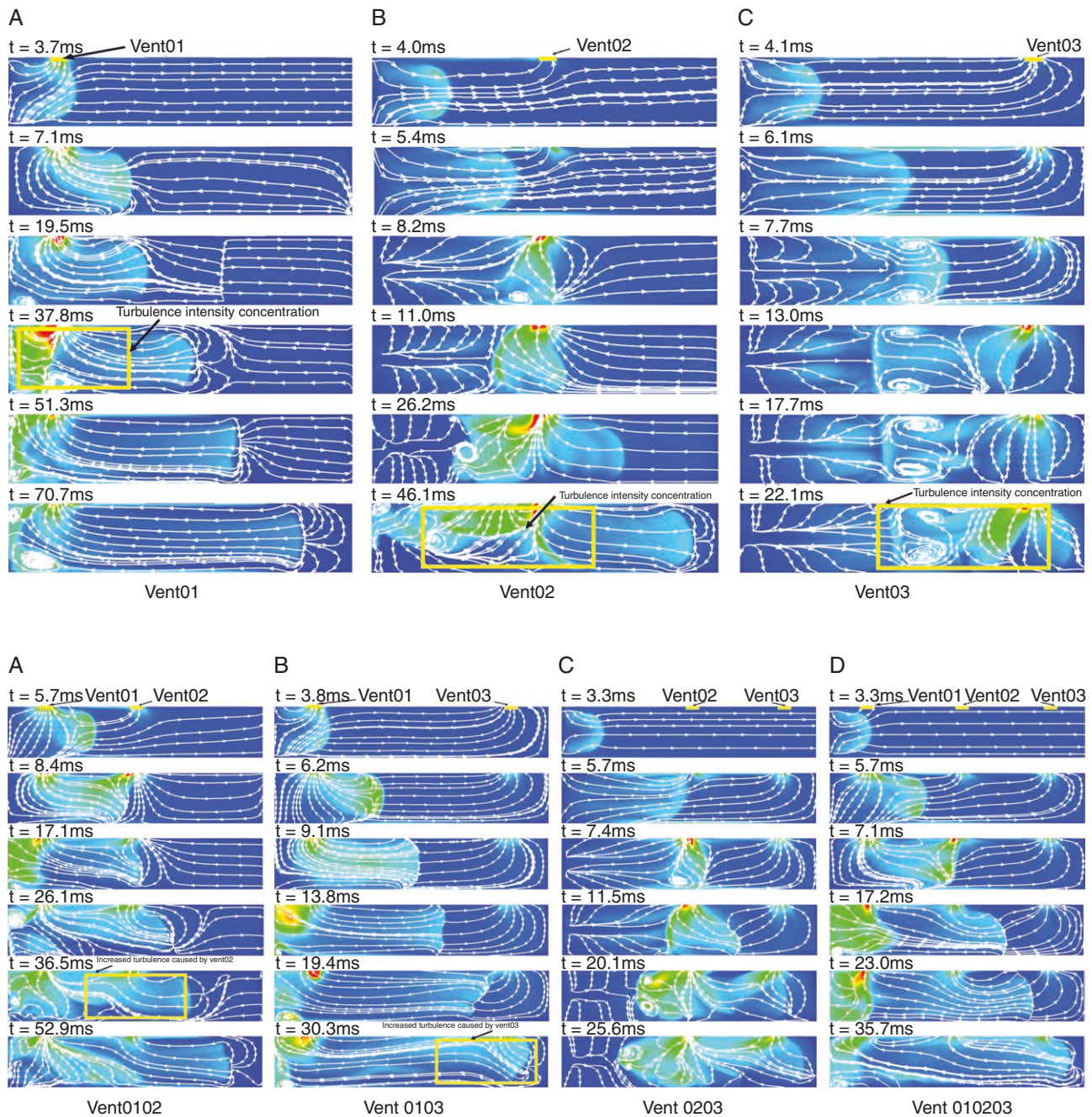


**Figure 11.** The turbulent intensity under different vent conditions.

expansive and symmetrical vortex zone is established within the flame as it spreads towards the middle duct. The expansion speed of the vortex is more rapid in vent0102 compared with the condition of vent01. The vortex grows to the mid-rear section of the duct at 51.5 ms in the vent01 case, whereas there is already a larger vortex distribution in the mid-rear duct at 26.1 ms in vent0102. In both vent0103 and vent0102 conditions, a long-lasting vortex is created in the duct near the ignition, and the vorticity is larger in this zone. The vortex grows in the middle and rear section of the duct and extends to the front side in the case of vent0203. However, in the case of vent010203, it can be observed that large vortices are present at all three vents. This phenomenon accelerates the release of flame, unburned gas and pressure from the internal space to the external space.

## 4. Conclusion

- (1) Internal peak overpressure at different locations is little different under single vent conditions, and the better vent efficiency is achieved when the vent is closer to the ignition. The accumulation of internal explosion overpressure increases as the vent is located farther from the ignition; when the vent is located at the end of the duct, peak internal explosion overpressure is 2.1 times that when the vent is located near the ignition. The pushing effect of the internal flame on the outside fluid enhances as the vent is closer to the end, inducing a larger volume combustible gas and external pressure. As the design of double

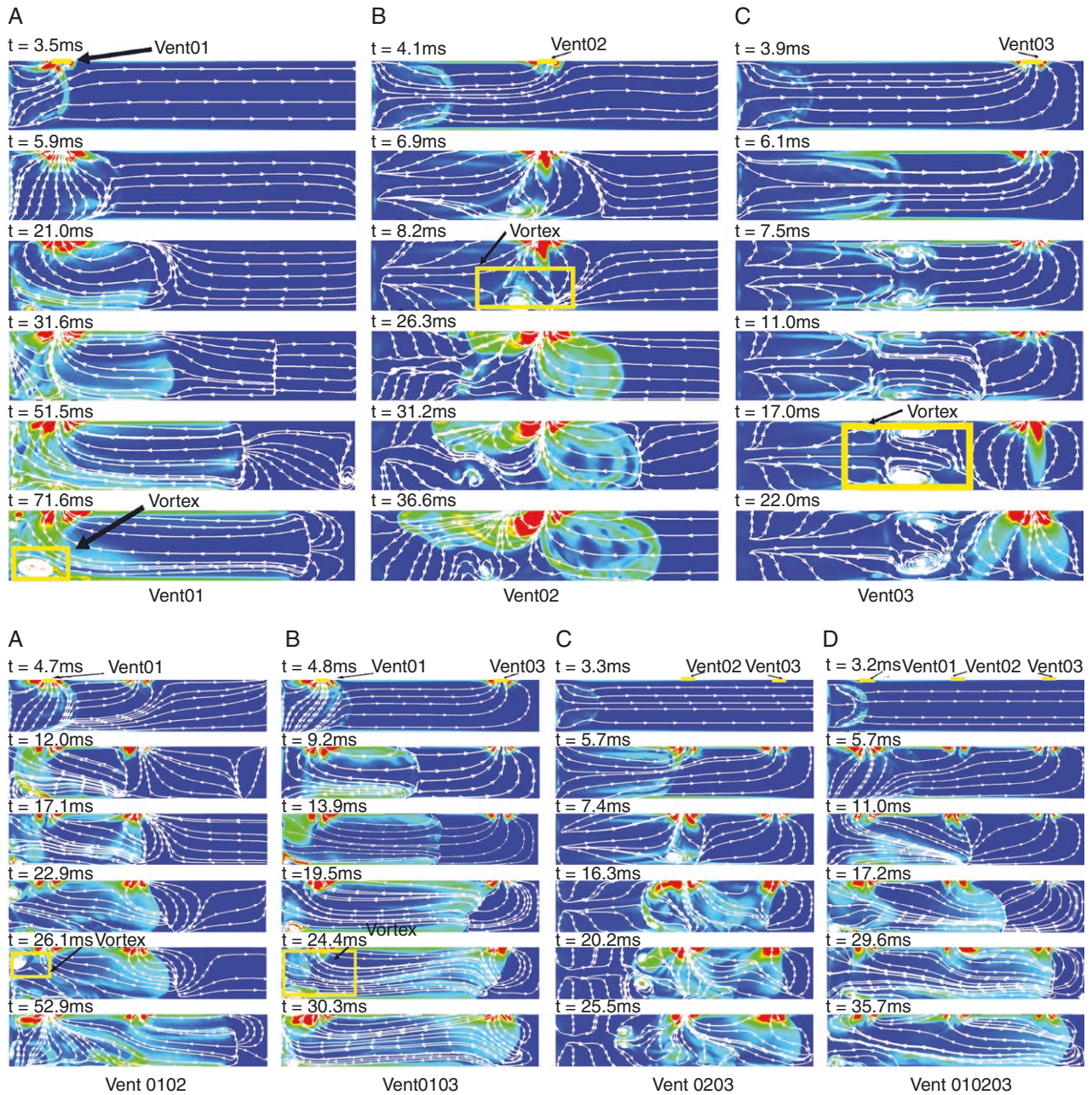


**Figure 12.** The vorticity magnitude under different vent conditions.

vents is adopted, the vents closer to the ignition enhance the venting efficiency. The release of internal high pressure and a large amount of external combustible gas lead to larger explosion overpressure and dynamic pressure in the external space under the working condition of vent0203. Fluid and can be expelled from more vents when employing three vents, thus resulting in the optimal venting efficiency under this condition.

- (2) The flame shape changes following the opening of the vent under the condition of the vent closer to the ignition. Conversely, the flame maintains a finger-shaped propagation for a longer time when the vent is arranged in the center of the duct. When the vent is situated at the end of the duct, the reflected pressure waves from the end wall generate a symmetric vortex region within the flame front

as the flame propagates towards the middle and back of the duct, which induces the compression and deformation of the flame. The coupling effect of combustion expansion and vent inhibition result in an internal reverse flow field that inhibits flame propagation, and even cause the flame to propagate in the reverse direction, which leads to a decrease in the flame speed. This phenomenon is more significant as the vent located near the vent. The vortex zone near the vent impedes the flame propagation in the vent side, while simultaneously promoting the flame propagation in the opposite side of the vent, resulting in the distortion of the flame. When the vents are positioned at the middle or end of the duct, the internal flame can maintain a finger-like shape for a longer duration under conditions with multiple vents. The arrangement and number

of vents have no discernible effect on the external shape of the flame, which exhibits a jet-like configuration. The flame speed reaches its peak value upon reaching the vent. The peak flame speed increases as the distance between the ignition source and the vent greater. The flame speed approximately increases to 2.1 times when the vent relocated from the ignition to the duct end. Peak flame propagation speed occurs under the condition of multiple vents, and the flame speed increases as vents are located away from the ignition. The arrangement and number of vents have no discernible effect on the external flame form, which exhibits a jet-like configuration.

- (3) Various factors such as rapid expansion and velocity shear layers contribute to the generation of significant vorticity near the vent following the high-speed discharge of gas. When the vent located near the ignition, the turbulence intensity propagates forward with the propagation of the flame. When the vent is situated at the end of the duct, the turbulence intensity expands from the end of the duct to the ignition. The level of turbulence intensity decreases when the vent is located closer to the ignition after the complete consumption of internal combustible gas.

## Author contributions

Han Sun (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Software [equal], Validation [equal], Writing—original draft [equal], Writing—review & editing [equal]), Guogang Yang (Funding acquisition [equal], Resources [equal], Supervision [equal]), Zhonghua Sheng (Resources [equal], Supervision [equal], Validation [equal]), Zhuangzhuang Xu (Formal analysis [equal], Methodology [equal], Resources [equal]), Xiaoxing Yang (Data curation [equal], Supervision [equal]), and Shengzheng Ji (Conceptualization [equal])

## Conflict of interest of statement

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data available on request.

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