Numerical Study on the Internal Flow Field of Air-breathing PDE with Central Cone-scales Valve

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Abstract: The paper derives the unstructured triangular grid CE/SE method to describe the changing process of internal flow field for an air-breathing Pulse Detonation Engine(PDE) with central cone-scales valve(CCSV) in detail. The paper also presents a numerical study on the valve. The research results indicate that the calculated rising edge of detonation wave in an air-breathing PDE with CCSV is steep, while the change laws of its peak pressure and pressure curve are in agreement with the experimental results, which proves that the unstructured triangular grid CE/SE method with source terms can be successfully applied to the calculation of internal flow field of air-breathing PDE with CCSV. Meanwhile, the change rule of pressure flow field in pipe is obtained through the analysis of pressure contour, which agrees with the experimental process.

Keywords: Air-breathing Pulse Detonation Engine(PDE); Central Cone-scales Valve(CCSV); CE/SE Method; Internal Flow Field; Deflagration to Detonation Transition(DDT)

1. Introduction

The Pulse Detonation Engine (PDE) is a new concept engine which uses the pulse detonation wave to produce thrust. It has the advantages of high thermal cycle efficiency and simple structure. In recent years, the PDE has attracted increasing interest from researchers at home and abroad [1-3]. Aiming at the periodic working characteristics of air-breathing PDE, a central cone-scales valve (CCSV) applied to air-breathing PDE was designed, and it was proven through the experimental verification that the CCSV had good one-way valve performance and backflow prevention in the literatures [4,5]. However, the pressure of the engine can be measured only at a few points due to the limited number of sensors available. Hence, it is a challenge to meticulously describe the detailed changing process of internal flow field in pipe using experimental data alone. As a result, the space-time conservation element and solution element method (CE/SE method) [6] was proposed by Chang, an American NASA scientist, in 1995, by which time and space were uniformly handled. It is a computational format with powerful capacity of capturing strong discontinuities, which emerge in the field of computational fluid mechanics. Based on the method of Chang, Wang [7] and Fu [8] et al put forward the division CE/SE method for unstructured grid, and the problem of grid limitation of CE/SE method was solved. Considering the complex geometrical structure of CCSV, this paper intends to adopt the unstructured triangular grid CE/SE method to carry out the numerical study on the internal flow field of air-breathing PDE with CCSV. Since the working process of air-breathing PDE is extremely complex, the atomizing and mixing processes of fuel oil, as well as the influence of combustion-enhancing apparatus in the detonation chamber, are ignored in the numerical simulation.

2. The Oretical Model of Air-breathing PDE with CCSV

The axial symmetry calculation model of air-breathing PDE with CCSV is shown in Fig. 1. The computational domain of internal flow field of detonation in the model is ABCDEFGHIJK. Inside, the area enclosed by BCD is the CCSV. AE is the central axis of symmetry, while AK is the inlet of air-breathing PDE, and EF is the outlet of air-breathing PDE. The overall length of air-breathing PDE is AE=0.92m, while the length of detonation chamber is GF=0.8m, and the radius is EF=0.04m.

2.1. The governing equation of axial symmetry two-phase detonation

According to the simplification and assumption in literature [9], the axial symmetry governing equation of air-breathing PDE with CCSV can be obtained as follows [8,9]:

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=R-\alpha\frac{H}{y} \tag{1}$$

For the meaning of each symbol in the equation, please see the details in literature [10].

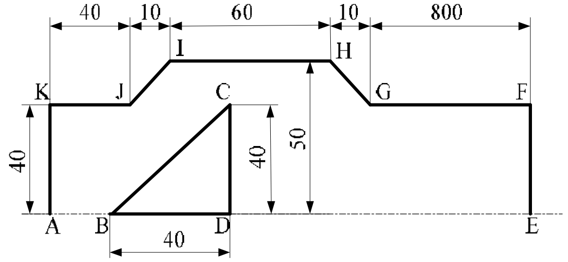


Figure 1. The axial symmetry calculation model of air-breathing PDE with CCSV

2.2. The CE/SE method of unstructured triangular grid

Based on the method of Chang, this paper derived the unstructured triangular grid CE/SE method with source terms which was applicable to the calculation of two-phase internal flow field of air-breathing PDE with CCSV[7,10].

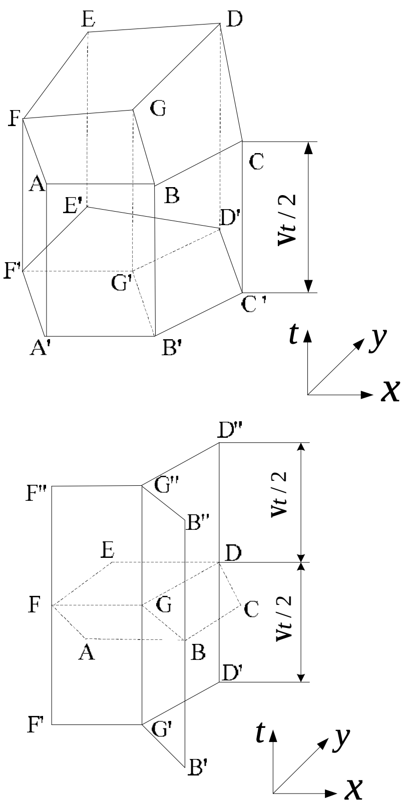


Figure 2. The conservation elements and solution elements of unstructured triangular grid CE/SE method

Conservation elements and solution elements in the unstructured triangular grid CE/SE method are defined in Fig.2. Let ABCDEF be the moment of t^n and A'B'C'D'E'F' be the moment of $t^{n-1/2}$. At the moment of t^n, the conservation elements of CE1(j,n), CE2(j,n) and CE3(j,n) corresponding to the point G(j,n) are the quadrangular prisms of ABGFA'B'G'F', BCDGB'C'D'G' and DEFGD'E'F'G', respectively, while the corresponding solution elements of SE(j,n) are G'G''B''B', G'G''D''D', G'G''F''F' and ABCDEF.

According to the thought of Chang in which time and space are uniformly handled [6], Equation (1) after integration is expressed by discrete flux, and the conservation equation of discrete quantity is solved on each conservation element shown in Fig.2. Then, the computational format of unstructured triangular grid CE/SE method is obtained. The details can be found in literature [10]. Inside, the two unknown terms U_x and U_y are solved by using differential reconstruction method [10].

2.3. Initial value conditions, boundary conditions and treatment of source terms

The initial conditions for the calculation are: air temperature is 293K, pressure is 0.1MPa, and airflow velocity in pipe is 0m/s. Meanwhile, total pressure of incoming flow Pin=0.115MPa, total temperature of incoming flow 305K, and density 1.204kg·m-3 are given. Under the function of incoming flow, the air inflow of air-breathing PDE is started till steady state i.e. (a stable airflow velocity is reached) is achieved in the pipe. Once the airflow velocity in the pipe is reached steady state, it can be regarded that the liquid drops of gasoline are uniformly full of pipe at the moment, and the radius of liquid drop is 50μm.

The computational boundary conditions are: the boundary condition of wall glide reflection and the axial symmetry boundary condition are adopted for the walls and the symmetric axis, respectively. During the intake process, the CCSV valve is opened. After the intake process is finished and the CCSV is closed, the boundary condition of wall reflection is used. Meanwhile, the non-reflecting free boundary condition is adopted for the outlet of detonation pipe.

The ignition condition is: one high-temperature and high-pressure ignition area is preset on the central axis located 0.12m away downstream from the inlet of air-breathing PDE.

The treatment of source terms is: the fourth-order Runge-Kutta method is adopted to handle the rigid source terms in this paper.

3. Calculation Results and Analysis

Fig.3 is the resulting curve pressure versus time of experiment and numerical calculation at the center point of the tail of air-breathing PDE. The peak pressure of detonation wave obtained by the numerical calculation is 1.976MPa, while the rising edge of detonation wave is steep and the value is 5.7μs. It explains that the strong discontinuities like detonation wave can be well captured by using this unstructured triangular grid CE/SE method. For air-breathing PDE with CCSV that share the same inner diameter, the peak pressure of detonation wave obtained by the experiment is 2.079MPa when the equivalent ratio is 1, which is close to the result of numerical calculation with the error of 5.2%. By comparing the two pressure curves in Fig.3, it can be seen that the variation trends of pressure curve obtained by the experiment and numerical calculation are similar. Since the factors of turbulent flow, resistance of wall surface and complex conditions during the experiment are not considered in the numerical calculation, any complex fluctuation situation of pressure curve does not appear in the experiment.

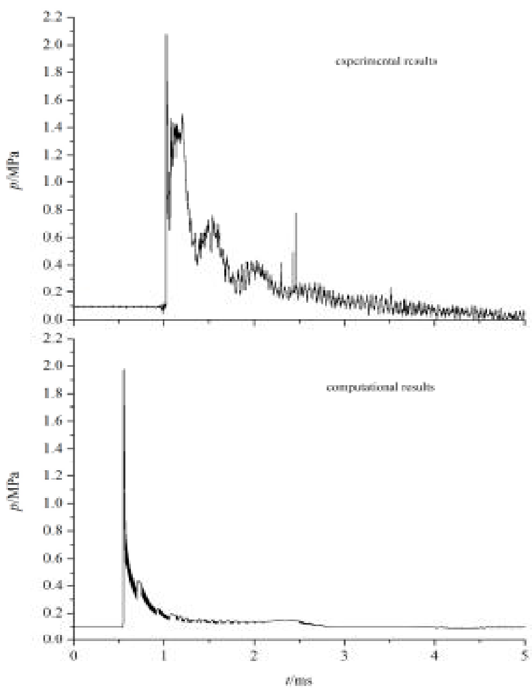


Figure 3. Results of experiment and numerical calculation showing the pressure-time change curve at center point of tail of air-breathing PDE

The distance between the thrust wall and the left inlet of air-breathing PDE is 0.08m, and the distance between the ignition position and the thrust wall is 0.04m, which are shown in Fig.1. Fig.4 is the change curve of pressure with x axis on the central axis of air-breathing PDE with CCSV at different time. In this paper, the pressure peak at center point of the tail of air-breathing PDE is defined as the stable pressure peak of detonation wave. When the pressure peak at some location on the central axis reaches 98% that of stable pressure peak of detonation wave, and its following pressure peaks all fluctuate within this range, this location is the formation position of detonation wave. The time from the time ignition is started till the detonation wave reaches this position is the ignition-detonation time tig-det, and the distance from the ignition position to this position is the detonation distance Sig-det. It is shown in Fig.4 that: as time goes on, the pressure peak in the detonation pipe continuously rises. At t=0.388ms, the peak pressure of pressure curve on the central axis is 1.939MPa. It is 98.1% that of the stable pressure peak(1.976MPa) of detonation wave, and the following peak pressures of pressure curve all fluctuate within the range of 1.939-1.976MPa. Thus, it can be regarded that the stable detonation wave has been formed at this moment, and the propagation velocity of detonation wave is 1445.4m·s-1. According to the above-mentioned definition, the ignition-detonation time tig-det is 0.388ms, and the ignition-detonation distance Sig-det is 0.564m.

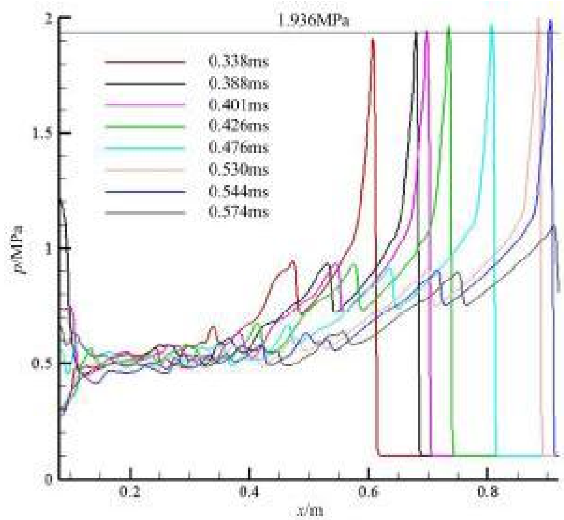
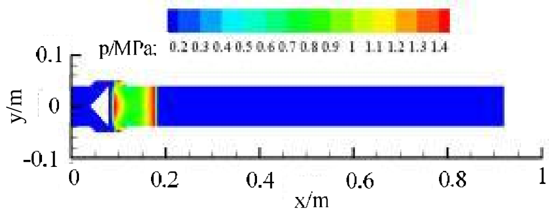


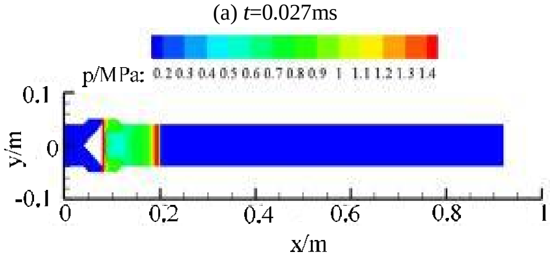
Figure 4. Change curve of pressure with x axis on the central axis of air-breathing PDE with CCSV at different time

Figure 5 is the contour of pressure in pipe of air-breathing PDE with CCSV at different time. At t=0.027ms, a leading shock wave is generated after the initial two-phase mixing, working medium is ignited, and the wave separately propagates in either upstream or downstream directions of air-breathing PDE, which is shown in Fig.5(a). At t=0.041ms, the leading shock wave propagating to the upstream direction of air-breathing PDE reaches the location of thrust wall, and enhances the pressure around the thrust wall. At this moment, the CCSV is closed, and a totally enclosed thrust wall is formed, which is shown in Fig.5(b). At the moment of 0.388ms, it is seen by combining Fig.4 and Fig.5(c) that:

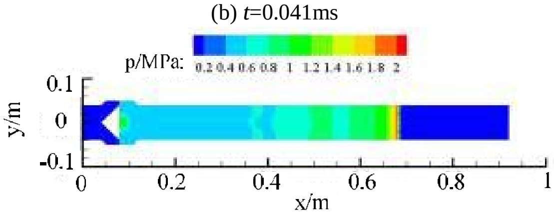
the stable detonation wave starts to be formed at the location 0.604m from the thrust wall in pipe of air-breathing PDE, while the peak pressure of detonation wave is 1.939MPa, and the propagation velocity is 1445.4m·s-1. At the moment of 0.544ms, the detonation wave propagates to the location 0.830m from the thrust wall, and is about to propagate out of the tail of detonation pipe, which is shown in Fig.4 and Fig.5(d). At the moment of 0.574ms, the detonation wave has propagated out of the detonation pipe. Meanwhile, a series of expansion waves generated in the tail start to pass into the detonation pipe and propagate to the tail so that the pressure in the detonation pipe is lowered, which is shown in Fig.4 and Fig.5(e). At t=5.439ms, the exhaust process is ended. The pressure in pipe of air-breathing PDE is lower than the total pressure of incoming flow, and the CCSV is opened so that the fresh air is passed into the air-breathing PDE, which is shown in Fig.5(f)



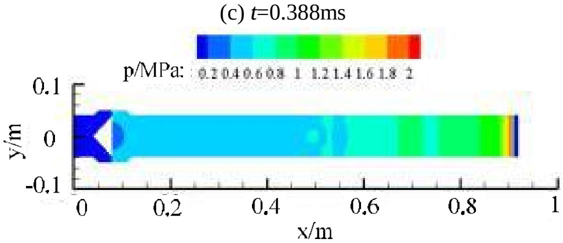
(a) t=0.027ms



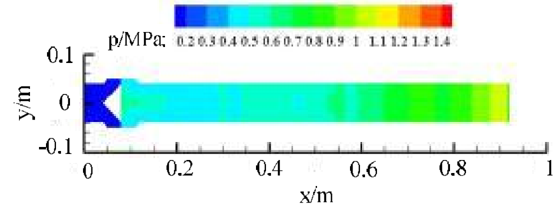
(b) t=0.041ms



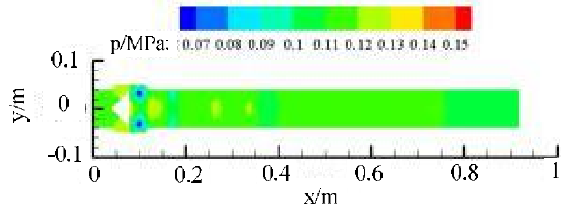
(c) t=0.388ms



(d) t=0.544ms



(e) t=0.574ms



(f) t=5.439ms

Figure 5. Contour of pressure in pipe of air-breathing PDE with CCSV at different time

It is seen by combining Fig.4 and Fig.5 that: as the initial two-phase mixing working medium of air-breathing PDE with CCSV is ignited, the compression waves propagating upstream and downstream in air-breathing PDE are generated. As a result, the pressure around the thrust wall is increased, so the CCSV is closed and a totally enclosed thrust wall is formed. After the detonation wave propagates out from the detonation pipe, a series of expansion waves pass into the detonation pipe, and the pressure in the detonation pipe is gradually reduced. When the pressure in pipe is lower than the total pressure of incoming flow, the CCSV is opened, and the incoming flow passes into the air-breathing PDE so that the next cycle is started, which is consistent with the experimental process of air-breathing PDE with CCSV.

4 . Conclusions

This paper derives the unstructured triangular grid CE/SE method which is applicable for calculating the internal flow field of air-breathing PDE with CCSV, and develops the programs to carry out the numerical study on the internal flow field of air-breathing PDE with CCSV. The research results are as follows:

The calculated rising edge of detonation wave in an air-breathing PDE with CCSV is steep, and the variation trends of its pressure peak and curve are basically coincident with the experimental results. It proves that it is successful in applying the unstructured triangular grid CE/SE method with source terms to the calculation of internal flow field of air-breathing PDE with central cone-scales valve.

It is shown from the calculated contour of pressure in pipe of air-breathing PDE with CCSV different time instances that: as the initial two-phase mixing working medium of air-breathing PDE is ignited, the compression waves separately propagate in either upstream or downstream directions of air-breathing PDE, and the pressure around the thrust wall is increased, so the CCSV is closed and a totally enclosed thrust wall is formed. After the detonation wave propagates out of the detonation pipe, a series of expansion waves pass into the detonation pipe, and the pressure in the detonation pipe is gradually reduced. When the pressure in pipe is lower than the total pressure of incoming flow, the CCSV is opened, and the incoming flow passes into the air-breathing PDE so that the next cycle is started, which is consistent with the experimental process.

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