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Study on the effects of ionization seeds on pulse detonation characteristics

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ABSTRACT

Ionization phenomenon is happened on the wave front due to the presence of high temperature and pressure in the detonation process. Plasma produced in the detonation process can be used as magnetohydrodynamic (MHD) generator or flow controlled by the external magnetic field. However, it is necessary to increase the ionization efficiency by adding metal ions with lower ionization potential owing to the limited amount of plasma produced by detonation. In this paper, a model of pulse detonation engine with ionization seeds was established. The Conservation Element and Solution Element (CE/SE) method was deduced to simulate the interaction between plasma and detonation process. The influence of ionization seed contents on the electrical conductivity and detonation characteristic parameters was analyzed, and the MHD control of detonation process was realized by adding the external electromagnetic field device. The results showed that it had a little influence on the detonation process but a great influence on the generation of detonation plasma by the addition of a certain amount of ionized seed. The ion mass fraction and electrical conductivity in the detonation tube were first increased and then decreased with the increase of ionization seed content, which reached the maximum at the ionization seed mass fraction of 0.05. The acceleration and deceleration process could be achieved by the MHD control.

1. Introduction

The pulse detonation engine (PDE) is an engine which uses the high temperature and high pressure gas generated by the pulse detonation wave [1–4]. Detonation is burning induced by the shock wave, which relied on shock compression to transmit energy. It has high energy efficiency and great thrust output owing to the detonation process can be approximately equal to constant volume combustion. In recent years, the related research work of PDE has been carried out by many scientific research institutions, but it has a lot of challenges to realize the engineering application of PDE.

Magnetic fluid acceleration technology with the process of artificial ionization technology as a wide application prospects in the field of aeronautics and astronautics, which is still in the exploratory stage to applied to the pulse detonation engine. Research indicates that the thrust of pulse detonation engine can be improved by magnetohydrodynamic (MHD) augmentation [5]. However, the core technology of MHD acceleration is the ionization of air low so that it is important to study the ionization of gas in the detonation process. An experimental study on the acceleration of magnetic fluid in arc shock tube is carried out by NASA Research Center, in which potassium carbonate power is injected to increase the electrical conductivity. Temperature and ionization seed concentration are measured by potassium spectrum, and conductivity is measured using a suspended voltage probe [6]. Different amounts of cesium seeds are added to study the interactions of magnetic field and detonation by Lord Kahil Cole [7]. Numerical study of the electrical conductivity in ionized gas mixtures produced by detonation is investigated in mixtures with and without potassium seeding by J.C. Schulz [8]. Simulations show that the detonation is sensitive to the amount of seeds injected into the flow. The detonation propagation is adversely affected by too high of the seed percentage, while the ions are increased with the increase of seed content within a certain range.

It is necessary to increase the electrical conductivity by adding metal ions with lower ionization potential owing to the limited amount of plasma produced by detonation. Therefore, to study the effect of different ionization seed contents on pulse detonation characteristics, a model of the pulse detonation engine with ionization seeds was established in this paper. An appropriate approach of Conservation Element and Solution Element (CE/SE) method was

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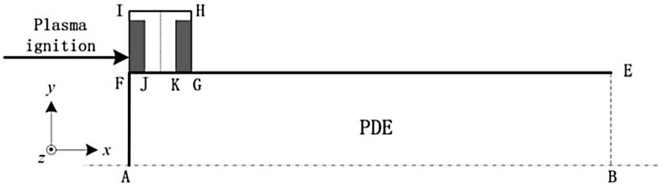

Fig. 1. Diagram of PDE with plasma jet ignition.

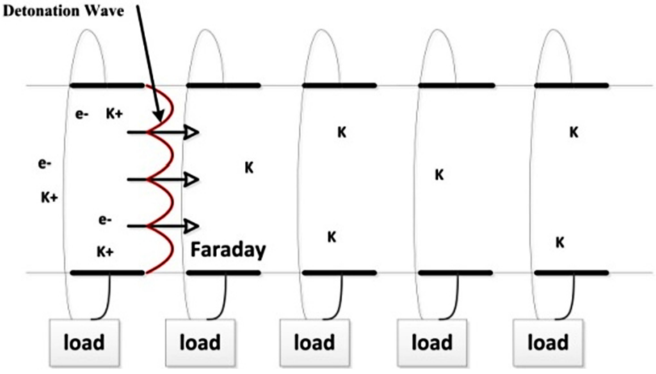

Fig. 2. Configuration of detonation chamber with an applied magnetic field.

attempted and deduced to calculate 2D detonation process with ionization seeds, which involved the coupling of hydrodynamics and magnetohydrodynamics.

2. Model and governing equations

2.1. Computational model

The diagram of PDE with plasma jet ignition is shown in Fig. 1. Since the stream of PDE is axisymmetric, it is appropriate to calculate rotary surface using two-dimensional model. The regions surrounded by ABEF, FGHI, indicate the PDE tube, plasma generator, respectively. AF, JK, BE, AB are thrust wall, plasma jet entrance, tube exit, the central axis of axisymmetric, respectively. The length EF = 1 m, radius AF = 0.04 m. And the structure mesh number is 1000 × 40.

The lighted gas mixtures burn in the form of deflagration once the pulse detonation engine starts the ignition, and the temperature and pressure rise rapidly. Stable detonation waves are formed when a series of compression waves reflected from the closed end and catch up with the compression wave on the open end.

Fig. 2 shows a configuration of the pulse detonation engine with ionized seed in the detonation tube under the applied magnetic field. The ionized material in the detonation tube is ionized under the action of high temperature, and circuit is formed by the ionized matter and applied electric field. The ion can be accelerated or decelerated under the action of the external magnetic field so as to realize the control of detonation process.

2.2. Governing equations of the pulse detonation engine with K seed

In order to simplify the process of the gas/liquid two-phase detonation with potassium (K) seed, it is assumed [9] that 1) the gas/liquid two-phase detonation is axisymmetric; 2) the interaction among droplets can be ignored; 3) each droplet does not break and keeps sphere while the detonation propagates; 4) the heat exchange between the wall of PDE and outside is neglected; 5) the export parameters of plasma generator are used as the entrance parameters of the ignition of pulse detonation engine. Based on the assumptions above, the following equations are the combination of the model from literature [7] and [9].

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

$$\boldsymbol{U}=\begin{bmatrix}\phi_g\rho_g\\ \phi_l\rho_l\\ \phi_g\rho_g u_g\\ \phi_g\rho_g v_g\\ \phi_l\rho_l u_l\\ \phi_l\rho_l v_l\\ \phi_g\rho_g E_g\\ \phi_l\rho_l E_l\\ \phi_g\rho_g Y_K\\ \phi_g\rho_g Y_{K+}\end{bmatrix},\quad \boldsymbol{F}=\begin{bmatrix}\phi_g\rho_g u_g\\ \phi_l\rho_l u_l\\ \phi_g(\rho_g u_g^2+p)\\ \phi_g\rho_g u_g v_g\\ \phi_l(\rho_l u_l^2+p)\\ \phi_l\rho_l u_l v_l\\ \phi_g u_g(\rho_g E_g+p)\\ \phi_l u_l(\rho_l E_l+p)\\ \phi_g\rho_g u_g Y_K\\ \phi_g\rho_g u_g Y_{K+}\end{bmatrix}$$

$$\boldsymbol{G}=\begin{bmatrix}\phi_g\rho_g v_g\\ \phi_l\rho_l v_l\\ \phi_g\rho_g u_g v_g\\ \phi_g(\rho_g v_g^2+p)\\ \phi_l\rho_l u_l v_l\\ \phi_l(\rho_l v_l^2+p)\\ \phi_g v_g(\rho_g E_g+p)\\ \phi_l v_l(\rho_l E_l+p)\\ \phi_g\rho_g v_g Y_K\\ \phi_g\rho_g v_g Y_{K+}\end{bmatrix},\quad \boldsymbol{H}=\begin{bmatrix}\phi_g\rho_g v_g\\ \phi_l\rho_l v_l\\ \phi_g\rho_g u_g v_g\\ \phi_g\rho_g v_g^2\\ \phi_l\rho_l u_l v_l\\ \phi_l\rho_l v_l^2\\ \phi_g v_g(\rho_g E_g+p)\\ \phi_l v_l(\rho_l E_l+p)\\ \phi_g\rho_g v_g Y_K\\ \phi_g\rho_g v_g Y_{K+}\end{bmatrix}$$

$$\boldsymbol{R}=\begin{bmatrix}I_d\\ -I_d\\ I_d u_l-F_{dx}\\ I_d v_l-F_{dy}\\ -I_d u_l+F_{dx}\\ -I_d v_l+F_{dy}\\ -Q_d+Q_c-(F_{dx}u_l+F_{dy}v_l)+I_d(E_l+p/\rho_l)\\ Q_d+(F_{dx}u_l+F_{dy}v_l)-I_d(E_l+p/\rho_l)\\ 0\\ 0\end{bmatrix}$$

$$\boldsymbol{S}=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\\ \dot{\Omega}_K\\ \dot{\Omega}_{K+}\end{bmatrix},\quad \boldsymbol{M}=\begin{bmatrix}0\\ (\boldsymbol{J}\times\boldsymbol{B})_x\\ (\boldsymbol{J}\times\boldsymbol{B})_y\\ \boldsymbol{J}\cdot\boldsymbol{E}\\ 0\\ 0\\ 0\\ 0\\ 0\\ 0\end{bmatrix}$$

where the subscripts g and l indicate the gas phase and liquid phase, respectively; Φ_g and Φ_l are the volume fraction of gas phase and liquid phase ($\Phi_g+\Phi_l=1$); p and ρ are the density and pressure, respectively; u and v are the axial velocity and radial velocity. Y_K, Y_{K+} are respectively the mass fraction of potassium and potassium ions.

The total energy E is defined as the sum of the internal energy and the kinetic energy, and it can be calculated as follows:

$$E=\frac{p}{\rho(\gamma-1)}+\frac{u^2+v^2}{2}+qY_{K+} \tag{2}$$