Optimization of the PDE operating regime

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1 Introduction and formulation of the problem

The interest that appeared to be arisen recently to problems of calculation of flows with propagating detonation waves could be explained by possible applications of obtained solutions at designing detonation engines that are quite perspective for propulsion. Since the detonation generates thrust on the walls of engine, then the question arises, whether it is possible to improve performance of such engine by defining special form of the walls. The given work examines pulse detonation engine (PDE) with axisymmetric nozzle form described by one arbitrary function. While calculating the flow in the channel the full two-dimensional non-steady pattern of the flow behind the detonation wave, distribution of velocity, density and pressure depending on coordinates and time is studied. Dependence of the average impulse and average specific impulse generated by the flow behind the detonation wave on the form of the channel is investigated. The aim of the investigation is to find optimal geometry of the channel that maximizes the thrust characteristics of pulse detonation engine.

The axisymmetric channel previously filled by detonating mixture is considered (Fig. 1). The axis of symmetry is marked x, the distance to the x-axis is marked r. The initiated detonation wave propagates through the mixture and the flow behind the wave generates thrust. The channel has a closed end of fixed radius and the detonation wave is initiated near its whole surface and moves from left to right. The thrust is generated on the closed end of the channel and on the lateral wall. The form of the channel wall is given by function $f(x)$ which can be chosen from some wide class, e.g. class of linear or parabolic functions.

It's proposed that the detonation wave reaction zone has width much less than the channel diameter and, thus, we can rely on the model of infinitely thin detonation wave.

The flow behind the detonation wave is described by the system of Euler equations

$$
\begin{aligned}
\frac{\partial(\rho r)}{\partial t} + \frac{\partial(\rho u r)}{\partial x} + \frac{\partial(\rho v r)}{\partial r} &= 0, \\
\frac{\partial(\rho u r)}{\partial t} + \frac{\partial[(p+\rho u^2) r]}{\partial x} + \frac{\partial(\rho u v r)}{\partial r} &= 0, \\
\frac{\partial(\rho v r)}{\partial t} + \frac{\partial(\rho u v r)}{\partial x} + \frac{\partial[(p+\rho v^2) r]}{\partial r} &= p, \\
\frac{\partial(e r)}{\partial t} + \frac{\partial[(e+p) u r]}{\partial x} + \frac{\partial[(e+p) v r]}{\partial r} &= 0, \\
e = \rho\left(\varepsilon + \frac{u^2+v^2}{2}\right),\ \varepsilon = \frac{p}{(\gamma-1)\rho}&.
\end{aligned}
\tag{1}
$$

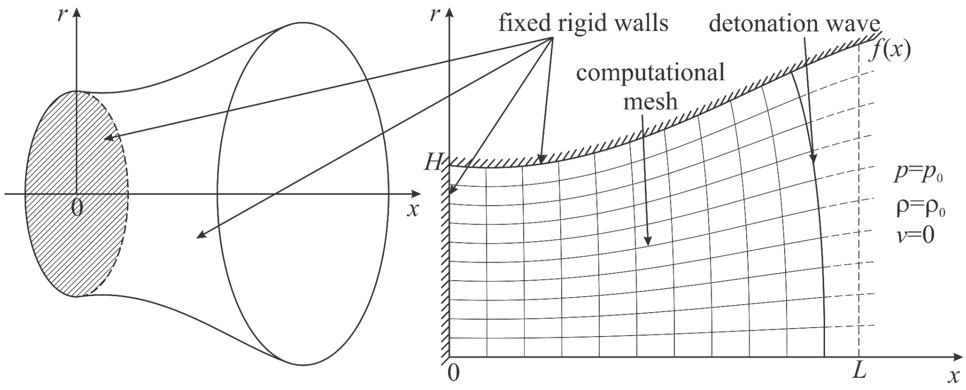

Figure 1: Channel geometry. Detonation wave propagates from left to right.

2 Calculation method

Godunov 2-D calculation method has been modified to correctly compute flows with infinitely thin detonation waves. 2-D calculations have been applied to calculate flows in axisymmetric channels with various wall forms. Model of infinitely thin detonation wave allows to perform numerical calculations of unsteady flows quite fast. It means that we have the possibility to vary form of the wall and to get thrust characteristics for every selected form quite quickly. The optimal forms of walls corresponding to the maximum of average impulse and average specific impulse have been found.

Fig. 2 shows the visualisation of pressure distribution obtained in typical calculation. The computational mesh stretches according to detonation wave propagation. Special calculation procedure has been developed for the purpose of getting appropriate form of the detonation wave.

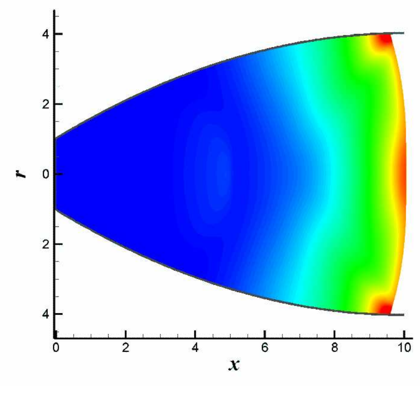

Figure 2: Pressure distribution.

The detonation wave is not considered a priori the Chapman-Jouguet wave. Overcompressed detonation wave is realized in convergent nozzles (Fig. 3).

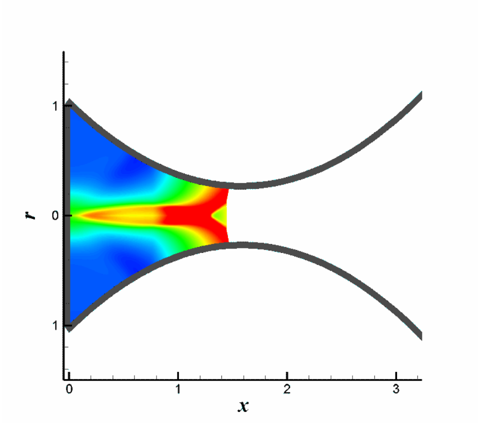

Figure 3: Pressure distribution in convergent nozzle.

3 Results of thrust characteristics maximization

In case of conic wall with length much greater than radius of the closed end the flow is close to asymptotic self-similar solution behind spherical detonation wave. This solution has been investigated for dependence on half-angle of the cone. The half-angle of conic wall corresponding to the maximum of average impulse with fixed burned mass of the mixture has been found.

It has been shown in 2-D numerical calculations that conic wall is not optimal. Chosen from wide classes of functions, optimal forms of the wall corresponding to the maximum of average impulse and average specific impulse have been found (Fig. 4).

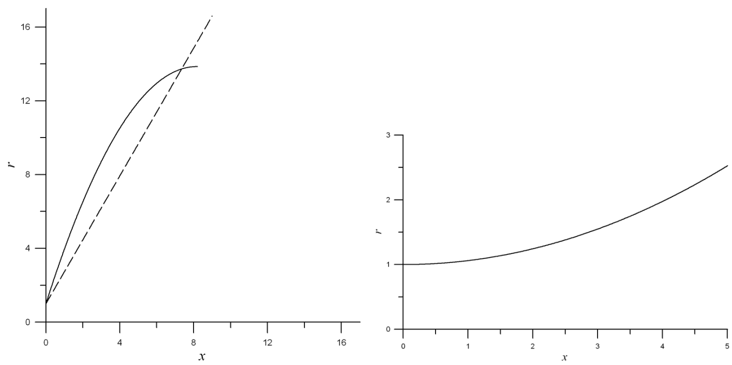

Figure 4: Channel wall forms corresponding to the maximum average impulse (left) and average specific impulse (right).

The developed calculation procedure has shown its ability to calculate quickly gas-dynamic flows with detonation wave and made it possible to perform optimization of PDE.

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