Rotating Detonation Wave Stability

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Abstract

In this paper the analysis of stability of rotating detonation wave in cylindrical channel is discussed. On the bases of comparison of the time of revolution of detonation wave around the cylindrical chamber to the time of new mixture formation, stability of detonation front as well as a numbers of rotating detonation heads can be predicted. Dimensionless parameter, so called detonation wave number “**W**” is proposed. The evaluation of this detonation wave number can allow prediction of stability of propagating rotating detonation wave as well and the prediction of the numbers of rotating detonation heads in cylindrical chamber.

Introduction

The stability of detonation wave is a problem discussed from the early beginning of discovery of detonation processes. Campbell and Woodhead [1] was first who discover spinning detonation wave and Voitsekhovskii, Mitrofanov and Topchiyan [2] first described in details complex structure of gaseous detonation. Many research were also carried out on the evaluation of critical parameter which allow transition of detonation between deferent channels as well as into open space. Recently research are focused on establishment of continuously rotating detonation wave(s) in cylindrical chambers [3-5]. Such research are related to the possibility of application of continuously rotating detonation wave to jet propulsion, especially into rocket, turbojet and ramjet propulsion. In this paper the problem of stability of such detonation is discussed.

Formulation of the problem

For application of the continuously rotating detonation wave into jet engines it is necessary to initiate rotating denomination wave in cylindrical chamber. Schematic diagram of such chamber is shown in Fig.1. In such case fuel and oxidizer is injected from one end through numbers of regularly arranged small holes and slit and detonation is traveling in a clockwise (or counterclockwise) direction. Detonation products flow toward the other end and can be discharged through a diverging nozzle at supersonic speed or drive a turbine stage which can propel fan or compressor. To explore this process into propulsion system it is necessary to organize a steadily propagating (rotating) detonation wave in such chamber. The numerical calculation of such process were already performed by Hishida et, all, Kobiera et all, Zhdan, Davidenko, Hayashi et all, Tae-Hyeong Yi et all and other[6-17]. Calculations were made initially for the 2-D case but some were also curried out for the 3-D case. The calculations, as well as experiments, shows, that for a proper initial conditions continuously rotation detonation wave can be achieved. However, in some case two headed rotating detonation can be achieved. Also, as was shown by Hayashi et all [16], if supply system of fresh mixture is not sufficient, only deflagrative combustion can be achieved.

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Detonation wave stability

Lets us consider simple system of rotating detonation wave propagation in the cylindrical channel. Fuel and oxidizer (air or oxygen) is supply into cylindrical chamber from one end and the detonation is propagating in tangential (circular) direction, consuming mixture which was created at front of it (or behind previously propagating detonation front). To allow such process to propagate continuously, it is necessary to create sufficient volume of fresh mixture in which approaching detonation front can propagate. If this volume is not sufficiently large, detonation will fail. It can be assumed that the volume in which detonation can propagate should have the size to accommodate critical number of cells, which at given geometry will support propagation of the detonation. If created mixture volume is too small, detonation will fail, however, close to critical conditions unstable propagation can be observed [15]. On the other site, if fresh mixture supply is sufficiently large, multi-head detonation will be form (two or more detonation heads will propagate in one direction). So in the cylindrical channel single or multi-headed detonation wave can be organized and if fresh mixture supply will not be sufficient initially some oscillation and then detonation failed can be observed.

Detonation Wave Number

Let's consider simple system, which is shown on Fig. 2. From left site fresh mixture is supply into the chamber and the detonation front is propagating circuitous from right to left (counterclockwise rotation). To retain stable detonation, mixture have to occupied zone in which critical numbers of cells can be created. The length of this zone will be l_{cr}. If the length of this zone is smaller then l_{cr} , detonation initially will be unstable and then fail. If this zone will be larger, eventually two heads of detonation will be created and thus the length of the zone will be decreased to value close to critical one (smaller time will be available to feel the zone with fresh mixture). Thus for stable operation of the chamber following condition have to be met:

Detonation wave number $\mathbf{W = t_r / t_{mf}}$ (1)

where:

$\mathbf{t_r = \pi\, d / u_D}$; time of revolution of the detonation wave around the cylindrical chamber of diameter d; $\mathbf{u_D}$ -detonation velocity;

and

$$\mathbf{t_{mf}} = V_{cr} \,/\, \dot{V}_{mix}$$

where:

$$V_{cr} = \pi/4\,(do^2 - di^2)\, l_{cr}\ [m^3];\ \text{volume of critical zone} \qquad (2)$$

where (do; di -chamber outside and inside diameter, l_{cr} - critical length of the fresh mixture zone)

and

$\dot{V}_{mix} = (\dot{m}_f + \dot{m}_{oxy})\, \upsilon_{mix}$ [kg/s · m³/kg] or [m³/s]; volumetric rate of supply of fresh mixture and υ_{mix} – mixture specific volume (1/ ρ_{mix});

Equation (1) can be reorganized in the following way:

$$\mathbf{W} = [\pi d/u_D][4\pi\dot{V}_{mix}/(d_0^2 - d_i^2) l_{cr}] = [4d/l_{cr}u_D][\dot{V}_{mix}/(d_0 + d_i)(d_0 - d_i)]$$

if we assume that: $d_0 + d_i \approx 2d$ then

$$\mathbf{W} = [4d/l_{cr}u_D][\dot{V}_{mix}/(2d)(d_0 + d_i)]$$

and with assumption that: $d_0 - d_i = h$, (h - detonation channel high), so we obtain:

$$\mathbf{W} = 2\dot{V}_{mix}/l_{cr}h\, u_D \quad (3)$$

Knowing all parameters one can easily calculate the detonation wave number for cylindrical chamber. If "**W**" is equal 1, 2, 3 …n, then in the chamber one will observe one, two, three or "n" number of detonation heads propagating in one direction.

Typical example of single head rotating detonation pressure record is show on Fig3, and calculation of rotating detonation with two heads on Fig.4. If "**W**" will be slightly less than one, unstable detonation will be observed first. In such case, after one revolution of detonation wave in the cylindrical chamber, fresh mixture will not be able to feel sufficient volume of the chamber and detonation will start to decay (and thus propagate in smaller velocity). Smaller propagation velocity will results in increasing time of detonation wave revolution and thus more fresh mixture will be supplied into chamber and detonation will accelerate and the process will be repeated over and over again, creating some form of "*galloping rotational detonation*". Typical examples of such process is shown on Fig.5. Mechanism of such "*galloping rotational detonation*" is different from classical galloping detonation, but behavior of the front wave velocity is very similar . If "**W**" will be much more less than one, rotating detonation will fail and deflagration combustion will be observed.

To accurately evaluate "**W**" it is necessary to known all parameters used for this calculation. Most of this parameters can be relatively easily find but the only uncertain parameter which should be used for this calculations is l_{cr}. The critical length of this zone will depend on many parameters, but basically it will depend from initial pressure and temperature, mixture composition and its uniformity (or non ideal mixing of fuel and oxidizer) and channel geometry. As it is seen from calculation made for the ideal mixture, critical zone of for hydrogen-oxygen-argon mixture [13] is close to 10 cell size, or 13 cell size – as criteria for detonation transition from the tube to open space, but for a real case of fuel-air mixture it can be even larger. So, the evaluation of the "l_{cr}" for different mixtures, different initial pressure and temperatures, different geometry and different system of mixture formation will be one of the most important task for future development of propulsion system based on rotating detonation.

Summary and conclusions

The new parameter, so call "detonation wave number" or "**W**" was proposed to describe propagation conditions of the rotating detonation in cylindrical chamber. This dimensionless parameter compare times of detonation revolution around cylindrical detonation chamber with the time of new mixture creation in space where detonation propagate. For the "detonation wave number" equal to one or higher one can observe stable single head or multi-heads detonation propagating in the cylindrical chamber. For the value slightly less than one, one can observe unstable detonation or so called "*galloping rotational detonation*". For the values much smaller than one, only detonation failure with deflagrative mode of combustion can be observed.

The detonation wave parameter "**W**" will be very useful parameter for design of proper geometry and supply system of cylindrical chamber used for continuously rotating detonation, however, it will be necessary to evaluate the l_{cr} - critical length for the zone at front of propagating detonation. The length of this zone will depend on many parameters, such as mixture composition and its uniformity, initial pressure and temperature as well as on geometry of cylindrical detonation chamber.

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Figures

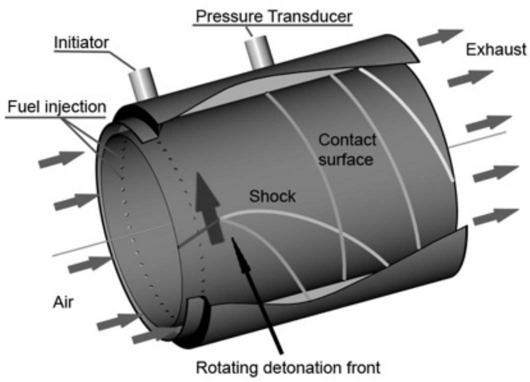

Fig. 1. Cylindrical detonation chamber

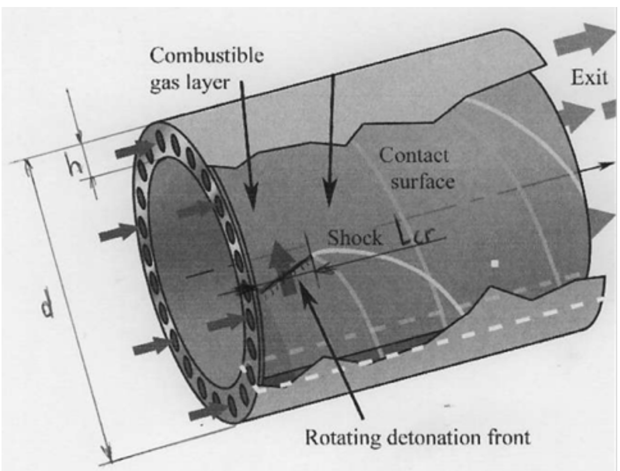

Fig. 2. Cylindrical detonation chamber with indicated dimensions

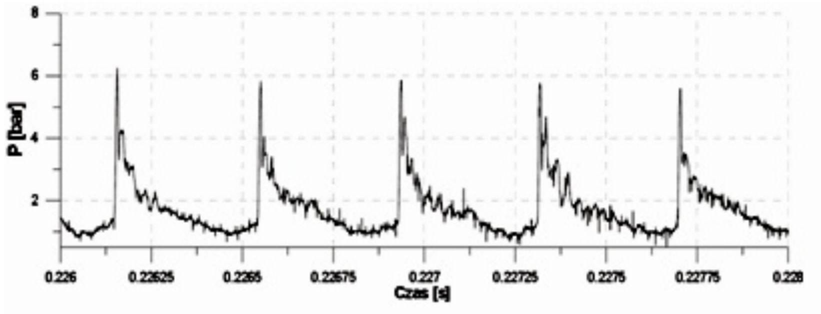

Fig. 3 Stable rotating detonation (experiment)

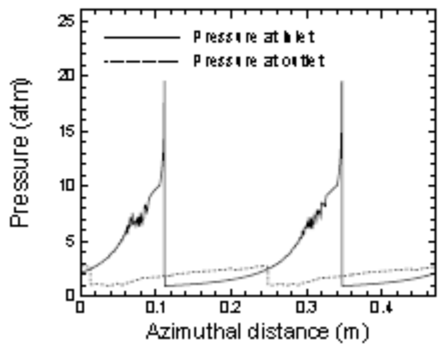

Fig.4 Rotating detonation with two heads (calculations)

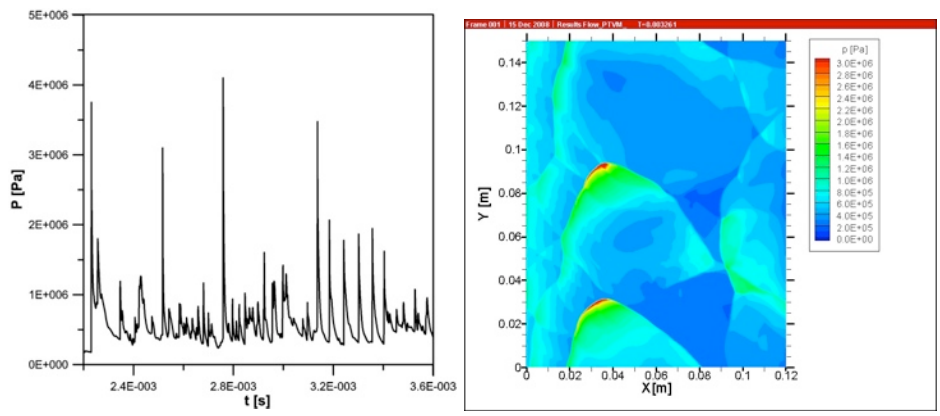

Fig. 5. Unstable (galloping) rotating detonation (calculations)