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Double-Front Detonation Waves

S.A. Gubin\textsuperscript{a*}, S.I. Sumskoi\textsuperscript{a}, S.B. Victorov\textsuperscript{b}

\textsuperscript{a} National Research Nuclear University MEPhI, Kashirskoye shosse 31, Moscow 115409, Russia
\textsuperscript{b} OpenSearchServer, Paris Incubateurs – Technologies Numeriques, 15 rue Jean-Baptiste Berlier, Paris 75013, France

Abstract

According to the theory of detonation, in a detonation wave there is a sound plane, named Chapman-Jouguet (CJ) plane. There are certain stationary parameters for this plane. In this work the possibility of the second CJ plane is shown. This second CJ plane is stationary as well. The physical mechanism of non-equilibrium transition providing the existence of the second CJ plane is presented. There is a non-equilibrium state, when the heat is removed from the reaction zone and the heat capacity decreases sharply. As a result of this non-equilibrium state, the sound velocity increases, and the local supersonic zone with second sonic plane (second CJ plane) appears. So the new mode of detonation wave is predicted. Equations describing this mode of detonation are presented. The exact analytical solution for the second CJ plane parameters is obtained. The example of double-front detonation in high explosive (TNT) is presented. In this double-front structure “nanodiamond-nanographite” phase transition takes place in condensed particles of detonation products.

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* Corresponding author. Tel.: +8-495-788-56-99(9035).
E-mail address: sagubin@mephi.ru
Nomenclature

\( c \) sound velocity
\( c_p \) heat capacity at constant pressure
\( M \) Mach number (\( M = u/c \))
\( \rho \) pressure
\( Q_r, Q_s \) heat release at detonation front and heat removal
\( R \) gas constant
\( T_r, T_s \) temperature and temperature of heat capacity change
\( t_1, t_2, t_3, t_\infty \) points of time, including infinite time
\( u, \rho, V \) mass velocity, density and specific volume (\( V = I/\rho \))
\( x \) distance
\( \gamma \) heat capacity ratio
\( \mu \) molecular weight

1. Introduction

Chapmen-Jugouet (CJ) detonation is self-sustained detonation regime. The model of CJ detonation wave is presented in Fig. 1. A plane, where energy release is finished and where the flow velocity is equal of local sound velocity, is called CJ plane. Parameters at CJ plane are called CJ parameters.

As the local sound velocity is equal of the flow velocity at CJ plane, the perturbation can’t penetrate through CJ plane into the reaction zone. So the stationary propagation of CJ detonation wave is possible: the flow behind CJ plane does not influence on the flow in the reaction zone.

For infinite space the parameters behind CJ wave will tend to CJ parameters. This trend is presented in Fig. 1 for such parameters as pressure, velocity, sound velocity and Mach number at different time moments, while distance functions are \( t_1, t_2, t_3 \) and \( t_\infty \).

So the key moment for CJ plane appearance is the presence of sound plane behind the zone of energy release. The next question is: if this CJ plane is unique or there are some others?

As it is seen in Fig. 1 (d), the Mach number is always more than 1 behind CJ plane. So for the second CJ plane appearance the Mach number has to decrease to 1 or less. The change of sound velocity in detonation products can be a reason of such Mach number decrease.

The schematic structure of a double-front detonation wave is presented in Fig. 2 for the case of sound velocity change (sharp decrease). It is well seen that after sharp decrease of sound velocity behind CJ plane the second sound plane can appear.

The presence of second CJ plane can considerably change the standard properties of explosive mixture. Therefore it is very important to investigate second CJ plane to predict these property correctly.

In this paper the possibility of the second sound plane is discussed in detail. For simplicity the case of ideal gas will be considered.

2. Criteria for double-front detonation

For ideal gas equation of state
\[
\frac{p}{\rho} = \frac{(RT)}{\mu}
\]

(1)

sound velocity can change when heat capacity (and heat capacity index) changes:

\[
\begin{align*}
\text{c''} &= \sqrt{\gamma_{II} \text{P}_{II} / \text{P}_{II}} \cdot \gamma_{II} \\
\text{c'} &\approx \sqrt{\gamma_{II} \text{P}_{II} / \text{P}_{II}} \cdot
\end{align*}
\]

(2)
As it follows from (2) if \( \gamma'_{VII} < \gamma''_{VII} \), then \( c'_{VII} < c''_{VII} \).

Change of heat capacity (and consequently the change of heat capacity index and sound velocity) can take place under various conditions. In this work to simplify relations we consider an ideal situation when change of heat capacity takes place at some temperature \( T_1 \). Density, pressure and molecular weight of gas are constant in this heat capacity transition. Obviously, in this transition enthalpy should conserve:

\[
 c_{p1}T_1 = c_{p2}T_1 + Q.
\]

Here \( Q \) is heat that removes, when \( c_{p1} > c_{p2} \) (\( \gamma_1 < \gamma_2 \)).

Let us introduce index “1” as the index for parameters at standard CJ plane, and “2” as the index for parameters at second possible CJ plane. Index “0” refers to initial state.

All possible states behind standard detonation wave are described by Hugoniot (H-1, \( \gamma_1 = \gamma_0 \) case):

\[
 p = \frac{\gamma_1 + 1}{\gamma_1 - 1} \frac{V}{V_0} + \frac{2\gamma_1}{\gamma_1 - 1} \frac{Q}{c_p T_0}.
\]

CJ regime is defined by H-1 touch (eq.(4)) and Relley line (RL):

\[
 p - p_0 = (\rho u_0)^2 (V - V_0).
\]

CJ detonation wave, defined by eq. (4)-(5) has the following velocity:

\[
 u_0 = \sqrt{\frac{\gamma_1 p_0}{\rho_0} + \frac{(\gamma_1^2 - 1) Q}{2} + \frac{(\gamma_1^2 - 1) Q}{2}}.
\]
If there is a second stationary sound plane generated by heat capacity decrease described by eq. (3) and if this sound plane has the same velocity of propagation as CJ detonation (eq.(6)), then, this second stationary sound plane will be described by an equation similar to (4) (Hugoniot 2, HA-2):

\[
\frac{P}{P_0} = \frac{\gamma_1 + 1}{\gamma_1 - 1} \frac{V}{V_0} + \frac{2\gamma_1}{\gamma_1 - 1} \left( Q - Q_0 \right) c_{v,0}^2, \quad (7)
\]

and eq. (5).

Eq. (4)-(7) describe stationary double-front detonation, when RL simultaneously touches H-1 and H-2. Solving eq. (4)-(7), one can find criteria for stationary double-front detonation:

\[
Q = -\frac{\gamma_3 P_0}{\rho_0 (\gamma_1 - 1)} \frac{u_0^2}{2} + Q - \frac{\gamma_2^2}{2(\gamma_2^2 - 1)} \frac{1}{\gamma_1 - 1} \left( \frac{P_0}{\rho_0} + u_0 \right)^2 \quad (8)
\]

3. A double-front detonation in high explosive

Now the question is, if it is possible to obtain double-front detonation in a real explosive system. We suppose that the answer is “yes”. The role of “sound velocity trigger” can be played by a phase transition, for example “nanodiamond-nanographite” phase transition, that takes place in condensed particles of detonation products. The results of one-dimensional simulation of the flow behind CJ plane in TNT with initial density \( \rho_0 = 1620 \) kg/m\(^3\) are presented in Fig. 3. This is the reproduction of calculations presented earlier in [1, 2]. The standard CJ plane is located at \( L = 0 \) mm. There are nanodiamond particles in this plane. But as detonation products expand, the nanodiamond particles convert into nanographite particles. This phase transition changes sound velocity and the second CJ plane appears at \( L = 0.65 \) mm. We suppose that the structure presented in Fig.3 isn’t completely stationary but the bend of mass velocity is the evidence of sound plane placement at this point. The equation of detonation product state used in this simulation is described in [3]. The SIN gas-dynamic code, used for flow simulation is described in picture [4].

![Fig. 3. The computed double-front detonation profile of the mass velocity behind the standard CJ plane (L = 0 mm) for TNT at \( \rho_0 = 1.62 \) g/cm\(^3\) at three points of time t = 1, 2, and 3\( \mu \)s.](image)

4. Conclusion

In this paper the criteria of the double-front detonation in ideal gas were obtained for the simplest case of heat capacity change at a certain temperature. It was shown that stationary double-front detonation is possible, when heat capacity decreases and simultaneously heat removal takes place. The amount of the heat removal is defined by eq.(8).
Phase transition in detonation products may be considered as a mechanism, that provides sound velocity change. TNT with high density ($\rho_0=1620$ kg/m$^3$) is an example of substance, where double-front detonation is possible due to the existence of “nanodiamond- nanographite” phase transition. The presence of the second sound velocity in detonation products of TNT was proved by numerical simulation. The double-front detonation may occur in many other explosive systems.

References