INTERACTION OF OBLIQUE SHOCK AND DETONATION WAVES

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Abstract

The interaction of an oblique shock wave and an oblique detonation wave which deflect the flow in the same direction is analyzed. The detonation wave is assumed to be an exothermic gasdynamic discontinuity. A criterion is developed and used to determine whether or not a theoretical solution of the problem describes a physically realizable interaction configuration. It is found that the reflected wave is, in general, a rarefaction wave. Only for very low values of the heat release parameter of the detonation wave the reflected wave has been found to be a shock wave. Domains of existence of such resulting wave interaction configurations are established for different values of the oncoming Mach number, \( 6 \leq M \leq 8 \), the heat release parameter, \( 3 \leq Q \leq 8 \), and the specific heat ratios for the combustion products behind the detonation wave, \( 1.30 \leq \gamma \leq 1.33 \). It is also found that double discontinuity configurations, representing the refraction of a detonation wave at a combustible/non-combustible interface (a limiting case of the considered interaction problem) can exist for certain values of the flow parameters involved and for different specific heat ratios of the gases in front of and behind the detonation wave. The magnitudes of the heat release parameter and specific heat ratio of the combustion products affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that the interaction problem considered be based on a detailed thermo-chemical analysis for given combustible mixtures of gases.
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## Notation

### Symbols
- \(a\) sound speed
- \(c_p\) specific heat at constant pressure
- \(c_v\) specific heat at constant volume
- \(M\) Mach number
- \(M_n\) normal Mach number
- \(p_{ij} = p_i/p_j\) pressure ratio
- \(q_{ij}\) heat release in the wave separating flow regions \(i\) and \(j\)
- \(Q_{ij} = q_{ij}/c_{p_i}T_j\) heat release parameter
- \(R\) gas constant
- \(T\) absolute temperature
- \(u\) component of flow velocity normal to discontinuity surface
- \(v\) component of flow velocity tangential to discontinuity surface
- \(V\) flow velocity
- \(\rho\) density
- \(\gamma\) specific heat ratio
- \(\delta\) flow deflection angle through a wave

### Subscripts
- \(i\) downstream of a wave
- \(j\) upstream of a wave
- \(CJ\) Chapman-Jouguet condition
- \(\ell\) lower limit
- \(u\) upper limit

### Superscripts
- \(o\) stagnation values of the corresponding flow variables
1. INTRODUCTION

The use of oblique detonation waves in ramjets that operate at hypersonic speeds have recently received considerable attention (Refs. 1, 2). A flow device utilizing this mode of combustion, as opposed to the supersonic diffusive burning mode, offers several advantages (see, for example, Ref. 3). Proposed diffuser-combustor model flow configurations involving plane oblique detonation waves (Refs. 1, 2, 4) entail, by necessity, the interaction of such combustion waves with the oblique shock waves formed on the forebody at high supersonic flight speeds. In view of such possible applications, the shock wave and detonation wave interaction problem depicted in Fig. 1 is investigated in the present Note. Fuel is injected along the wall AB of the inlet into the supersonic stream and is assumed fully mixed with the air at station B. A detonation wave across BO stabilized by means of a second wedge interacts with the oblique shock wave AO formed by the forebody. Of primary interest are the nature and magnitude of the resulting possible wave configurations, as well as their domains of existence as functions of the oncoming flow Mach number, the strengths of the shock and detonation waves, the amount of heat released by the burning reaction per unit mass of gas, and the specific heat ratios of the combustion product behind the detonation wave.

It is easy to visualize that in order to equilibrate the pressures in the airstreams on both sides of the intersection point O, the transmitted discontinuity must be a shock wave, OE; a contact discontinuity, OC, must then separate the airstreams of different entropies passing through the two different sets of discontinuities. However, such a "triple discontinuity" configuration where only a reflected Mach wave exists represents a special limiting case of the more general resulting flow pattern when a reflected shock or rarefaction wave is present between the detonation wave OB and the contact surface OC. Figures 1(b) and 1(c) represent the resulting discontinuity patterns when the reflected wave is a rarefaction wave and a shock wave, respectively. It can be easily shown that there can be no other discontinuities in the interaction flow pattern, i.e., no discontinuity other than the reflected rarefaction or shock wave can exist between the detonation wave and the contact surface; also, no other discontinuity can exist between the transmitted shock wave, OE, and the contact surface, OC (see Ref. 5, Ch. 11).

A Chapman-Jouguet detonation wave is adopted in the present Note. According to this model the detonation wave consists of a shock wave in which chemical reactions occur instantaneously, i.e., the detonation wave is considered as an exothermic gasdynamic discontinuity. Although for most fuels utilized in ramjets the temperature behind the detonation wave would be too high to consider the flowing medium as a perfect gas, in the present Note real-gas effects are neglected for the sake of simplicity. The effects of chemical reactions, as well as of the various fuel/air mixture ratios are accounted for by different constant specific heat ratios before and after the detonation wave, and by different values of the heat release parameter.

The shock and detonation wave interaction was also investigated by Rues (Ref. 6) for the particular case when the resulting wave configuration contains only a reflected Mach wave; no allowance was made for the change of specific heat ratios across the detonation wave. A qualitative analysis of a limiting case of the interaction problem, i.e. the refraction of a detonation wave at a combustible/non-combustible gas interface, is given in Ref. 7.
2. OBLIQUE DETONATION WAVE RELATIONS

Figure 2 is a sketch of the two-dimensional flow through a plane oblique detonation wave. The laws of conservation of mass, momentum and energy applied to the plane oblique exothermic discontinuity considered yield the following relationships:

Continuity:
\[ \rho_j u_j = \rho_i u_i \]  
\( (1) \)

Momentum:
\[ p_j + \rho_j u_j^2 = p_i + \rho_i u_i^2 \]  
\( (2) \)

and
\[ v_j = v_i \]  
\( (3) \)

Energy:
\[ \frac{u_j^2 + v_j^2}{2} + \frac{a_j^2}{\gamma_j - 1} + q_{ij} = \frac{u_i^2 + v_i^2}{2} + \frac{a_i^2}{\gamma_i - 1} \]  
\( (4) \)

The premixed gaseous mixture of reactants, and the gaseous reaction products are assumed to be perfect gases with equations of state of the form
\[ p_k = \rho_k R_k T_k \]  
\( (5) \)

Manipulation of the above equations yields the following relationships for the determination of the flow variables behind the detonation wave in functions of the pressure ratio \( p_{ij} = p_i/p_j \):

Normal velocity ratio (or density ratio):
\[ \frac{\rho_j}{\rho_i}u_j = \frac{u_i}{b_i} = \frac{p_{ij} + b_j + \bar{Q}}{b_j p_{ij} + 1} ; \quad \bar{Q}_{ij} = \frac{2 \gamma_j}{(\gamma_j - 1)} q_{ij} ; \quad Q_{ij} = \frac{a_{ij}}{c_p T_j} ; \quad b_k = \frac{\gamma_k + 1}{\gamma_k - 1} \]  
\( (6) \)

Temperature ratio:
\[ \frac{T_i}{T_j} = \frac{R_j}{R_i} p_{ij} \frac{p_{ij} + b_j + \bar{Q}_{ij}}{b_j p_{ij} + 1} \]  
\( (7) \)

Mach number ratio:
\[ \frac{M_i}{M_j} = \sqrt{\frac{\gamma_j^2 \frac{1}{\gamma_j P_{ij}} 1 - \frac{p_{ij} - 1}{\gamma_j M_{jn}^2}}{\gamma_i P_{ij}^2 1 - \frac{p_{ij} - 1}{\gamma_i M_{jn}^2}}} \]  
\( (8) \)

where the normal component of the Mach number of the flow before the detonation wave, \( M_{jn} \), is given by
\[ M_{jn}^2 = \frac{(P_{ij} - 1)(b_1 P_{ij} + 1)}{\gamma_j \left[ \frac{2}{\gamma_i - 1} P_{ij} - \frac{2}{\gamma_j - 1} \bar{Q}_{ij} \right]} \]  

(9)

Normal Mach number ratio:

\[ \frac{M_{in}}{M_{jn}} = \sqrt{\frac{\gamma_j}{\gamma_i} \frac{1}{P_{ij}} \frac{P_{ij} + b_j + \bar{Q}_{ij}}{b_1 P_{ij} + 1}} \]  

(10)

Total pressure ratio:

\[ \frac{P_i^0}{P_j} = P_{ij} \left[ \frac{1 + \frac{\gamma_i - 1}{2} M_j^2 \left( \frac{M_i}{M_j} \right)^2}{1 + \frac{\gamma_j - 1}{2} M_j^2} \right] \left( \frac{\gamma_i}{\gamma_j} \right)^{-1} \]  

(11)

Total temperature ratio:

\[ \frac{T_i^0}{T_j} = \frac{\gamma_j}{\gamma_i} \left( \frac{R_j}{R_i} \right) \left[ 1 + \frac{Q_{ij}}{1 + \frac{\gamma_j - 1}{2} M_j^2} \right] \]  

(12)

For strong detonations considered here, the ratio \( P_{ji} = P_j/P_i \) will vary in the interval

\[ 0 < P_{ji} < P_{jiCJ} \]  

(13)

where \( P_{jiCJ} = 1/P_{ijCJ} \) can be determined from Eqs. (9) and (10) with \( M_{in} = 1 \). We get

\[ P_{ijCJ} = \frac{\gamma_i + 1}{\gamma_j - 1} \left[ 1 + \frac{\gamma_j - 1}{2} \bar{Q}_{ij} \right] + \sqrt{\left( \frac{\gamma_j + 1}{\gamma_j - 1} \left[ 1 + \frac{\gamma_j - 1}{2} \bar{Q}_{ij} \right] \right)^2 - b_1 (b_j + \bar{Q}_{ij})} \]  

(14)

The flow deflection angle is given by

\[ \delta_{ij} = \pm \tan^{-1} \left\{ \frac{P_{ij} - 1}{[\gamma_j M_j^2 - (P_{ij} - 1)]^{\gamma_j M_j^2 [(b_1 - 1) P_{ij} - (b_j - 1) - \bar{Q}_{ij}]}}{\left( P_{ij} - 1 \right) \left( b_1 P_{ij} + 1 \right)} \right\} \]  

(15)

where the upper sign corresponds to a clockwise deflection. When \( \gamma_i = \gamma_j \) and \( q_{ij} = 0 \), the above equations reduce to the usual oblique shock wave relations. Equation (15) is plotted on Figs. 3-5 for various values of \( Q_{ij}, \gamma_i \) and \( M_j \).
3. BASIC EQUATIONS AND SOLUTION OF THE INTERACTION PROBLEM

The three possible interaction configurations are depicted in Fig. 1. In regions (1)-(5) divided by the waves the flow is uniform. In terms of the pressure ratio $P_{ij}$ and the flow deflection angle $\delta_{ij}$ across the wave separating region $i$ after the wave from region $j$ before it, we can write the following conditions:

$$P_{51} = P_{43} P_{32} P_{21}$$

or

$$\log P_{51} = \log P_{43} + \log P_{32} + \log P_{21} \quad (16)$$

and

$$\delta_{51} = \delta_{21} + \delta_{32} + \delta_{43} \quad (17)$$

valid across the contact discontinuity OC. The deflection angles in Eq. (17) are given by Eq. (15) with the appropriate values of $\gamma_j, Q_{ij}, M_j$ and $P_{ij}$ on the corresponding discontinuity (in the case of a shock discontinuity, the relevant value of $\gamma$ is assumed conserved across the shock wave and $Q_{ij} = 0$). In the case of a reflected rarefaction wave, the corresponding deflection angle is given by

$$\delta_{43} = b_3 \tan^{-1} \sqrt{\frac{M_4^2 - 1}{b_3}} - \tan^{-1} \sqrt{\frac{M_4^2 - 1}{b_3}} - b_3 \tan^{-1} \sqrt{\frac{M_3^2 - 1}{b_3}} + \tan^{-1} \sqrt{M_3^2 - 1} \quad (18)$$

where

$$M_4 = \sqrt{\frac{2}{\gamma_3 - 1} \left[ \frac{1 + \frac{\gamma_3^2 - 1}{2} M_3^2}{P_{43}} - 1 \right]} \quad (19)$$

Elimination of $P_{43}$ from Eqs. (16) and (17) yields the following equations for the single unknown $P_{51}$:

$$\delta_{21}(P_{21}, \gamma_1, M_1) + \delta_{32}[P_{32}, \gamma_2, \gamma_3, M_2(P_{21}, \gamma_1, M_1), \bar{Q}_{32}] \pm$$

$$\pm \delta_{43} \left[ \frac{P_{51}}{P_{32} P_{21}}, \gamma_3, M_3(P_{32}, \gamma_2, \gamma_3, M_2(P_{21}, \gamma_1, M_1), \bar{Q}_{32}) \right] -$$

$$- \delta_{51}(P_{51}, \gamma_1, M_1) = 0 \quad (20)$$

For given $M_1, P_{21}, P_{32}, \gamma_1, \gamma_3$ and $Q_{32}$ (given fuel/air mixture), we can determine $P_{51}$ from Eq. (20). Equations (6)-(15) and Eqs. (18) and (19) will then yield the values of all the flow variables of interest in the considered interaction problem. In the case of vanishingly small reflected wave (triple discontinuity configuration) $P_{51} = P_{32} P_{21}$; Eq. (20) is then solved for $P_{32}$ for given values of $P_{21}$.
A graphical illustration of the solution is presented on Fig. 6 for the case when $M_1 = 7$, $P_{21} = 2.6$ ($M_2 = 5.92$), $\gamma_3 = 1.3$ and $Q_{32} = 8$. Only the right-hand halves of the incident shock polar I and detonation polar II are considered in the present investigation, as it is assumed that the shock and detonation waves deflect the flow in the same direction. The intersection point A of the detonation polar II and the shock polar I would then represent the resulting interaction pattern with a reflected Mach wave [triple discontinuity configuration, case (a) in Fig. 1]. Hence, for values of $P_{32} > P_{32A}$, the value of $P_{32}$ at point A, we would have reflected rarefaction wave configurations [case (b) in Fig. 1] determined by points B and B' of intersection of the corresponding epicycloid IV with the shock polar I, and for $P_{32} < P_{32A}$, either the reflected shock configuration [case (c) in Fig. 1] determined by point C of intersection of the shock polar III drawn from Point $P_{32}$ and the shock polar I, or the reflected rarefaction wave configuration determined by point C' of intersection of the epicycloid IV drawn from point $P_{32}$ and the shock polar I. For $P_{32} = P_{32A}$ a reflected rarefaction wave interaction configuration given by point A' of intersection of the epicycloid drawn from point $P_{32A}$ and the shock polar I, is also possible. Thus for a given combination of $P_{21}$ and $P_{32}$, it is possible to have two sets of solutions corresponding respectively to points A, B, C and A', B', C' in Fig. 6. It is obvious that not all the solutions are physically realizable. Whether a mathematical solution of Eq. (20) is physically realizable or not depends on the stability of the resulting triple discontinuity configuration to small perturbations.

4. STABILITY CRITERION FOR REFLECTED MACH WAVE CONFIGURATIONS

Let us superimpose a small pressure disturbance $\Delta p$ on the flow regions (3), (4) and (5) [Fig. 1(a)] downstream of the discontinuities OB and OE. This small pressure disturbance will cause variations in the flow deflection angles across the reflected Mach wave and the transmitted shock wave OE, $\Delta \delta_R$ and $\Delta \delta_T$, respectively, and will not affect the flow in regions (1) and (2). If the rate of change of the flow deflection angle across the reflected Mach wave is less than the rate of change of the flow deflection angle across the transmitted shock wave, i.e., if

$$\frac{d \delta}{dp} \bigg|_R < \frac{d \delta}{dp} \bigg|_T$$

then the reflected Mach wave configuration is stable and, hence, physically realizable. Indeed, if $\Delta p > 0$, then from Eq. (21), $\Delta \delta_R < \Delta \delta_T$ and the streamlines crossing these waves will diverge and result in a pressure decrease which will restore the equilibrium state. If $\Delta p < 0$, then $\Delta \delta_R > \Delta \delta_T$, and the streamlines will converge and result in a pressure increase which will restore the equilibrium state. It is easy to see that if condition (21) is violated, the reflected Mach wave configuration becomes unstable and hence physically not realizable. Equation (21) can be written in a more convenient form

$$\frac{d \delta}{d \Delta p} \bigg|_R < \frac{d \delta}{d \Delta p} \bigg|_T$$

Substitution of the expressions for the derivatives in the above equation, derived in the Appendix, yields
where

\[ P_{51} \]

\[ \frac{A(P_{51} - P_{51\text{max}})}{[\gamma_1 M_1^2 - (P_{51} - 1)]^2 (AP_{51} + 1)} - 1 \]

\[ = \frac{A[(AP_{51} + 1)(2P_{51} - P_{51\text{max}}) - (P_{51} - P_{51\text{max}})(2AP_{51} - A + 1)]}{2(A(51 + 1))^2 [\gamma_1 M_1^2 - (P_{51} - 1)]} \]

\[ \leq \frac{(M_3^2 - 1)^{1/2}}{\gamma_3 M_3^2} \quad (23) \]

Equation (23) is the necessary and sufficient condition for the stability of the resulting limiting triple discontinuity configuration of the interaction problem considered.

Because the slope of the isentrope in the \( \delta, p \) plane, \( (d\delta/d\ln p)_R \), is always negative [see Eq. (A5)], condition (23) is always satisfied for mathematical solutions with a reflected Mach wave which are on the weak branch of the transmitted shock polar, where \( (d\delta/d\ln p)_T > 0 \) always. However, condition (23) can also be satisfied on a certain portion of the strong branch of the transmitted shock polar, where \( (d\delta/d\ln p)_T < 0 \), resulting in physically realizable reflected Mach wave configurations. These triple discontinuity configurations represent the limiting cases for physically possible interaction patterns with reflected shock or rarefaction waves.

Condition (23) is not satisfied at point A in Fig. 6. Hence, the reflected Mach wave interaction configuration represented by this point for the flow conditions considered, as well as points C and B corresponding to reflected shock wave and reflected rarefaction wave configurations, respectively, are not physically realizable. The only stable and physically possible solutions are given in this case by points B', A' and C'.

5. ANALYSIS OF WAVE CONFIGURATIONS

From Section 3, it is clear that the solution of the considered interaction problem reduces to finding the roots of Eq. (20), i.e. the values of \( P_{51} \) for a given set of flow parameters \( M_1, P_{21}, P_{32}, \gamma_2, \gamma_3 \) and \( Q_{32} \). Whether the solution obtained is physically realizable or not is determined by using the criterion developed in Section 4. Moreover, the intervals within which \( P_{21} \) and \( P_{32} \) can vary depend on the oncoming flow Mach number \( M_1 \) and the fuel/air mixture considered, i.e. on \( \gamma_2, \gamma_3 \) and \( Q_{32} \). The procedure for determining these intervals, as well as the domains of existence of the resulting physically possible interaction configurations and the strengths of the resulting
waves is here given for the particular case when $M_1 = 7.0$, $\gamma_1 = \gamma_2 = 1.40$, $\gamma_3 = 1.30$ and $Q_{32} = 8.0$.

It is obvious that the lower limit of the interval of variation of $P_{21}$, $P_{21u} = 1$. The upper limit of this interval, $P_{21u}$, is determined by the condition that for given $M_1$, $\gamma_2$, $\gamma_3$ and $Q_{32}$ there is a Mach number $M_2$ in region 2 for which the detonation wave is operating at the single Chapman-Jouguet condition [see Fig. 9(d)]. Letting $M_3 = M = 1$ in Eqs. (8)-(10) and eliminating $M_2$ and $P_{32}$ from these equations, we get the following equation to determine $M_2$:

\[
\frac{1}{(\gamma_3 - 1)^2} \left( \frac{2 \gamma_2 M_2^2}{\gamma_3 - 1} \frac{2 \gamma_2 M_2^2}{\gamma_2 - 1} \right) = 0
\]

Elimination of $M_2$ from Eqs. (8) and (9) will then yield an equation from which the value $P_{21u}$ is computed. For the numerical example considered $M_2 = 5.4$ and $P_{21u} = 4.04$.

For each value of $P_{21}$ in the interval $P_{21} \leq P_{21} < P_{21u}$, and hence for each value of $M_2$ between $M_{2u} = M_1$ (when $P_{21} = P_{21u} = 1$) and $M_{2u}$ (when $P_{21} = P_{21u}$) determined from Eq. (21), we can plot detonation polars, as shown in Fig. 7. For strong detonation waves considered in the present Note, the lower limit of the interval of variation of $P_{32}$, $P_{32u}$, should be its Chapman-Jouguet value given by Eq. (14), $P_{32u} = P_{32CJ} (= 17.85$ for the numerical example considered). The upper limit for the variation of $P_{32}$, $P_{32u}$, is given by the condition $M_3 = 1$. Eliminating again $M_2$ from Eqs. (8) and (9) and letting $M_3 = 1$, we arrive at an equation from which the value $P_{32u} = P_{32s}$, i.e. the value of $P_{32}$ giving sonic flow behind the detonation wave, is obtained. It should be noted that this value of $P_{32s}$ is a function of $P_{21}$. Figure 8 depicts the domain of variation of $P_{21}$ and $P_{32}$ for the specific numerical example treated (shaded area). The horizontal line AB represents the lower, constant, Chapman-Jouguet limit of $P_{32}$. The curve BEC is the locus of values of $P_{32s}$, and the curve BFG that of $P_{32 \text{max}}$ (resulting in normal detonation waves). The curve DHE is the locus of pairs of values of $P_{21}$ and $P_{32}$ of the strength of the interacting shock and detonation waves which result in a configuration with a reflected Mach wave.

Numerical calculations show that for all these solutions on line DHE the criterion (23) is not satisfied. Therefore they are not physically realizable. On the other hand, calculations show that, for every point in the domain ABEC (Fig. 8), there is a solution with a reflected rarefaction wave. Figures 9(a)-(d) show the graphical solution of the interaction problems with reflected rarefaction waves. Note that in Fig. 9(d) the detonation polar has shrunk to a point. The strengths of the transmitted shock waves and reflected rarefaction waves for different values of the strengths of the interacting waves are plotted in Figs. 10(a)-(d).* For the numerical example considered, it has been found that all physically possible interactions result in configurations with a reflected rarefaction wave.

*Tables of numerical values of strengths of all waves involved in the interaction process and the corresponding Mach numbers in different flow regions for the range of values: $M_1 = 6, 7, 8$; $Q_{32} = 3, 4, 5, 6, 7, 8$ and $\gamma_3 = 1.30, 1.315, 1.33$ are available upon request from UTIAS.
Similar calculations were performed for different values of $M_1$ and $Q_{32}$. The corresponding domains of existence of interaction configurations with a reflected rarefaction wave are presented in Figs. 11(a)-(j) (areas under the corresponding curves). It should be noted that as the values of the heat release parameter are decreased the upper limit of the interval of variation of $P_{32}$ ceases to be $P_{32_s}$, as the epicycloid III describing the rarefaction wave issuing from the point $P_{32_s}$ on the detonation polar 11 does not intersect the shock polar I, and therefore, there is no solution of the interaction problem. This is clear from the graphical solution presented in Fig. 12. For $P_{32} = P_{32CJ} = P_{32_s} = 15.74$ or for $P_{32} = 22.0$ there are solutions represented by the points A and B, respectively, in the polar I, whereas for $P_{32} = 29.0 < P_{32_s}$, there is no solution. In these cases the upper limit of the interval of variation of $P_{32}$ is determined numerically as the point where the roots of Eq. (20), if they exist, coincide. The domain of existence of reflected rarefaction wave configurations is then represented by the area under the line ABCDE in Fig. 11(b).

If we further decrease the value of $Q_{32}$ (for example, $Q_{32} = 4$ and $M_1 = 8$) the aforementioned domain of existence splits in two subdomains ABCGK and DHE [see Fig. 11(e)]. There are no solutions for $P_{21}$ in the interval GH and for $P_{32} > P_{32CJ}$. The reason for this splitting is clear from the graphical solution presented in Fig. 13. This figure depicts the case when $P_{32}$ is kept constant at $P_{32} = P_{32CJ}$ and $P_{21}$ assigned the values: $P_{21} = 11.5, 13.0$ and $14.5$. The corresponding epicycloids for the reflected rarefaction waves issuing from points $P_{32} = P_{32CJ}$ intersect the shock polar I for $P_{21} = 11.5$ and $14.5$ but not for the intermediate value $P_{21} = 13.0$.

Stable, and hence physically possible, reflected Mach wave configurations have been found to exist for very low values of the heat release parameter $Q_{32}$. Figure 14 presents results of numerical calculations for the case $M_1 = 7$, $\gamma_1 = \gamma_2 = 1.4$, $\gamma_3 = 1.33$ and $Q_{32} = 1.0$. Curve EDC is the locus of stable [according to criterion (23)], and hence physically realizable, reflected Mach wave configurations separating regions where stable interaction configurations with reflected shock (area EDCF) and rarefaction waves (area EDCGBA) occur. Points on the ED portion of this curve correspond to configurations with transmitted shock waves on the weak branch of the shock polar, whereas for points on the DC portion, the transmitted shock wave is on the strong branch of the shock polar. There are no regular interaction solutions in the region above the curve BGCF. Curve HIJ is the locus of points for which the Mach number behind the detonation wave is exactly sonic, $M_3 = 1$.

It is of interest to consider the particular case when $P_{21} = 1.0$, always (line AEF in Fig. 14). The problem then reduces to the refraction of a detonation wave at a combustible/non-combustible gas interface. The equilibration of pressures behind the detonation wave and the shock wave (to which the detonation wave degenerates in the non-combustible gas mixture) is achieved through a shock wave if the strength of the detonation wave $P_{32}$ lies in the interval EF, and through a rarefaction wave if $P_{32}$ is in the interval AE. Point E corresponds to a double discontinuity situation, i.e. only the detonation and the shock waves are present, the equilibration of pressures taking place across a Mach wave. Thus for the case considered (where $\gamma_1 = \gamma_2 = \gamma_5 \neq \gamma_3$) such a double discontinuity configuration, with energy addition on one of the discontinuities, is possible. Rues (Ref. 6) has shown that for $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_5$ such a configuration is impossible. Calculations performed for the particular case considered, assuming constant
specific ratio everywhere, have also shown that such a double-discontinuity configuration does not exist. This example again shows the importance of the value of the specific heat ratio of the combustion products $\gamma_3$ for the interaction problem considered.

6. DISCUSSION AND CONCLUSIONS

The transmitted shock wave is usually on the weak solution branch of the shock polar. However, when $P_{32}$ approaches $P_{32u}$, the transmitted shock wave may be on the strong solution branch, as exemplified by Fig. 15. Both theoretical solutions are on the strong branch of the shock polar with $P_{51} = 66.44$ and 65.46; the latter solution is physically possible according to solution continuity arguments.

The upper limit of the interval of variation of $P_{21}$, $P_{21u}$, is fixed by the Chapman-Jouguet condition of the detonation wave. The higher the oncoming flow Mach number and the lower the value of the heat release parameter of the detonation wave, the larger $P_{21u}$ is. When $P_{21u}$ is large, for some values of the incident shock wave strength, $P_{21}$, there is no solution to the regular interaction problem considered and the interval of variation of $P_{21}$ becomes discontinuous.

In the problem of the interaction of a shock wave with a detonation wave which deflect the flow in the same direction, of primary interest is the determination of the nature of the reflected wave. It has been found that for most combustible mixtures of gases ($3 \leq Q_{32} < 8; 1.30 < \gamma_3 < 1.33$) the reflected wave is always a rarefaction wave. Using criterion (23), it has been shown that triple discontinuity configurations (reflected Mach wave) and hence configurations with a reflected shock wave and rarefaction wave are physically possible for combustible gases with low heat release and are very sensitive to the values of the specific heat ratio of the combustion products behind the detonation wave. Considering the particular case of refraction of a detonation wave at a combustible/non-combustible gas interface, it has been found that for low values of $Q_{32}$ ($Q_{32} = 1.0$) and $\gamma_1 = \gamma_2 = \gamma_5 \neq \gamma_3$ double discontinuity configurations, where only the detonation and shock waves are present (the equilibration of pressures behind the detonation and shock waves takes place across a Mach wave), can exist.

In general, the magnitudes of the heat release parameter, $Q_{32}$, and specific heat ratio, $\gamma_3$, of the combustion products behind the detonation wave affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that for given particular flow configuration of the interacting shock and detonation waves and combustible mixture of gases, a detailed thermochemical analysis be made in order to determine the actual values of the heat release parameter, $Q_{32}$, and the specific heat ratio of the combustion product, $\gamma_3$. The nature of the resulting interaction pattern could then be established by using these actual values of $Q_{32}$ and $\gamma_3$.

The interaction problem considered in the present Note was also investigated by Rues (Ref. 7) for the particular case when the resulting interaction pattern involves only a reflected Mach wave; no allowance was made for the change of specific heat ratios across the detonation wave. For this particular situation, the results obtained in the present work
coincide with those of Ref. 7. However, according to criterion (23), all triple discontinuity configurations studied by Rues are not stable and hence physically not realizable. When $Q_{32} = 0$ and $\gamma_2 = \gamma_3 = 1.4$, the results obtained in the present Note coincide with those of Ref. 8, where the similar interaction problem of two shock waves is considered.
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APPENDIX

DERIVATION OF THE DERIVATIVES OF THE FLOW DEFLECTION ANGLE THROUGH THE WAVE

WITH RESPECT TO THE PRESSURE BEHIND THE WAVE

For the general case of a detonation wave, the flow deflection angle through the wave, Eq. (15), can be rewritten as:

\[
\delta = \pm \tan^{-1} \left\{ \frac{P-1}{\gamma M_1^2 - (P-1)} \left[ \frac{A(P-P_{\text{max}})(P-P_{\text{min}})}{(P-1)(AP+1)} \right]^{1/2} \right\}
\]

(A1)

where \( P = p/p_1 \), \( p = \) pressure behind the wave, \( A = \gamma_2 + 1/\gamma_2 - 1 \), and

\[
P_{\text{max}} = \frac{\gamma M_1^2}{\gamma_2 + 1} + \frac{1}{\gamma_2 + 1} \pm \left\{ \left( \frac{\gamma M_1^2}{\gamma_2 + 1} + \frac{1}{\gamma_2 + 1} \right)^2 - \frac{1}{A} \left[ \frac{2 \gamma M_1^2}{\gamma_2 - 1} (1 + \gamma_1 Q) - 1 \right] \right\}^{1/2}
\]

(A2)

subscript 2 denoting the flow region behind the wave. From Eq. (A1) we have

\[
\pm \frac{d\delta}{dp} = \frac{\cos^2 \delta}{P_1} \left\{ \frac{\gamma M_1^2}{\gamma M_1^2 - (P-1)} \left[ \frac{A(P-P_{\text{max}})(P-P_{\text{min}})}{(P-1)(AP+1)} \right]^{1/2} - \frac{A[(P-1)(AP+1)(2P-P_{\text{max}} - P_{\text{min}}) - (P-P_{\text{max}})(P-P_{\text{min}})(2AP-A+1)]}{2(P-1)(AP+1)^2[\gamma M_1^2 - (P-1)]^{1/2}} \right\}
\]

(A3)

where the + sign corresponds to the right-half of the detonation wave polar. Taking into account Eq. (A1), the above equation can be finally written in the form

\[
\pm \frac{d\delta}{d\ln p} = \frac{P}{A(P-1)(P-P_{\text{max}})(P-P_{\text{min}})} \left\{ \frac{\gamma M_1^2}{[\gamma M_1^2 - (P-1)]^2 (AP+1)} \right\} \times \left[ \frac{A(P-P_{\text{max}})(P-P_{\text{min}})}{(P-1)(AP+1)} \right]^{1/2}
\]

(A4)
Equation (A4) gives also the value of the derivative in the case of a shock wave if we let \( Q = 0, \gamma_1 = \gamma_2 \) and \( p_{\min} = 1 \).

For isentropic rarefaction or compression waves, we have (see, for example, Ref. 9, p. 422)

\[
\frac{d\delta}{d\ln p} = -\frac{\sqrt{\gamma}}{M^2}
\]

where \( \delta \) is assumed positive when it increases in the clockwise direction. Hence \( d\delta/d\ln p \) for an isentropic wave is always negative. Letting \( d(\delta/d\ln p)/dM = 0 \), we will have

\[
\left| \frac{d\delta}{d\ln p} \right| \leq \frac{1}{2\gamma}
\]

\( (A6) \)
FIG. 1. POSSIBLE DISCONTINUITY CONFIGURATIONS RESULTING FROM THE INTERACTION OF A SHOCK WAVE WITH A DETONATION WAVE. S-SHOCK WAVE, D-DETONATION WAVE, R-RAREFACTION WAVE, C-CONTACT DISCONTINUITY. (a) CONFIGURATION WITH A REFLECTED MACH WAVE; (b) CONFIGURATION WITH A REFLECTED RAREFACTION WAVE; (c) CONFIGURATION WITH A REFLECTED SHOCK WAVE.
Uniform Flow of Gaseous Pre-mixed Reactants

FIG. 2. PLANE OBLIQUE DETONATION FLOW MODEL.
FIG. 3. OBLIQUE DETONATION AND DEFLAGRATION WAVE POLARS FOR DIFFERENT VALUES OF THE HEAT RELEASE PARAMETER Q AND SPECIFIC HEAT RATIOS $\gamma_2$. 

- $Q=0, \gamma_2=1.4$
- $Q=4, \gamma_2=1.4$
- $Q=8, \gamma_2=1.3$

$M=6$
FIG. 4. OBLIQUE DETONATION WAVE POLARS FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER.
FIG. 5. OBLIQUE DETONATION WAVE POLARS FOR DIFFERENT VALUES OF THE SPECIFIC HEAT RATIO OF COMBUSTION PRODUCTS.
FIG. 6. INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT VALUES OF $P_{32}$.  

- $Q_{32} = 8$
- $M_1 = 7$
- $P_{21} = 2.6$
- $\gamma_3 = 1.3$

TURNING ANGLE IN DEGREES

PRESSURE RATIO (LOG)
FIG. 7. SHOCK AND DETONATION POLARS FOR DIFFERENT VALUES OF $P_{21}$. 

$Q_{32} = 8$

$M_1 = 7$

$\gamma_3 = 1.3$
FIG. 8. DOMAIN OF EXISTENCE (SHAD ED AREA) OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION IN THE $P_{21}$, $P_{32}$ PLANE.
FIG. 9(a). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT $P_{32}$. 

- $P_{32} = P_{32S} = 35.73$
- $P_{32} = 25.00$
- $P_{32} = P_{32CJ} = 17.85$

$Q_{32} = 8$
$M_1 = 7$
$P_{21} = 1.269$
$\gamma_3 = 1.3$
FIG. 9(b). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT $P_{32}$. 

$Q_{32} = 8$

$M_1 = 7$

$P_{21} = 2.6$

$\gamma_3 = 1.3$
FIG. 9(c). GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE FOR DIFFERENT $P_{32}$. 

- $Q_{32} = 8$
- $M_1 = 7$
- $P_{21} = 3.172$
- $\gamma_3 = 1.3$
FIG. 9(d).  GRAPHICAL SOLUTION OF THE INTERACTION OF A DETONATION WAVE WITH A SHOCK WAVE AT $P_{21} = P_{21u}$.

$Q_{32} = 8$
$M_1 = 7$
$P_{21} = 4.039$
$\gamma_3 = 1.3$
FIG. 10(a). PRESSURE RATIO ACROSS REFLECTED RAREFACTION WAVES AS A FUNCTION OF PRESSURE RATIOS ACROSS DETONATION WAVE FOR DIFFERENT SHOCK WAVE STRENGTHS.
FIG. 10(b). PRESSURE RATIO ACROSS REFLECTED RAREFACTION WAVES AS A FUNCTION OF PRESSURE RATIOS ACROSS SHOCK WAVE FOR DIFFERENT DETONATION WAVE STRENGTHS.
Fig. 10(c). Pressure ratio across transmitted shock wave as a function of pressure ratios across shock wave for different detonation wave strengths.
FIG. 10(d). PRESSURE RATIO ACROSS TRANSMITTED SHOCK WAVE AS A FUNCTION OF PRESSURE RATIOS ACROSS DETONATION WAVE FOR DIFFERENT SHOCK WAVE STRENGTHS.

Q32 = 7
γ3 = 1.3
FIG. 11(b). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE $P_{21}, P_{32}$ PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER $M_1$ (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(c). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M1 (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(d). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE FOR DIFFERENT VALUES OF THE ONCOMING FLOW MACH NUMBER M₁ (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(e). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE $P_{21}$, $P_{32}$ PLANE (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(f). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE $P_{21}, P_{32}$ PLANE (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(g). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE $P_{21}$, $P_{32}$ PLANE (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(h). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE (AREAS UNDER THE CORRESPONDING CURVES).

Q32 = 3
M1 = 8
\gamma3 = 1.3
Q32 = 3
M1 = 7
γ3 = 1.3

FIG. 11(i). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 11(j). DOMAIN OF EXISTENCE OF INTERACTION CONFIGURATIONS WITH A REFLECTED RAREFACTION WAVE IN THE P21, P32 PLANE (AREAS UNDER THE CORRESPONDING CURVES).
FIG. 12. ILLUSTRATION OF THE UPPER LIMIT OF $P_{32}$ BEING LOWER THAN $P_{32s}$.
FIG. 14. DOMAINS OF EXISTENCE OF VARIOUS INTERACTION CONFIGURATIONS. 
S- WITH A REFLECTED SHOCK WAVE; R- WITH A REFLECTED RAREFACTION WAVE.
FIG. 15. INTERACTION BETWEEN DETONATION WAVE AND SHOCK WAVE WITH TRANSMITTED SHOCK WAVE ON THE STRONG BRANCH.
The interaction of an oblique shock wave and an oblique detonation wave which deflect the flow in the same direction is analyzed. The detonation wave is assumed to be an exothermic gasdynamic discontinuity. A criterion is developed and used to determine whether or not a theoretical solution of the problem describes a physically realizable interaction configuration. It is found that the reflected wave is, in general, a rarefaction wave. Only for very low values of the heat release parameter of the detonation wave the reflected wave has been found to be a shock wave. Domains of existence of such resulting wave interaction configurations are established for different values of the oncoming Mach number, 0 < M < 8, the heat release parameter, 0 < Q < 8, and the specific heat ratios of the combustion products behind the detonation wave, 1.30 < T < 1.35. It is also found that double discontinuity configurations, representing the refraction of a detonation wave at a combustible/non-combustible interface (a limiting case of the considered interaction problem) can exist for certain values of the flow parameters involved and for different specific heat ratios of the gases in front of and behind the detonation wave. The magnitudes of the heat release parameter and specific heat ratio of the combustion products affect significantly the interaction pattern of shock and detonation waves. It is, therefore, concluded that the interaction problem considered be based on a detailed thermochemical analysis for given combustible mixtures of gases.

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