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Abstract

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INTERACTION OF A WEAK ENTROPY WAVE WITH A FLAME FRONT

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The problem of the interaction of a flame front with a contact discontinuity is a particular case of the problem of the decay of an arbitrary discontinuity in a combustible mixture, considered in work ([1]). The formation of pressure waves by a flame front when the thermodynamic parameters of the combustible mixture change was also investigated in ([2]). In both works it was assumed that the flame propagation velocity remained unchanged during the interaction. However, experiments show ([3]) that, when a flame front interacts with compression waves, amplification of these waves is possible; this is explained by a change in the flame velocity during the interaction ([4]). A gas-dynamic treatment of the interaction of weak pressure waves with a flame front was carried out in ([5]). It is of interest to consider the interaction of a flame front with an entropy wave, taking into account the change in the flame propagation velocity caused by this wave.

We shall regard the entropy wave as weak and use a linear approximation. The system of waves formed in such an interaction is shown in Fig. 1. The disturbance in the combustible mixture consists of the incident entropy wave $\delta\rho_1$ and the pressure wave δp_1 that is formed. In the combustion products there arise an entropy wave $\delta\rho_2$ and a pressure wave δp_2. These disturbances are related by the equations of conservation of mass, momentum, and energy at the flame front. Neglecting in these equations small quantities of order $(U/c_1)^2$ and higher, where U is the flame propagation velocity and c_1 is the sound velocity, we obtain

$$\rho_1\delta U + U\delta\rho_1 + U\delta\rho_1 = \rho_2(\delta u_1 - \delta u_2 + \delta U) + \frac{\rho_1}{\rho_2}U\delta\rho_2 + \frac{\rho_1}{\rho_2}U\delta\rho_2;$$

$$\delta p_1 = \delta p_2 + 2\rho_1 U(\delta u_1 - \delta u_2); \tag{1}$$

$$\delta w_1 + \delta w_1 + U\,\delta U = \delta w_2 + \delta w_2 + \frac{\rho_1}{\rho_2}U(\delta u_1 - \delta u_2 + \delta U).$$

Fig. 1: schematic showing the flame front, entropy wave, and perturbations δp_1^{e}, δp_1, δp_2, δp_2^{e}.

Figure 1: Fig. 1: schematic showing the flame front, entropy wave, and perturbations δp_1^{e}, δp_1, δp_2, δp_2^{e}.

In addition, the following relations hold on the waves:
for the incident entropy wave

$$\delta w_1 = -\frac{c_1^2}{\rho_1(\gamma_1 - 1)}\,\delta\rho_1;$$

for the pressure wave in the combustible mixture

$$\delta u_1 = \frac{c_1}{\gamma_1}\frac{\delta p_1}{\rho_1}, \qquad \delta\rho_1 = \frac{\delta p_1}{c_1^2}; \tag{2}$$

for the pressure wave in the combustion products

$$\delta u_2 = -\frac{c_2}{\gamma_2}\frac{\delta p_2}{\rho_2}, \qquad \delta\rho_2 = \frac{\delta p_2}{c_2^2};$$

for the entropy wave in the combustion products

$$\delta w_2 = -\frac{c_2^2}{\rho_2(\gamma_2 - 1)}\,\delta\rho_2.$$

We assume that the change in the flame-propagation velocity is related to changes in the thermodynamic parameters of the combustible mixture by the relation

$$\delta U = A\,\delta p_1 + B\,\delta p_1^{\mathrm{e}}, \tag{3}$$

Fig. 1

where

$$A = \left(\frac{\partial U}{\partial p_1}\right)_{T_1} + \frac{\gamma_1 - 1}{\gamma_1}\frac{T_1}{p_1}\left(\frac{\partial U}{\partial T_1}\right)_{p_1};$$

$$B = -\frac{c_1^2}{\rho_1 c_{p1}(\gamma_1 - 1)}\left(\frac{\partial U}{\partial T_1}\right)_{p_1}.$$

Here we regard the dependence $U(p_1 T_1)$ as determined experimentally or theoretically.

Using (1), (2), (3), we find:

for the pressure wave in the combustible mixture

$$\delta p_1 = \frac{\left[(\rho_1-\rho_2)c_2 B + U c_2 - \frac{\gamma_2-1}{\gamma_1-1}c_1^2\frac{U}{c_2}\right]\delta p_1^{\mathrm{e}}}{\left\{1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A - \left[(\gamma_2-1)\frac{c_1}{c_2} + 2 - (\gamma_2-3)\frac{c_2}{c_1}\right]\frac{U}{c_1}\right\}}; \qquad (4)$$

for the pressure wave in the combustion products

$$\delta p_2 = \frac{\left[(\rho_1-\rho_2)c_2 B + U c_2 - \frac{\gamma_2-1}{\gamma_1-1}c_1^2\frac{U}{c_2} - 2(\rho_1-\rho_2)c_2 B\left(1+\frac{c_2}{c_1}\right)\frac{U}{c_1}\right]\delta p_1^{\mathrm{e}}}{\left\{1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A - \left[(\gamma_2-1)\frac{c_1}{c_2} + 2 - (\gamma_2-3)\frac{c_2}{c_1}\right]\frac{U}{c_1}\right\}}, \qquad (5)$$

for the entropy wave in the combustion products

$$\delta p_2^{\mathrm{e}} = \frac{\left[2\frac{\rho_2 c_2}{\rho_1 c_1} - (\gamma_2-1)\frac{c_1}{c_2} + (\gamma_2-3)\frac{c_2}{c_1}\right](\rho_1-\rho_2)c_2 B}{\left\{1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A - \left[(\gamma_2-1)\frac{c_1}{c_2} + 2 - (\gamma_2-3)\frac{c_2}{c_1}\right]\frac{U}{c_1}\right\}}\frac{\rho_2}{\rho_1}\frac{\delta p_1^{\mathrm{e}}}{c_1 c_2} +$$

$$+\frac{\left[1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A\right]\frac{\gamma_2-1}{\gamma_1-1}c_1^2\frac{c_1}{c_2}}{\left\{1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A - \left[(\gamma_2-1)\frac{c_1}{c_2} + 2 - (\gamma_2-3)\frac{c_2}{c_1}\right]\frac{U}{c_1}\right\}}\frac{\rho_2}{\rho_1}\frac{\delta p_1^{\mathrm{e}}}{c_1 c_2}.$$

In the case when there is a perturbation of the heat release δQ in the combustible mixture, expressions for the quantities δp_1, δp_2, and δp_2^{e} can likewise be obtained. In this case $\delta U = A\,\delta p_1 + D\,\delta Q$, where $D = (\partial U/\partial Q)_{p_1 T_1}$.

For example, the expression for δp_1 has the form:

$$\delta p_1 = \frac{\left[(\rho_1-\rho_2)c_2 D + (\gamma_2-1)\rho_2\frac{U}{c_2}\right]\delta Q}{\left\{1+\frac{\rho_2 c_2}{\rho_1 c_1} - (\rho_1-\rho_2)c_2 A - \left[(\gamma_2-1)\frac{c_1}{c_2} + 2 - (\gamma_2-3)\frac{c_2}{c_1}\right]\frac{U}{c_1}\right\}}. \qquad (7)$$

The presence in the combustible mixture of perturbations δp_1^{e} and δQ leads to the appearance of waves whose intensity is the sum of the intensities of the waves caused by each of these perturbations separately. From expressions (4), (7), in the special case when the variation of the flame-propagation velocity is zero, one can obtain expressions for the intensity of pressure waves given in work [2].

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Note: Figure translations are in progress. See original paper for figures.