https://doi.org/10.15407/ujpe71.6.521

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MAGNETIC-FIELD EFFECT ON DETONATION INTENSITY

The detonation of an ideal gas flow moving in a magnetic field has been studied theoretically. A modified Hugoniot equation was obtained, which takes the influence of the magnetic field on the detonation process and the detonation wave parameters into account. It was demonstrated that under the influence of a magnetic field, combustion products move away from the detonation front at supersonic speeds. With the increasing magnetic field strength, the velocity of the detonation products also increases. A dependence was obtained that makes it possible to estimate the influence of heat release on the detonation parameters.

Keywords: shock waves, detonation, magnetic field, Hugoniot equation, Jouguet detonation process, detonation product velocity.

1. Introduction

Studies of the influence of magnetic fields on combustion and explosion processes have aroused great interest in a wide range of technical applications, from energy to aerospace engineering; see, e.g., Refs. [1–3]. In particular, it was found that the magnetic field has practically no effect on the detonation pressure, but substantially affects the structure of the shock wave front. In Ref. [3], it was shown that the magnetic field affects the shock wave structure and increases the speed of the combustion front; in particular, a magnetic field with induction from 0.4 to 0.5 T was found to strongly affect the combustion front propagation.

Electromagnetic waves arising from the explosion of trinitrotoluene (TNT) have been experimentally studied, in particular, in Ref. [4]. Observations showed that electromagnetic radiation indeed emerges after the detonation of powerful charges. The expansion of detonation products has a strong effect on the surrounding air. This causes an intense heat wave with temperatures $T \sim 11 \times 10^3$ K and a duration of about 20 μs. Such temperatures strongly ionize the air and induce electric and magnetic fields.

Citation: Avramenko A.A., Basok B.I., Gavryushenko D.A., Anastasiev D.V., Kovetskaya M.M. Magnetic-field effect on detonation intensity. *Ukr. J. Phys.* **71**, No. 6, 521 (2026). https://doi.org/10.15407/ujpe71.6.521.

The mechanism of the generated magnetic disturbance was proposed in Ref. [5] on the basis of the model of thermodynamic equilibrium at ionization and the magnetohydrodynamic (MHD) model, taking magnetic diffusion into account. In particular, the magnetic disturbance caused by the electromagnetic wave generated by the explosion was simulated, and the obtained results were compared with experimental data.

A qualitative analysis of the electromagnetic field structure during the detonation of a condensed explosive in a magnetic field was performed in Ref. [6]. It was shown that under the action of detonation wave, the magnitude of electric current increases. The effect of magnetic field on the explosion of alkanes was experimentally analyzed in Ref. [7]. The influence of the magnetic field on the maximum explosion pressure, the pressure growth rate, and the flame propagation rate was determined. It turned out that the magnetic field reduces all these parameters in alkane gas, which diminishes the explosion intensity. The authors of Ref. [8] presented the results of their study of the influence of electromagnetic field on the explosion of methane with a concentration of 9.5% in air. As a main result, an increase in the burning rate under the influence of the electromagnetic field was found.

The authors of Refs. [9, 10] analyzed the propagation of converging cylindrical detonation waves in ideal [9] and non-ideal [10] gases with various initial densities and for a variable azimuthal magnetic field. Three cases were considered: 1) weakly ionized gas, 2) strongly ionized gas, and 3) intensive ionization of non-ionized gas as a result of the detonation front passage. It was found that the azimuthal magnetic field has a damping effect on the detonation front approach.

The propagation of shock waves in ideal and nonideal gases was studied in Refs. [11–14]. The influence of flow turbulence [11, 14], the presence of nanoparticles in the gas [13], and the van der Waals gas parameters [12] on the intensity of heat and mass transfer during the shock wave front passage was revealed and explained.

The study of heat and mass transfer during the propagation of shock waves in microchannels was carried out in papers [15, 16]. A comprehensive study of detonation propagation in micro- and macrochannels [15] showed that the flame acceleration modes in those channels are different. In microchannels, the main influence on the flow interaction with the wall is provided by the detonation wave propagation, which leads to the loss of momentum and, as a result, to a reduction in the detonation velocity. The mechanism of detonation breakdown in macro- and microscale channels has been experimentally studied in Ref. [16]. It was shown that the mechanism of detonation propagation in microchannels is mainly affected by the boundary conditions.

In Ref. [17], the process of flame propagation in a closed tube during the explosion of a propane/air gas mixture in a gradient electromagnetic field was studied experimentally. The experiments showed that the gradient electromagnetic field slows down the combustion process and suppresses the explosion pressure growth and the flame propagation velocity.

The effects of magnetic fields on combustion and hydrocarbon emissions of magneto-conditioned hydrocarbon fuels were reviewed in Ref. [18]. The influence of magnetic fields on the hydrocarbon structure, flame behavior, and internal combustion engine operation was analyzed. Most studies showed that the engine performance can be improved. However, the results for pollutant emissions were contradictory and require further in-depth studies.

In Ref. [19], combustion and magnetohydrodynamic processes in advanced pulsed-detonation rocket engines were reviewed. The study was focused on identifying those potential rocket engine systems that incorporate magnetohydrodynamic phenomena.

As shown in the review above, the strong physicochemical coupling created by the interaction between the magnetic fields and detonation phenomena has many potential applications: from detonation engines and power generation to aerospace applications and nuclear explosions. Current research is focused, in particular, on the influence of the magnetic field on the combustion process in high-speed flows of the air–propane mixture. A wide range of geophysical problems is associated with the study of electromagnetic effects during seismic activity and in the processes of rock deformation and destruction in mines. The studies of the interaction between the electromagnetic field and the shock wave are associated with the need to control nuclear tests.

Despite the fact that detonation waves in a magnetic field have been studied for a long time [20], data on the influence of the magnetic field on the detonation wave parameters are contradictory [18] and

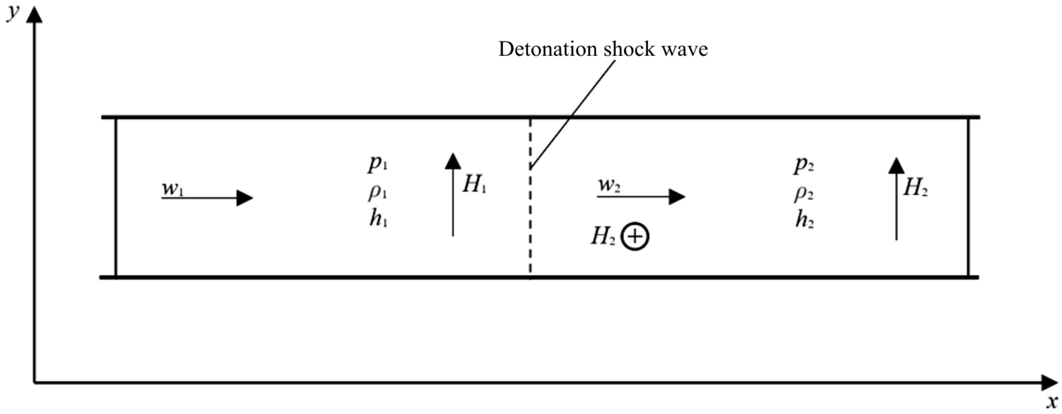

Fig. 1. Schematic diagram of interaction between the flow and the detonation wave

require further study. In particular, the results of research [3] showed that the magnetic field does not affect the detonation pressure, but affects the shock wave structure and increases the pressure front velocity. An increase in the detonation wave velocity under the action of the electromagnetic field was also found in Ref. [18]. The results of experimental studies [7, 17] showed that the electromagnetic field slows down the combustion process and suppresses the rate of flame propagation.

The aim of this work is a theoretical study of the influence of a magnetic field on the detonation process in gases, including its effect on the Jouguet detonation process [21, 22].

2. Mathematical Model

The interaction of an ideal gas flow with a normal detonation wave in a magnetic field is considered. The gas flow is directed along the x-axis, and the magnetic field is directed perpendicularly to it (Fig. 1).

The system of equations describing detonation in a stationary one-dimensional flow with a perpendicular magnetic field has the form [28]

$$\frac{d(\rho w)}{dx} = 0, \tag{1}$$

$$\rho w \frac{dw}{dx} = -\frac{dp}{dx} + \frac{d\tau}{dx} + \mu_e H \frac{dH}{dx}, \tag{2}$$

$$\rho w \frac{de}{dx} = -p\frac{dw}{dx} + \frac{dq}{dx} - \tau\frac{dw}{dx} + \mu_e \nu_H \left(\frac{dH}{dx}\right)^2, \tag{3}$$

where e is the specific internal energy, ρ is the gas density, w is the gas velocity, p is the pressure; x is the coordinate, $\tau = \frac{4}{3}\mu\frac{dw}{dx}$ is the friction stress, μ is the dynamic viscosity, $q = \lambda\frac{dT}{dx} + Q$ is the heat flux consisting of the heat conduction flux and the heat release Q at detonation, λ is the thermal conductivity coefficient, $T(x)$ is the temperature, H is the magnetic field strength, μ_e is the magnetic permeability, $\nu_H = 1/(\sigma_e \mu_e)$ is the magnetic viscosity, and σ_e is the electrical conductivity.

To close the system of equations (1)–(3), it is necessary to obtain an equation for the magnetic field. For this purpose, let us consider Maxwell's equations in general form,

$$\text{rot } \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J} + \varepsilon\frac{\partial \mathbf{E}}{\partial t}, \tag{4}$$

$$\text{rot } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\mu_e\frac{\partial \mathbf{H}}{\partial t}, \tag{5}$$

where $\mathbf{H}$ is the magnetic field strength vector, $\mathbf{E}$ is the electric field strength vector, $\mathbf{J}$ is the electric current density vector, t is the time, $\mathbf{D} = \varepsilon\mathbf{E}$ is the electric induction vector (the electrical displacement), ε is the dielectric constant, and $\mathbf{B} = \mu_e\mathbf{H}$ is the magnetic induction vector. Given the condition [23]

$$\frac{Rc}{Re_M} \ll 1, \tag{6}$$

where $Rc = w^2/c^2$, $\mathbf{w}$ is the gas velocity vector, c is the speed of light, and $Re_M = |\mathbf{w}|\, L/\nu_H$, Ohm's law has the form

$$\mathbf{J} = \sigma_e\,(\mathbf{E} + \mu_e \mathbf{w} \times \mathbf{H}). \tag{7}$$

In approximation (6), the displacement current (the second term on the right-hand side of Eq. (4)) is infinitesimally small, so, by combining Eqs. (4) and (7), we can write

$$\mathbf{E} = \frac{1}{\sigma_e} \text{rot } \mathbf{H} - \mu_e \mathbf{w} \times \mathbf{H}, \tag{8}$$

$$\text{rot } (\mathbf{w} \times \mathbf{H}) - \nu_H \text{ rot rot } \mathbf{H} = \frac{\partial \mathbf{H}}{\partial t}. \tag{9}$$

The gas velocity and magnetic field strength vectors have the following form in Cartesian coordinates. The velocity vector $\mathbf{w}$ is directed along the x-axis,

$$\mathbf{w} = (w, 0, 0), \tag{10}$$

and the magnetic field strength vector $\mathbf{H}$ is directed along the y-axis,

$$\mathbf{H} = (0, H, 0). \tag{11}$$

In this case, Eq. (9) for the stationary regime acquires the obvious form

$$\frac{d(wH)}{dx} = \nu_H \frac{d^2 H}{dx^2}. \tag{12}$$

Theoretically, to describe the behavior of shock and detonation waves, it is more convenient to use the energy equation, expressed in terms of the specific enthalpy $h = e + \frac{p}{\rho}$, because this allows the energy equation to be integrated,

$$\rho w \left(\frac{dh}{dx} + w \frac{dw}{dx} \right) = \frac{dq}{dx} + \frac{d\,(w\tau)}{dx} - \\ - \mu_e \frac{dH}{dx} \left(wH - \nu_H \frac{dH}{dx} \right) = \\ = \frac{dq}{dx} + \frac{d\,(w\tau)}{dx} - \mu_e \frac{dH}{dx} F, \tag{13}$$

where the continuity equation [24, 25]

$$wH - \nu_H \frac{dH}{dx} = F = \text{const}$$

is taken into account.

By integrating Eqs. (1), (2), (12), and (13), we obtain the following system of equations for the conservation of mass, momentum, and energy, which are the Rankine-0Hugoniot relations [28]:

$$\rho_1 w_1 = \rho_2 w_2, \tag{14}$$

$$p_1 + \rho_1 w_1^2 + \frac{\mu_e H_1^2}{2} = p_2 + \rho_2 w_2^2 + \frac{\mu_e H_2^2}{2}, \tag{15}$$

$$\rho_1 w_1 \left[r \left(h_1 + \frac{w_1^2}{2} \right) + Q^* \right] + \mu_e w_1 H_1^2 = \\ = \rho_2 w_2 \left(h_2 + \frac{w_2^2}{2} \right) + \mu_e w_2 H_2^2, \tag{16}$$

$$w_1 H_1 = w_2 H_2, \tag{17}$$

where $Q^* = -\frac{Q}{\rho_1 w_1} = -\frac{Q}{\rho_2 w_2}$is the heat removed ($Q^* < 0$) or released ($Q^* > 0$) per unit mass in the corresponding process that occurs across the shock, subscripts "1" and "2" denote the parameters ahead of the shock wave front and behind it, respectively.

The system (14)–(17) is obtained without taking into account the diffusion and dissipative effects, as well as the longitudinal variation of the magnetic field. This system is a modified system of Rankine–Hugoniot equations [28]. To construct its solution, it is necessary to close it with the thermal equation of state of matter. The theory of detonation proposed by Jouguet [21, 22] is based on the assumption that the thermal equation of state of matter in shock waves is satisfactorily described by the equation of state of an ideal gas.

Using the equation of state of an ideal gas,

$$p = \rho R T, \tag{18}$$

where $R = \frac{k-1}{k}$ is the universal gas constant; $k = c_p/c_v$ is the adiabatic index; c_p and c_v are the specific heats at constant pressure and volume, respectively, to close system (14)–(17), Eq. (16) can be rewritten as follows:

$$\frac{k}{k-1} \frac{p_1}{\rho_1} + \frac{w_1^2}{2} + Q^* + \frac{\mu_e H_1^2}{\rho_1} = \frac{k}{k-1} \frac{p_2}{\rho_2} + \frac{w_2^2}{2} + \frac{\mu_e H_2^2}{\rho_2}. \tag{19}$$

Here, for the enthalpy of the ideal gas, we used one of the forms of the calorific equation of state for an ideal gas, $h = c_p T$.

3. Modified Hugoniot Equation

The system of equations (14), (15), (17), and (19) gives rise to the following equation:

$$\left(1 - \frac{p_2}{p_1} \right) \left(1 + \frac{\rho_1}{\rho_2} \right) - \left(1 + \frac{\rho_1}{\rho_2} \right) \frac{\mu_e H_1^2}{2 p_1} \left(\frac{\rho_2^2}{\rho_1^2} - 1 \right) = \\ = \frac{2k}{k-1} \left(1 - \frac{p_2 \rho_1}{\rho_2 p_1} \right) + 4 \frac{\mu_e H_1^2}{2 p_1} \left(1 - \frac{\rho_2}{\rho_1} \right) + \frac{2 Q^* \rho_1}{p_1}. \tag{20}$$

ISSN 2071-0194. Ukr. J. Phys. 2026. Vol. 71, No. 6

By solving this equation with respect to the ratio p_2/p_1 and performing nondimensionalization, we can obtain the modified Hugoniot equation for detonation,

$$P = \frac{\gamma - r^{-1} + K + \frac{(r-1)^3}{r}M}{\gamma r^{-1} - 1}, \tag{21}$$

where $P = \frac{p_2}{p_1}$, $r = \frac{\rho_2}{\rho_1}$ is the gas compression degree, $\gamma = \frac{k+1}{k-1}$,

$$K = 2Q^* \frac{\rho_1}{p_1} = 2kQ^* \frac{\rho_1}{kp_1} = 2\frac{kQ^*}{a_1^2}$$

is the dimensionless heat release, a_1 is the speed of sound, and $M = \frac{\mu_e H_1^1}{2p_1}$ is the dimensionless magnetic field strength. For a flow with no influence of the magnetic field and no heat release or removal, Eq. (21) can be written in the form

$$P = \frac{\gamma - r^{-1}}{\gamma r^{-1} - 1} = \frac{\gamma - \sigma}{\gamma\sigma - 1}, \tag{22}$$

which is the Hugoniot shock adiabat for an ideal gas [25, 26]. Note that $r^{-1} = \sigma$ in this case.

Equation (21) has the asymptote

$$r = \gamma. \tag{23}$$

This is a classical relation for the maximum degree of gas compression during the shock wave passage, which shows that for an ideal gas ($k = 1.4$), max $r \leq 6$.

4. Maximum Compression and Velocity Characteristics

In order to determine which point on the Hugoniot curve corresponds to a stable normal detonation with a minimum velocity, we use the Jouguet selection rule [21, 22]. Point D on the Hugoniot curve is the required one if the tangent passing through this point also passes through the point $(P,\sigma) = (1, 1)$ (Fig. 2). Point E is the boundary between weak and strong deflagration. As can be seen from Fig. 2, the equation for the tangent is defined as follows:

$$\frac{\Pi - 1}{1 - \sigma} = \frac{d\Pi}{d\sigma}. \tag{24}$$

From Eq. (21), we find that

$$\frac{\Pi - 1}{1 - \sigma} = \frac{d\Pi}{d\sigma} = \frac{1 + \gamma\Pi}{1 - \gamma\sigma} + \frac{(2 + \sigma)(1 - \sigma)^2}{\sigma^3(1 - \gamma\sigma)}M. \tag{25}$$

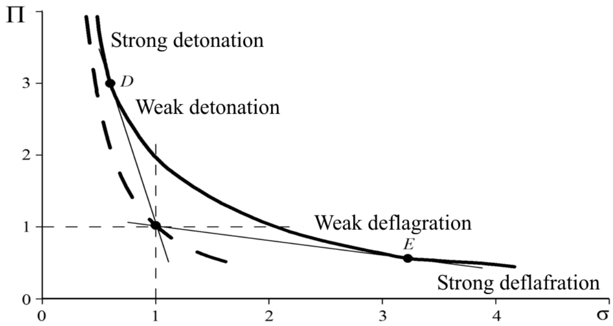

Fig. 2. Jouguet selection rule

Let us define the tangent slope. To do this, we can obtain the following formulas from Eqs. (15) and (16):

$$w_1 = \sqrt{\frac{p_2 - p_1 + \frac{\mu_e}{2}(H_2^2 - H_1^2)}{\rho_2 - \rho_1}\frac{\rho_2}{\rho_1}} =$$

$$= \sqrt{\frac{p_2 - p_1 + \frac{\mu_e}{2}H_1^2\left(\frac{H_2^2 w_2^2}{H_1^2 w_1^2}\frac{w_1^2\rho_1^2}{w_2^2\rho_2^2}\frac{\rho_2^2}{\rho_1^2} - 1\right)}{\rho_2 - \rho_1}\frac{\rho_2}{\rho_1}} =$$

$$= \sqrt{\frac{\Pi - 1 + (\sigma^2 - 1)M}{1 - \sigma}\frac{p_1}{\rho_1}}, \tag{26}$$

$$w_2 = \sigma\sqrt{\frac{\Pi - 1 + (r^2 - 1)M}{1 - \sigma}\frac{p_1}{\rho_1}}. \tag{27}$$

From Eq. (26), we find the slope at point D,

$$\tan(\alpha) = -\frac{\Pi_D - 1}{1 - \sigma_D} = -kMa_1^2 + \frac{r_D^2 - 1}{1 - \sigma_D}M. \tag{28}$$

On the other hand, the same slope is defined using Eq. (24) as follows:

$$\tan(\alpha) = \left(\frac{d\Pi}{d\sigma}\right)_D =$$

$$= \frac{1 + \gamma\Pi_D}{1 - \gamma\sigma_D} + \frac{(2 + \sigma_D)(1 - \sigma_D)^2}{\sigma_D^3(1 - \gamma\sigma_D)}M. \tag{29}$$

The solution of the system of equations (28) and (29) gives the coordinates of point D on the Hugoniot curve. However, this solution is very cumbersome, so it is not presented here. In the absence of a magnetic field ($M = 0$), this solution leads to the well-known Jouguet relations

$$\Pi_D = \frac{1 + kMa_1^2}{1 + k}, \tag{30}$$

$$\sigma_D = \frac{1 + kMa_1^2}{(1+k)\, Ma_1^2}. \tag{31}$$

The solution limit for σ_D at a velocity approaching infinity ($Ma \to \infty$) does not depend on the magnetic field strength and can be expressed as follows:

$$r_D = \left(\frac{\rho_2}{\rho_1}\right)_D = \frac{1+k}{k}. \tag{32}$$

This equation determines the maximum compression at detonation satisfying the Jouguet condition.

For detonation engines, the velocity of detonation products is a very important characteristic. To determine this parameter, Eq. (25) can be rewritten in the form

$$\frac{\Pi - 1}{1-\sigma} = k\frac{\Pi}{\sigma} + \frac{(2+\sigma)\,(1-\sigma)^2}{\sigma^3\,(1-\gamma\sigma)} M. \tag{33}$$

Here we take into account that the derivatives of the Poisson isentropes and the Hugoniot adiabats (22) are equal at point D in the absence of magnetic field [21, 22]. Multiplying Eq. (33) by σ^2, we obtain

$$\sigma^2\frac{\Pi - 1}{1-\sigma} = a_2^2\frac{\rho_1}{p_1} + \frac{(2+\sigma)\,(1-\sigma)^2}{\sigma\,(1-\gamma\sigma)} M. \tag{34}$$

Let us transform Eq. (27) for the velocity of detonation products as follows:

$$w_2^2 = \sigma^2\frac{\Pi - 1}{1-\sigma}\frac{p_1}{\rho_1} + \sigma^2\frac{\left(r^2-1\right) M}{1-\sigma}\frac{p_1}{\rho_1}. \tag{35}$$

Then, Eq. (35) can be rewritten as follows:

$$\sigma^2\frac{\Pi - 1}{1-\sigma}\frac{p_1}{\rho_1} + \sigma^2\frac{\left(r^2-1\right) M}{1-\sigma}\frac{p_1}{\rho_1} = \\ = a_2^2 + \frac{(2+\sigma)\,(1-\sigma)^2 M}{\sigma\,(1-\gamma\sigma)}\frac{p_1}{\rho_1} + \sigma^2\frac{\left(r^2-1\right) M}{1-\sigma}\frac{p_1}{\rho_1}. \tag{36}$$

By comparing Eqs. (35) and (36), we arrive at the following equation for the velocity of detonation products:

$$w_2^2 = a_2^2 + \frac{a_2^2}{\Pi\sigma}\left(\frac{(2+\sigma)\,(1-\sigma)^2}{\sigma\,(1-\gamma\sigma)} + \sigma^2\frac{\left(r^2-1\right)}{1-\sigma}\right)\frac{M}{k}, \tag{37}$$

or, in dimensionless form,

$$Ma_2^2 = 1 + \left(1 + \sigma + \frac{2 - 3\sigma + \sigma^3}{\sigma\,(1-\gamma\sigma)}\right)\frac{M}{k\Pi\sigma}. \tag{38}$$

In Eqs. (37) and (38), the parameter P can be eliminated using the modified Hugoniot equation (22).

Equations (37) and (38) show that in a zero magnetic field, the combustion products flow out of the detonation front at a critical (sonic) speed. With increasing magnetic field strength, the velocity of the detonation products increases. It is obvious that due to the Lorentz force, the magnetic field energy increases the kinetic energy of the averaged flow behind the detonation wave.

The above results are qualitatively consistent with the results of Ref. [27]. In that study, the influence of a magnetic field on the detonation wave propagation in a gaseous explosive mixture was demonstrated. With an increase in the magnetic field from 0 to 5 T, the detonation wave velocity increases from 2800 to 6608 m/s.

The thermal effect weakens the influence of the magnetic field. This fact follows from the generalized equation for the first and second laws of thermodynamics,

$$dq = de - \frac{p}{\rho}d\rho - Hdj, \tag{39}$$

where e is the internal energy, and j is the magnetization.

At detonation, the velocity before the shock wave is not an independent quantity but is determined by thermal effects. Let us find this dependence. For this purpose, we exclude the pressure from Eqs. (22) and (26). As a result, we obtain

$$Ma_1^2 = 2\frac{\sigma(K^* + k(1-\sigma)) + M(2 - k(1-\sigma))}{k\sigma(1-\sigma)(1+\sigma-k(1-\sigma))}, \tag{40}$$

where

$$K^* = K\frac{k-1}{2}. \tag{41}$$

From Eq. (40), it follows that both the thermal effect and the magnetic field lead to the flow acceleration in front of the shock wave.

5. Conclusions

In this paper, the detonation process in an ideal gas flow in a magnetic field has been considered. The novelty of the study itself and its results consists in the fact that the Hugoniot equation was obtained, in which the thermal effect and the influence of the magnetic field are taken into account. The influence of the thermal effect and the magnetic field on the Jouguet point on the Hugoniot curve, which corresponds to a stable normal detonation with a minimum velocity, has been demonstrated.

A differential equation for the maximum compression at detonation has been obtained, which includes the influence of the magnetic field. It has been shown that the relationships for the maximum pressure and density do not include the magnetic field.

An equation has been obtained for the velocity of detonation products. At zero magnetic field, the combustion products flow away from the detonation front at a critical (sonic) speed. As the magnetic field strength increases, the velocity of the detonation products increases. The magnetic field energy increases the kinetic energy of the averaged flow behind the detonation wave due to the Lorentz force. A relationship was obtained that makes it possible to estimate the effect of heat release on the detonation parameters. The thermal effect weakens the magnetic field effect. It was shown that the velocity behind the detonation wave exceeds the speed of sound, whereas the velocity in front of the shock wave depends on the thermal effect and the magnetic field.

The work was carried out within the framework of the fundamental project of the Institute of Engineering Thermophysics of NAS of Ukraine "Aerodynamics and heat transfer in innovative translucent structures and in heat and mass exchange equipment, and their use for the post-war restoration of buildings damaged by blast waves in Ukraine".

The proposed approaches to thermophysical simulation will be used in the future for project No. 2025.06/0054 "Absorption and prevention of the propagation of infrared electromagnetic radiation and the development of thermal masking means" submitted to the competition of the National Research Foundation of Ukraine "Science for strengthening the defense capability and national security of Ukraine".

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Received 18.11.25.
Translated from Ukrainian by O.I. Voitenko

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ВПЛИВ МАГНІТНОГО ПОЛЯ
НА ІНТЕНСИВНІСТЬ ПРОЦЕСУ ДЕТОНАЦІЇ

У роботі теоретично досліджено детонацію в потоці ідеального газу, який рухається в магнітному полі. Отримано модифіковане рівняння Гюґоніо з урахуванням впливу магнітного поля на процес детонації, та параметри детонаційної хвилі. Показано, що під дією магнітного поля продукти горіння віддаляються від фронту детонації з надзвуковою швидкістю. Із збільшенням напруженості магнітного поля зростає й швидкість продуктів детонації. Отримано залежність, яка дає можливість оцінити вплив тепловиділення на параметри детонації.

Ключові слова: ударні хвилі, детонація, магнітне поле, рівняння Гюґоніо, процес детонації Жуґе, швидкість продуктів детонації.