*Article*

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# Transverse and Longitudinal Thermomagnetic Waves in Conducting Media

The excited thermomagnetic wave in anisotropic conducting media is analyzed theoretically at different directions of the gradient of the temperature $\vec{\nabla} T$, relative to the wave vector $\vec{k}$. It is shown that at $\vec{k} \perp \vec{\nabla} T$ (transverse wave) and at $\vec{k} \parallel \vec{\nabla} T$ (longitudinal wave) the oscillation frequency has different values. In these two cases, the excited thermomagnetic waves are increasing. The increment of the increase in each case has different values. It is shown that the values in different directions of electrical conductivity for the excitation and for the increase of thermomagnetic waves play a major role. Depending on the selected conditions, the frequency of thermomagnetic waves changes significantly. In both cases (i.e. $\vec{k} \perp \vec{\nabla} T$ and $\vec{k} \parallel \vec{\nabla} T$), the choice of coordinate systems does not affect the theoretical calculation at all. The frequency and increment of thermomagnetic waves do not depend on the choice of coordinate systems. However, the choice of coordinate systems significantly affects the choice of the direction of the magnetic field and the temperature gradient. The velocity of hydrodynamic motions of charge carriers turns towards the temperature gradient. The excited magnetic field upon excitation of charge carriers (electrons) depends very much on the direction of the temperature gradient. The oscillation frequency of excitation of thermomagnetic waves depends linearly on the value of the temperature gradient. The increment of growth of excited thermomagnetic waves has different values for different values of the tensor of electrical conductivity of the medium $\sigma_{ik}$. It is stated that if the wave vector of excited waves and the constant gradient of the temperature are directed at an angle, i.e. $\left(\vec{k}\vec{\nabla} T = k\nabla T\cos\alpha, \left[\vec{k}\vec{\nabla} T\right] = k\nabla T \sin\alpha\right)$ theoretical calculation of the oscillation frequency and the increment of growth fails due to the high degree of the dispersion equation relative to the oscillation frequency. This theory does not consider the electric field created by the redistribution of charge carriers. The theory takes into account that the constant temperature $T_0$, external field $E_0$, and the mean free path of charge carriers satisfy the relation $k_0 T_0 \ll eE_0 l$, $k_0$ is a constant. At $k_0 T_0 \sim eE_0 l$ and $k_0 T_0 > eE_0 l$ a very high temperature is required, i.e. melting of the medium begins.

*Keywords*: excitation, frequency, increment, thermomagnetic, dispersion equation, temperature gradient, wave, wave vector

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## *Introduction*

In the work of L.E. Gurevich [1] it was shown that hydrodynamic movements in a nonequilibrium plasma, in which there is a temperature gradient, lead to the emergence of magnetic fields.

In the same work it was found that plasma with gradient of the temperature $\vec{\nabla} T$ has oscillatory properties that are noticeably different from the properties of ordinary plasma. Even in the absence of an external magnetic field and hydrodynamic motions, transverse thermomagnetic waves are possible in it (i.e., $\vec{k} \perp \vec{\nabla} T$, $\vec{k}$ — wave vector), in which only the magnetic field oscillates. If there is a constant external magnetic field $\vec{H}_0$, then the wave vector of thermomagnetic waves should be perpendicular to it and lie in the plane ($\vec{H}_0, \vec{\nabla} T$). In addition, the usual Alphen wave splits into two hydrothermomagnetic waves, in which the vectors $\vec{V}$ and are perpendicular to $\vec{H}'$. The spectrum of magnetosonic waves can change noticeably if the propagation speed of thermomagnetic waves is comparable to the speed of sound and the speed of Alphen waves.

If there is a uniform magnetic field in a plasma with gradient of the temperature, then under the influence of thermomagnetic fields it gradually turns in the direction of the temperature gradient.

Research of thermomagnetic waves in homogeneous conducting media (in semiconductors and metals) was carried out in works [2–11]. However, there is no excitation of thermomagnetic waves in anisotropic conducting media. In this theoretical work we will analyze some conditions for the excitation of stable thermomagnetic waves in anisotropic conducting media without an external magnetic field $\vec{H}_0 = 0$ and in the presence of a constant temperature gradient.

*Theory*

In the presence of an electric field $\vec{E}$, gradient of electron concentration $\nabla n$, temperature $\vec{\nabla} T = const$ and hydrodynamic movements $\vec{V}\left(\vec{r},t\right)$, the electric current density in a homogeneous medium has the form:

$$\vec{j} = \sigma \vec{E}^* + \sigma' \left[\vec{E}^* \vec{H}\right] - \alpha \vec{\nabla} T - \alpha' \left[\vec{\nabla} T \vec{H}\right]; \tag{1}$$

$$E^* = \vec{E} + \frac{\left[\vec{V}\vec{H}\right]}{c} + \frac{T}{e}\frac{\vec{\nabla} n}{n}(e>0). \tag{2}$$

In (2), $\vec{E}$ is the external electric field, $\frac{\left[\vec{V}\vec{H}\right]}{c}$ is the electric field created by hydrodynamic motion, $\frac{T}{e}\frac{\vec{\nabla} n}{n}$ is the electric field created by the electron concentration gradient. Substituting (2) into (1), we obtain an equation of the form

$$\vec{x} = \vec{a}\left[\vec{b}\vec{x}\right]; \tag{3}$$

$$\vec{x} = \vec{E}.$$

From (3) we obtain:

$$\vec{E} = -\frac{\left[\vec{V}\vec{H}\right]}{c} - \Lambda'\left[\vec{\nabla} T \vec{H}\right] + \frac{c}{4\pi\sigma}\operatorname{rot}\vec{H} - \frac{c\sigma'}{4\pi\sigma^2}\left[\operatorname{rot}\vec{H},\vec{H}\right] + \frac{T}{e}\frac{\vec{\nabla} n}{n} + \Lambda\vec{\nabla} T. \tag{4}$$

Here $\Lambda = \frac{\alpha}{\sigma}$, $\Lambda' = \frac{\alpha'\sigma - \alpha\sigma'}{\sigma^2}$, $\operatorname{rot} H' = \frac{4\pi}{c} j$, $\frac{\partial H'}{\partial t} = -c \operatorname{rot}\vec{E}'$, $\sigma$ —conductivity coefficient, $\Lambda$ — differential thermoelectric power, $\Lambda'$ —coefficient of the Nernst-Ettinghausen effect.

We will investigate some conditions of thermomagnetic waves in anisotropic conducting media and therefore we will write the electric field in isotropic media

$$\vec{E} = \eta\vec{j} + \eta'\left[\vec{j}\vec{H}\right] + \eta''\left(\vec{j}\vec{H}\right)\vec{H} + \Lambda\frac{\partial T}{\partial x} + \Lambda'\left[\nabla T, H\right] + \Lambda''\left(\nabla T, H\right)\vec{H}; \tag{5}$$

in anisotropic media

$$E_{ik} = \eta_{ik}E_k + \eta'_{ik}\left[\vec{j}\vec{H}\right]_k + \eta''_{ik}\left(\vec{j}\vec{H}\right)H_k + \Lambda_{ik}\frac{\partial T}{\partial x_k} + \Lambda'_{ik}\left[\nabla T, H\right]_k + \Lambda''_{ik}\left(\nabla T, H\right)\vec{H}_k. \tag{6}$$

Here $\eta_{ik}$ is the tensor of the inverse value of the ohmic resistance, $\Lambda_{ik}$ is the tensor of the differential thermoelectric power, $\Lambda'_{ik}$ is the tensor of the Nernst-Ettinghausen coefficient, we will consider in an anisotropic body an external magnetic field $\vec{H}_0$. Then in (6) the terms containing of $\eta'_{ik}, \eta''_{ik}, \Lambda''_{ik}$ are equal to zero. Then for our problem we obtain the following system of equations

$$\begin{gathered} E'_i = \eta_{ik} j'_k + \Lambda'_{ik}\left[\vec{\nabla} T H'\right]_k; \\ \operatorname{rot}\vec{E}' = -\frac{1}{c}\frac{\partial \vec{H}'}{\partial t}; \\ \operatorname{rot}\vec{H}' = \frac{4\pi}{c}\vec{j}' + \frac{1}{c}\frac{\partial \vec{E}'}{\partial t}. \end{gathered} \tag{7}$$

Let us assume that all variables have the form of a monochromatic wave

$$\left(E', H', j'\right) \sim e^{i\left(\vec{k}\vec{r} - wt\right)} . \tag{8}$$

Considering (8) from (7) we obtain:

$$E_i' = \frac{ic^2}{4\pi w} \eta_{ik} \left(\vec{k}\vec{E}'\right) K_k + \frac{iw^2 - ic^2 k2}{4\pi w} \eta_{ik} E_k' + \frac{c\Lambda_{ik}'}{w} \left(\vec{\nabla} T \vec{E}'\right) K_k - \frac{c\Lambda_{ik}'}{w} \left(\vec{k}\vec{\nabla} T\right) K_k' . \tag{9}$$

Here $\vec{k}$ —wave vector, $(i, k = 1,2,3)$.

Let's write

$$E_i' = \delta_{ik} E_k', \delta_{ik} = \begin{cases} 1, & i = k; \\ 0, & i \neq k. \end{cases} \tag{10}$$

Substituting (10) into (9) we obtain:

$$\begin{gathered} \delta_{ik} E_k' = \left( A\eta_{ik} K_l K_k + B\eta_{ik} + \frac{c\Lambda_{il}'}{w} K_l \frac{\partial T}{\partial x_k} \right) E_k'; \\ A = \frac{ic^2}{4\pi w}; \; B = \frac{i\left(w^2 - c^2 k^2\right)}{4\pi w}. \end{gathered} \tag{11}$$

From (11) next dispersion equation is obtained:

$$\left| \Phi_{ik} - \delta_{ik} \right| = 0 ; \tag{12}$$

$$\Phi_{ik} = A\eta_{ik} K_l K_k + B\eta_{ik} + \frac{c\Lambda_{il}'}{w} K_l \frac{\partial T}{\partial x_k} . \tag{13}$$

*Transverse thermomagnetic waves* $\vec{k} \perp \vec{\nabla} T$

At the condition $\vec{k} \perp \vec{\nabla} T$, a coordinate system can be chosen

$$k_1 \neq 0, k_2 = k_3 = 0, k_1 \frac{\partial T}{\partial x_1} = 0, \frac{\partial T}{\partial x_2} \neq 0, \frac{\partial T}{\partial x_3} = 0 .$$

Having written out (13) by components and expanding the determinant (12), we obtain the following dispersion equation in the case $\vec{k} \perp \vec{\nabla} T$.

$$\begin{gathered} i(a-b)w^5 + 4\pi(a_1 - b_1)w^4 + \left[2ic^2k^2(b-a) + i16\pi^2\eta + 4\pi\tilde{w}\eta_1^2\right]w^3 + \\ + \left[4\pi c^2k^2\eta_2^2 + i16\pi^2\left(w_{11}\eta_{21} - w_{21}'\eta_{33} + w_{31}\eta_{23}\right) - 64\pi^3\right]w^2 + \\ + \left[ic^4k^4(a-b) + 4\pi c^2k^2\left(w_{11}\eta_{23}\eta_{31} - w_{11}\eta_{21}\eta_{33} + w_{21}\eta_{11}\eta_{33} + w_{31}\eta_{21}\eta_{13} - \right.\right. \\ \left.\left. - w_{31}\eta_{11}\eta_{33} - w_{21}\eta_{13}\eta_{31}\right) - i16\pi^2c^2k^2\left(\eta_{22} + \eta_{33} + 64\pi^3 w_{21}\right)\right]w + \\ + 4\pi c^4k^4\left(\eta_{22}\eta_{33} - \eta_{32}\eta_{23}\right) + i16\pi^2c^2k^2\left(w_{21}\eta_{33} - w_{31}\eta_{23}\right) = 0. \\ \eta = \eta_{11} + \eta_{22} + \eta_{33} . \end{gathered} \tag{14}$$

From (14) it is easy to see that the general solution is very complicated and therefore we assume the following conditions

$$\begin{gathered} w_{21}\eta_{33} = w_{31}\eta_{23}; \\ \eta_{22}\eta_{33} = \eta_{32}\eta_{23}; \\ \eta = \eta_{21} = \sigma_{21}. \end{gathered} \tag{15}$$

Condition (15) is the choice of the environment.

Substituting (15) into (14) we obtain the following distance equation

$$w^2+\left(w_{11}+i\frac{4\pi}{\eta}\right)w-\frac{c^2k^2\left(\eta-\eta_{11}\right)}{\eta}=0\,. \tag{16}$$

From (16)

$$w_{1,2}=-\frac{w_{11}}{2}-i2\pi\sigma_{21}\pm\frac{w_{11}}{2}\left[1-\frac{16\pi^2\sigma_{21}^2}{w_{11}^2}+\frac{4c^2k^2\left(\frac{1}{\sigma_{21}}-\frac{1}{\sigma_{11}}\right)\sigma_{21}}{w_{11}^2}+i\frac{16\pi\sigma_{21}}{w_{11}}\right]^{1/2} \tag{17}$$

is obtained.

From (17) it is clear that if $\frac{ck}{\sigma_{21}}=2\pi,\ \frac{\sigma_{11}w_{11}}{2c^2k^2}=1$

$$\begin{aligned}
w_{1,2}&=-\frac{w_{11}}{2}-i2\pi\sigma_{21}\pm w_{11}\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^{1/2}\left(1+i\right);\\
w_{1}&=-\frac{w_{11}}{2}-i2\pi\sigma_{21}+ w_{11}\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^{1/2}\left(1+i\right);\\
w_{2}&=-\frac{w_{11}}{2}-i2\pi\sigma_{21}- w_{11}\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^{1/2}\left(1+i\right).
\end{aligned} \tag{18}$$

From (18) it is clear that $w_2$ is decaying wave. A wave with frequency $w_0=-\frac{w_{11}}{2}+w_{11}\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^{1/2}$ can be growing if $w_{11}\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^{1/2}>2\pi\sigma_{21}$ or $w_{11}^{1/2}>2\pi^{1/2}\sigma_{21}^{1/2}$, $\left(\frac{w_{11}}{\sigma_{21}}\right)^{1/2}>2\pi^{1/2}$,

$$w_{11}>4\pi\sigma_{21}. \tag{19}$$

Conditions (19) are satisfied in a certain anisotropic medium. Thus, at $\vec{k}\perp\vec{\nabla}T$ with a frequency

$$w_0=w_{11}\left[\left(\frac{\pi\sigma_{21}}{w_{11}}\right)^2-\frac{1}{2}\right]\approx-\frac{w_{11}}{2}=-\frac{ck\nabla_2T\Lambda_{11}'}{2}$$

in an anisotropic crystal a purely thermomagnetic wave is excited.

*Longitudinal thermomagnetic waves* $\vec{k}\parallel\vec{\nabla}T$

Given the condition, one can choose the axes so that

$$k_1=k,k_2=k_3=0,\frac{\partial T}{\partial x}=\frac{\partial T}{\partial x_1}\neq0,\frac{\partial T}{\partial x_2}=\frac{\partial T}{\partial x_3}=0\,;$$

$$\begin{aligned}
&i\left(a-b\right)w^5+4\pi\left(a_1-b_1\right)w^4+\left[2ic^2k^2\left(a-b\right)+i16\pi^2\eta+4\pi\tilde{w}\eta_1^2\right]w^3+\\
&+\left[4\pi c^2k^2\left(a_1-b_1\right)+i16\pi^2\tilde{w}\eta_2-64\pi^3\right]w^2+\\
&+\left[ic^4k^4\left(a-b\right)+4\pi c^2k^2\tilde{w}_2\eta_3^2+i16\pi^2w_3^2\eta_4-i16\pi^2\left(\eta_{22}+\eta_{33}\right)-\right.\\
&\left.-64\pi^3\left(w_{22}+w_{33}\right)\right]w+4\pi c^4k^4\left(\eta_{22}\eta_{33}-\eta_{23}\eta_{32}\right)+64\pi^3\left(w_{23}w_{32}-w_{22}w_{33}\right)+\\
&+i16\pi^2c^2k^2\left(w_{23}\eta_{32}+w_{32}\eta_{23}-w_{33}\eta_{22}+w_{22}\eta_{33}\right)=0.
\end{aligned} \tag{20}$$

$$\eta_{22}\eta_{33} = \eta_{23}\eta_{32};$$
$$w_{32}\eta_{23} = w_{33}\eta_{22}; \qquad (21)$$
$$w_{22}\eta_{33} = w_{23}\eta_{32}.$$

Substituting (21) into (20):

$$-64\pi^3 w^2 - \left[i16\pi^2\eta c^2k^2 + 64\pi^3\left(w_{22} + w_{33}\right)\right]w + 64\pi^3\left(w_{23}w_{32} - w_{22}w_{33}\right) = 0 \qquad (22)$$

is obtained.

From solution (22):

$$w_{1,2} = -\frac{w_{22} + w_{33}}{2} - i\frac{c^2k^2\eta}{8\pi} \pm \left[\left(\frac{w_{22} + w_{33}}{2} + i\frac{c^2k^2\eta}{8\pi}\right)^2 + w_{22}w_{33} - w_{23}w_{32}\right] \qquad (23)$$

is obtained

is $\eta c^2k^2 = 4\pi\left(w_{22} + w_{33}\right)$

$$w = \frac{w_{22} + w_{33}}{2}\left[-1 + \frac{1}{\sqrt{2}}\left(\sqrt{\alpha^2 + \beta^2} + \alpha\right)\right]^{1/2} + \frac{w_{22} + w_{33}}{2}\left[-1 + \frac{1}{\sqrt{2}}\left(\sqrt{\alpha^2 + \beta^2} - \alpha\right)^{1/2}\right]; \qquad (24)$$

$$\alpha = \left(\frac{w_{22} + w_{33}}{\Omega}\right)^2; \beta = \frac{1}{16\pi}, \Omega^2 = w_{22}w_{33} - w_{23}w_{32}. \qquad (25)$$

Considering (25), analysis of (24) shows that when

$$\left(\sqrt{\alpha^2 + \beta^2} - \alpha\right)^{1/2} > 1 \qquad (26)$$

with a frequency

$$w_0 = \frac{w_{22} + w_{33}}{2}\left[-1 + \frac{1}{\sqrt{2}}\left(\sqrt{\alpha^2 + \beta^2} + \alpha\right)^{1/2}\right]$$

an unstable wave is excited and when performing (26) it is required

$$\left(\frac{1}{16\pi}\right)^2 > \frac{2\left(w_{22}w_{33} - w_{23}w_{32}\right)}{\left(w_{22} + w_{33}\right)^2} + 1. \qquad (27)$$

Inequality (27) is satisfied if $w_{23}w_{32} > w_{22}w_{33}$. Then

$$\left(\frac{1}{16\pi}\right)^2 > 1 - \frac{2w_{23}w_{32}}{\left(w_{22} + w_{33}\right)^2}.$$

If $w_{22} = w_{33}$

$$\left(\frac{1}{16\pi}\right)^2 > 1 - \frac{w_{23}w_{32}}{2w_{22}^2}$$

or

$$\frac{w_{23}w_{32}}{2w_{22}^2} > 1.$$

Then the frequency of the thermomagnetic wave

$$w_0 = w_{22}\left[-1 + \frac{1}{\sqrt{2}}\left(\sqrt{\alpha^2 + \beta^2} + \alpha\right)^{1/2}\right] \qquad (28)$$

and the growth increment

$$w_1 = w_{22}\left[-1+\frac{1}{\sqrt{2}}\left(\sqrt{\alpha^2+\beta^2}-\alpha\right)^{1/2}\right]. \quad (29)$$

From (28–29) it is clear that $w_1 < w_0$.

*Conclusion*

Thus, in anisotropic conducting media, a transverse $\vec{k} \perp \vec{\nabla} T$ and longitudinal $\vec{k} \parallel \vec{\nabla} T$ growing thermomagnetic wave is excited. The frequencies of these waves $w_0\left(\vec{k} \perp \vec{\nabla} T\right)$ and $w_0\left(\vec{k} \parallel \vec{\nabla} T\right)$ are determined by the conductivities in different directions.

$w_0\left(\vec{k} \parallel \vec{\nabla} T\right)$ depends only on the frequency $w_{22} = c\Lambda'_{22} k \nabla_2 T$, and $w_0\left(\vec{k} \perp \vec{\nabla} T\right)$ depends only on the frequency $w_{11} = c\Lambda'_{11} k \nabla_2 T$ and therefore the values of these frequencies are different. The increment of growing $w_1\left(\vec{k} \parallel \vec{\nabla} T\right)$ and $w_1\left(\vec{k} \perp \vec{\nabla} T\right)$ also depend on different values of the frequency of thermomagnetic waves. The Nernst-Ettinizhausen coefficient $\Lambda'_{ik}$ is different in different directions. Of course, studies of thermomagnetic waves in the presence of an external magnetic field certainly lead to different dependencies $w_0\left(\vec{k} \perp \vec{\nabla} T\right)$ and $w_0\left(\vec{k} \parallel \vec{\nabla} T\right)$.

The obtained expressions for frequency, expressions for increment in this theoretical work, are valid for waves propagating perpendicular to the temperature gradient, when parallel to the temperature gradient the conditions of excitation of waves in the medium will be different. It is possible to conduct corresponding experiments based on the results of this theoretical work and apply them to GaAs-type semiconductors. As for the application of the obtained results, it is necessary to experimentally measure The Nernst-Ettinizhausen coefficient $\Lambda'_{ik}$ in anisotropic conducting media. After measuring this coefficient, it is possible to control significantly the frequencies $\omega_0$ and $\omega_1$. This can lead to an improvement in the preparation of generators based on these thermomagnetic waves.



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## Өткізгіш орталардағы көлденең және бойлық термомагниттік толқындар

Температура градиентінің $\vec{\nabla}T$ толқындық векторға $\vec{k}$ қатысты әртүрлі бағыттарында анизатропты өткізгіш ортада қоздырылатын термомагниттік толқынға теориялық талдау жүргізіледі. $\vec{k} \perp \vec{\nabla}T$ (көлденең толқын) және $\vec{k} \parallel \vec{\nabla}T$ (бойлық толқын) жағдайларында тербеліс жиілігі әртүрлі мәнге ие болатыны көрсетілген. Бұл екі жағдайда да қоздырылатын термомагниттік толқындар арттырушы сипатқа ие. Әрбір жағдайда толқынның күшею инкременті әртүрлі болады. Термомагниттік толқындардың қозуы мен күшеюіне анизотропты ортаның әртүрлі бағыттарындағы электрөткізгіштік $\sigma_{ik}$ мәндері басты рөл атқаратыны дәлелденген. Таңдалған шарттарға байланысты термомагниттік толқынның жиілігі елеулі түрде өзгереді. Екі жағдайда да (яғни, $\vec{k} \perp \vec{\nabla}T$ и $\vec{k} \parallel \vec{\nabla}T$ ), координаттар жүйесін таңдау теориялық есептеулерге әсер етпейді. Термомагниттік толқындардың жиілігі мен күшею инкременті координаттар жүйесіне тәуелді емес. Алайда, координаттар жүйесін таңдау магнит өрісі мен температура градиенті бағытын таңдауға елеулі әсер етеді. Гидродинамикалық қозғалыс жылдамдығы температура градиенті бағытына қарай бағытталады. Заряд тасымалдаушылар (электрондар) қоздырылған кезде пайда болатын магнит өрісі температура градиенті бағытына қатты тәуелді. Термомагниттік толқындардың қозу тербеліс жиілігі температура градиентінің шамасына сызықты түрде тәуелді. Қоздырылатын термомагниттік толқындардың күшею инкременті ортаның электрөткізгіштік $\sigma_{ik}$ тензорының әртүрлі мәндерінде түрліше болады. Қоздырылатын толқынның толқындық векторы мен тұрақты температура градиенті $\left(\vec{k}\vec{\nabla}T = k\nabla T\cos\alpha, \left[\vec{k}\vec{\nabla}T\right] = k\nabla T\sin\alpha\right)$ бір-біріне белгілі бір бұрышпен бағытталған жағдайда, тербеліс жиілігіне қатысты дисперсиялық теңдеудің дәрежесі болуына байланысты тербеліс жиелігі мен күшею инкрементінің теориялық есептеулері орындалмайтындығы дәлелденген. Бұл теорияда заряд тасымалдаушылардың қайта таралуы нәтижесінде пайда болатын электр өрісі есепке алынбаған. Теорияда температураның тұрақты мәні $T_0$, сыртқы өріс $E_0$, және заряд тасымалдаушылардың еркін жүріс ұзындығы $k_0T_0 \ll eE_0l$, $k_0$ мына шартқа сәйкес келетіні қарастырылған. Егер $k_0T_0 \sim eE_0l$ және $k_0T_0 > eE_0l$ жағдайында болса, ортаның балқу процесі басталатындай өте жоғары температура қажет етіледі.

*Кілт сөздер:* қозу, жиілік, инкремент, термомагнит, дисперсиялық теңдеу, температура градиенті, толқын, толқындық вектор

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## Поперечные и продольные термомагнитные волны в проводящих средах

Теоретически анализируется возбуждаемая термомагнитная волна в анизотропных проводящих средах при различном направлении градиента температуры $\vec{\nabla}T$, относительно волнового вектора $\vec{k}$. Показано, что при $\vec{k} \perp \vec{\nabla}T$ (поперечная волна) и при $\vec{k} \parallel \vec{\nabla}T$ (продольная волна) частоты колебаний имеют разные значения. В этих двух случаях возбуждаемые термомагнитные волны являются нарастающими. Инкремент нарастания в каждом случае имеют разные значения. Показано, что значения в разных направлениях электропроводности $\sigma_{ik}$ для возбуждения и для нарастания термомагнитных волн играют основной роль. В зависимости от выбранных условий значения частоты термомагнитных волн существенно меняется. В обоих случаях (т.е. $\vec{k} \perp \vec{\nabla}T$ и $\vec{k} \parallel \vec{\nabla}T$ ) выбор координатных систем совсем не влияет на теоретический расчёт. Частота и инкремент термомагнитных волн не зависят от выбора координатных систем. Однако выбор координатной системы существенно влияет на выбор направления магнитного поля и градиента температуры. Скорость гидродинамических движений носителей заряда поворачивается в сторону градиента температуры. Возбуждаемое магнитное поле при возбуждении носителей заряда (электронов) очень сильно зависит от направления градиента температуры. Частота колебания возбуждения термомагнитных волн линейно зависит от значения градиента температуры. Инкремент нарастания возбуждаемых термомагнитных волн имеет разные значения при разных значениях тензора электропроводности среды $\sigma_{ik}$. Утверждено, что если волновой вектор возбуждаемых волн и постоянный градиент температуру направлен под углом, т.е. $\left(\vec{k}\vec{\nabla}T = k\nabla T\cos\alpha, \left[\vec{k}\vec{\nabla}T\right] = k\nabla T\sin\alpha\right)$ теоретический расчёт частоты колебания и инкремент нарастания не удаётся из-за высокой степени дисперсионного уравнения относительно частоты колебания. В этой теории не учтены электрическое поле, создаваемое перераспределением носителей заряда. В теории учтены, что постоянная температура $T_0$, внешнее поле $E_0$, длина свободного пробега носителей

заряда удовлетворяют соотношению $k_0T_0 \ll eE_0l$ , $k_0$ -постоянная. При $k_0T_0 \sim eE_0l$ и $k_0T_0 > eE_0l$ требуется очень высокая температура, т.е. начинается плавление среды.

*Ключевые слова:* возбуждение, частота, инкремент, термомагнит, дисперсионное уравнение, градиент температуру, волна, волновой вектор

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