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Characteristic times of acoustic and condensation instability in heat-releasing gas media

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Abstract

We investigate wave evolution in gas media with non-adiabatic heating and cooling processes depending on temperature and density. In this work, the temporal instability of acoustic disturbances in a heat-releasinguniform gas medium is under consideration. We neglect the influence of shear viscosity and thermal conduction. During the investigation, we describe the dispersion relation for the dynamics of two acoustic modes propagating in opposite directions and condensation (thermal) mode. The condensation mode haspurely imaginary frequency and describes local changes of temperature and density under constant pressure. Furthermore, analytical expressions for temporal increments of acoustic and condensation modes are obtained. Features of obtained solutions depending on the ratio of low- and high-frequency adiabatic indexes are shown. The relationship between the acoustic temporal increment and the second (bulk) viscosity coefficient is described as well.

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*Keywords:*Thermal instability, bulk viscosity, condensation mode ;

1. Introduction

Thermalinstabilitiesplayanimportantroleinthe formation of a variety of spatio-temporal structures in the solar chromosphere and corona, interstellar media (ISM) and planetary nebulae.They are associated with the appearance of shock waves, the formation of solar prominences and condensations in suchmedia. In these media, there are non-adiabatic heating and cooling processes due to the radiation cooling, chemical reactions, etc. Such processes are

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described analytically usingthe generalized heat-loss function $\Im(\rho,T)=L(\rho,T)-\Gamma(\rho,T)$, depending on temperature and density. In a homogeneousmedium with stationary values of temperature T_0 and density ρ_0 ,heating $\Gamma(\rho,T)$ and cooling processes $L(\rho,T)$ compensate each other, i.e. $\Im(\rho_0,T_0)=0$. The heat-source poweris changed with density and temperature perturbations. Under certain conditions, the positive feedback between acoustic disturbances and the active medium appears.It was previously shown in [1] that in such active media three types of instabilities can be realized: isentropic, isobaric and isochoric. The firstis responsible for the acoustic waves amplification propagating in such a medium. Isobaric and isochoric instabilities are responsible for condensation growth and occurrence of convective flows, respectively. Another consequence of non-adiabatic heating and cooling processes is the dispersion of sound speed and decrement (increment) of acoustic disturbances due to the presence of the characteristic time of heating:

$$\tau_0=\frac{k_B T_0}{m\Gamma_0}; \qquad \Gamma_0=\Gamma(\rho_0,T_0). \tag{1}$$

Here k_B is the Boltzmann constant; m is a mean mass of the particles.

Relative to this value, one can dividethe entire frequency spectrum into tworanges.The propagation of sound in the low-frequency part of the spectrum $(\omega\tau_0 \ll 1)$, in contrast toits high-frequency part $(\omega\tau_0 \gg 1)$,is determined by the parameters of heat source. It can be described by the effective low-frequency heat capacities at constant volume C_{V0} and pressure C_{P0} [2, 3]:

$$C_{V0}=\frac{k_B T_0 \Im_{T0}}{m\Gamma_0}; \quad C_{P0}=\frac{k_B\left(T_0\Im_{T0}-\rho_0\Im_{\rho 0}\right)}{m\Gamma_0}; \quad \Im_{T0}=\left(\frac{\partial\Im}{\partial T}\right)_{\rho=\rho_0,T=T_0}; \quad \Im_{\rho 0}=\left(\frac{\partial\Im}{\partial\rho}\right)_{\rho=\rho_0,T=T_0}. \tag{2}$$

Dispersion relation for magnetoacoustic waves taking into account thermal conduction and electrical conductivity was obtained in previous works [4-8].The spatial increments of magnetoacoustic waves as well as their values in the solar coronawere obtained considering the frequency and wavenumber to be real and complex, respectively. Anothercase(real wavenumber and complex frequency) can be analyzed as well. In this case, we obtain temporal increments for travelling acoustic (or magnetoacoustic) waves and for the condensation (entropy) mode.The condensation mode has purely imaginary frequency and describes local changes of temperature and density under constant pressure. The behavior of condensation mode has been the subject of research of many authors, because its instability is related to the formation of solar prominences and condensations in ISM. In previous works [1, 9-13],the magnetic field, thermal conduction, electrical conductivity, viscosity and partial ionization effects were extensively studied. However, the influence of heat source parameters on dispersion properties of acoustic and condensation modes was left without proper attention. Thus, the main goal of present work is the investigation of low-frequency adiabatic index $\gamma_0=C_{P0}/C_{V0}$ influence on temporal increments of acoustic and condensation modes. To simplify the analytical investigation,wewill consider the heat releasing gas mediumneglecting the dissipation. Also, the medium is assumed to be homogeneous. In other words, we assume that density and temperature gradients at the wavelength of perturbations are small.

2. Analytical investigation

2.1. Expressions for temporal increments of acoustic and condensation modes

Thebasicsetofgasdynamicequationswithheatsourcedependingontemperatureanddensityconsistsofequations of continuity, motion, heat transfer and equation of state. Neglecting dissipation, it can be written in the vector form as follows:

$$\frac{\partial\rho}{\partial t}+div\rho\vec{V}=0; \quad \rho\frac{d\vec{V}}{dt}=-\nabla P; \quad C_{V\infty}\frac{dT}{dt}-\frac{k_B T}{m\rho}\frac{d\rho}{dt}=-\Im(\rho,T); \quad P=\frac{k_B\rho T}{m}. \tag{3}$$