# PRODUCTION OF SOUND SELF-OSCILLATIONS AS A RESULT OF VAPOR CONDENSATION

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Summary The problem devoted to spontaneous production of sound in nonuniformly heated acoustic resonator under heterogeneous vapor condensation is investigated analytically. It is shown that the condensation plays a critical role in this effect. The regions of oscillation instability in this system are found on the basis of exact solution of full system of linearized hydrodynamic equations.

## INTRODUCTION

It is known [1], that nonuniform heating of various gaseous systems can promote production and maintenance of sound oscillations. However, presence of vapors of volatile liquids is not taken into account when the problems are considered. Meanwhile the importance of last condition was noted by De la Rive ([1], Ch.XVI, 322*i*). The self-sustained oscillations in two-phase condensing flow systems are studied in works of Bhatt and Wedekind [2,3]. These and our [4] experimental data suggest that condensation is a determining condition for initiation of sound self-oscillations in nonuniform heated system.

The basic results of the experiments devoted to checking of this hypothesis, are given in [4]. The experiments were carried out with steel and glass acoustic resonators contained heater and cooler (a cooled neck - tubule). The basic qualitative results of the experiments are: a) mass of liquid, condensed on cooled neck, was equaled to mass of the vapor contained in the resonator; b) sound self-excited oscillations were generated only at presence of a temperature gradient along the resonator; c) gas-vapor mixture made piston movement in the resonator neck; d) a thin layer of condensate covered the resonator cooler.

## MATHEMATICAL MODEL

We shall seek the analytical solution of the problem due to great number of parameters, and also with the purpose of best understanding of the effect. The mathematical model of spontaneous production of sound self-oscillation in nonuniform heated vapor-filled resonator has the following assumptions:

1. The open resonator filled in vapor of volatile liquid contains the cooler and the heater. The temperature of the cooler and the pressure of the gas near to its flat surface correspond to phase transition "vapor-liquid".
2. There are no condensation centers in the volume of the resonator. The surface of the cooled neck is wetted with a liquid.
3. In the resonator at isothermal conditions at condensation point the total mass of volatile liquid consists of the thin layer of a liquid (phase $i$=1), enveloping the cooler, and the vapor (phase $i$=2) which fills in all resonator volume.
4. The kinetic coefficients (thermal diffusivity $\chi_i$, thermal conductivity $\kappa_i$, dynamic viscosity $\eta_i$, volume viscosity $\zeta_i$ and kinematic viscosity $\nu_i$, specific heat at constant pressure $C_{pi}$ ; specific heat of phase transition $L$) are constant. The temperature and saturation vapor pressure are related by Clapeyron-Clausius equation.
5. The investigations are limited by the analysis of small sound oscillations. It is assumed that variations of density ρ, temperature $T$ and pressure $p$ in vapor are small in comparision with their equilibrium values $p=C\rho+DT$, where the constants $C$ and $D$ are determined by Van der Waals equation.
6. The most simple mathematical model, taking into account all features of the experiments [3], is a vapor-filled volume $-h_2 \le z \le 0$, and the layer of liquid $0 \le z \le h_1$. The constant temperatures $T_2 > T_1$ are hold on surfaces $z = -h_2$ and $z = h_1$ respectively.
7. It is assumed that at initial time a steady nonconvectional heat transfer regime is established. It is characterized by linear distribution of temperature $T_{20} = -A_2 z$; $T_{10} = -A_1 z$; $\kappa_2 A_2 = \kappa_1 A_1$.

Under these assumption the evolution of disturbances of velocities $\mathbf{v}_i$, pressures $p_i$ , densities $\rho_i$ ,temperatures $T_i$ in both phases and interface displacement ε is determined by the following system of hydrodynamic equations and boundary conditions :

$$\frac{\partial \mathbf{v}_i}{\partial t} = -\frac{\nabla p_i}{\rho_{i0}} - \nu_i \nabla \times (\nabla \times \mathbf{v}_i) + (\frac{\varsigma_i}{\rho_{i0}} + \frac{4}{3}\nu_i)\nabla(\nabla \mathbf{v}_i) \tag{1}$$

$$\frac{\partial T_i}{\partial t} + \mathbf{v}_i \nabla T_{i0} = \chi_i \Delta T_i; \qquad \frac{\partial \rho_i}{\partial t} + \rho_{i0}\nabla \mathbf{v}_i = 0; \qquad p_i = C_i \rho_i \tag{2}$$

$$z = h_1 : T_1 = 0; \mathbf{v}_1 = 0 \; ; \qquad z = h_2 : T_2 = 0; \mathbf{v}_2 = 0 \tag{3}$$

$$z = \varepsilon : \quad (\rho_{20} - \rho_{10}) \frac{\partial \varepsilon}{\partial t} = \rho_{10} v_{1z} - \rho_{20} v_{2z}; T_1 = T_2 + (A_1 - A_2)\varepsilon; \tag{4}$$

$$p_1 - p_2 = 2\eta_1 \frac{\partial v_{z1}}{\partial z} - 2\eta_2 \frac{\partial v_{z2}}{\partial z} + (\varsigma_1 + \frac{2}{3}\eta_1)\mathrm{div}\mathbf{v}_1 - (\varsigma_2 + \frac{2}{3}\eta_2)\mathrm{div}\mathbf{v}_2 \tag{5}$$

$$\kappa_1 \frac{\partial T_1}{\partial z} = \kappa_2 \frac{\partial T_2}{\partial z} - \frac{L\rho_{10}\rho_{20}}{(\rho_{20} - \rho_{10})}(v_{1z} - v_{2z}) \tag{6}$$

$$\frac{\partial T}{\partial t} = \gamma(T + A_2\varepsilon) \; ; \qquad \frac{1}{\gamma} \approx \tau_T \tag{7}$$

The Navier-Stokes (1), heat transfer and continuity equations (2) are linearized in disturbances. Equation of state in (2), which is relation between displacements of pressure $p_i$ and density $\rho_i$ from equilibrium values, is written with the assumption that the phases are undeformed thermally.

The boundary conditions for equations (1)-(2) are: a) requirements of absence of velocity and temperature disturbances (3) on solid isothermal surfaces of the cooler $z = -h_2$ and the heater $z = h_1$; b) continuity of fluxes of mass, temperature and heat, and normal stresses (4) - (6) on interface z = ε; c) the kinetic condition (7) is written with assumption that the rate of restoration of equilibrium of temperature value from condensate point to metastability region is determined by kinetic equation of the type $dT/dt = -\gamma T$.

The exact solution of dimensionless equations (1)-(7) for disturbances of "piston" type is found. The system of dimensionless equations has 12 independent parameters. Ten of them ($\mathrm{Pr}=\nu_2/\chi_2$; $\zeta_i=\zeta_i/\eta_2$; $C_i=C_i(s/\nu_2)^2$; $\chi=\chi_1/\chi_2$; $\kappa=\kappa_1/\kappa_2$; $\nu=\nu_1/\nu_2$; $\eta=\eta_1/\eta_2$; $\rho=\rho_{10}/\rho_{20}$) determine physical and chemical properties of phases; $A_i = A_i\, s^3\gamma/\eta_2$ – are analogues of Grashoff numbers, $h_i = h_i/s$ – are geometric factors ($i$=1,2), $\lambda=\lambda s^2/\nu_2$ – is separation constant (decrement).

## CONCLUSIONS

The final equation, determining the values of decrements $\lambda=\mathrm{Re}\lambda+i\omega$ as functions of 12 parameters, can be solved for any specific heterogeneous system. Constructed neutral curves ($\mathrm{Re}\,\lambda = 0$, $\mathrm{Im}\lambda \equiv \omega \neq 0$) in a plane ($\lg A_2$, $\lg h_2$) determine the regions of oscillation instability.

Finally, the production of sound self-oscillations can be explained with the following reasoning. Let us suppose that the portion of liquid was vaporized from the surface of a liquid film. As that, the layers cooled as a result of evaporation, direct in the areas with the high temperature where the process of their heating takes place. The temperature of the liquid surface decreases both due to evaporation and to displacement in the cooler direction. Besides the evaporated volumes of a liquid increase the pressure in the system, that also causes displacement of the figurative point of the system on the phase diagram ($p$, $T$) in the direction of a liquid. The cooling of the surface and increasing of the pressure cause the return flux of vapor molecules to the interface with the subsequent condensation on it. But now the heated vapor directs to the interface. This vapor, being condensed, increases the temperature of the surface, causing the next act of evaporation. This repeating process is possible at the certain values of temperature gradient $A_2$ and various thicknesses of liquid and vapor layers.

**References**


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