Distribution of the Heat Flux on the Axis in a Uniform Closed Tube with Highly Non-Linear Resonant Gas Oscillations

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Abstract. The results of an experimental study of the acoustothermal effect, which is large for nonlinear gas oscillations in a closed pipe at a resonant frequency, are presented. The distribution of the heat flow along the tube is obtained. It was found that at the ends of the closed tube, the heat flow takes maximum and positive values, which indicates the heating of the gas. In the middle of the tube, the gas takes on minimum values, which indicates cooling in this area.

1. Introduction
The study of nonlinear effects arising from resonant gas oscillations is relevant for fundamental research and in practical applications. Of particular interest are such effects as secondary flows, heat generation, and thermoacoustic processes in tubes. The work [1] on experimental and theoretical studies of the distribution of heat flow along a closed tube under resonant gas oscillations is known. In [2], the features of the flow of heat flow in a closed cylindrical tube at resonant frequencies are analytically justified. Thanks to the thermoacoustic effects, energy is converted, which can be used in the creation of heat pumps and refrigerators. Nonlinear effects in thermoacoustic refrigerators caused by an acoustic source are considered in [3]. In the article [4], the conditions of homeostatic periodic motion of a thermoacoustic system are discussed and analyzed. The paper [5] presents the results of theoretical and experimental studies of thermal secondary effects arising from nonlinear gas oscillations in an open tube. The distributions of the heat flow along the tube during the transition through the resonance for different amplitudes of the piston displacement are obtained. The results of the research can be useful in the production of heat pumps and refrigerators. In this paper, we study the effect of forced longitudinal gas oscillations on the distribution of heat flow in a closed tube at resonance.

2. Experimental unit
The research was carried out on an experimental installation (Figure 1) based on the TIRAvib S5220/LS vibration stand 1, with a TIRA BAA 1000-ET power amplifier and a cooling fan. In order to prevent the oscillation of the vibration stand from being transmitted to the floor, it was placed on pneumatic shock-absorbing cushions. On the table of the vibration generator 2, a flat piston 7 with a diameter of $2R = 0.1$ m was installed with the help of a rod, which
moved according to a sinusoidal law in a cylinder 3 of a similar diameter. Quartz tube 4 with a diameter of $2R = 0.1$ m was glued into the upper and lower nozzles and held in a vertical position by means of screeds. The passive end of the tube was hermetically sealed. The total length of the tube from the piston to the upper nozzle $L = 0.938$ m.

![Figure 1. Scheme of the experimental unit: 1-vibration generator, 2-vibration table, 3-cylinder, 4-quartz tube, 5 - probe with thermistors, 6-pressure sensor, 7-piston, 8-accelerometer, 9 - probe when approaching](image)

The vibrator was controlled and monitored using a piezoelectric accelerometer 8 4513 from Bruel & Kjaer (Denmark) and a VR9500 controller from Vibration Research Corporation (USA) using a special software VibrationVIEW, where the values of the frequencies and the swing of the piston $2l$ were set with an accuracy of $10^6$ Hz and $10^7$ m, respectively. A piezoelectric pressure sensor 6, 5 mm in diameter, model 8530C-15 (Bruel & Kjaer, Denmark), was twisted into the hole of the lower nozzle, the signal from which was fed to a digital oscilloscope through a three-channel bridge voltage amplifier. To measure the temperature, a thermistor model B57861-S 103-F40 (Figure 2) was used, soldered to the probe 5 located on the tube axis. The studies were carried out at a distance $x = 0.1$ m between each measurement along the tube. A thermistor was a semiconductor device whose electrical resistance changes with temperature and decreases with increasing temperature (NTC). The sensor has high accuracy and stability of readings in a wide temperature range, the measurement error is 1%. The resistance readings taken from the sensor were converted to temperature values, which was required to calculate the heat flux in a closed tube relative to the ambient temperature.

In the operating temperature range, the dependence of the resistance of the thermistor on temperature can be described by the formula:

$$R_t = R_N\exp\left[ B \left( \frac{1}{t} - \frac{1}{t_N} \right) \right]$$
Table 1. Technical parameters

| application area | temperature measurement |
|------------------|--------------------------|
| design           | a drop                   |
| resistance at 25 C, ohm | 10000                |
| accuracy         | 1%                       |
| temperature sensitivity coefficient | 3988               |
| case diameter, mm | 2.41                    |
| body length, mm  | 6.5                      |
| Working temperature | (-55...155°C)          |

3. Results and its discussion

As a result of experimental studies, the results of nonlinear gas oscillations were obtained near the resonance frequency \( v_1 = 182 \) Hz for the piston stroke amplitude \( l = 0.375 \) mm \([7]\). The oscillogram in Figure 3b, it can be seen that the waveform is continuous. However, at the resonant excitation frequency, a strong deformation of the waveform is observed, when the leading front of the wave is much shorter in time than the trailing one and the gas oscillations are close to the shock one. The theoretical resonance frequency was estimated using the known dependence \([6]\):

\[
v_1^* = \frac{c_0 n}{2L(1 + \beta')}, \beta' = \frac{1}{2} \left(1 + \frac{\chi - 1}{\sqrt{Pr} \delta R}\right),
\]

where \( c_0 \) is the equilibrium speed of sound and \( \beta' \) is the absorption coefficient, \( \chi \) is the adiabatic index, \( Pr \) is the Prandtl number, \( \delta \) is the thickness of the acoustic boundary layer, \( R \) is the tube radius, \( n = 1 \). There is a coincidence of theoretical and experimental results. Based on the experimental temperature values, the heat flux was calculated by the formula:

\[
q = \lambda (T_e - T),
\]

where \( \lambda \) is the coefficient of thermal conductivity of air, \( T_e \) is the ambient temperature. Based on the data obtained, the distributions of the heat flux along the tube are plotted in Figure 3a, where it can be seen that different sections along the tube length in resonance are
heated unevenly. At the ends of the tube, the heat flux is positive and causes heating of the corresponding sections of the tube walls. In the middle of the tube, the heat flux decreases to zero and becomes negative. This indicates that in the middle of the tube, the gas is cooled relative to the ambient temperature.

**Figure 3.** a - dependence of the heat flux $q$ on the position of the sensor along the tube $x$, at a resonant frequency of gas oscillations of 182 Hz for an excitation amplitude of 0.375 mm, B - oscillogram of the gas pressure at resonance. Points are experimental data, solid line is Lorentz approximation.

### 4. Conclusion

The acoustothermal effect is experimentally investigated for nonlinear gas oscillations in a closed tube at the resonant frequency of gas excitation. The uneven distribution of the heat flow along the tube was revealed. It is shown that near the piston and at the passive end of the tube, the heat flux is positive and maximum, which indicates the heating of the gas in these sections, corresponding to pressure antinodes. In the middle of the tube, the heat flux is negative, which indicates that the gas is cooling in this region, where the gas velocity is maximum.

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