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GAS OSCILLATIONS IN A CLOSED TUBE AT RESONANCE

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Summary Periodic gas oscillations in a closed tube are investigated experimentally and numerically. At resonance, these oscillations are accompanied by shock waves traveling back and forth along the tube. Gas temperature and pressure measurements are reported. It is found that the gas temperature changes substantially along the tube. A two-dimensional numerical model of turbulent gas oscillations is formulated and verified by comparison with experiments. It is found that the experimental data of temperature and pressure inside the resonance tube are well correlated by this model. Using the numerical model, turbulence and acoustic streaming at resonance are investigated. It is shown that the normalized pressure amplitude, as well as other flow characteristics, are functions of a single parameter, which is a combination of the acoustic Reynolds number and dimensionless tube length.

INTRODUCTION

When a gas in a closed tube is excited by an oscillating piston driven at the fundamental resonance frequency, periodic shock waves arise within the tube.[1] The shock waves travel back and forth along the tube with a frequency equal to that of the oscillating piston and velocity close to that of sound. As a result of the shock waves, the heat and mass transfer processes within the resonance tube are enhanced significantly compared to those outside the resonance band. Other interesting phenomena taking place in a resonance tube are temperature and pressure gradients along the tube, as well as particle drift and agglomeration, which could be used for new commercial applications.

An analytical model for resonant oscillations in a closed tube[2] predicts that within a narrow resonance band the disturbances in the thermodynamic variables are of the order of $O(\varepsilon)$, and the axial gas velocity of $O(\varepsilon C_0)$; while for non-resonant frequencies, the disturbances are of order $O(\varepsilon^2)$, and the gas velocity of $O(\varepsilon^2 C_0)$, where $\varepsilon = \sqrt{\pi l / L}$ is a small parameter and C_0 is the speed of sound. Here, l and L are the piston amplitude and tube length, respectively.

Ilgamov et al.[3] reviewed many recent theoretical and experimental studies on resonance oscillations, and found that the discrepancy between theory and experiments increases with ε. They concluded that all existing theories are unsatisfactory when $\varepsilon \geq 0.1$, indicating the necessity to account for viscous and thermal effects, which can notably modify gas oscillations.[4] Moreover, experiments have shown that for relatively large ε, oscillatory flow in closed tubes at resonance is turbulent.[5] Since there is no reliable analytical model for unsteady turbulent flow accompanied by shock waves, we are forced to analyze numerically such flows.

In the present study, we investigate numerically and experimentally gas flow in closed resonance tubes. We perform temperature and pressure measurements in several tubes filled with air and simulate numerically resonance gas oscillations. We solve by a finite-difference algorithm the two-dimensional Navier-Stokes equations supplemented by a two-equation turbulence model. We verify the applicability of this numerical model by comparison with experimental data. The developed model is used to study resonant gas oscillations, including turbulence and acoustic streaming. We also perform a parametric numerical investigation of gas oscillations in closed tubes at resonance.

NUMERICAL MODEL

Two-dimensional axisymmetric flow of a perfect gas is governed by the equations of continuity, momentum and energy, written for mean variables of turbulent flow. These equations have to be supplemented by a turbulence model. We use a two-equation k-ω turbulence model of Wilcox.[6] Thus, a closed set consisting of six differential equations describing turbulent gas motion can be formulated. To solve these equations, we employ a non-iterative finite-difference implicit scheme developed by Beam and Warming.[7] We use a rectangular grid, which is clustered in the physical domain near the tube wall within the boundary layer. The grid spacing in the axial direction is time dependent and chosen to fit the distance between the plug and the moving piston. The simulations are started with the uniform initial conditions and continued up to the moment when a time periodic solution is obtained.

EXPERIMENTAL SETUP

The experiments are performed with air inside a vertical tube fitted with a vibrating piston at one end and closed by a plug at the other. We perform the experiments with several tubes of different lengths, L, and internal diameters, D, and measure the gas temperature and pressure inside the resonance tube.[8] An Endevco 85306-15 pressure sensor is mounted on the tube plug. Three chromel-alumel thermocouple sensors, with 0.1 mm junction diameters, are used for temperature measurements. The first sensor is used for measuring the gas temperature and can be moved to different positions along the tube. The second thermocouple sensor measures the inner tube surface temperature and the last sensor, installed at a fixed point at the tube wall, is used as a reference thermocouple.

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RESULTS

It is found that the proposed numerical model provides a plausible description of the flow inside the resonance tube, as verified by experimental data. In particular, this model predicts accurately the temperature distribution inside the tube and pressure variations on the plug. Our experiments show that the average gas temperature has a minimum at the tube middle and increases toward the tube ends. This temperature distribution is due to the non-linearity of flow with periodic shocks and to turbulence intensity along the tube.

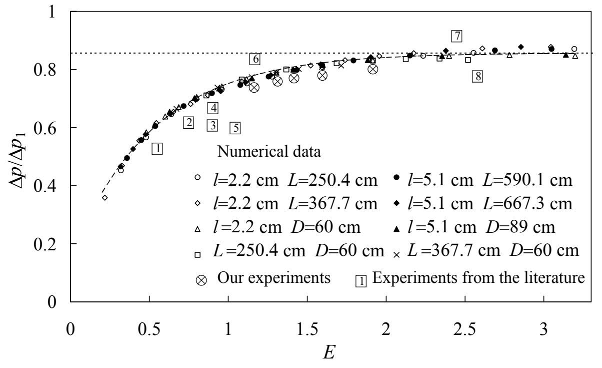

Fig. 1 Normalized pressure amplitude at resonance versus dimensionless parameter $E = \mathrm{Re}_a^{1/3}/\Lambda$. The horizontal dotted line presents the maximal pressure amplitude $\Delta p/\Delta p_1 = 6/7$, while the dashed line is an approximation. The dots present our numerical results, while the circles with crosses indicate our experimental data. The squares with numbers indicates experimental data from the literature by: 1 – Lettau;[9] 2 – Merkli and Thomann;[10] 3 – Lehmann;[11] 4 – Temkin;[12] 5 – Cruikshank;[13] 6 – Saenger and Hudson;[1] 7 – Sturtevant;[14] 8 – Galiev et al.[15]

We show that the flow in a resonance tube is governed by the following dimensionless parameters: tube parameter $\varepsilon = \sqrt{\pi d/L}$, acoustic Reynolds number $\mathrm{Re}_a = C_0 l/\nu$, dimensionless tube length $\Lambda = L/D$, and dimensionless frequency $\phi = (f - f_{res})/f\varepsilon$. Here, ν is the kinematic viscosity, f the piston frequency and $f_{res} = C_0/2L$. It is found that at resonance the normalized pressure amplitude $\Delta p/\Delta p_1$, is a function of a single parameter $E = \mathrm{Re}_a^{1/3}/\Lambda$, where Δp_1 is the pressure amplitude at resonance according to the isentropic model.[2] This is shown in Fig. 1, where we have drawn data from our experiments and calculations, as well as from the literature. Experiments from different sources, although scattered, seem to follow the general shape of the curve. The parameter E is found to be the governing parameter for other flow characteristics as well.[8]

It is found that the numerical model predicts in a plausible manner flow transition to turbulence. As demonstrated by our simulations, the turbulent energy sharply increases behind the shock wave, although, the flow remains practically laminar near the tube ends. These results agree qualitatively with experimental observations.[5]

Simulations show that strong acoustic streaming arises within the tube at resonance. Our calculations predict two large flow patterns, in which the fluid near the wall moves toward the tube middle cross-section, while the flow at the tube centerline is directed toward the tube ends. Notably, the flow in these streaming patterns is in the reverse direction to that occurring at non-resonant frequencies. At frequencies about the resonance band, the number of streaming patterns increases, which is in agreement with experimental observations.[5] We show that within the resonance band, the streaming velocity is of the order of $O(\varepsilon^2 C_0)$, while outside this band, where flow is continuous, it is of the order of $O(\varepsilon^4 C_0)$. This implies that all processes of heat and mass transfer related to acoustic streaming are enhanced dramatically, when the flow is at the resonance band and is accompanied by periodic shock waves.

CONCLUSIONS

We investigated experimentally and numerically gas flow in a closed tube at resonance, accompanied by periodic shock waves traveling back and forth along the tube. Good agreement was found between the proposed numerical model and experimental results. The numerical model was used to investigate resonance gas oscillations including turbulence and acoustic streaming, showing that only one parameter $E = \mathrm{Re}_a^{1/3}/\Lambda$ governs averaged flow characteristics.

References

[1] Saenger R.A. and Hudson G.E.: Periodic shock waves in resonating gas columns. *J. Acoustic Soc. Am.* **32**:961, 1960.
[2] Chester W.: Resonant oscillations in closed tube. *J. Fluid Mech.* **18**:44, 1964.
[3] Ilgamov M.A., Zaripov R.G., Galiullin R.G. and Repin V.B.: Nonlinear oscillations of a gas in a tube. *Appl. Mech. Rev.* **49**:137, 1996.
[4] Alexeev A., Goldshtein A. and Gutfinger C.: Heat interaction in a resonance tube. *Phys. Fluids* **14**:1812, 2002.
[5] Merkli P. and Thomann H.: Transition to turbulence in oscillating pipe flow. *J. Fluid Mech.* **68**:567, 1975.
[6] Wilcox D. C.: Turbulence modeling for CFD. La Canada, 1993.
[7] Beam R.M. and Warming R.F.: An implicit factored scheme for the compressible Navier-Stokes equations. *AIAA J.* **16**:393, 1978.
[8] Alexeev A. and Gutfinger C.: Resonance gas oscillations in closed tubes − numerical study and experiments. *Phys. Fluids* **15**:3397, 2003.
[9] Lettau E.: Messungen an schwingungen von gassaulen mit stellen fronten in rohrleitungen. *Deutsche Kraftfahrtforschung* **39**:1, 1939.
[10] Merkli P. and Thomann H.: Thermoacoustic effects in a resonance tube. *J. Fluid Mech.* **70**:161, 1975.
[11] Lehmann K.D.: Die dampfungsverluste bei starken schallschwingungen in rohren. *Ann. Phys.* **21**:101, 1934.
[12] Temkin S.: Nonlinear gas oscillations in a resonance tube. *Phys. Fluids* **11**:960, 1968.
[13] Cruikshank D.B.: Experimental investigation of finite-amplitude acoustic oscillations in closed tubes. *J. Acoustic Soc. Am.* **52**:1024, 1972.
[14] Sturtevant B.B.: Non-linear gas oscillations in pipes. Part 2: experiment. *J. Fluid Mech.* **63**:97, 1974.
[15] Galiev S.U., Ilgamov M.A. and Sadykov A.V.: Periodic shock waves in gas. *Izv. Akad. Nauk SSSR Mekh. Zhidk. Gaza* **2**:57, 1970.