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Study on gas and wave in a receiving tube

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The gas and wave's motion in a receiving tube are investigated numerically and experimentally in the present paper. The results show that, velocity of the contact face rises rapidly as gas is injected into the receiving tube, and then drops sharply after a steady propagation. However, velocity of the wave in the tube is almost linear and the wave can be reflected at the close end of the receiving tube. With increasing of inlet pressure, velocity of the wave and steady velocity of contact face also increase. There is obvious thermal effect as the wave sweeps the gas. The reflected wave can heat the exhausting gas in the open end. As an absorber, an expander and a shrink in the tube can almost completely absorb the reflected wave.

Keywords: contact face; wave; receiving tube; absorber

Introduction

When a jet flow from a high pressure nozzle is injected into a receiving tube closed at one end alternatively and periodically, it can cause high temperature effect at the closed end and refrigeration at the open end. This phenomenon has been investigated by a number of researchers [1-6]. As the compressed gas is injected into the receiving tube alternatively and periodically, a contact face forms between the driving gas and the driven gas, and a wave appears in front of the contact face moving in the same direction. As the wave sweeps, the driven gas is compressed and its temperature becomes higher. In the injecting phase, the energy of the wave driving the gas is supplied by the high pressure gas from the nozzle, and the gas behind the contact face gets a high velocity after expanding, then the static temperature drops down. While in the exhausting phase, the energy of the wave is supplied by jet flow in the receiving tube. Refrigeration can be realized at the open end with the total temperature dropping down [7]. Fig. 1 shows the process of the injecting and exhausting. t-in is the time when the gas is injecting into the receiving tube. t-out is the time when the gas is exhausting from the tube. The contact face(C) and the wave(S) also are described in the receiving tube.

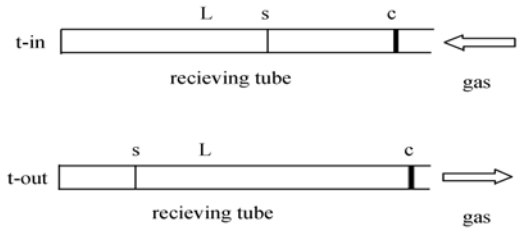

Fig. 1 Wave and contact face in the receiving tube

As the theory of the wave motion, many good wave solutions have been investigated analytically and numerically in the last few years [8,9]. Energy exchange, momentum transport, and the refrigeration effect all take place in the receiving tube, and all these progresses are in relation with the contact surface and the wave. Yu H. has described the wave pattern and flow progress in receiving tube [10]. Li X. has investigated the movement of the contact face by theoretical method under some assumptions [11]. Natazawa studied the oscillatory flow in the thermoacoustic sound wave generator [12]. All investigations mentioned above focus on tubes closed in one end and this can be applied in some applications such as gas wave refrigerators[13,14]. The wave arrives at the close

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end and it can be reflected and then moves towards the open end of the receiving tube.

In this paper, a Computational Fluid Dynamics (CFD) method and experimental research are carried out to analyze the movement of the gas and the wave in a receiving tube. Detailed motions of the contact face and the wave and their thermal effect are investigated. It is shown that experimental data is well in agreement with the numerical results.

Physical model

A two-dimensional finite volume code is used to simulate the flow in the open ends receiving tube. For high pressure and velocity of the jet flow, a renormalization group (RNG) $k-\varepsilon$ model is built [15,16]. Inevitably, there is supersonic flow in the receiving tube, and the wave may occur. To catch the wave, a MUSCL (Monotonic Upwind Scheme for Conservation Laws) format [17] is coupled.

The whole governing equation can be written as:

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial(\rho u\phi)}{\partial x}+\frac{\partial(\rho v\phi)}{\partial y}=$$
$$\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)+S_\phi$$

where x and y denote Cartesian coordinates, ρ the mass density, p the pressure, u and v velocity in x and y direction respectively, ϕ the universal variable including velocity u, v, pressure p, turbulent kinetic energy k, turbulent dissipation ε, Γ_ϕ the universal diffusion coefficient, and S_ϕ the universal source term.

As to the continuity equation, momentum equations, k and ε

$$\phi=\begin{bmatrix}1\\u\\v\\k\\\varepsilon\end{bmatrix},\quad \Gamma_\phi=\begin{bmatrix}0\\\mu+\mu_t\\\mu+\mu_t\\\mu+\dfrac{\mu_t}{\sigma_k}\\\mu+\dfrac{\mu_t}{\sigma_\varepsilon}\end{bmatrix}$$

$$S_\phi=\begin{bmatrix}0\\-\dfrac{\partial p_{eff}}{\partial x}+\dfrac{\partial}{\partial x}\left(\mu_{eff}\dfrac{\partial u}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\mu_{eff}\dfrac{\partial v}{\partial x}\right)\\-\dfrac{\partial p_{eff}}{\partial y}+\dfrac{\partial}{\partial x}\left(\mu_{eff}\dfrac{\partial u}{\partial y}\right)+\dfrac{\partial}{\partial y}\left(\mu_{eff}\dfrac{\partial v}{\partial y}\right)\\G_k-\rho\varepsilon\\C_{\varepsilon 1}\dfrac{\varepsilon}{k}G_k-C_{\varepsilon 2}\rho\dfrac{\varepsilon^2}{k}\end{bmatrix}$$

where turbulent viscosity $\mu_t=c_\mu\rho k^2/\varepsilon$, $\mu_{eff}=\mu+\mu_t$ is the total viscosity, $p_{eff}=p+p_t=p+\frac{2}{3}\rho k$ is the total effective pressure, including static pressure and dynamic pressure, and

$$G_k=\mu_t\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right\}$$

As to the energy equation, the governing equation is

$$\frac{\partial(\rho T)}{\partial t}+div\left(\rho\vec{V}T\right)=$$
$$div\left(\frac{\lambda}{C_p}gradT\right)+\frac{1}{C_p}\frac{Dp}{Dt}+\frac{h_c}{C_p}W_m$$

The whole fluid properties are shown in Table 1.

Table 1 Fluid properties

Pro	Unit	Definition
$\boldsymbol{l}$	s	time
u	m/s	velocity in x direction
v	m/s	velocity in y direction
T	K	temperature
p	Pa	pressure
ρ	kg/ m3	density
Φ		Universal variable
Γ_Φ		diffusion coefficient
S_Φ		universal source term
μ	kg/m.s	viscosity

Computational method

The Navier-Stokes equations are solved using finite volume formulation. The continuity equation and pressure are solved using the SIMPLE algorithm [18]. The grid spacing is 0.2mm, below which the computational results are grid independent. The boundary condition can be set as follows: initial inlet pressure of the gas is 2MPa, and it changes in a scope. The original temperature is 300K, and the outlet pressure and outlet temperature are 1MPa and 300K respectively. The grid time is 2e-5 s. The gases used in the receiving tube are ideal gases, and the viscosity μ is 1.17894×10^{-5} Kg/m.s.

Results and discussion

Motion of the wave

Fig. 2 shows the moving distance of the wave in the receiving tube. The length of the receiving tube is 3m long. B is for the different pressure ratio of the injecting gas and the exhausting gas. It clearly shows the velocity of the wave in the receiving tube almost keeps constant even the pressure ratio is a little different. In the close end, the wave is reflected and the gas then arrives the open end of the tube almost in a same speed. The velocity of the wave is about 250m/s.

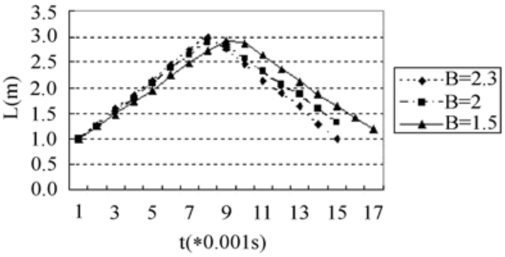

Fig. 2 Wave's distance in the receiving tube

Motion of contact face

Fig. 3 shows the position of the contact face. As the wave sweeps, the temperature of the gas rises. So the contact face can be illustrated by the temperature. 0.002, 0.004…0.014 is the time interval during which the gas is injecting. We can conclude that as the gas is injected into the tube, the contact face rapidly arrives at a distance of about 0.4m, and keep for a while, at the time of 0.002S, 0.004S and 0.006S, and then exhausts. At the time of 0.008S, 0.01S and 0.012S, the temperature curves are almost flat, and it denotes that there is no contact face in the receiving tube, that is to say, the gas is exhausting.

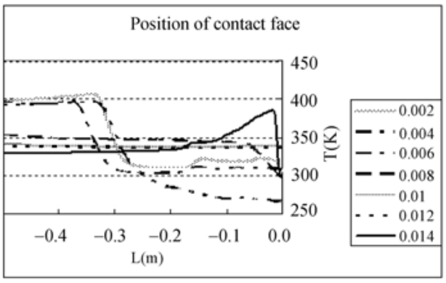

Fig. 3 Position of contact face

Fig. 4 is the motion of the contact face under different pressure ratio. It shows that, even the pressure ratio is different, the maximum distance of the contact face in a 3m long tube is about 0.4m, 13% in the receiving tube. The contact face's motion is not in the same speed. It almost keeps still after a speedup.

Reflection of wave

Fig. 5 clearly shows the reflection of the wave and the injecting wave. The left of the figure is the close end of the receiving tube and the right is the open end.

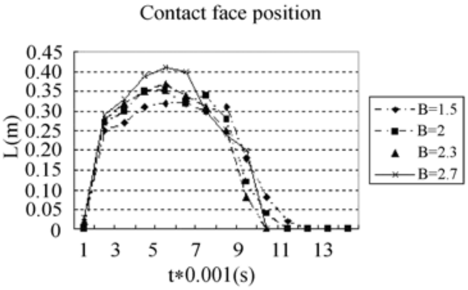

Fig. 4 Contact face's motion in the tube

The injecting wave and the reflected wave propagate in different direction. When the reflected wave sweeps, it can heat the gas about 20K under the pressure ratio of 2. If the exhaust gas is used for refrigeration, the reflected wave is not good.

Fig. 6 shows the exhausting temperature in the open end of the receiving tube under different pressure ratio. As mentioned above, X axis, L is the distance from the open end of the tube. Under less pressure ratio, the gas temperature is higher than the temperature under higher

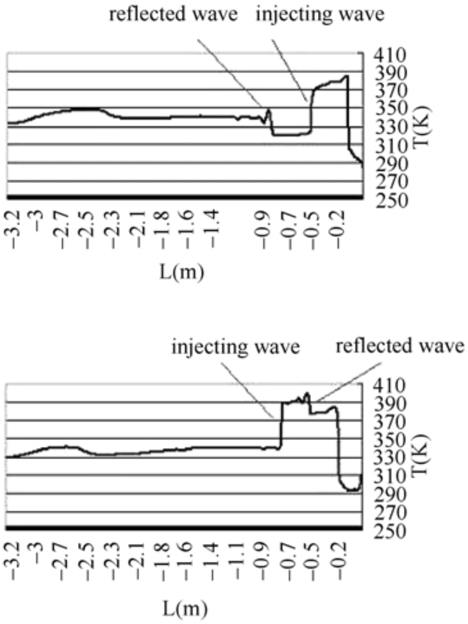

Fig. 5 Reflection of wave

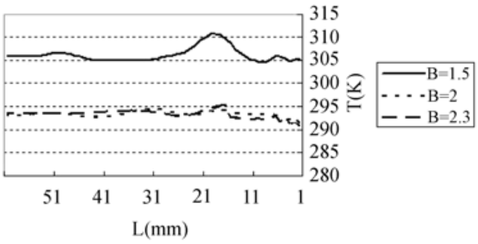

Fig. 6 Exhausting temperature in the open end

pressure ratio. But as the pressure ratio rises to an extent, the temperature almost does not drop.

Wave absorber

Fig. 7 is the sketch of two types of wave absorber in the end of the receiving tube. A is the traditional long receiving tube. B is for absorber 1, with an expander 7 times in diameter compare to the receiving tube in the end. C is for absorber 2, with a same expander and a half shrink in the end.

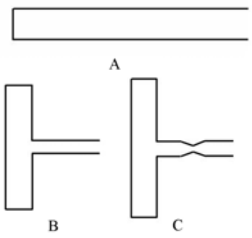

Fig 7 Sketch of wave absorber

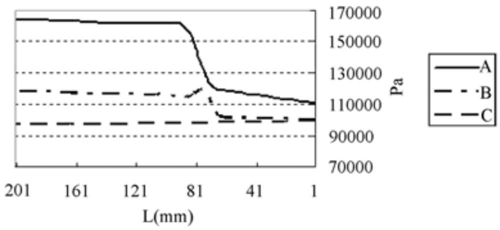

Fig. 8 Pressure intensity of the three types of tubes

Fig. 8 shows the pressure in the receiving tube under three types of receiving tubes. We define pressure intensity as P1/P2. P1 is the pressure in front of the reflected wave and P2 is the pressure behind the reflected wave. In a traditional long receiving tube, the pressure intensity is fairly large, about 1.5. Absorber 1 is about 1.2. Under the action of absorber 3, there is almost no reflected wave in the exhausting end. The reflected wave is almost completely absorbed.

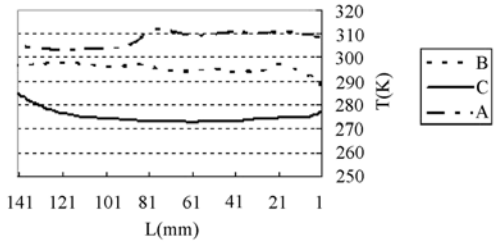

Fig. 9 Exhausting temperature

Fig. 9 shows the exhausting temperature of three types of receiving tube. A receiving tube with an absorber can get much lower temperature in the open end. The reason can be concluded as the thermal effect of the reflected wave.

Experiment system

A schematic diagram of experimental setup is illustrated in Fig. 10.

The experiment program is described as follows:

High pressure gas from the air compressor 1 flow into the sonic oscillator 8 through air storage 2 and buffer jar 4. During the course, the gas pressure can be adjusted by inlet valve 5. The temperature and the pressure are measured by thermometer 6 and manometer 7. The gas is exhausted after the flow meter 17. The outlet pressure is controlled by valve 15.

Pressure test system is composed of pressure sensor 10, amplifier 13, transistor 14, computer 16 and manometer 11. As the wave arrives at the end of the receiving tube, it can not be reflected, and the efficiency is the highest and the exhausting temperature is the lowest[19]. We change the pressure of the injecting gas and keep the inlet temperature as a constant of 300K. By controlling the mass flow of the gas and the pressure, we get different exhausting temperature.

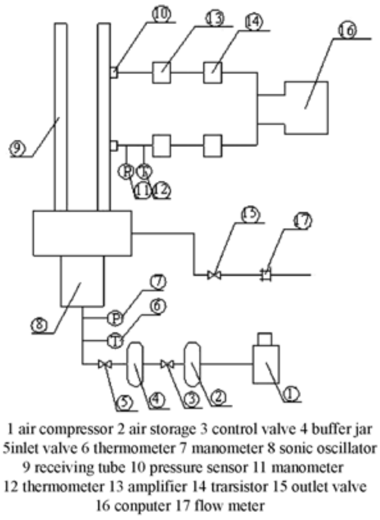

Fig. 10 Schematic diagram of experimental setup

Fig. 11 shows the oscillating flow generated by a sonic oscillator. Y-coordinate is the mass flow rate from the

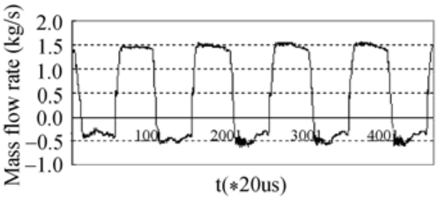

Fig. 11 Frequency of the sonic oscillator

Table 2 The experimental and numerical value of temperature of the exhausting gas

Pressure ratio	B=1.5	B=2	B=2.3
Numerical value(K)	308	292	290
Experimental value(K)	300	291	289

outlet of the sonic oscillator. It can inject into the receiving tube alternatively and periodically. Under receiving tube A of Fig 7, temperature of the exhausting gas can be measured.

The result shows that the numerical value is a little higher than the experimental value, especially under lower pressure ratio. The reason may lie in the operation condition and the heat exchange. Under lower pressure ratio, the wave can heat the gas in the closed end and the heat can easily be transferred to the open end. As a whole, the experimental results are consistent with the numerical simulation.

Conclusion

In this paper, the motion of gas and wave in a receiving tube are studied. Under different pressure ratio, the velocity of the wave in the tube is almost linear and the wave can be reflected at the close end of the receiving tube and then it will keep moving towards the open end in the same speed. The results show that, velocity of the contact face rises rapidly as gas is injected into the receiving tube, and drops sharply after a steady propagation. However, with increasing of inlet pressure, velocity of the wave and steady velocity of contact face also increase. There is an obvious thermal effect as the wave sweeps the gas. The gas in the close end of the receiving tube can be heated and in the open end, it will be cooled. The reflected wave can heat the exhausting gas in the open end. As an absorber, different shape of the absorber has different absorbing effect. Totally, an expander and a shrink in the tube can almost completely absorb the reflected wave.

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