초음속 습공기 유동에서 비정상 공동유동의 진동

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The Unsteady Cavity Flow Oscillation in Supersonic Moisture Air Stream

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ABSTRACT

Numerical simulations have been carried out for a supersonic two-dimensional flow over open, rectangular cavities (length-to-depth ratios are L/D = 1.0) in order to investigate the effect of non-equilibrium condensation of moist air on supersonic flows around the cavity for the flow Mach number 1.83 at the cavity entrance. In the present computational investigation, a condensing flow was produced by an expansion of moist air in a Laval nozzle. The results obtained showed that in the case with non-equilibrium condensation for L/D = 1.0, amplitudes of oscillation in the cavity became smaller than those without the non-equilibrium condensation. Furthermore, the occurrence of the non-equilibrium condensation reduced the peaks of power spectrum density and the frequency of the flow field oscillation increased in comparison with the case of $S_0 = 0$.

Key Words: Compressible Flow, Supersonic Cavity Flow, Non-equilibrium Condensation, Shock Wave

1. Introduction

Numerical simulations have been carried out for a supersonic two-dimensional flow over open, rectangular cavities (length-to-depth ratios are L/D = 1.0) to investigate the effectiveness of the non-equilibrium condensation as a means of controlling pressure oscillations. The necessity of controlling intense pressure oscillations that occur in supersonic flows past open cavities represents an important issue to be solved because of its detrimental effects in many aerodynamic applications such as severe structural vibration and fatigue of aircraft wheel wells and weapon bays. The supersonic flow over cavity indicates that a shear layer separates from the upstream lip, a series of vortices travel downstream in the cavity and reattaches rear wall with the generation of compression waves. These compression waves propagate upstream within the cavity and further excite the shear layer at the cavity upstream lip. As a result, the process is sustained by completing the feedback loop described by Krishnamurty [1]. Modification of

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the shear layer continues by the subsequent excitations and consequently resonance occurs when the frequency and the phase of the shear layer match those of the compression waves. The resonance, thus produced, largely amplifies the cavity pressure fluctuations.

In the present computational investigation, a condensing flow was produced by an expansion of moist air in a Laval nozzle to study the effect of non-equilibrium condensation on supersonic internal flows around the cavity for the flow Mach number 1.83 at the cavity entrance. As a result, it was shown that the occurrence of the non-equilibrium condensation affected amplitudes and frequencies of the oscillation.

2. CFD Analysis

2.1 Governing equations

Assumptions using in the present calculation of the two phase flow are as follows; Both velocity slip and temperature difference do not exist between condensate particles and gas mixture, and the effect of the condensate particles on pressure is neglected. As the governing equations, the unsteady compressible Navier-Stokes equations and a rate of liquid-phase production [2] were used in the simulation. Latent heat, nucleation rate, critical radius of the nuclei, radius growth rate, density of liquid phase and surface tension were given by Ref. [3]. The unsteady compressible Navier-Stokes equations in two-dimensional coordinate system (x,y) is as follows:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial x}+\frac{\partial \boldsymbol{F}}{\partial y}=\frac{1}{Re}\left(\frac{\partial \boldsymbol{R}}{\partial x}+\frac{\partial \boldsymbol{S}}{\partial y}\right)+\boldsymbol{H}+\boldsymbol{Q}$$

where U is the conservative vector, E and F are inviscid flux vector and R and S are viscous flux vectors. H and Q are the source terms corresponding to turbulence and condensation, respectively.

The governing equation systems that are non-dimensionalized with reference values at the inlet conditions upstream of the nozzle are mapped from the physical plane into a computational plane of a general transform. To close the governing equations, a modified k-Rmodel [4] is employed in computations. A third-order TVD (Total Variation Diminishing) finite difference scheme with MUSCL [5] is used to discretize the spatial derivatives, and a second order-central difference scheme for the viscous terms, and a second-order fractional step is employed for time integration.

2.2 Computational Conditions

Figure 1 shows computational grids of a supersonic flow field with a cavity. The height of the main flow section at the entrance of the cavity H is 24 mm. The cavity depth D is 12 mm, and the lengths L are 12 mm and 36 mm. S1, S2, S3 and S4 in this figure denote measuring positions of static pressure. The number of grids for L/D = 1.0 is 300×80 in the region of the nozzle and 50×60 in the

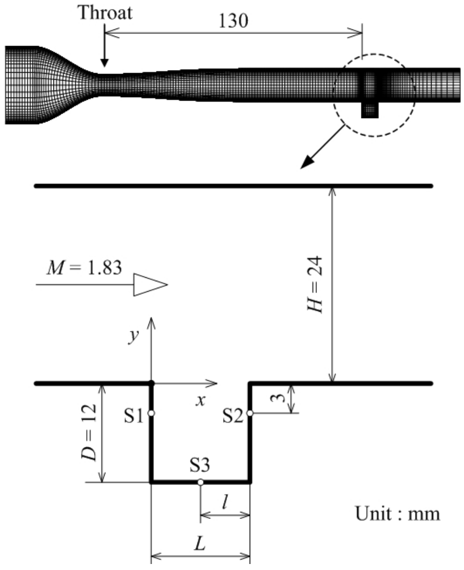


Fig.1 Computational grids

cavity. The origin in x-y coordinate is located at the corner of the cavity leading edge.

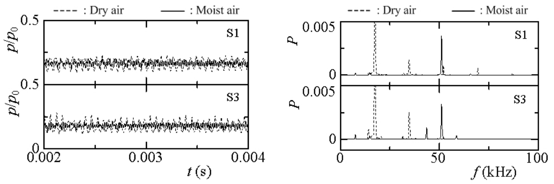
In the present study, moist air is used as a working gas and assumed to be thermally and calorically perfect. The oncoming boundary layer is laminar. Pressure p_0 and temperature T_0 in the reservoir are 101.3 kPa and 298 K, respectively. Values of the initial degree of supersaturation S_0 (= $p_{v0}/p_{s,\infty}$) are 0 and 0.6. The inlet Mach number at the entrance of the cavity is 1.83. The Reynolds number is 3.5×10^5. Non-slip velocity and no heat transfer are constrained on the solid wall. Condensate mass fraction g = 0 is set at the wall.

3. Results and Discussion

In case of S_0 = 0.6, the non-equilibrium condensation occurred downstream of the nozzle throat. As a result, the flow Mach number decreased by approximately 7.1 % (M = 1.70) and total pressure loss was 4.0 % at the position of x/D = -5.0. For L/D = 1.0, a dominant frequency for M = 1.70 and S_0 = 0 was 16.4 kHz at each position in cavity and the frequency was almost the same as that for M = 1.83 and S_0 = 0.

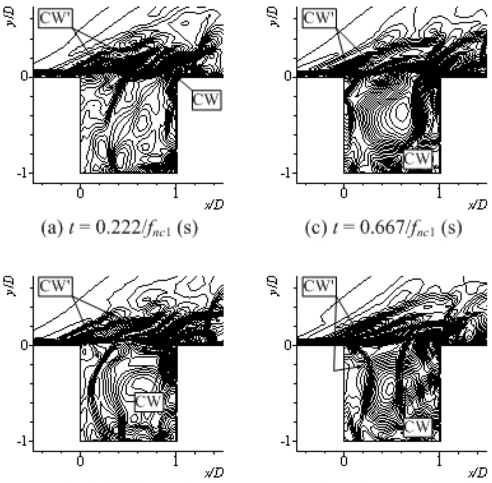
Figure 2(a) shows static pressure histories at positions of S1 and S3 for L/D = 1.0 and both cases of S_0 = 0 (dry air) and S0 = 0.6 (moist air) are shown in this figure. Distributions of power spectrum density obtained from static pressure histories for both cases are shown in Fig.2(b). In the case of S_0 = 0 (dry air), it is found from these figures that amplitudes of oscillation are almost the same at both positions and there is a dominant frequency at 17.5 kHz.

In the case of S_0 = 0.6 (moist air), amplitudes of oscillation are smaller than those without the non-equilibrium condensation and



(a) Time histories of static pressure (b) Distributions of power spectrum density

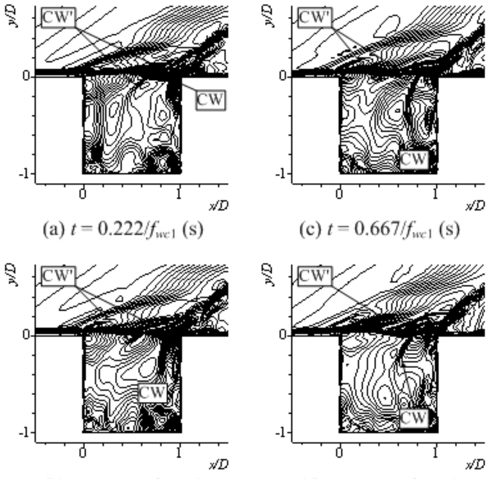
Fig. 2 Static pressure variations and distributions of power spectrum density in cavity (L/D=1.0)



(a) $t = 0.222/f_{nc1}$ (s) (c) $t = 0.667/f_{nc1}$ (s)

(b) $t = 0.444/f_{nc1}$ (s) (d) $t = 0.889/f_{nc1}$ (s)

Fig.3 Contour maps of density showing flow field oscillation (L/D=1.0, S_0=0)



(a) $t = 0.222/f_{wc1}$ (s) (c) $t = 0.667/f_{wc1}$ (s)

(b) $t = 0.444/f_{wc1}$ (s) (d) $t = 0.889/f_{wc1}$ (s)

Fig. 4 Contour maps of density showing flow field oscillation (L/D=1.0, S_0=0.6) there is a strong peak at 51.1 kHz in contrast to the case of S_0 = 0. The frequency was almost the same as that obtained at the position S4 in Fig.1. The position S4 is close to the shear layer shown in Fig.4. Furthermore, the peak value of power spectrum for the dominant frequency becomes small in comparison with the case of S_0 = 0. As seen from this figure, the non-equilibrium condensation affects strongly the oscillation in the flow field.

Figures 3 and 4 show contour maps of density during one period of flow oscillation for S_0 = 0 and 0.6, respectively (L/D = 1.0). f_{nc1} and f_{wc1} are frequencies in cases of no condensation and the occurrence of condensation, respectively. In Fig.3, a compression wave (CW) from the trailing edge of the cavity moves upstream as time proceeds. The compression wave CW in Fig.3(d) becomes an upstream travelling compression wave (CW′ shown in Fig.3(a)). The upstream travelling compression wave CW′ reaches the front of the cavity (Fig.3(c)). Hence the shear layer is largely deflected by the compression wave and the instability of the shear layer regenerates the compression wave (CW) at the trailing edge of the cavity.

In Fig.4 (S_0 = 0.6), a compression wave (CW) from the trailing edge of the cavity moves upstream as time proceeds. However, the strength seems to be weak in comparison with one in Fig.4. This is considered to be due to the occurrence of non-equilibrium condensation at the region close to the trailing edge. Furthermore, deflection of the shear layer waveform becomes small in comparison with that in Fig.3.

4. Conclusion

Numerical simulation was carried out for a supersonic two-dimensional internal flows over a rectangular cavities of L/D = 1.0 at a free stream of M = 1.83. The results obtained showed that in the case with non-equilibrium condensation for L/D = 1.0, amplitudes of oscillation in the cavity became smaller than those without the non-equilibrium condensation. Furthermore, the occurrence of the non-equilibrium condensation reduced the peaks of power spectrum density and the frequency of the flow field oscillation increased in comparison with the case of S_0 = 0.

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