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Passive Control of the Condensation Shock Wave Using Bleed Slots

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Key Words : Condensation Shock Wave, Nonequilibrium Condensation Passive Control, Transonic Nozzle, Internal Flow, Compressible Flow

Abstract

The current study describes experimental and computational work on the passive control of the steady and unsteady condensation shock waves, which are generated in a transonic nozzle. The bleed slots are installed on the contoured wall of the transonic nozzle in order to control the magnitude of the condensation shock wave and its oscillations. For computations, a droplet growth equation is incorporated into the two-dimensional Navier-Stokes equation systems. Computations are carried out using a third-order MUSCL type TVD finite-difference scheme with a second-order fractional time step. Baldwin-Lomax turbulence model is employed to close the governing equations. An experiment using an indraft transonic wind tunnel is made to validate the computational results. The current computations represented well the experimental flows. From both the experimental and computational results it is found that the magnitude of the condensation shock wave in the bleed slotted nozzle is significantly reduced, compared with no passive control of solid wall. The oscillations of the condensation shock wave are successfully suppressed by a bleed slot system

1. Introduction

Condensation shock wave has long been subject of scientific researches, and many thermodynamic and fluid dynamic aspects of the nonequilibrium condensation and condensation shock wave are now well known(1,2). The condensation shock wave almost always leads to large energy losses as well as the flow instability due to condensation shock wave oscillations(3,4), which can frequently give rise to a noise and vibration problem in the flow system. It is necessary that the magnitude of the condensation shock wave and its oscillations should be alleviated by a proper control strategy.

According to the previous experimental work(5) with regard to the condensation shock oscillations, there are three different types of oscillations in transonic nozzle. A brief description of these oscillation modes is given; 1) Mode A oscillation: a condensation shock builds up periodically in the divergent section of transonic nozzle and moves upstream the nozzle throat. 2) Mode B oscillation: a condensation shock builds up periodically in the divergent section of transonic nozzle, moving upstream but it dies out before it reaches the nozzle throat. 3) Mode C oscillation : No periodic condensation shock motions build up but the condensation shock oscillates around a certain time-mean location in the divergent section of transonic nozzle.

Several types of passive control strategies have been applied to shock wave/boundary layer interaction in transonic/supersonic flows(6,7). For instance, a porous wall and cavity system underneath, when it was applied at the foot of the shock wave, was known to be the most effective in alleviating undesirable adverse pressure gradient of the shock wave/boundary layer interaction. Recently the authors have applied this passive control method to the condensation shock wave and its oscillations in a transonic nozzle flow, and obtained a considerable amount of reduction of the magnitude of condensation shock wave(8). They also reported that the three modes of the oscillations were successfully suppressed by their passive control(9). However this control method essentially led to large viscous turbulence losses caused by the porous walls, which could overcompensate the control benefit against the condensation shock wave.

The experience gathered throughout the experiments and computations of the porous wall/cavity controlled flows points out us to investigate the other control strategies without large turbulence losses. In the present study, the passive control using a bleed slot is applied to both the steady and unsteady condensation shock waves in a transonic nozzle. The primary objective of the present study is to investigate the effectiveness of this kind of passive control against the condensation shock wave in a transonic nozzle, and to get insight into the flow mechanisms associated with the reduction in the magnitude of condensation shock wave and its oscillations, relative to no passive control. From both the experimental and computational results it is found that the magnitude of the condensation shock wave in a bleed slotted nozzle is significantly reduced, com-

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pared with no passive control of solid wall. The motions of the condensation shock wave are successfully suppressed by the bleed slot system.

2. Computational Analysis

For simplicity of the present computations, several of assumptions are made ; there is no velocity slip and no temperature difference between condensate particles and medium gas flows, and due to very small condensate particles the effect of the particles on pressure can be neglected. The resulting governing equations are the unsteady, two-dimensional, compressible, Navier-Stokes equations, and these equations and detailed numerical processes are in details described in Ref.(10). Baldwin-Lomax model is employed in computations. A third-order TVD(total variation diminishing) finite difference scheme with MUSCL is used to discretize the spatial derivatives, and a second order central difference scheme for the viscous terms. A first order upwind TVD scheme is applied to the droplet growth equation, and a second order fractional step is employed for time integration.

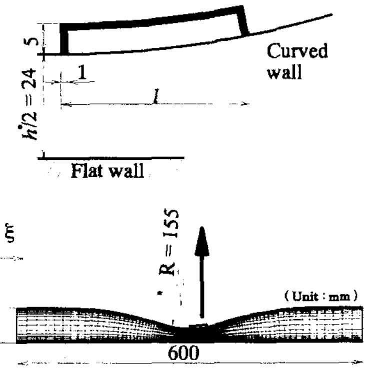


Fig. 1 Slotted nozzle flow field for computations

Fig. 1 shows the schematics for the passive nozzle flow computations. The transonic nozzle has a 60mm high at both the inlet and outlets and it has a 600mm long. The contoured wall of the transonic nozzle consists of a circular arc of a radius of R*=155mm. The nozzle throat is a 24mm high(=$h^*/2$), where h* is yielded as a characteristic length scale in the present study.

Two slots, which have the same width of w=1.0mm, are installed into the contoured wall, one being located just at the nozzle throat and the other at l downstream apart from the throat. Two slots are connected with a bypass to allow the flow communications through the slots, and the bypass has the same width as the slot. In the present study, the interval l between the slots is varied in the range of 20mm to 40mm, but the depth of the slot is fixed at 5.0mm.

Moist air is used as a working fluid and assumed to be thermally and calorically perfect. To obtain different condensation shock waves in the transonic nozzle, two different values of the initial degree of supersaturation S_o of moist air are S_o=0.6 and 0.8. At the upstream plenum chamber, total temperature T_0 and total pressure P_0 is kept constant at 303.15K and 101.3 kPa, respectively. Inlet and outlet boundaries are constrained to the free boundary conditions. No-slip wall velocity is assumed on adiabatic wall condition of no heat transfer. Further, condensate mass fraction g=0 is given at the solid walls and the symmetry condition on the nozzle centerline.

The fineness of computational grid was examined to assure that the obtained solutions were independent of the grid employed. The resulting grids were 102×301 for the nozzle flow and 61×150 for the bypass. The grids are clustered in regions with large gradients, such as condensation shock waves, boundary layers, so that those provide more reasonable predictions. A solution convergence was obtained when the residuals for each of the conserved variables have reduced below the order of a magnitude 4. Another convergence criterion is to directly check the conserved quantities through the computational boundaries. The net mass flux was investigated if there were an applicable imbalance through the computational boundaries.

3. Experimental Work

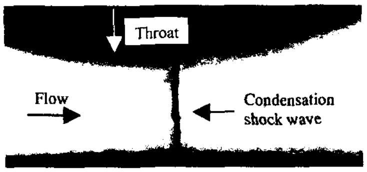
An experimental work using an indraft transonic wind tunnel is made to validate the computational results. Moist air at atmospheric conditions in the upstream plenum chamber flows through a transonic nozzle into a vacuum chamber having a volume of 7.0m^3. A two-dimensional transonic nozzle is installed into the top wall of a duct of 60mm high and 38mm wide. The lower flat wall of the duct consists of the bottom wall of the nozzle. The wind tunnel provides approximate 20 seconds for steady test.

The same slots as employed in the computational work are installed into the contoured top wall. The intervals l between the slots are l=20mm and 30mm. The temperature and relative humidity at the upstream plenum chamber are controlled by a heater and steam generator system and give different values of the initial degree of supersaturation S_o. The stagnation pressure in the plenum chamber is kept constant at Po=101.3kPa.

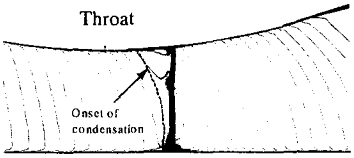
Measurements of static pressures are made along both the contoured wall and bottom flat wall surfaces. A multiple of semiconductor pressure transducers are mounted flush on the wall surfaces. An analog-to digital converter, in conjunction with a personal computer, records the amplified output from the transducers into an x-y recorder system. The pressure transducers are calibrated both statically and dynamically, before experiments. Using the calibration information, the error associated with the pressure measurements is estimated to be approximately 1.5%. These estimations are based on the maximum possible fluctuations in the measurements. A Schlieren method is employed for visualization of the passive flow field through the nozzle. The light source for the Schlieren system is provided by Mg strobrite spark lamp. The duration of the light is about 2 microseconds.

4. Results and Discussion

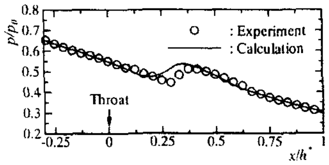
Fig. 2 and 3 show the comparison between the computed and experimented results for both the solid and slotted nozzle flows, where for the slotted nozzle l=30 mm and S_o = 0.60.



(a) Schlieren photograph



(b) Computer schlieren picture

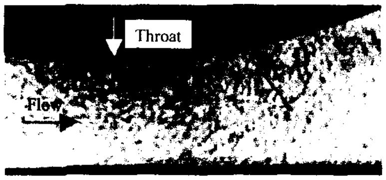


(c) Static pressure distributions on flat wall

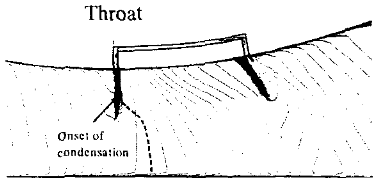
Fig. 2 Experimental and computational results without passive control($S_0 = 0.6$)

Fig. 2(a) and 3(a) are the Schlieren pictures showing the flow visualization results, Fig. 2(b) and 3(b) the computed density contours showing the onset of condensation and condensation shock waves, and Fig. 2(c) and 3(c) are the static pressures along the nozzle axis. With no passive control of solid nozzle, the non-equilibrium condensation of moist air causes a normal condensation shock wave a little downstream of the nozzle throat.

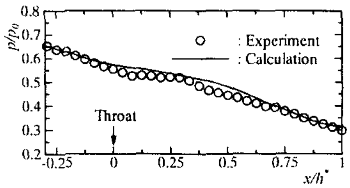
For the slotted nozzle, the normal condensation shock seems to be a lambda pattern and its magnitude seems to be somewhat weaker, compared with no passive nozzle. From both the Schlieren pictures and computed density contours, the agreement between computations and experiments is quite good. It is also found that the current computations predict well the static pressures along the nozzle axis, although there seems to be some discrepancies near at the condensation shock wave, i.e., the static pressure jump, which occurs downstream of the nozzle throat. From the measured and predicted static pressures



(a) Schlieren photograph

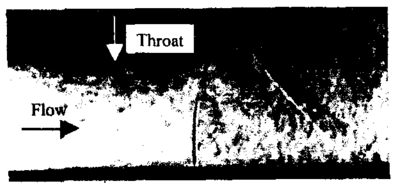


(b) Computer schlieren picture

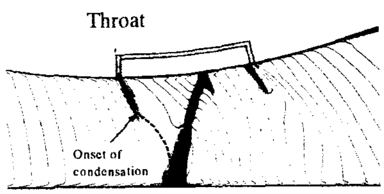


(c) Static pressure distributions on flat wall

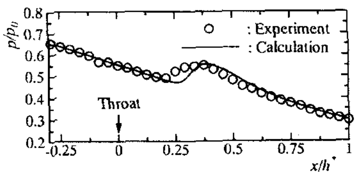
Fig.3 Experimental and computational results with passive control($l = 30mm$ and $S_0 = 0.6$)



(a) Schlieren photograph



(b) Computer schlieren picture



(c) Static pressure distributions on flat wall

Fig.4 Experimental and computational results with passive control($l = 30mm$ and $S_0 = 0.8$)

shown in Fig. 2(c) and 3(c), it seems that the magnitude of the condensation shock wave in the slotted nozzle, i.e. the pressure ratio (p_2/p_1) just downstream and upstream of the condensation shock wave, is little reduced compared with that in the solid nozzles. It should be, however, noted that the effect of the bleed slot on the magnitude of condensation shock depends on l and S_o.

The effect of the passive control on the time-mean condensation shock wave can be found in Fig. 4, where l=30 mm and S_o = 0.80. A clear condensation shock wave is no longer observed close to the nozzle axis. From the static pressures along the nozzle axis it is also known that there is no any applicable pressure jump that is caused by the condensation shock wave.

Fig. 5 shows the predicted static pressures p/p_o, Mach numbers Ma, nucleation rates I, and condensate mass fractions g along the contoured nozzle surface, where the distance x, which has an origin at the nozzle throat, is normalized by the characteristic length h^*, and the local static pressure p by the total pressure p_o at the upstream plenum chamber.

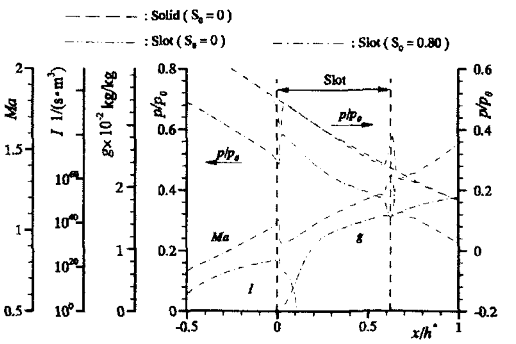


Fig. 5 Predicted distributions of static pressure, Mach number, nucleation rate and condensate mass fraction($S_0 = 0.6$)

For the dry air flow (S_o =0) through the solid nozzle the flow is nearly isentropic. It is found from the dry air of the slotted nozzle(l=30mm) that a strong expansion wave occurs at the edge of the upstream slot, and a compression wave at the edge of the downstream slot. The flow between the slots somewhat differs from that of the solid nozzle.

For the solid nozzle flow of S_o=0.6, a condensation shock wave occurs at a location of x/h^*=0.33 between the slots. Due to the condensation shock, the static pressure suddenly rises and Mach number decreases. The pressure rise seems to be rather gradual and is found even far upstream of x/h^*=0.33. This can be partly due to the upstream communications of the pressure rise through the wall boundary layer and partly due to the fact that the non-equilibrium condensation begins to occur far upstream of x/h^*=0.33. This fact is also known from the distributions of the nucleation rate and condensate mass fraction; the non-equilibrium condensation does not occur suddenly but does over a finite zone. It begins to occur at the location where the static pressure starts to rise, and the resulting condensate mass fraction starts to steeply rise at this location.

With the slotted nozzles, the condensation shock occurs little downstream, compared with that of the solid nozzle. It is interesting to note that the magnitude of the wave systems, which are generated at both the upstream and downstream slots, is weaker in the moist air flow of S_o=0.6 than that in the dry air flow. This is due to non-equilibrium condensation effect in the passive slotted nozzle flows.

Fig. 6 shows the relationship between l/h^* and the magnitude of condensation shock wave p_2/p_1. For the slotted nozzles of l/h^* less than 0.53, there is no applicable reduction in the magnitude of the condensation shock wave. It is, however, found that a slotted nozzle of $l/h^* \geq 0.53$ gives a considerable reduction in the magnitude of the condensation shock wave.

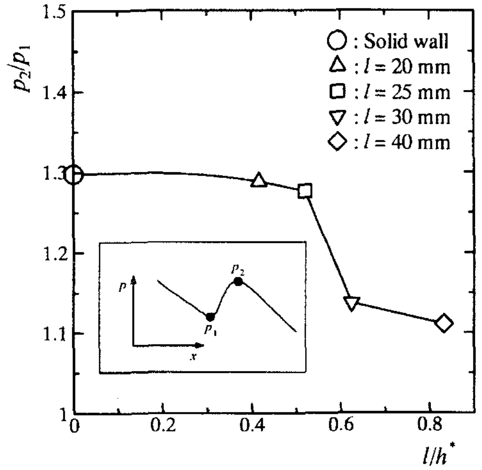


Fig. 6 Relationship between the magnitude of condensation shock(p_2/p_1)and slot interval(l/h^*)

For solid nozzle test of S_o=0.80, the present experiments showed Mode A oscillations of the condensation shock wave, its frequency being of f=1227Hz, while in the present computations it was of f=1309Hz. Thus it is believed that the current computations predict the complicated periodic behavior of the unsteady condensation shock waves with fairly good accuracy.

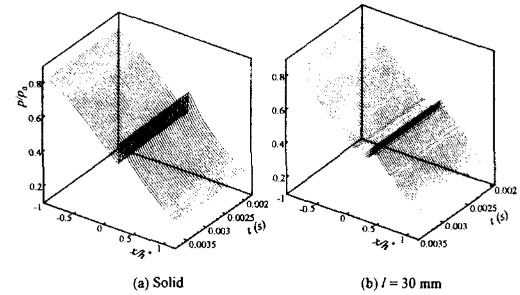


Fig. 7 Predicted static pressure time histories for solid nozzle

The frequency somewhat varied depending on the value of S_o. Fig. 7 shows the time dependence of the condensation shock motions for both the solid and slotted nozzles, where S_o=0.60. The predicted static pressures are taken along a horizontal line of $y/h^*/2$= 12 away from the bottom flat wall. This is to investigate pure condensation shock motions free from the complicated condensation shock and boundary layer interaction occurring on both the contoured top and flat bottom walls. It is found that any discernible motions of the condensation shock wave do not occur in both the solid and slotted nozzles. For the slotted nozzles having different l at a fixed value S_o =0.6, no any motions of the condensation shock wave were observed in the present study.

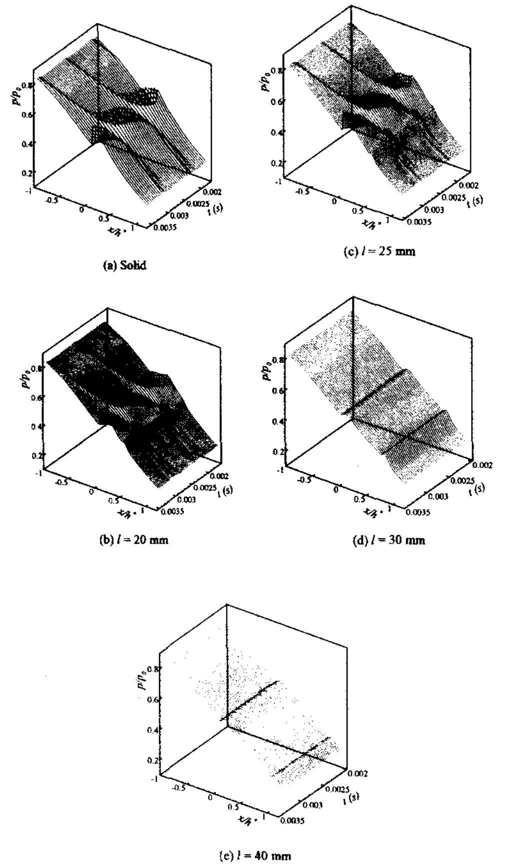


Fig. 8 Predicted static pressure time histories for solid and slotted nozzles($S_0 = 0.8$)

Fig. 8 shows the time histories of the predicted static pressures for S_o=0.80. The periodic condensation shock motions are found in the solid nozzle. The condensation shock wave, which was at a location downstream of the nozzle throat, moves upstream with time and it moves upstream beyond the nozzle throat, finally disappearing far upstream of the nozzle throat. Then a new condensation shock occurs at a location downstream of the nozzle throat, thus forming a complete cycle of the oscillation. The frequency of the periodic motion of the condensation shock wave is estimated by 1309Hz. For the slot-

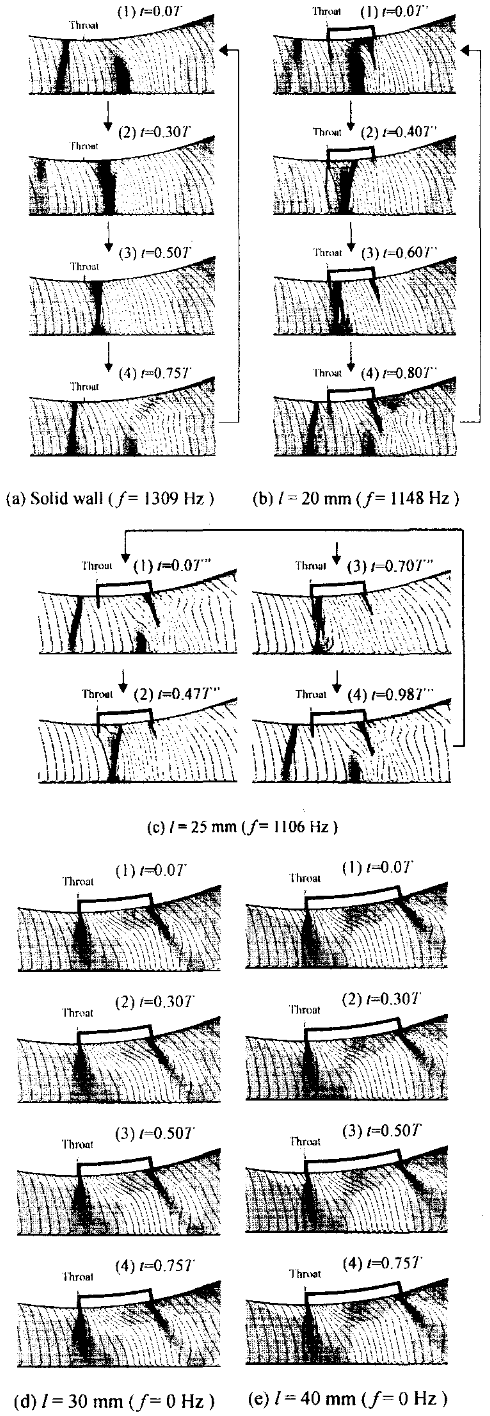


Fig. 9 Predicted density contours for solid and slotted nozzles($S_0 = 0.8$)

ted nozzle of l=20mm, the condensation shock motion is qualitatively quite similar to those in the solid nozzle, but the frequency seems to be slightly lower, compared with the solid nozzle. It becomes lower with an increase in l. It is, however, interesting to note that the condensation shock motions do no longer occur in the slotted nozzles of $l \geq$30mm. There are only the stationary expansion and compression waves produced at the upstream and downstream slots, respectively.

The periodic condensation shock motions for S_0=0.80 are also found in Fig. 9, where T, T' and T'' are a cycle of each of the periodic condensation shock motions. For the solid nozzle without the slots, a condensation shock occurs at a location in the divergent section of the transonic nozzle, moving upstream the nozzle throat with time and then a new condensation shock occurs in the divergent section of the transonic nozzle again; Mode A oscillation. The same trend of the condensation shock motions is found in the slotted nozzles of l =20 and 25mm. However no any motions of the condensation shock for the slotted nozzles of l =30 and 40mm are found in Fig. 9. It seems that some weak condensation shock waves are generated near the slot edges. These are the expansion wave systems due to the bleed effects of the flow through the bypass. The present results obviously show that the motions of the condensation shock are completely suppressed in the bleed slotted nozzle having a slot interval l over 30mm.

It is found from Fig. 9 that a weak condensation shock occurs near the upstream slot. It is likely that the expansion waves are strong so that the condensation shock occurs near the upstream slot. The pressure difference between two slots would be increased with the slot interval. Thus the expansion waves, which occur at the upstream slot, would be stronger with an increase in the slot interval l, as is shown in Fig. 9. However for a small l the present passive method seems not to be effective in suppressing the condensation shock motions. The reason is that the expansion waves are not strong enough to cause condensation shock at the upstream slot, as is shown Fig. 9(b) and (c). Therefore there seems to be a minimum slot interval required to suppress the condensation shock motions. Besides the slot interval, there are many geometrical factors associated with the control effects of the bleed slot. The slot depth, width, inclination, etc. could be involved in these parameters. Before discussing in details the bleed slot configurations to achieve the control benefit of the steady and unsteady condensation shock waves, further study is required. The present results showing the passive control effects of the bleed slots are limited to only the slot interval l. Nevertheless from the viewpoints of practical design cost and energy losses as well, it may be thought that the slotted nozzle of l=30mm is the most desirable.

5. Concluding Remarks

The passive control using a bleed slot is applied to both the steady and unsteady condensation shock waves in a transonic nozzle. The magnitude of the condensation shock wave and its oscillations, which are generated in the slotted nozzles, are compared with the results of no passive nozzle to investigate the effectiveness of the present passive control. Computations represent the experimented flows quite well. Both the computational and experimental results show that the magnitude of the condensation shock wave is considerably reduced to a negligible magnitude in the slotted nozzles with the slot intervals of $l/h^* \geq 0.53$, where is a characteristic length. The present computations also predict the periodic motions of the condensation shock wave with good accuracy. For the slotted nozzles of $l/h^* \geq 0.53$ the condensation shock motions are completely suppressed by the present passive method. It is found that there is a minimum interval between slots necessary to control the steady and unsteady condensation shock waves. Consequently it is believed that the present passive control method would be useful to alleviate both the steady and unsteady condensation shock waves. It is further noted that the present computations are very useful to disclose the complicated flow physics involved in the passive steady condensation shock wave and the periodic motions of the condensation shock wave as well.

Acknowledgement

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