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Engineering Notes

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Quasi-One-Dimensional Numerical Analysis of Payload Venting of Satellite Launch Vehicle

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I. Introduction

DURING the atmospheric flight, the heat shield compartment of a satellite launch vehicle needs venting to prevent abnormal pressure buildup, which can be detrimental to the structure. The differential pressure depends mainly on the location of the vent holes, the effective volume of air to be evacuated, and the trajectory of the launch vehicle. To model the venting process and predict the differential pressure–time history reasonably for the design, a compressible flow loss coefficient is essential for the mass flux calculation. The international reference guide [1] to space launch gives the maximum differential pressure and rate of change of pressure inside the fairings. The NASA monograph [2] describes the design criteria of compartment venting for space vehicles during ascent and reentry period. Earlier studies were carried out by Mironer and Regan [3] and Murri [4] to determine the venting design criteria for space shuttle payload, using a nominal ascent, payload bay pressure profile. An analytical approach of the discharge process of a compartment into a decreasing time-dependent pressure environment has been published by Sanz-Andres et al. [5]. The effective discharge coefficient for flow through the multirow payload fairing vents on the Titan IV launch vehicle has been numerically simulated by Huseman and Chern [6] using a three-dimensional analysis. The discharge coefficient has been obtained for a range of external flow Mach numbers and internal-to-external pressure ratios applicable to the Titan IV flight trajectory. Experiments were conducted by Johns and Jones [7] in the 8×6 ft supersonic wind tunnel of the NASA Lewis Research Center to find the effective discharge coefficient for the application of the Titan/Centaur launch vehicle. Fay and Hengel [8] analyzed the flow through the vent connecting the multicompartment using a quasi-steady isentropic equation with empirical discharge coefficient. A postflight analysis [9] of the space shuttle showed that the differences between the preflight prediction and measured values were primarily due to difference between external pressures, which are based on subscale wind-tunnel test data and the actual vehicle external pressure measured during the flight. Most of the predictions of the discharge coefficient are based on the flight-derived vent port pressure coefficients, because the wind tunnel does not adequately define the orbiter ascent pressure environment. Alternatively, an inverse analysis [10] can be carried out to estimate the discharge coefficient of the vent hole in conjunction with the measured internal pressure.

The computational cost of a typical discretization of time-dependent three-dimensional full Navier–Stokes equations is generally very large, due to simulation of the flowfield at each time of trajectory of the launch vehicle. Therefore, a new reduced-spatial-dimension model of the multidimensional payload venting is proposed for numerical simulation of differential pressure inside the heat shield, similar to those used for the quasi-one-dimensional nozzle problem. The venting of the payload fairing through a small orifice into a large domain having time-dependent ambient conditions is schematically shown in Fig. 1. The compartment air is discharging through the vent hole into the quiescent atmosphere. The reduced-spatial-dimension model of the compartment venting has several advantages. First, this approach considers conservation of mass momentum and energy. Second, the quasi-one-dimensional model is computationally much more efficient, compared with two-dimensional and three-dimensional numerical simulations of the orifice flow. Third, the reduced-spatial-dimension model retains important features of the realistic venting parameters, such as area of the vent hole and volume of the compartment, but does not require the value of the discharge coefficient of the orifice a priori. The model has an ability to account for the compressibility effects inherent in the venting analysis to make it an efficient tool for quantitative study of the venting performance as a function of trajectory of the launch vehicle. The present Note presents a new reduced-spatial-dimension model for a venting from a heat shield of a typical satellite launch vehicle into the quiescent atmosphere during the ascent period of the flight. The quasi-one-dimensional Euler equations are solved using a finite volume technique. The semidiscretized equations are explicitly integrated in time with a three-stage Runge–Kutta time-stepping scheme, which takes into consideration changing external conditions as the launcher altitude changes.

II. Governing Equations and Numerical Scheme

A key idea of the reduced-spatial dimension model is to numerically simulate the pressure inside the heat shield of the satellite launch vehicle by employing the time-dependent compressible quasi-one-dimensional Euler equations. The governing fluid dynamics equations can be written in conservation law form as follows:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \boldsymbol{S} = 0 \tag{1}$$

where

$$\boldsymbol{U} = A\begin{bmatrix} \rho \\ \rho u \\ \rho e \end{bmatrix}, \qquad \boldsymbol{F} = A\begin{bmatrix} \rho u \\ \rho u^2 + p \\ u(\rho e + p) \end{bmatrix}, \qquad \boldsymbol{S} = -\begin{bmatrix} 0 \\ p\frac{\partial A}{\partial x} \\ 0 \end{bmatrix}$$

where $\boldsymbol{U}$ is the vector of conserved variables, $\boldsymbol{F}$ is the flux vector, $\boldsymbol{S}$ is the source term due to the area variables, and A is the cross-sectional area of the quasi-one-dimensional depressurization equation for the venting. It is assumed that A is a continuously differentiable function that is independent of time. Therefore, A is a function of axial distance x and can be expressed as $A = A(x)$. The variables ρ, u, p, and e are the density, velocity, pressure, and total specific energy,

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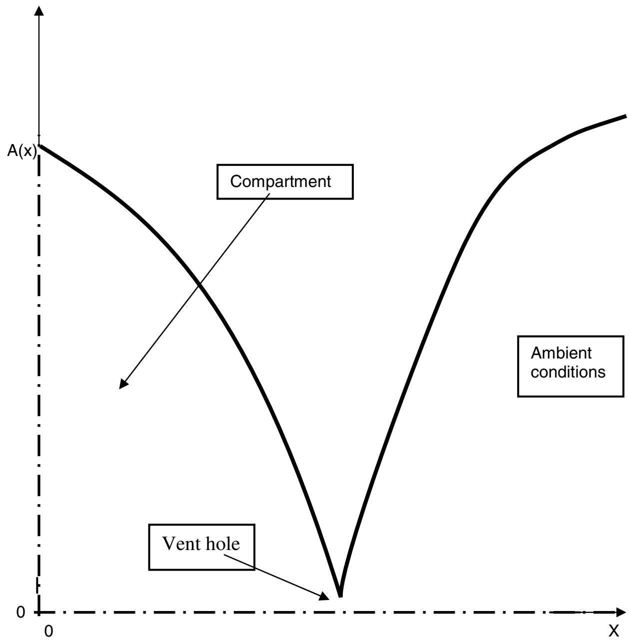

Fig. 1 Schematic of payload compartment venting.

respectively. The equation of state for perfect gas is

$$p = (\gamma - 1)\rho(e - \tfrac{1}{2}u^2) \tag{2}$$

where γ is the ratio of specific heats for air.

The numerical algorithm employs a finite volume discretization technique. The computational domain is divided into a number of small cell intervals in one dimension. The convective flux balance over the cell is approximated by taking average flux vectors on each grid cell with its magnitude and the outer normal for its direction. The scheme is a central-difference scheme on a Cartesian grid. Artificial dissipation terms [11] are used to damp numerical oscillations. The spatial discretization reduces the governing equations to semi-discrete ordinary differential equations. The integration is carried out using a three-stage Runge–Kutta time-marching method [11].

The governing equations are closed with the following boundary conditions. A symmetric condition is imposed on the centerline of the payload fairing. This gives two-way venting of the compartment air to the surrounding. At the other end of the fairing (i.e., at the vent hole location), the ambient condition is used, based on the trajectory of the satellite launch vehicle. The ambient pressure, temperature, and density are taken from the standard atmospheric data [12]. The ambient conditions of the vent depend on the trajectory of the satellite launch vehicle.

III. Compressible and Isentropic Flow

A compressible and isentropic flow equation is solved to validate the aforementioned quasi-one-dimensional model for the payload venting of the satellite launch vehicle. The thermodynamic properties inside the compartment are considered homogeneous, and no spatial gradients are considered for computing the pressure inside the heat shield fairing. The flow through the vent hole is considered quasi-steady, because the residual time of the flow properties in the vent hole is supposed to be much smaller than the characteristic variation of the boundary conditions. The flow can be taken as one-dimensional, adiabatic, inviscid, up to the exit section. This allows the isentropic expansion (with $n = \gamma = 1.4$) to be used to calculate the depressurization rate. The compartment pressure is calculated using following expression [5]:

$$\frac{\mathrm{d}\rho_c}{\mathrm{d}t} = -C_D \frac{A_H}{V_C}\left(\frac{2\gamma}{\gamma-1}\right)^{\frac{1}{2}}\left[\left(\frac{p_i}{p_e}\right)\left(\frac{\rho_c}{\rho_i}\right)^n\right]\left[\frac{p_i}{\rho_i^n}\right]^{\frac{1}{2}}\left(\rho_c^{(\frac{n+1}{2})}\right) \times \left[1 - \left\{\left(\frac{p_i}{p_e}\right)\left(\frac{\rho_c}{\rho_i}\right)\right\}^{\frac{\gamma-1}{\gamma}}\right]^{\frac{1}{2}} \tag{3}$$

where n is polytropic coefficient and C_D is discharge coefficient of the vent hole. Subscripts c, i, and e are the conditions inside the fairing, initial condition, and ambient, respectively. A_H and V_C are the area of the vent hole and compartment volume, respectively. Equation (3) is nonlinear, containing the outer pressure (ambient pressure) $p_e(t)$ as a function of time. A fourth-order Runge–Kutta method is used to compute the compartment density and pressure. The outer pressure is obtained from the atmospheric table [12] as a function of the altitude of the launch vehicle. The pressure inside the compartment is calculated using the isothermal law, as

$$p_c(t) = \left[\frac{\rho_c(t)}{\rho}\right]p_i \tag{4}$$

The differential pressure can be computed as

$$\Delta p = (p_c - p_e) \tag{5}$$

The differential pressure is an important parameter for the structural load and proper functioning of the electronic components inside the payload fairing. It is important to note here that the value of the discharge coefficient of the orifice is an input quantity.

IV. Results and Discussion

To evaluate the accuracy and limitations of the new reduced-spatial-dimension model, the internal pressure inside the payload fairing is computed by solving quasi-one-dimensional compressible time-dependent Euler equations. The internal pressure is computed for two different types of heat shields, referred to as M1 and M2 for different flight trajectories. The volume of air to be evacuated in the M1 heat shield of a typical launch vehicle is about 42 m^3 and the vent area is about 0.0472 m^2. The vent area is distributed in a number of circular holes. The payload fairing of M2 is 49 m^3 and the vent area is about 0.0331 m^2. The Reynolds number based on the velocity at the exit of the vent hole and based on the orifice diameter varies in the range of 3×10^4–1.2×10^5. The ambient pressure p_e is taken using the atmospheric table [12] corresponding to the vehicle altitude at that instant of time. The compartment pressure is computed using the aforementioned numerical simulation based on three-stage Runge–Kutta time-stepping. The computational domain is divided into about 500 grid points. The computations are started by considering sea-level conditions inside the heat shield compartment. The numerical simulation is carried out up to the end of the trajectory.

Figure 2 displays the internal compartment pressure and ambient pressure for M1 and M2 payload fairings. The internal pressure is higher than the ambient pressure, as observed in the figure. It can be observed from the figure that the computed compartment pressure is decreasing with the flight time. Figure 3 shows a variation of

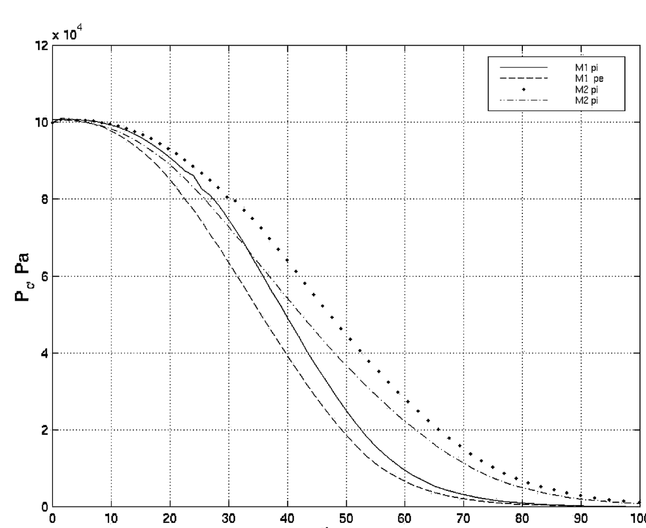

Fig. 2 Variation of internal and external pressure inside the fairing.

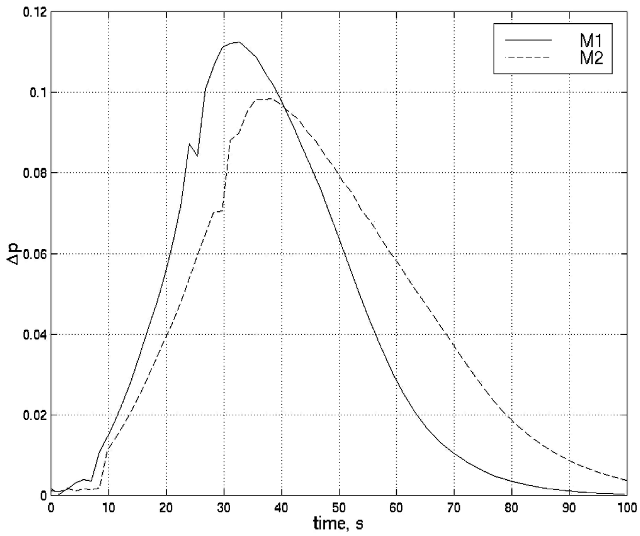

Fig. 3 Variation of differential pressure as a function of time.

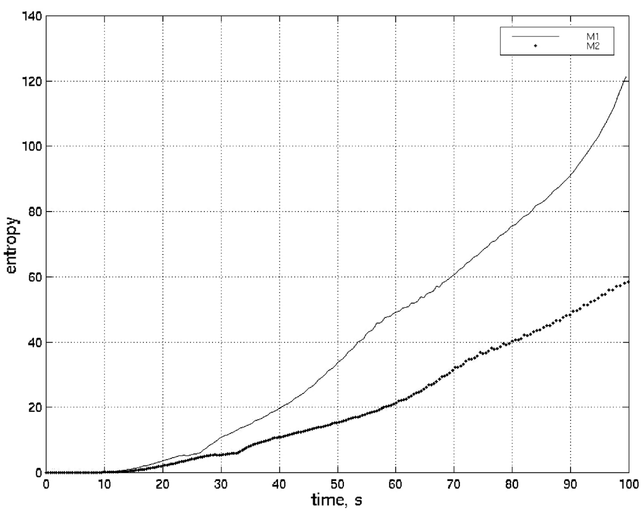

Fig. 4 Variation of entropy as a function of time.

differential pressure Δp (in $\mathrm{kg/cm^2}$) for the payload fairing M1 and M2. The differential pressure is defined as the difference between the internal pressure of the fairing and the ambient pressure. The maximum differential pressure occurs for M1 payload fairing at about 32 s, whereas for the M2 payload fairing, the maximum differential pressure is found at about 35 s. The variation of entropy is also computed for both heat shields and is shown in Fig. 4. The entropy increases with flight time. The entropy of the M1 payload fairing is higher when compared with the M2 heat shield. The variation of discharge coefficient of the vent hole, C_D, is shown as a function of flight time in Fig. 5 for the fairing of M1 and M2 launch vehicles. The discharge coefficient is defined here as the actual mass flow rate divided by the ideal mass flow rate through the vent hole. The value of the discharge coefficients as a function of Mach number is taken from [10] to solve Eq. (3). The internal pressure from the compressible and isentropic relations is compared with the calculated internal pressure obtained by solving compressible and isentropic flow equations, and results show good agreement between them.

V. Conclusions

The new reduced spatial dimension of a payload venting of a satellite launch vehicle was proposed and validated. The central idea of the present approach is based on the quasi-one-dimensional compressible inviscid equations. The governing flow equations

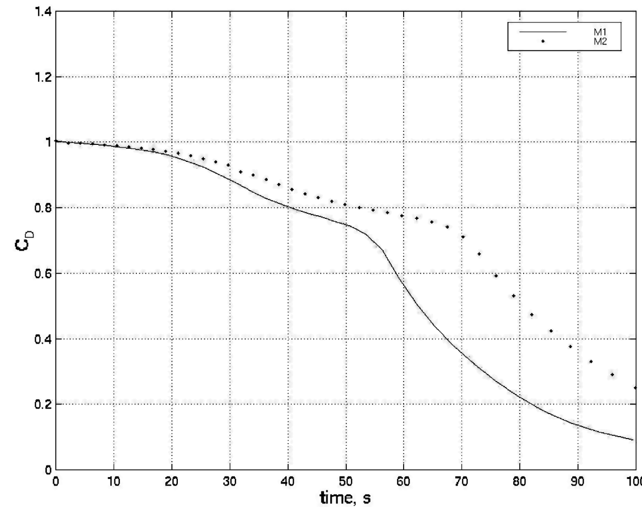

Fig. 5 Variation of discharge coefficient as a function of time.

satisfy the conservation laws. The quasi-one-dimensional model takes into consideration the volume of the air in the compartment at the time of launch, area of the vent holes, and time-dependent ambient conditions. The compartment air is vented into the quiescent air. The numerical simulation of the Euler equations does not require information of the discharge coefficient of the vent hole. Comparisons were presented between numerical simulation with the compressible and isentropic flow, and it is shown that the quasi-one-dimensional model provides good accuracy.

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