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Analysis of payload compartment venting of satellite launch vehicle

R. C. Mehta*

Department of Aeronautical Engineering, Noorul Islam University, Kumaracoil, 629180, India

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Abstract. The problem of flow through the vent is formulated as an unsteady, nonlinear, ordinary differential equation and solved using Runge-Kutta method to obtain pressure inside payload faring. An inverse problem for prediction of the discharge coefficient is presented employing measured internal pressure of the payload fairing during the ascent phase of a satellite launch vehicle. A controlled random search method is used to estimate the discharge coefficient from the measured transient pressure history during the ascent period of the launch vehicle. The algorithm predicts the discharge coefficient stepwise with function of Mach number. The estimated values of the discharge coefficients are in good agreement with differential pressure measured during the flight of typical satellite launch vehicle.

Keywords: depressurization; discharge coefficient; heat shield; inverse problem; numerical analysis; reentry module; satellite launch vehicle; venting

1. Introduction

At the time of launch, the pressure inside the payload fairing of a satellite launch vehicle is at sea level. The ambient atmospheric pressure decreases rapidly during the ascent trajectory of the vehicle, causing a build-up of differential pressure across the heat shield. 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. A compressible flow loss coefficient is essential for the mass flux calculation under polytropic process to model the venting process and to predict the differential pressure-time history reasonably to maintain permissible structural load.

The space vehicle design criteria monograph (NASA 1970) describes design criteria of compartment venting during ascent and reentry phase of space vehicles. The international reference guide (Isakowitz *et al.* 2004) to space launch gives the maximum differential pressure and rate of change of pressure inside the fairing. The problem becomes more critical for large or complex rockets (Pritchett *et al.* 2016) such as Titan launch vehicle (Rogers *et al.* 2015), Viking and Space Shuttle. More complex configurations such as the space shuttle require venting in which a quantity of small experimental package may be kept in a large payload container within a cargo

∗Corresponding author, Professor, E-mail: drrakhab.mehta@gmail.com

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bay and exposed to various conditions of the ascent and reentry trajectory conditions.

Experimental studies were carried out by Mironer and Regan (1983) to determine the venting design criteria for the space shuttle payload, using a nominal ascent trajectory, and payload bay pressure profile. Murri (1987) has experimentally studied venting design criteria for space shuttle payloads using worst case ascent phase trajectory, and payload bay pressure profile. They obtained a single curve that indicates the maximum differential pressure which can be expected for a given vent hole diameter. Flow areas for series and parallel compartment venting to satisfy pressure differential requirements have been studied by Kirby and Ivy (1973). Experiments were conducted by John and Jones (1974) in the 8×6 ft supersonic wind tunnel of the NASA Lewis Research Centre to find the effective discharge coefficient for the venting analysis and application of the Titan/Centaur launch vehicle. It is very difficult to obtain the discharge coefficient from experiments.

Murca (1967) has considered aerodynamically-induced loads in the design of a sounding rocket, which are due to differential pressures occurring across internal bulk heads and across the vehicle outer surface. Fay and Hengel (1993) analyzed the flow through the vent connecting the multi-compartment using a quasi-steady isentropic equation with empirical discharge coefficient. Space shuttle post flight analysis (Lutfi *et al.* 1983) has revealed discrepancies between measured and computed values of the differential pressure inside the shuttle which are attributed to external local pressure based on the subscale model of the wind tunnel test data as compared to the actual vehicle external pressure measured during the flight of the space shuttle. 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 orbital ascent pressure environment. An inverse analysis has been carried out by Mehta (2003) to estimate the discharge coefficient of the orifice in conjunction with the measured internal pressure during the flight.

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.* (1997). A closed-form expression for the isothermal (Mehta 1999) and isentropic (Mehta 2002) venting has been presented using small time-steps during the short time of depressurization. Dykhuizen *et al.* (2012) have derived analytical solutions to calculate the internal pressure of vented enclosure during launch.

The effective discharge coefficient for multi-row vent-holes on the payload fairing of Titan IV launch vehicle has been numerically obtained using three-dimensional Computational Fluid Dynamics (CFD) technique by Huseman and Chern (1997). The discharge coefficient of vent holes has been obtained for a range of external flow Mach numbers and internal-to-external pressure ratios applicable to Titan IV flight trajectory. Brower (2006) has reported the internal payload fairing compartment pressure inside the Titan launch vehicle. Analytical solutions to compute the decompression of pressurized aircraft cabin are derived by Pagani and Carrera (2016) under constant ambient pressure conditions and used for computing structural loads on hinged panes.

Many closed-form solutions for isothermal, polytropic, and isentropic decompression were derived for re-pressurization for aircraft and spacecraft by Mavriplis (1963). The discharge coefficients were obtained through measurements, CFD analyses (Breard *et al.* 2004) or sensitive analyses (Daidzic and Simones 2010). Venting analysis of a Boeing 747 aircraft fuel tank has been carried out by Jensen (2000). It is worth to mention here the major difference between the depressurization process of aircraft and launch vehicle is that in the case of aircraft the back pressure is equal to the atmospheric pressure of ambient air and remains constant during the process of decompression but in the case of space launch vehicles the ambient pressure falls rapidly.

The computational cost of a typical discretiztion of time-dependent three-dimensional full Navier-Stokes equations is generally very large, due to simulation of the flow field at each time of trajectory of the launch vehicle. Quasi-one-dimensional compressible inviscid equations are solved by Mehta (2008) using a finite volume technique to compute differential pressure inside the heat shield taking into consideration changing external conditions at the launcher altitude changes.

Epstein and Ruth (1997) have conducted experiment on honeycomb sandwich structures and observed that failures occur due to internal pressure when the external environment is reduced in ambient pressure. They recommended that the honeycomb sandwich structure for space system to be adequately vented in order to minimize the likely hood of failure. A reduced-spatial-dimension model (Mehta 2009) of the multi-compartment payload venting has been employed for numerical simulation of differential pressure inside the heat shield.

Moraes and Pereira (2005) have presented verification of the computed and measured differential pressure inside the satellite vented compartment of the Brazilian satellite launch vehicle. The external pressure in the vicinity of the vent holes is taken by them from the wind-tunnel data.

Vents are essential in the payload fairing of satellite launch vehicle in order to maintain the design limit for structural loads as well as for the satisfactory performance of the electronic packages. The entrapped air is vented throughout the flight. The number and size of vent holes on heat shield of satellite launch vehicle have to maintain the structural integrity. The appropriate location of the vent holes is also important factor to vent out the trapped air. Normally vent holes are drilled at locations which are free from high pressure and also from the presence of shocks. The preferred location on the heat shield is at the far end of the cylinder, where nearly ambient pressures prevail. Discharge coefficient is function of vent area, shape, local Mach number and interaction of outgoing stream with external pressure. In the present study, flight measurement of a launch vehicle is used to derive discharge coefficient variation.

2. Analysis

A compressible and isentropic flow equation (Shapiro 1953, Liepmann and Roshko 2007) is employed to compute the differential pressure inside the payload faring 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 to be quasi-steady, because the residence 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 to be used to calculate the depressurization rate.

2.1 Governing equations

The differential equation for the venting of a payload compartment is obtained employing mass conservation equation. The mass flow rate through the vent can be written as

$$\dot{m}_c = C_D A u \rho_c \tag{1}$$

where $\dot{m}_c$ is outflow through the vent and ρ is the density of the air inside the compartment and u

is the air velocity at the exit of the hole. The discharge process is modeled as isentropic. This is a reasonable assumption, as the outflow is very rapid and the orifice is relatively short. Here, C_D is the discharge coefficient of the vent orifice. A is the area of the vent hole. The discharge coefficient is defined as the ratio between the actual diabatic irreversible outflow and the theoretical maximum possible or isentropic outflow. The discharge coefficients used should be applicable in terms of orifice Reynolds number and pressure ratio across the orifice. The local external flow conditions of Mach number and boundary layer thickness and profile should be accounted for in orifice flow analysis.

Using the first law of thermodynamics for an isentropic process and employing the pressure-density-temperature relationship in the form of perfect gas law, one obtains isentropic relationship (Liepmann and Roshko 2007) as a function of the internal pressure level as

$$\rho_a = \rho_c \left(\frac{p_a}{p_c} \right)^{\frac{1}{\gamma}} \tag{2}$$

where p is pressure and subscripts a and c represent the conditions at ambient and inside the compartment, respectively and γ is ratio of specific heats. The velocity u is a function of pressure and density (Shapiro 1953) and can be written as

$$u = \sqrt{\frac{2\gamma}{\gamma - 1} RT_c \left\{ 1 - \left(\frac{p_a}{p_c} \right)^{\frac{(\gamma-1)}{\gamma}} \right\}} \tag{3}$$

Substituting Eq. (3) and introducing the perfect gas law into Eq. (1) and yields (Haber and Glamann 1953)

$$\dot{m}_c = \frac{C_D A p_c}{\sqrt{RT_c}} \sqrt{\frac{2\gamma}{\gamma - 1} \left(\frac{p_a}{p_c} \right)^{\frac{2}{\gamma}} \left\{ 1 - \left(\frac{p_a}{p_c} \right)^{\frac{(\gamma-1)}{\gamma}} \right\}} \tag{4}$$

The maximum mass flow rate equation (Shapiro 1953) for choked flow is

$$\dot{m}_{max} = \frac{C_D A P_c \sqrt{\gamma}}{\sqrt{RT_c}} \left(\frac{2}{\gamma + 1} \right)^{-\frac{(\gamma+1)}{2(\gamma-1)}} \tag{5}$$

Considering the speed of sound a in the compartment is

$$a = \sqrt{\gamma R_c T_c} \tag{6}$$

The maximum flow equation can be written as

$$\dot{m}_{max} = C_D a \rho_c A \left(\frac{2}{\gamma + 1} \right)^{-\frac{(\gamma+1)}{2(\gamma-1)}} \tag{7}$$

and the compartment air pressure versus atmospheric pressure ratio decrease to a critical pressure ratio (Shapiro 1953) as

$$\frac{p_a^*}{p_c} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 0.5283 \tag{8}$$

where (p_a^*/p_c) is the ratio of minimum internal pressure for sonic discharge to ambient pressure p_a. Differentiating Eq. (2) yields

$$d\rho_c = \frac{1}{\gamma}\cdot\frac{\rho_a}{p_c}\left(\frac{p_a}{p_c}\right)^{\frac{1-\gamma}{\gamma}}\cdot dp_c \tag{9}$$

A relatively simple expression for the rate of pressure decrease resulting from escape of air through a vent can be obtained when $p_a^*>p_c$. It is important to say that the decompression process does not depend on the ambient pressure. In the case of subcritical case the rate of discharge is proportional to the differential pressure rather than the process itself. When the time for an acoustic wave to cross the compartment is far less than the time for a change in the boundary condition, i.e., $\{(t/L)a\}>>1$. L is the characteristic length of the compartment. The problem of flow in compartment and through the vent system can be formulated as an unsteady, nonlinear, differential equation system and obtain as

$$\frac{dp_a}{dt} = -C_D\,\frac{A\cdot a}{V_c}\cdot p_c\cdot\gamma\cdot\sqrt{\frac{2}{\gamma-1}}\cdot\left(\frac{p_a}{p_c}\right)\cdot\sqrt{1-\left(\frac{p_a}{p_c}\right)^{\frac{\gamma-1}{\gamma}}} \tag{10}$$

where V_c is the area of the vent hole and compartment volume. The equation can be written by introducing a similarity parameter $\tau = [(A\cdot a/V_c)\cdot t]$ and Eq. (10) can be rewritten as

$$\frac{d\left(\frac{p_a}{p_c}\right)}{d\tau} = -C_D\cdot\gamma\cdot\sqrt{\frac{2}{\gamma-1}}\cdot\left(\frac{p_a}{p_c}\right)\cdot\sqrt{1-\left(\frac{p_a}{p_c}\right)^{\frac{\gamma-1}{\gamma}}} \tag{11}$$

Here $\tau=(A\cdot a/V_c)\cdot t$ is a characteristic time during which pressure or other boundary conditions change. It is worth to mention here that the above equation can be used to compute energy of explosion (Kinney and Graham 1985). A small time constant τ means a short time of decompression that is a fast decompression. The discharge coefficients used should be applicable in terms of orifice Reynolds number and pressure ratio across the orifice. The local external flow conditions of Mach number and boundary layer thickness and profile should be accounted for in the orifice flow analysis. The external pressure history in the vicinity of the vent should be calculated on the basis of the vehicle's trajectory in the atmosphere. Separating the variables and integrating the above equation yield exact solutions and are used for studying the effect of re-pressurization for aircraft and spacecraft by Mavriplis (1963), and for payload fairing of satellite launch vehicle by Mehta (1999), (2002).

Eq. (11) is an ordinary nonlinear differential equation. It contains the ambient pressure $p_a(t)$ as a function of time. A fourth-order Runge-Kutta method is used to compute the compartment pressure. C_D is depends on the vent area, location and local Mach number. The time step in the numerical analysis should be compatible with the (V_c/Aa).

The differential pressure can be calculated as

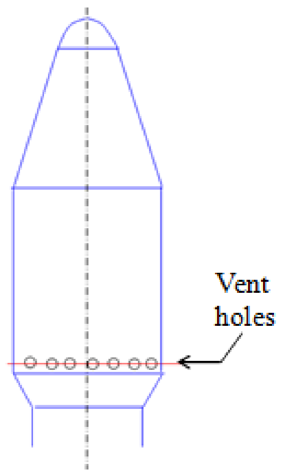

Fig. 1 Typical payload fairing with vent holes

$$\Delta p = p_c - p_a \tag{12}$$

3. Flowfield analysis over the payload fairing

3.1 Payload fairing and vent holes

The volume of air to be evacuated in the 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 as a number of circular holes. 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_a is interpolated using the atmospheric table (Anathasayanam *et al.* 1987) corresponding to the instantaneous vehicle altitude. To evaluate the performance of the depressurization process during the ascent phase of the satellite launch vehicle, two pressure transducers have been used to measure the heat shield compartment pressure and outside pressure in the vicinity of the vent. To find the most appropriate location for the venting orifice a criteria was established (NASA 1970) which recommends that the difference between the static pressure at the vent location over the payload fairing surface and the ambient pressure close to zero. In the next section a numerical analysis is carried out and described.

3.2 Flow field and pressure distribution over the payload fairing

A flow solver code is developed by Mehta (1997) to solve the turbulent axisymmetric Reynolds-averaged Navier-Stokes equations using finite volume method in conjunction with three-stage Runge-Kutta time-stepping scheme with Baldwin-Lomax turbulence model. Numerical simulation has been performed to obtain pressure distribution over a bulbous payload shroud at zero angle of attack in the Mach number range of 0.8-3.0 and Reynolds number range of 3.314×10^7/m–4.682×10^7/m. Fig. 1 shows the typical heat shield of satellite launch vehicle and Fig.

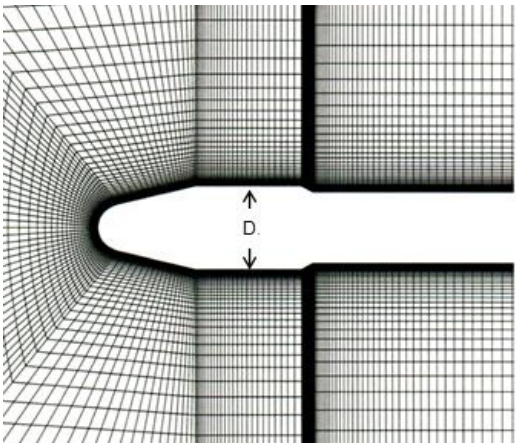

Fig. 2 Enlarged view of computational grid

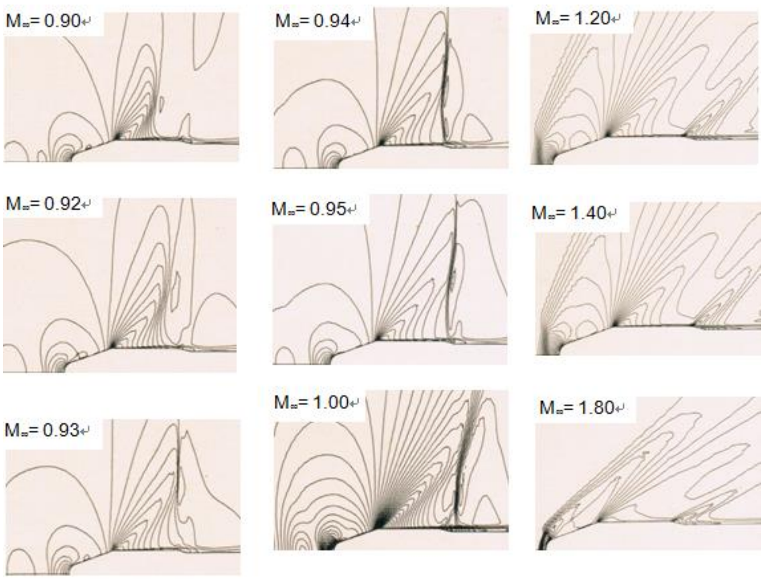

Fig. 3 Density contour over payload shroud

2 depicts an enlarged view of the computational grid used in numerical simulations.

Fig. 3 displays density contour plots at various freestream Mach numbers. The density contour plots will help to locate a suitable location of the vent holes in order to avoid strong transonic shock. The surface pressure coefficient C_p versus x/D along the length of the launch vehicle for various values of freestream Mach numbers is depicted in Fig. 4. Here D is the diameter of the heat shield as depicted in Fig. 2. The pressure distribution is used to find out the most appropriate location for the vent holes over the payload fairing where the ambient pressure should be nearly zero and the compartment pressure should be greater than the ambient and their difference should be close to zero. Fig. 4 shows the very high axial pressure gradient in the boat tail region of the payload shroud. The cylindrical region of the heat shield and the boat tail region is the most suitable location for vents orifices.

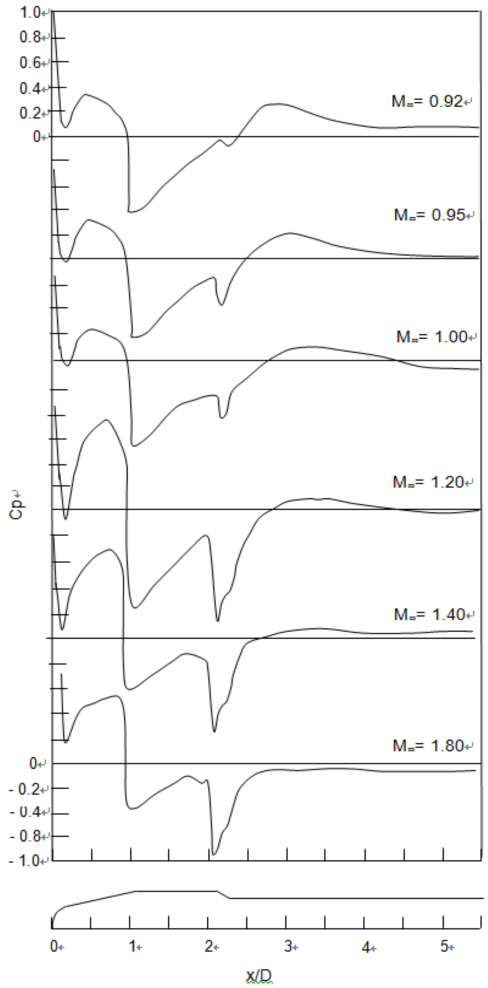

Fig. 4 Pressure distribution along the launch vehicle

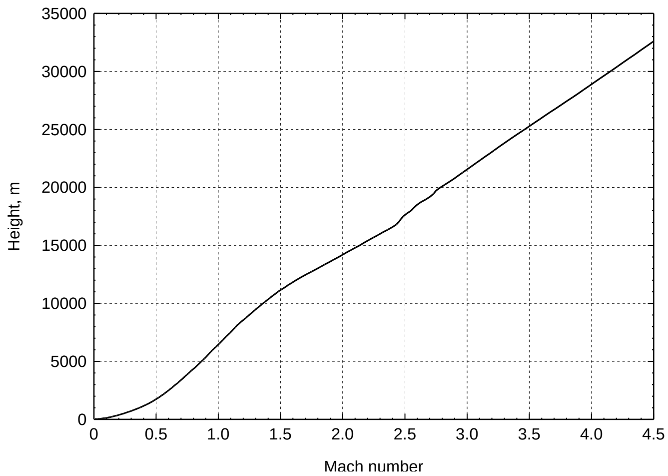

Fig. 5 Trajectory of the launch vehicle

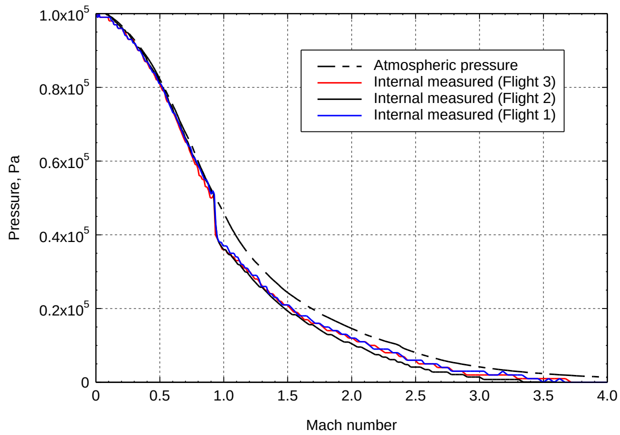

Fig. 6 Internal compartment and ambient pressure

Table 1 Estimated values of C_D

Mach number range	C_D
M ≤ 0.5	0.90
0.5 < M ≤ 0.75	0.70
0.75 < M ≤ 1.00	0.40
1.00 < M ≤ 1.25	0.20
1.25 < M ≤ 1.50	0.15
1.50 < M ≤ 2.00	0.10
3.00 < M ≤ 4.50	0.10

4. Results and discussion

4.1 Estimation of discharge coefficient

The present paper includes a controlled random search technique Price (1978) for the estimation of the discharge coefficient C_D from the pressure-time history measured during the ascent phase of a satellite launch vehicle. The controlled random search method does not need calculation of the sensitivity coefficient and the future-pressure information. The CRS algorithm does not need computation of derivatives but depends on function $F(C_D)$ evaluation alone. The function $F(C_D)$ is difference between measured and calculated values of the differential pressure. It works even when the differentiability requirements cannot be assured in the feasible region of variable C_D. For initiating CRS algorithm no initial guess value, except for an estimate of C_D, is required. The algorithm does not depend on the future-pressure information.

The CRS algorithm is implemented in two steps. In the first step, random feasible points generated from C_D and $F(C_D)$ are computed at each point and information stored as a matrix. The maximum and minimum values $F_M(C_D)$, $F_L(C_D)$ of $F(C_D)$ and corresponding points M and L are then identified. In the second step, these random points are manipulated iteratively to yield a better candidate for global solutions. To this extent at each iteration arbitrary distinct points are selected from matrix.

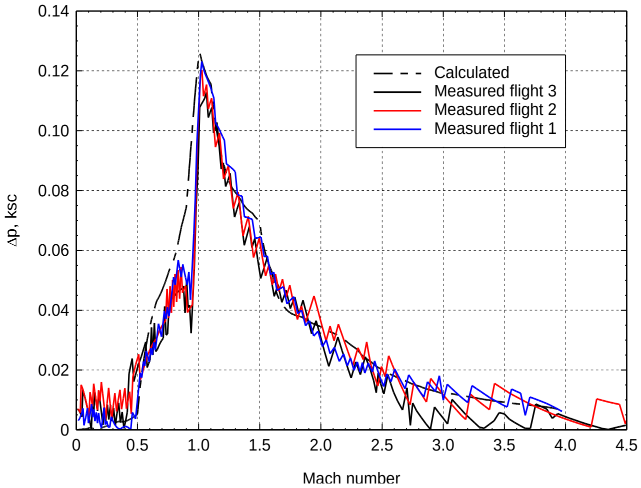

Fig. 7 Reconstructed differential pressure using predicated discharge coefficients

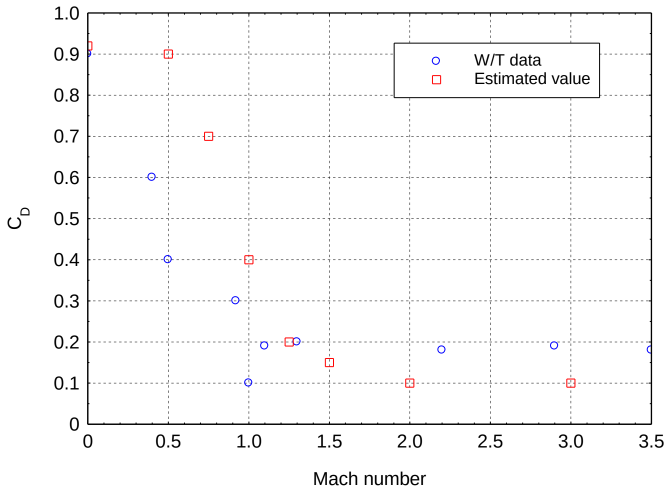

Fig. 8 Comparison between estimated and experimental discharge coefficients

The details of controlled random search algorithm are described in the estimation of convective heat transfer coefficient by Mehta and Tiwari (2007). The CRS algorithm predicts the discharge coefficient as a function of stepwise Mach number. The trajectory of the vehicle is depicted in Fig. 5. The ambient pressure is computed using the atmospheric data (Anathasayanam *et al.* 1987) in conjunction with the vehicle trajectory. Fig. 6 displays the measured internal pressure inside the payload fairing for different flights (Sachdeva and Mehta 2008). The measured (Sachdeva and Mehta 2008) and reconstructed differential pressures with respect to the freestream Mach number are shown in Fig. 7. The differential pressure for the payload compartment should not exceed 0.15×10^5 Pa. The maximum differential pressure is seen in the vicinity of sonic Mach number, which is attributing the choked condition in Fig. 7. Reconstructed differential pressures show good agreement with the numerical results. It is important to mention here that the maximum differential pressure and the rate of decrease as the differential pressure are within the permissible limits as mentioned (Isakowitz *et al.* 2004). Table 1 shows the estimated value of discharge coefficient in the Mach number range. The predicted value of the discharge coefficient is compared with measured value (John *et al.* 1974) and shown in Fig. 8.

The comparisons between the estimated values obtained using the controlled random search method and experimental values depict good agreement between them.

5. Conclusions

Venting analysis of a typical launch vehicle payload compartment is carried out by solving the first order nonlinear differential equation using a fourth order Runge-Kutta method. The discharge coefficients have been estimated employing the controlled random search method using compartment pressure measurements from the first flight. The estimated discharge coefficients show good agreement for the subsequent flights. The measured compartment pressures are found to be consistent with the reconstructed differential pressure in conjunction with estimated discharge coefficient as a function of the flight Mach number.

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