Design and Development of Depressurization System of Launch Vehicle Fairings

Muhammad Tanveer Iqbal, Abdul Majid

Abstract— **During ascent of space launch vehicle in atmosphere, the payload compartment pressure should be leveled with the atmospheric pressure. At high altitudes, this pressure difference becomes more destructive. It produces crushing or bursting loads in the form of tension, compression or shear on satellite and launch vehicle. Even small differentials may be critical when imposed with compressive axial loads. In history of launch vehicles, at least two flights were failed due to improper depressurization of fairing [1]. Pressure equalization is attained through venting ports located on the periphery of fairing. The main constraint of depressurization system is to ensure the minimal pressure difference between fairing payload compartment and the atmosphere. However, fulfilling this constraint is difficult due to the continuous variation in flow velocity, from subsonic to hypersonic, during flight. The size, location and number of venting ports dictate effectiveness of depressurization system.**

In this paper, an innovative approach is used for the design and mathematical model development of depressurization system of launch vehicle fairing. For this purpose, MATLAB/SIMULINK toolbox Simscape is customized as per requirement. The quantity and size of venting ports are estimated by considering minimum pressure differential during atmospheric flight and at fairing separation. The suitable location of ports is estimated where static pressure at the port location over the fairing surface and the uninterrupted atmospheric pressure are equal.

In order to verify the results, a scale down experimental setup is developed. One-way solenoid valves with three different orifice sizes are used as venting ports. Depressurization is performed at highest pressure difference, expected during flight. Numerical and experimental results are compared and it is found that numerical results are in good agreement with the experiment.

Keywords—space launch vehicle; fairing; depressurization; vent port; sanville's equations; experimental setup

I. Introduction

Space launch vehicle (SLV) contains 3 to 4 propulsive stages (solid or liquid) and payload which is enclosed by fairing. Fairing protects the satellite against harsh environmental loadings; which include aerodynamic, thermal and acoustic loadings. During ascent of SLV through atmosphere, there is high pressure decay rate and subsonic to hypersonic velocity variation along the outer surface of fairing. In the absence of equalization of internal and external pressure, a force is produced between internal and external surface of fairing due to the high pressure decay rate, which can cause severe bursting or crushing loads on the satellite and SLV. Allowable pressure difference and pressure decay rates for space launch vehicles are given in international reference guide [1]. For large rockets/launch vehicles, venting problem becomes perilous [2] as in case of Titan [3] and Space Shuttle [4].

To avoid pressure loadings, depressurization system is designed which consist of equally spaced vent holes along the circumference of fairing wall. Vents are made usually at position which is shock-load free and pressure-load free [5]. Depressurization design criteria for space launch vehicle in worst-case scenario was considered by Murri [6]. In which maximum differential pressure was predicted for a given vent hole during flight.

Depressurization system should also able to take care of prelaunch venting requirements such as purging and air conditioning of payload compartment [7]. Therefore, vent holes contain one-way check valves which make it compatible with prelaunch requirements and also ensure one way flow during ascent. 5-m payload fairing of Atlas-500 series [8] describing ground conditioning system and depressurization system is presented in fig. 1.

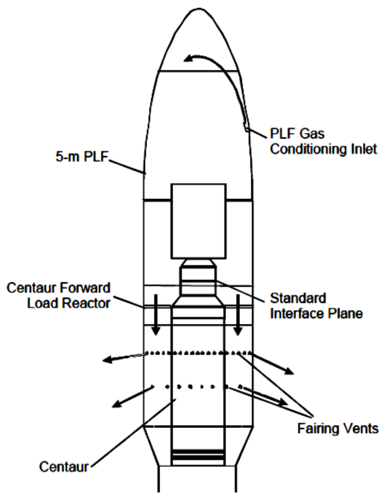

Fig. 1: Atlas 5-m Payload Fairing (PLF)

II. Given Parameters

For the purpose of fairing depressurization system designing, Vega (SLV of European Space Agency) is taken as reference. Fairing parameters of Vega are given in table I.

TABLE I
GIVEN PARAMETERS FOR FAIRING DEPRESSURIZATION SYSTEM

Fairing Internal Volume	1.75m^3
Maximum Allowable Pressure Difference	7.0kPa
Pressure difference at fairing separation	2.0kPa

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Fairing depressurization system has to be cautious to maintain atmospheric pressure inside fairing compartment within the allowable pressure difference limit. The fairing internal pressure variation of Vega [9] during ascent is shown in fig. 2.

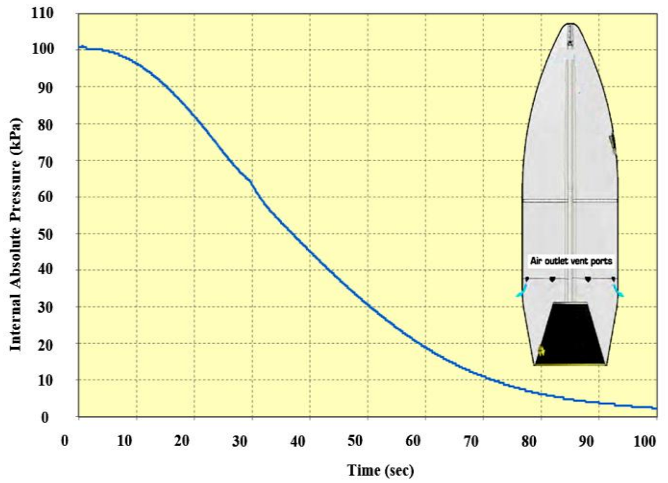

Fig. 2. Fairing internal pressure variation during ascent of SLV – Vega

At launch of VEGA, static pressure inside fairing is equal to atmospheric pressure i.e. 101.325 kPa. During ascent, payload section is depressurized using one-way vents. Rate of depressurization remains under 2 kPa/sec during flight, except at maximum dynamic pressure it exceeds to 4.5 kPa/sec for 2sec.

III. DESIGNING OF DEPRESSURIZATION SYSTEM

Design and modeling of depressurization system includes finding optimize quantity, size and location of vent port.

A. Vent Port Sizing

Vent port sizing has very important role in designing fairing as if vent ports are small, bulging effect will be occurred during flight and increasing the size of vent ports could harm the structural integrity of fairing. For sizing of vent port, mathematical modeling of depressurization system is done in SIMULINK/Simscape using dynamics flow equations. Some assumptions for mathematical modeling are 1) The gas is ideal 2) Cp and Cv are constant 3) There is no heat in or out during depressurization. 4) Orifice is sharp edged and its Cd is 0.6. Modeling of depressurization system is shown in fig. 3.

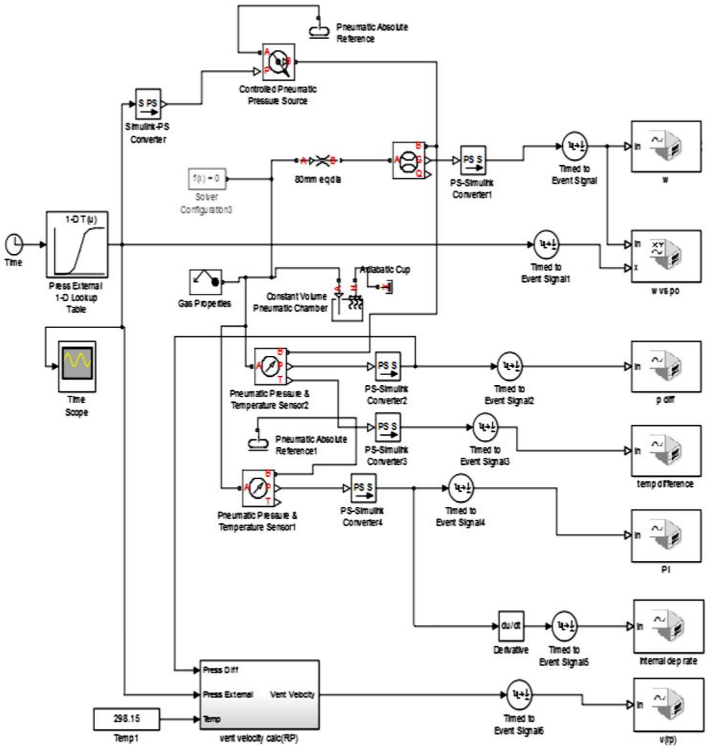

Fig. 3. : Depressurization system model in SIMULINK

Orifice is based on Sanville's equations [10] which cater for laminar, subsonic and choked flows.

$$G = \begin{cases} k_1 \cdot p_i \left(1 - \frac{p_o}{p_i}\right)\sqrt{\frac{T_{ref}}{T_i}} \cdot sign(p_i - p_o) & \text{if } \frac{p_o}{p_i} > \beta_{lam} \text{ (laminar)} \quad (1) \\ p_i \cdot C \cdot \rho_{ref}\sqrt{\frac{T_{ref}}{T_i}} \cdot \sqrt{1 - \left(\frac{\frac{p_o}{p_i} - b}{1 - b}\right)^2} & \text{if } \beta_{lam} > \frac{p_o}{p_i} > b \text{ (subsonic)} \quad (2) \\ p_i \cdot C \cdot \rho_{ref}\sqrt{\frac{T_{ref}}{T_i}} & \text{if } \frac{p_o}{p_i} <= b \text{ (choked)} \quad (3) \end{cases}$$

$$k_1 = \frac{1}{1 - \beta_{lam}} \cdot C \cdot \rho_{ref}\sqrt{1 - \left(\frac{\beta_{lam} - b}{1 - b}\right)^2}$$

Where;

β_{lam} - Pressure ratio at laminar flow
ρ_{ref} - Gas density at which the sonic conductance was measured
C - Sonic conductance
C_d - Discharge coefficient
C_p - Coefficient of pressure
C_v - Flow coefficient
D - Diameter of orifice
G - Mass flow rate
P_e - Absolute pressure values at outlet
P_i - Absolute pressure values at inlet

q - Mass flow rate
T_e - Absolute temperature values at exit
T_i - Absolute temperature values at inlet
T_{ref} - Gas temperature at which the sonic conductance was measured

Simulation is carried out for external pressure varying with respect to time (as in actual SLV flight) and constant atmospheric pressure for comparison with results of experimental setup of depressurization system.

For simulating in-flight pressure variation with respect to time, real trajectory was reconstructed [11] using NASA-NOAA-USAF, 1976 standard atmosphere [12]. Selection of vent port size is done by considering 1) Flow velocity after exiting orifice should be subsonic 2) Flow should not choked.

For fairing of given volume, 32 vent ports of 6mm are required to fulfill parameters given in table 1. Pressure – time curve simulated for actual flight conditions in SIMULINK is shown in fig. 4.

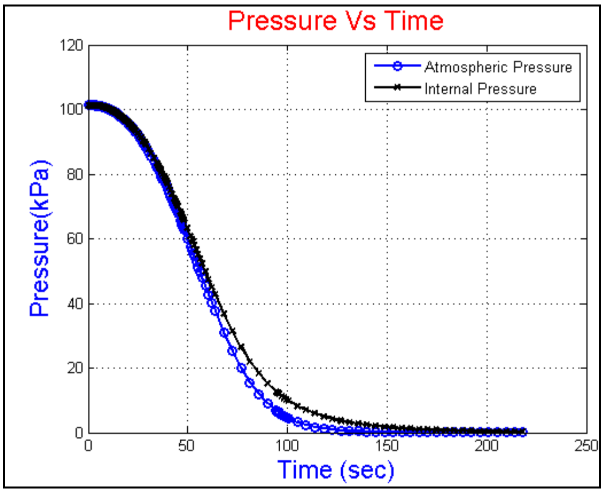

Fig. 4. Simulated pressure - time curve for actual flight conditions

Maximum pressure difference achieved during simulated flight is 6.5kPa at 98.5sec. While pressure difference at fairing separation (i.e. 155sec) is 1.97kPa.These results can be verified by developing a setup placed in vacuum chamber, having capability of achieving pressure variation from 101kPa to vacuum in given time or through actual flight of SLV. First option will be carried out in future. Later option is too expensive and requires 5 to 6 years.

For authentication of flow dynamics equations implemented in SIMULINK, simplest process is adopted in which simulation is done at constant atmospheric pressure (101kPa). Depressurization is accomplished from fairing's internal pressure of 200kPa to room pressure (101kPa). Vent port sizes varying from 2 to 6mm are used. Simulated results of depressurization system are shown in fig. 5.

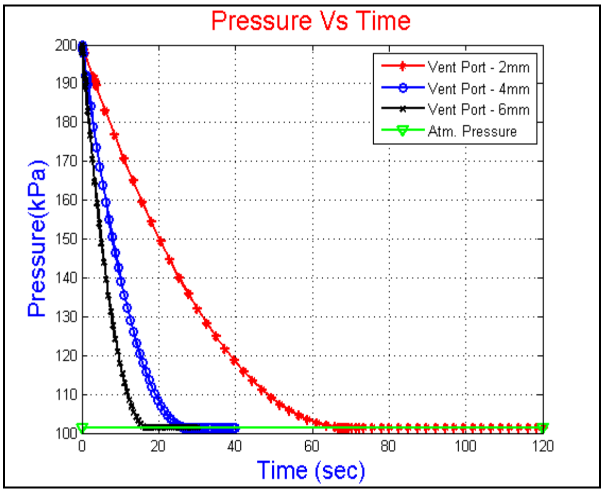

Fig. 5. Simulated pressure - time curves for constant external atmospheric pressure

Depressurization time from 200kPa to atmospheric pressure for 2, 4 and 6mm vent port is 69.5, 27.4 and 17.1sec respectively.

B. Vent Port Location

For defining location of vent ports from nose tip of fairing, a criteria is selected [13]. It states that static pressure over the vent port on fairing surface and the external atmospheric pressure must be equal, which means that pressure coefficient 'Cp' must be zero. Cp is defined as the difference between the static pressure over particular location and the external atmospheric pressure divided by dynamic pressure. Mathematically;

$$C_p = \frac{P_x - P_\infty}{q_\infty} \tag{4}$$

Where;

Px is the static pressure acting on a position 'x' over the fairing surface, P∞ is the undisturbed atmospheric pressure, and q∞ is the dynamic pressure which is defined as:

$$q_\infty = \frac{\rho_\infty * V_\infty^2}{2} \tag{5}$$

Where;

ρ∞ is the local atmospheric density, and V∞ is the vehicle velocity

In addition to Cp approaches to zero, rate of change of Cp with respect to location (dCp/dx) must also be approaches to zero for all Mach numbers; if not, minor location change would significantly upset vent flow. The Cp distribution along the surface of fairing for transonic region is shown in fig. 6.

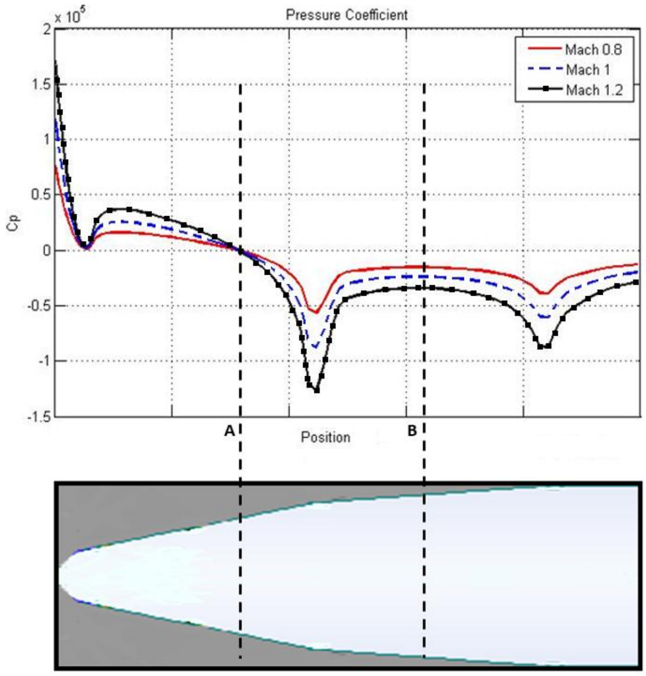

Fig. 6. Coefficient of pressure distribution along the surface of fairing

The obvious option for placing vent ports is location 'A' because Cp is zero for different Mach numbers at that location. But rate of change of Cp with respect to change in location is very high and small variances such as manufacturing tolerances of vent port, high angle of attacks and boundary layer separation at that location could create trouble in vent flow. Thus making location 'A' unsuitable for placement of vent ports. Then location 'B' (3.2m from nose tip of fairing) is selected, as Cp gradient (dCp/dx) is very low. Value of Cp is not zero at location B, but difference between local static pressure and external atmospheric pressure is less than desired allowable pressure difference.

IV. Development of Experimental Setup

An experimental setup is constructed having volume of 32 times smaller than actual fairing volume. Solenoid valve is used as vent port with 2, 4 and 6mm orifice diameter for the verification of simulated results. Solenoid valve is shown in fig. 7. Pressure transducer is used to measure and record the internal pressure of setup.

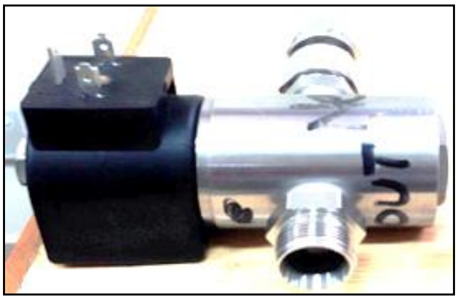

Fig. 7. Solenoid valve

To test the behavior of vent port, air is filled up to 200kPa using regulated pressure system in the experimental setup through inlet port while external atmospheric pressure is 101kPa. After filling and maintaining the pressure of 200kPa, solenoid valve is opened and pressure is continuously recorded using pressure transducer. Experimental setup of depressurization system is shown in fig. 8.

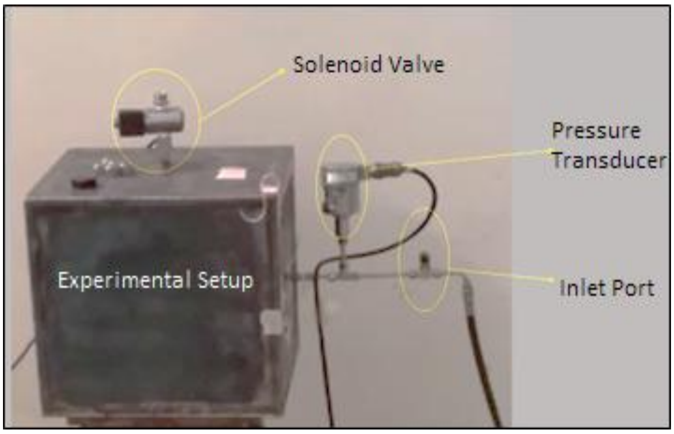

Fig. 8. Experimental setup of depressurization system

V. Results and Analysis

Pressure vs time curves for all three vent ports, obtained through pressure transducer are curve fitted using 5th order polynomial and compared with simulated results as shown in fig. 9, 10 and 11.

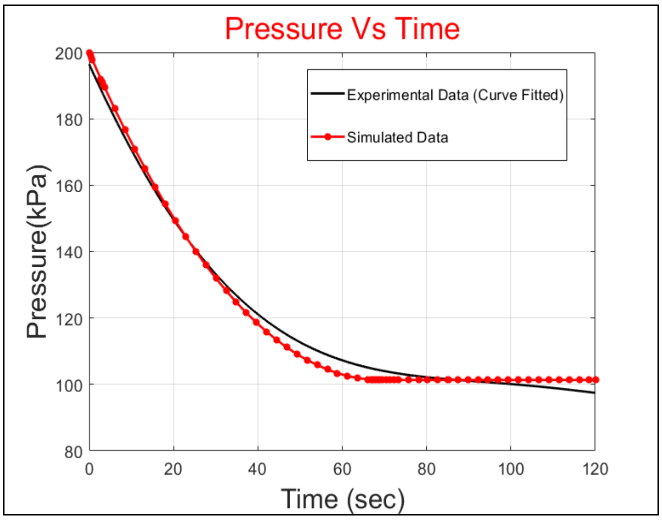

Fig. 9. Experimental pressure - time curve for 2mm vent port

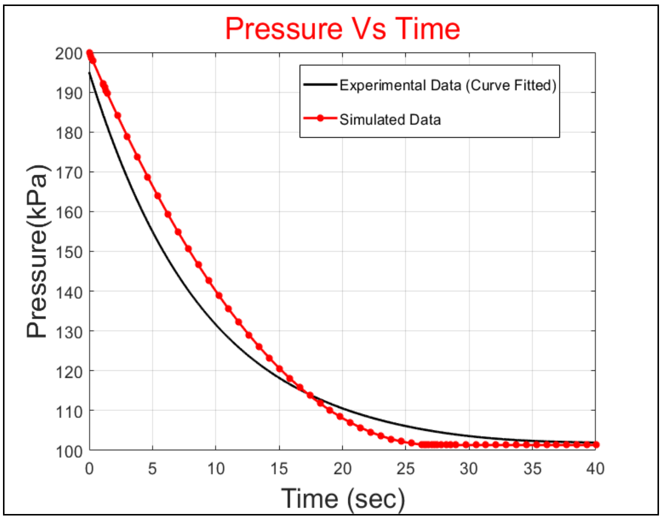

Fig. 10. Experimental pressure - time curve for 4mm vent port

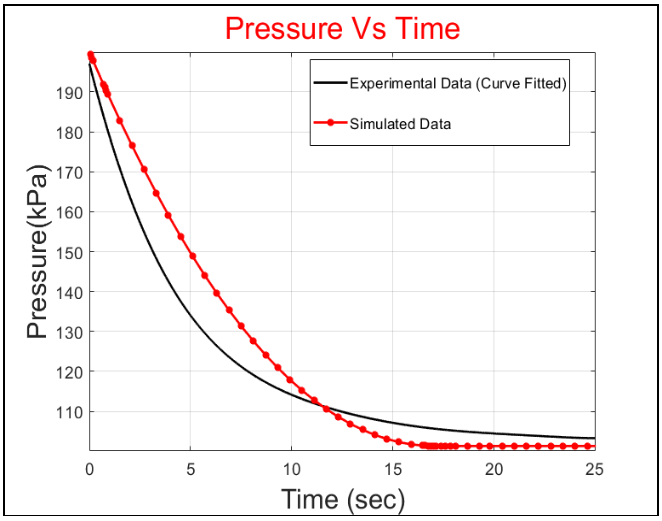

Fig. 11. Experimental pressure - time curve for 6mm vent port

For 2mm vent port, experimental data shows that internal pressure matched with external pressure in 80sec. Whereas, it equalized in 63sec for numerical analysis. For 4mm vent port, pressure equalization is achieved in 40sec and 26sec for experimental and numerical analysis respectively. In case of 6mm vent port, equalization time is 25sec for experimental analysis while 17sec for simulated analysis.

Experimental and simulated results are accurately close to each other with maximum deviation of 15kPa. Deviation in simulated results from experiment is due to assumption of discharge coefficient. For 2mm vent port, Cd used for simulated analysis was precisely correct. However for 4mm & 6mm orifice, Cd value needs adjustment for close matching of simulated and experimental results. In future, further steps can be taken to precisely predict the discharge coefficient using experimental analysis.

VI. Conclusion

The main purpose was to design and model a dynamic depressurization system which adequately equalized the fairing internal pressure with the external atmospheric pressure. Designing of fairing depressurization system includes defining size, quantity and location of vent ports on fairing which is accomplished using flow dynamics equations.

For estimating location of vent ports, a place was found at which values Cp and dCp/dx approaches to zero. For finding size and quantity of vent port, mathematical flow equations are implemented using SIMULINK's toolbox 'Simscape'. Optimum vent port size and quantity is achieved by considering given parameters. Simulations were done for actual in-flight conditions but verification of results is difficult and expensive. Therefore simple methodology was implemented in which depressurization was achieved at constant atmospheric pressure using three different vent port sizes.

For authentication of this simple methodology, an experimental setup was developed and depressurization was conducted. Simulated and experimental results were compared and found in good agreement with each other. For future, vacuum chamber may be designed in which already developed setup will be placed to replicate actual ascending conditions to verify the simulated in-flight results.

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