Engineering Notes

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Flow Areas for Series-Parallel Compartment Venting to Satisfy Pressure Differential Requirements

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Introduction

SPACE vehicles may contain internal compartments whose walls may be subjected to critical loads imposed by pressure differentials during an ascent trajectory. The NASA Space Vehicle Design Criteria Monograph on Compartment Venting[1] points out in its state of the art section that a one or two compartment system, venting to the external atmosphere, is sometimes adequate for analysis purposes.

However, venting problems become more critical for large or complex projects such as Viking. The seven compartment configuration shown in Fig. 1 is being used at NASA Langley Research Center for this venting analysis. More complex configurations will be required for the Shuttle in which a quantity of small experimental packages may be stored in a large payload container within a cargo bay and exposed to a variety of ascent and re-entry trajectories. No acceptable method exists for determining the interconnecting areas required to vent a large number of series-parallel connected compartments to an externally varying atmosphere.

The purpose of this Note is to present a unique method for solving the problem. The associated analytical technique for determining the transient pressure in each compartment is also presented.

Analytical Model

Consider a compartment j connected to adjacent compartments n through orifices of area A_{jn} as in Fig. 2. The density variation can be expressed as a function of the mass flow rates to or from compartment j as

$$\dot{\rho}_j = \frac{1}{V_j}\sum_{i=1}^{n} \dot{M}_{j,i} \tag{1}$$

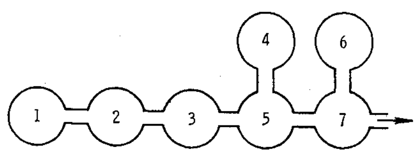

Fig. 1 Venting compartment schematic for project Viking spacecraft.

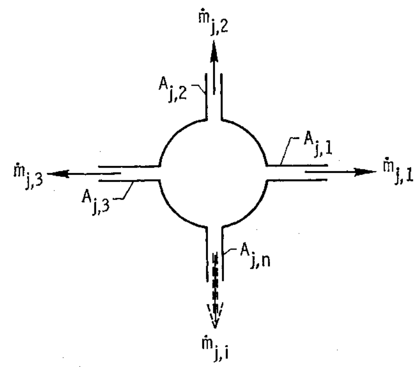

Fig. 2 *J*th compartment of a multicompartment system.

Differentiating the isentropic equation for the relationship between density and pressure and setting the result equal to Eq. (1) gives the pressure variation in compartment j as

$$\dot{P}_j = \frac{\gamma(P_{0j})^{1/\gamma}(P_j)^{\frac{\gamma-1}{\gamma}}}{P_{0j}V_j}\sum_{i=1}^{n} \dot{M}_{j,i} \tag{2}$$

Assuming quasi-steady isentropic flow of a perfect gas, the mass flow rate out of compartment j through an orifice with a discharge coefficient of $C_{j,i}$ is given by[2]

$$-\dot{M}_{j,i} = C_{j,i}A_{j,i}\left\{\frac{2\gamma}{\gamma-1}\rho_j P_j\left[\left(\frac{P_i}{P_j}\right)^{\frac{2}{\gamma}} - \left(\frac{P_i}{P_j}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{1/2} \tag{3}$$

where γ is the ratio of specific heats of the gas and

$$(2/\gamma + 1)\gamma/(\gamma - 1) \leq P_i/P_j \leq 1.00$$

Equations (2) and (3) written for each compartment, form a set of nonlinear first-order differential equations in the dependent variables P_j ($j = 1, 2, 3, \ldots n$). This set of equations is solved using an integration subroutine. The discharge coefficients are called by the computer from a tabulation as a function of local Reynolds number and pressure ratio for each orifice. Heat generation within the compartments or heat losses and additions can be included by relatively simple modifications utilizing the methods of Wolsefer.[3]

Area Prediction Method

First consider the venting of a single compartment with a pressure downstream of its outlet orifice as shown in Fig. 3. Assume that the compartment is to be vented without the

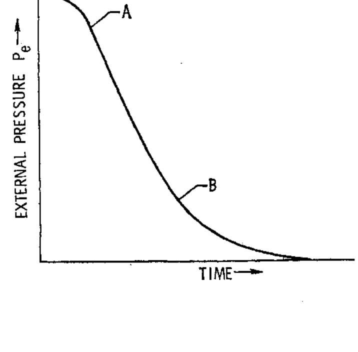

Fig. 3 Typical ambient pressure profile for a launch vehicle.

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pressure differential across the orifice exceeding some given magnitude, ΔP_{des}. As the slope of the curve gets steeper (i.e., $\dot{P}_e$ increasing in magnitude) the mass flow rate out of the compartment must be permitted to increase to prevent exceeding ΔP_{des}. However, $\dot{P}_e$ is approximately the same from point A to point B of Fig. 3. If $\dot{P}_e$ is the same from A to B, then the mass flow rate out of the compartment must also be the same. The available pressure ratio to produce this mass flow rate is limited by ΔP_{des}. Equation (3) shows that a larger area is necessary at point B to permit the same mass flow rate. The parameter $(\dot{P}_e/P_e)_{max}$ which occurs at point B appears to be suitable for use in determining the orifice area.

A convenient feature of this parameter is that it determines a minimum area for venting of the compartment. This much area must be provided since the condition at point B will occur and the pressure in the compartment at this time cannot be lower than $P_e + \Delta P_{des}$. However, it is possible for the actual pressure in the compartment to be higher than $P_e + \Delta P_{des}$ at point B. The area required to pass the maximum flow rate at point B may not have been large enough at some earlier time in the flight, when small pressure differentials existed, to produce sufficient flow rates through the available area. Iterations to produce more accuracy will therefore always require increases in area.

Now consider a multicompartment system as shown in Fig. 1, being vented to an externally varying pressure. For such a system which has been designed to meet a small ΔP_{des} requirement, the pressures in any compartment will have a pressure-time profile similar to Fig. 3. The smaller the ΔP_{des} the closer the pressure in all compartments will track the exterior profile.

Therefore, for any compartment, j, within the system, assume that the pressure in a downstream compartment with which it communicates is varying just like the known external pressure profile $P_e(t)$. The pressure in compartment j is then taken to be greater than the pressure in the immediate downstream compartment by an amount equal to the imposed maximum pressure differential which is not to be exceeded, that is

$$P_j = P_{i,d} + \Delta P_{des} \tag{4}$$

where $P_{i,d}$ denotes any downstream compartment and it is assumed that $P_{i,d}$ varies like the external ambient pressure. For calculations in the vicinity of point B and assuming that the pressure vs time histories of all the compartments are similar, the isentropic equation for the relationship between temperature and pressure can be used to determine the approximate temperature of any compartment at this time.

The mass of gas in any tank at this time is given by

$$M_j = P_e V_j / gRT_j \tag{5}$$

where g is the constant of gravitation and R is the universal gas constant. At some small interval of time, Δt, later the pressure in compartment j is assumed to be

$$P_j' = P_e - \dot{P}_e \Delta t \tag{6}$$

and the mass in compartment j is given by

$$M_j' = P_e' V_j / gRT_j' \tag{7}$$

where primes denote values after the time interval Δt. The mass flow rate out of compartment j is then

$$\dot{M}_{j,i} = -(M_j - M_j')/\Delta t \tag{8}$$

The outlet area of compartment j must accommodate the mass flow rate from all upstream compartments with which it com-

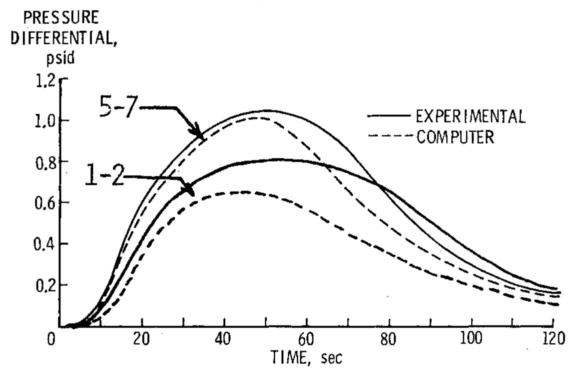

Fig. 4 Pressure differential between compartments 1 and 2, 5 and 7.

municates in addition to its own mass flow rate out. The outlet area is thus given by

$$A_{j,i} = \frac{\dot{M}_{j,i} + \sum_{iu} \dot{M}_{j,iu}}{C_{j,i}\left\{\frac{2\gamma}{\gamma - 1}\rho_j P_j\left[\left(\frac{P_e}{P_j}\right)^{\frac{2}{\gamma}} - \left(\frac{P_e}{P_j}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{1/2}} \tag{9}$$

where the subscript iu denotes all upstream compartments which communicate with compartment j.

Discussion

Analytical experience and tests simulating the Viking configuration of Fig. 1 indicate that this area prediction method works reasonably well when designing for values of $\Delta P_{des} < 1.0$. Accuracy improves as ΔP_{des} is decreased. Representative experimental results utilizing the facility developed by Muraca[4] are shown in Fig. 4 along with the analytically predicted curves. Orifice areas were calculated to provide a maximum pressure differential of 1.0 psia between any two interconnected compartments.

Concluding Remarks

Determination of interconnecting areas by the method presented is a considerable improvement over existing trial and error procedures, especially in multicompartment systems. A computer program based on the analytical model described can determine the pressure, temperature, pressure differentials, and mass flow rates into and out of each compartment at subsonic or sonic velocities. Accuracy of the method appears to be adequate for practical use.

References

[1] "NASA Space Vehicle Design Criteria Monograph," *Compartment Venting*, NASA SP-8060, Nov. 1970.

[2] Eskinazi, S., *Principles of Fluid Mechanics*, Allyn and Bacon Inc., Boston, Mass., 1965, pp. 343–395.

[3] Wolsefer, D. W., "Non-Adiabatic Two Compartment Venting Program," TN-AE-65-107, July 1965, Engineering Dept., Chrysler Corp., New Orleans, La.

[4] Muraca, R. J., "A Method for Determining the Time-Dependent Pressures in a Series of Chambers Connected to an External Pressure Whose Variation With Time is Known," M. S. thesis, Aerospace Engineering Dept., 1968, Univ. of Virginia, Charlottesville, Va.