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REGULAR PAPER

Base heating and stage separation of launch vehicles

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Abstract

This paper presents the results of the experimental study carried out to address the issues of base heating and smooth separation of the stage of launch vehicles. The pressure at the base of a convergent-divergent circular nozzle, from which Mach 1.8 jet emanates, attached to an annular shroud of larger area is controlled by providing air vents on the shroud. On the shroud, vent holes were made at different azimuthal locations, to entrain the surrounding air mass at a higher pressure, $p_{a,}$ to increase the low-pressure, p_b, at the base region, caused by the suction creating large-scale vortices formed owing to the sudden expansion of the jet emerging from the nozzle into the shroud. For different number and size of the vents on the shroud, the base pressure was measured. This measurement was done at five levels of overexpansion of the nozzle in the range from –64% to –58%. It is found that increase in vent area results in increase of base pressure, up to some limiting level of the area. Also, the increase of base pressure for the case of vents closer to the nozzle exit is found to be marginally more than the increase caused by vents at distances away from the nozzle exit. Increase of base pressure can be regarded as an advantage not only from base heating point of view but also from the point of view of deflection of the plume to the shroud wall for uniform melting of the pyro layer bonding the stages of the launch vehicle, leading to a smooth separation of the launch vehicle stages.

Nomenclature

A_e	nozzle exit area
A_s	shroud area
A_{vent}	vent area
d_e	nozzle exit diameter
ds	shroud diameter
NPR	p_{01}/p_a
p_a	atmospheric pressure
p_b	base pressure
p_{01}	settling chamber total pressure
R_1	radial distance of base pressure tap 1
R_2	radial distance of base pressure tap 2
x	axial distance from the nozzle exit

1.0 Introduction

One of the serious issues to be addressed with at most care is the stage separation of multi-stage rocket motors. Multi-stage motors are commonly used in launch vehicles meant for satellite launching. In these motors, say, two-stages, the first-stage motor is referred to as the booster. The booster is the one that sits on the launch pad and takes the rocket carrying the satellite to a pre-decided altitude and then gets separated and falls down. On reaching the specified altitude, the next stage (second stage, bonded to the booster) rocket will be operated. The hot exhaust gas emanating from this rocket nozzle will flow

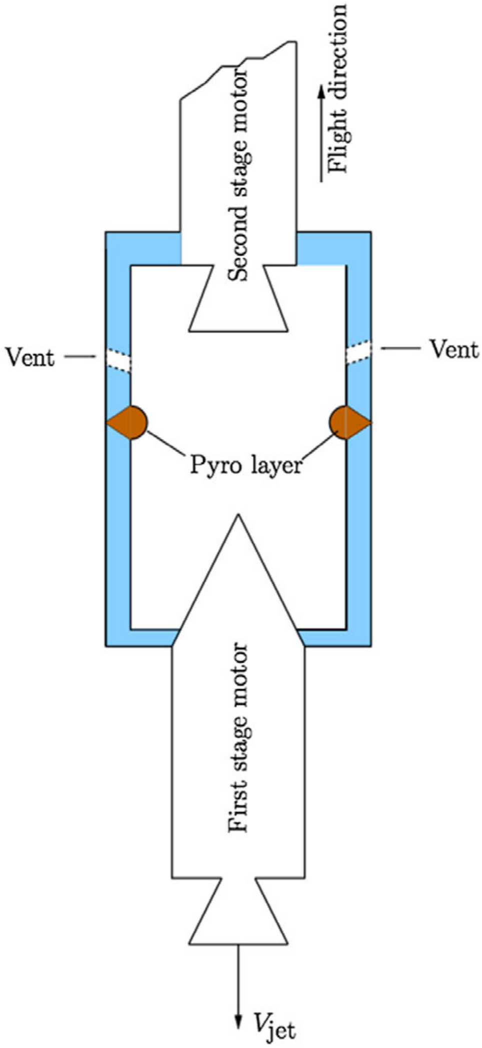

Figure 1. *Two-stage launch vehicle.*

through the shroud connecting the second stage rocket with the booster (first stage) rocket, as illustrated in Fig. 1. A launch vehicle will get heated up, during the flight, by the high temperature engine exhaust plume and the base of the vehicle will receive most of the heat, if the low-pressure established at the base because of the suction created by the large-scale vortices formed due to the sudden expansion of the nozzle exhaust into the shroud. Now, it is essential to ensure that the hot exhaust plume emerging from the rocket nozzle is not allowed to heat the base of the rocket motor and made to flow smoothly in the downstream direction. This is because of the following reasons: (a) the base heating is undesirable from the utility point of view of the portion inside the motor, which can be used for keeping electrical and electronic gadgets meant for the operation and navigation of the launch vehicle, and (b) the hot exhaust moving downstream should heat the pyro layer that fastens the first stage with the booster. If the pyro layer is heated uniformly all over the diameter of the shroud where it is kept, the booster motor shell will get separated evenly and fall down smoothly, without imparting any undesirable force to the first stage. This must be ensured for the successful mission of the launch vehicle. If the separation of the booster is uneven, the force caused by the improper separation of the booster will force the launch vehicle to deviate from its programmed path or even might force it to get into nose-dive and get destroyed.

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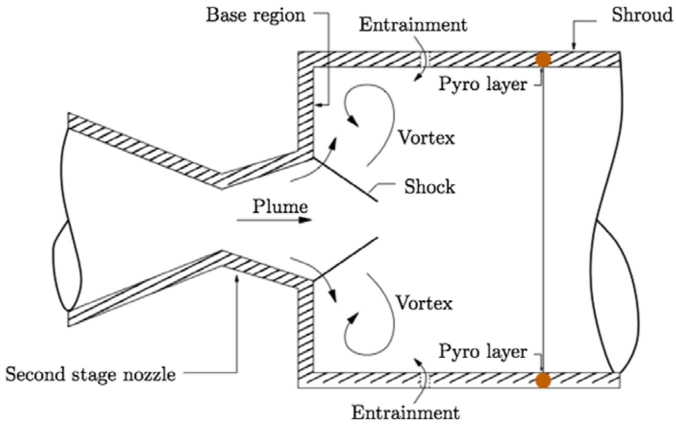

Figure 2. *Base region and vortex formation for suddenly expanded overexpanded flow.*

As illustrated in Fig. 2, the flow emerging from the rocket nozzle expands into the shroud, with is an annular shell. Thus, the flow is essentially a suddenly expanded flow. Therefore, the flow coming out of the nozzle will turn towards the base region. Since the flow is a supersonic one there will be an expansion fan at the nozzle exit to turn the flow, in accordance with the supersonic flow theory that change in the state of the flow or flow direction will take place only through waves [1]. The flow from the nozzle expanding suddenly into the shroud of larger area and the formation of a large-scale vortex are illustrated in Fig. 2. It is well known from vortex theory that large-scale vortex is a suction creator [2, 3]. Therefore, the vortex formed will establish a low-pressure region over the base region. The low-pressure at the base is popularly known as base pressure. This low-pressure not only would attract the plume emanating from the rocket towards the base region, leading to base heating, but also would result base drag. In some cases this base drag can be of the order of even about 30% of the total drag [4]. Reducing the suction level at the base region of a suddenly expanded passage is an advantage from the point of view of (i) reducing the base heating, (ii) reducing base drag and (iii) uniform melting of the bonding agent that keeps together the stages in a multi-stage rocket motor.

Even though this is an important issue in the field of launch vehicle design, multi-rocket guided missile, etc. hardly any published material is available in open literature. This may be because of the classified nature of this highly complex problem. Another aspect to be noted is that most of the available material is based on numerical prediction [5]. For this kind of prediction to be of use to application it will be of value to gain an understanding before venturing onto proposing and executing a numerical scheme. With the aim of understanding and controlling the base pressure leading to the control of base heating, base drag and uniform melting of the material joining the stages, an attempt is made in this work to control the base pressure by inducting the surrounding air into the duct connecting the stages, with vent at two specified locations of the shroud in this study, involving experimental measurements to provide flow control based on cold flow.

2.0 Experimental setup and procedure

The experiments were conducted in the open jet facility at the high-speed aerodynamics laboratory, Indian Institute of Technology Kanpur, India. Schematic diagram of the experimental setup is shown in Fig. 3. The test model is fixed at the end of the settling chamber by a slot holder arrangement, which is a short pipe-like protrusion with embedded O-ring to prevent leakage. Model to be studied is placed over the O-ring, over which an annular retaining sleeve with internal threads is screwed tightly.

The settling chamber total pressure (p_{01}), which was the controlling parameter in this investigation, was maintained constant during a run by controlling the pressure-regulating valve. The stagnation pressure (p_{01}) level in the settling chamber gives the different nozzle pressure ratios (NPR), defined as the

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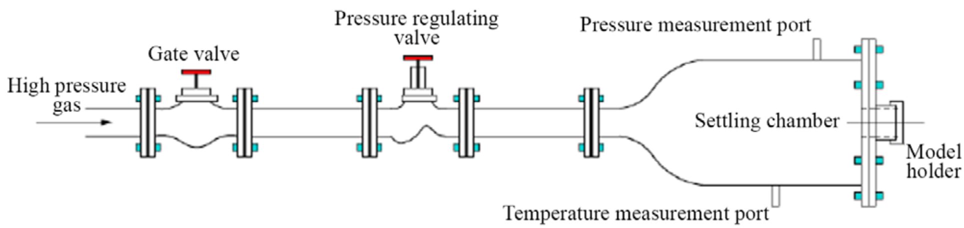

Figure 3. *Experimental setup.*

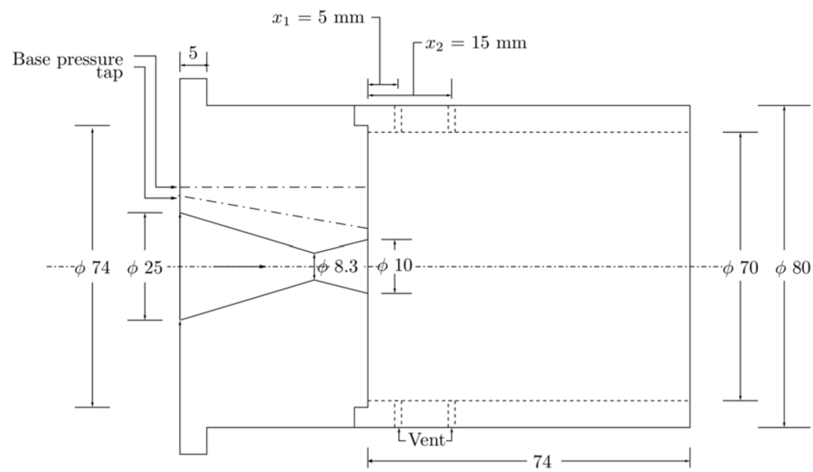

Figure 4. *Convergent-divergent nozzle and shroud with vents (all dimensions in mm).*

ratio of stagnation pressure to the backpressure (p_{01}/p_b) required for any study. The settling chamber temperature is the same as the ambient temperature and the backpressure is the ambient pressure into which the jets were discharged. The ambient temperature of the room was almost constant within ± 0.5 during one experimental run. The stagnation pressure was maintained with an accuracy of $\pm 0.1\%$. During the experimental runs, a pressure transducer measured the settling chamber pressure, and a thermometer measured the room temperature. Atmospheric pressure (p_a) was measured by a Fortin barometer.

Experimental model

A convergent-divergent nozzle of throat diameter 8.3 mm and exit diameter 10 mm was used to generate Mach 1.8 jet. The jet emanating from the nozzle is discharged into the axisymmetric shroud of diameter 70 mm with vents, as shown in Fig. 4. Vents on the shroud were provided at $x_1 = 5$ mm and $x_2 = 15$ mm, as shown in Fig. 4. Two cases of vents, with 6 mm and 10 mm diameter, were studied. For the case of 6 mm vents, two vents at diametrically opposite locations and four vents at 90-degree interval along the circumference of the shroud at x_1 and x_2 were used. For the case of 10 mm diameter, two vents at diametrically opposite locations, four and six vents, at equidistance along the circumference of the shroud at x_1 and x_2 (Fig. 4) were studied. The jet was operated at nozzle pressure ratio (NPR), p_{01}/p_a, 2.1, 2.2, 2.3, 2.35 and 2.4, with the intention of measuring the base pressure at close intervals of overexpansion level. For different combinations of the flow and geometrical parameters of the present study, the pressure, p_b, prevailing over the base region was measured using the wall pressure taps at R_1 and R_2, shown in Fig. 5. At both these radial locations four pressure taps made at 90-degree interval were used for the base pressure measurement and the average of the measured values are taken as representative value of

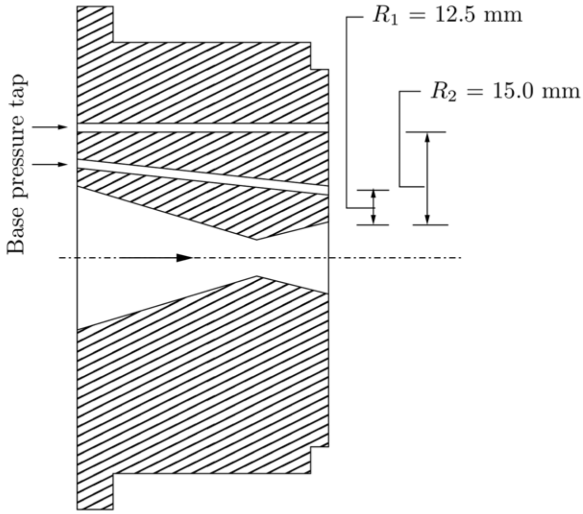

Figure 5. *Base pressure taps details.*

the base pressure, p_b. Correctly expanded NPR for Mach 1.8 nozzle is 5.747. Therefore, the NPRs of the present experiments correspond to over expansion levels of Mach 1.8 flow with adverse pressure gradient of −63.5%, −61.4%, −60.2%, −59.1% and −58.2%, respectively, for NPR 2.1, 2.2, 2.3, 2.35 and 2.4. Schematic diagram of the experimental model consisting of the nozzle and vented shroud, showing the geometrical detail, is shown in Fig. 4. The pressure taps made for measuring the base pressure are shown in Fig. 5.

The flow field associated with the plume emanating from the nozzle suddenly expanded into the shroud of area ratio; ratio of shroud cross sectional area, A_s, to the nozzle exit area, A_e, of about 55, consisting of the vortex formed at the base region, the low-pressure at the base region controlled by the air mass from the surrounding environment entrained through the vents provided on the shroud is illustrated in the cartoon in Fig. 2. One of the serious issues to be addressed for the smooth jettisoning of the shell (shroud) connecting the stages of a multi-stage launch vehicle is to make the pyro layer (Fig. 2) bonding the two stages to melt evenly, by making the plume emerging the rocket nozzle to flow uniformly over the surface of pyro layer, heating it uniformly all over its surface. This will melt the pyro layer evenly and give way for the smooth separation of the rocket stages. Now, the requirement is to ensure that the plume flows axi-symmetrically over the inner surface of the shroud. For this, the base region should not have any asymmetrical pressure field. Also, the suction created by the vortices formed due to the sudden expansion of the plume into the shroud should be nullified or weakened, to prevent the flow of thermal flux to the base region leading to a reduced base heating. These requirements demand that the pressure over the base region is uniform, and the suction-creating large-scale vortices formed at the base, illustrated in Fig. 2, would not cause any asymmetry and the air mass entrained through the vents at the shroud wall flows to the base region leading to reduced suction at the base.

To achieve these desired results of minimisation of base heating and uniform melting of the pyro layer, leading the smooth separation of the stages of launch vehicle, it is essential to understand the flow process that is likely to introduce asymmetry at the base. Gaining this knowledge is essential to minimise the suction at the base, which is the key for controlling the base heating and tuning uniform melting of the pyro-layer ring fastening the stages of the launch vehicle. For a suddenly expanded flow, such as the present one, it is well known that symmetrical and simultaneous formation of the vortices formed at diametrically opposite edges of the nozzle exit is possible only when the nozzle from its inlet to exit is perfectly symmetric, and the boundary layer growing over the inner surface of the nozzle from the inlet to exit is also symmetric. However, it is not possible to have the nozzle geometry perfectly

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symmetrical, since everything, even in NATURE, is with some degree of asymmetry. Also, the boundary layer, which is a thin layer adjacent to a solid boundary within which the velocity increases from zero to the freestream level, is essentially a vortex-dominated region [6] and hence cannot possess perfect symmetry. From these aspects, it is evident that the vortices formed at the opposite edges of the nozzle are bound to have some degree of asymmetry. That is, when the formation of a vortex at some location of the nozzle exit begins, it would grow in size and leave the nozzle-edge and rotate in the base region, scoop the fluid mass from there and move it to the downstream direction. This kind of mass removal by the mass-entraining large-scale vortices would establish a low-pressure at the base. Till a vortex formation initiated at a point grows and leaves the edge, it would not allow the vortex forming at the diametrically opposite locations of the nozzle exit grow in size. Once the first vortex leaves the edge, the one begins to form at the opposite edge would grow and leave the edge and act similar to the first vortex. Thus, there would be alternating vortex formation at the opposite locations of the nozzle exit. If the nozzle were fabricated with care to ensure a reasonable symmetry in its geometry, the frequency of this alternating nature would be very high. However, whatever be the attention paid in the fabrication, it is not possible to prevent this alternating nature of vortex shedding. If the base flow field established by this vortex pattern is not controlled, the heat flux thrown by the hot exhaust over the pyro-bond would not be uniform all over the diameter of the pyro-layer ring. This environment would make the pyro-ring melting uneven, leading to an uneven separation of the booster motor. This process would introduce a side-force, making the first-stage to deviate from its programmed trajectory, which is highly undesirable. Therefore, it is mandatory on the part of the designer to make sure that the unsymmetrical motion of the plume flow inside the shroud is eliminated or at least minimised. To meet this essential requirement, a set of vent provided at some distance from the nozzle exit, as illustrated in Fig. 4, to induct air from the surrounding environment into the wake region, as shown in Fig. 2, resulting in an increase of the pressure in the low-pressure zone at the base caused by the vortices. This increase of base pressure caused by the entrained air mass not only would reduce the oscillatory nature of the flow but also would abate the base heating caused by the deflection of the heat flux from the plume towards the base region. Once the oscillatory flow is rendered smooth, the heat imparted by the thermal flux on the pyro-layer also would become reasonably uniform over its entire annular ring surface. This kind of uniform heating would ensure proper separation of the booster from the first-stage motor.

From the above discussion it clear that, the vents provided on the shroud that integrates the stages of a multi-stage launch vehicle is highly desirable from the application point of view. Indeed this kind of vents would reduce the base heating and ensure smooth separation of the stage. In addition to these, the entrained air mass moving to the base would increase the base pressure, leading to a reduction of base drag. The present study aims at investigating the base pressure increase caused by the vents provided on the shroud, by measuring the base pressure for different combinations of the vent area and vent location, and the overexpansion level of the nozzle.

3.0 Results and discussion

Base pressure for the case of shroud without vent, shroud with two vents of 6 mm diameter, located at directly opposite locations ($A_{\text{vent}}/A_e = 0.72$), and four vents ($A_{\text{vent}}/A_e = 1.44$) at 90-degree interval at opposite locations, at a distance of $x_l/d_e = 0.5$ and 1.50 were measured for nozzle pressure ratios, 2.1, 2.2, 2.3, 2.35 and 2.4. Base pressure, p_b/p_a, variation with the nozzle pressure ratio, NPR, as a function of vent location $x_l/d_e = 0.5$, $R_l/d_e = 1.25$, and vent area $A_{\text{vent}}/A_e = 0.0$, 0.72, 1.44 is shown in Fig. 6.

For the same x_l/d_e, $A_{\text{vent}}/A_e = 2.0$, 4.0 and 6.0 with two, four and six vents of 10 mm diameter were provided to entrain the surrounding air in to the shroud. For this combination of geometrical parameters also, the base pressure was measured at NPR 2.1, 2.2, 2.3, 2.35 and 2.4. The results of these base pressure variation with NPR are presented in Fig. 7.

The base pressure, p_b/p_e, shown in the plot (Fig. 6) is the average of the pressures measured with the four pressure ports, located at equidistance over a circumference at the base region, at $R_l/d_e = 1.25$. From the results in Fig 6 it is seen that, for both the cases of vent area of 0.72 and 1.44, compared

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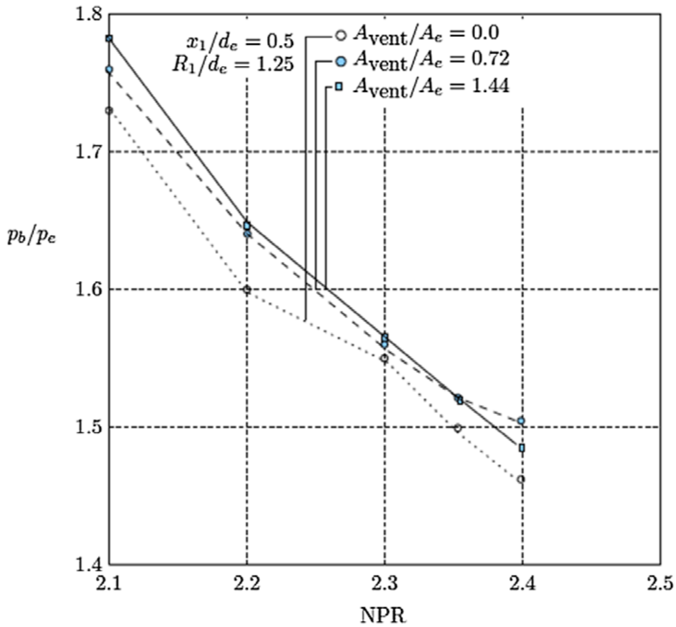

Figure 6. *Base pressure variation with NPR for the vents at* $x_1/d_e = 0.5$*, for vent area ratio 0.0, 0.72 and 1.44.*

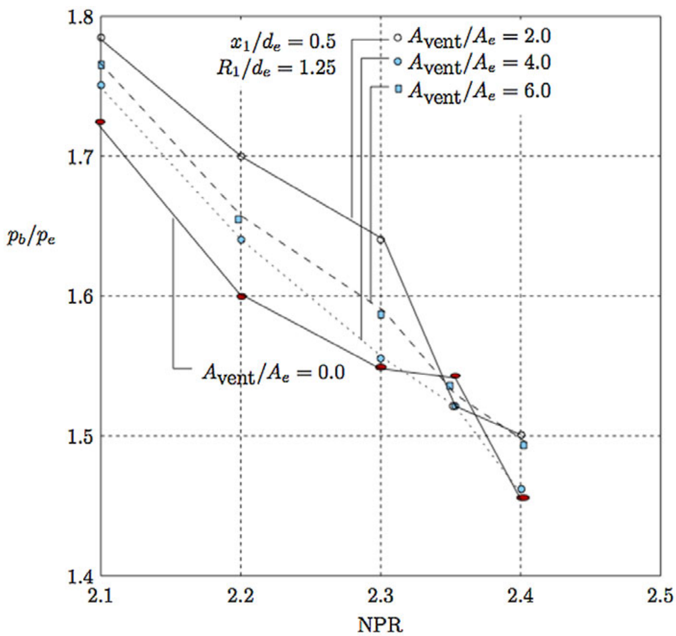

Figure 7. *Base pressure variation with NPR for the vents at* $x_1/d_e = 0.5$*, for vent area ratio 0.0, 2.0, 4.0 and 6.0.*

to the unvented case, the base pressure increases at all levels of the overexpansion tested. Among the overexpansion studied, adverse pressure gradient of −61.4% (NPR 2.2) is found to be the state resulting in the highest increase in the base pressure of about 6.25% and 5.2%, for vent area ratio (A_{vent}/A_e) 0.72 and 1.44, respectively. This may be taken as an advantage from all the three counts that are desirable for launch vehicles. This increase of 6.25% in the base pressure (given by the product of the pressure

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and base area) may be taken as 6.25% reduction in the base drag. Also, this increase of base pressure would result in reduced level of heat flux deflection to the base of the rocket, leading to a reduction of base heating caused by the plume emanating from the rocket nozzle. The third aspect, which is desirable from stage separation point of view, is the cause associated with reduced heat flux flow to the base. This would result in plume flow in the downstream direction moving with higher temperature and improved uniformity. This kind of flow would make the pyro-layer that bonds the second stage to the first stage to melt evenly all over the circumference of the shroud (Fig. 2). Uniform melting of the pyro-layer would result in a smooth separation of the first stage from the second stage. This kind of smooth separation would ensure the travel of the second stage in the trajectory programed for it.

Base pressure ratio, p_b/p_e, variation (for the near pressure tab [$R_1/d_e = 1.25$]) as a function of over-expansion level and vent area is shown in Fig. 6. For the low values of vent area ratio 0.72 and 1.44, (Fig. 6) it is seen that, larger the vent area the higher is the increase of base pressure. This increasing trend of base pressure is found to be independent of the level of adverse pressure gradient present (i.e. NPR) at the nozzle exit. However, it is evident from the results that the largest increase of base pressure is caused by vent area ratio of 1.44 at NPR 2.2, which corresponds to an adverse pressure gradient of –61.4%.

Base pressure variation with NPR, for vent area $A_{vent}/A_e = 0$, 2, 4 and 6, for the vent location $x_1/d_e = 0.5$, measured at pressure tap at $R_1/d_e = 1.25$, is shown in Fig. 7. Base pressure caused by vent area ratio 2 is found to be superior to 4 and 6 up to NPR 2.3. Also, the base pressure increase caused by vent area ratio 2 is the highest of around 6.25%, at NPR 2.2. At NPR 2.2, the base pressure increase caused by vent area ratio 4 and 6 are only around 1.88% and 1.93%, respectively. It is essential to note that even a fractional increase in base pressure can result in a great advantage relating to reduction of base heating, decrease of base drag and uniform melting of the pyro-bond layer. Therefore, though the additional pressure increase of base pressure caused by vent area 2 at NPR 2.2 is only around 6%, this can be regarded as a great advantage for the case of launch vehicle application.

Another important aspect inferred from Figs 6 and 7 is that, with decrease of adverse pressure gradient, the base pressure decreases for both with and without vent opening. This implies that the vortex formed at the suddenly expanded base region progressively becomes stronger with decrease of adverse pressure gradient. This may be because the plume tries to occupy the base region is traversed by the strongest oblique shock cone formed at the nozzle exit, for the case of NPR 2.1, which corresponds to the highest level of adverse pressure gradient of −63.5%. When the overexpansion level comes down, the adverse pressure gradient decreases and this situation makes the oblique shock formed at the nozzle exit weaker. Now, the plume traversed by the shock and turned to the base would have a higher velocity, than that at a higher overexpansion level, leading to the formation of a stronger vortex. This feature of the flow leading to the formation of progressively stronger vortex (with increasing NPR) at the base, causing larger suction at the base, is seen from the results in Figs 6 and 7. Another interesting aspect seen from the results shown in Figs 6 and 7 is increase of base pressure continues with increase in the vent area up to $A_{vent}/A_e = 2.0$. Increase of vent area ratio beyond 2 does not show any advantage from base pressure increase point of view. Also, all the advantages associated with vent are confined to NPR up to 2.3 only.

The base pressure ratio, p_b/p_a, measured at $R_1/d_e = 1.25$, for the cases of without vent ($A_{vent}/A_e = 0$) and vent at $x_2/d_e = 1.5$, for $A_{vent}/A_e = 0.72$ and 1.44 as a function of NPR is shown in Fig. 8. From these results also it is seen that, when the vent area is increased, through increasing the number of vents, keeping the vent diameter the same for all the vents, leading to area ratio 0.72 for two vents and 1.44 for four vents, the base pressure increases with increase of vent area. Similar trend is seen for the base pressure measured using the pressure tap at $R_2/d_e = 1.5$ (Fig. 9). Another important feature seen from Fig. 9 is that when the vent area is increased to 6.0 (six vents) the base pressure increase further comes down. The results in Figs 7 and 9 indicate that there is a limiting level for the vent area for achieving the best possible increase of base pressure. Also, it appears that this limiting value is expected to be in between $A_{vent}/A_e = 2$ and 4.

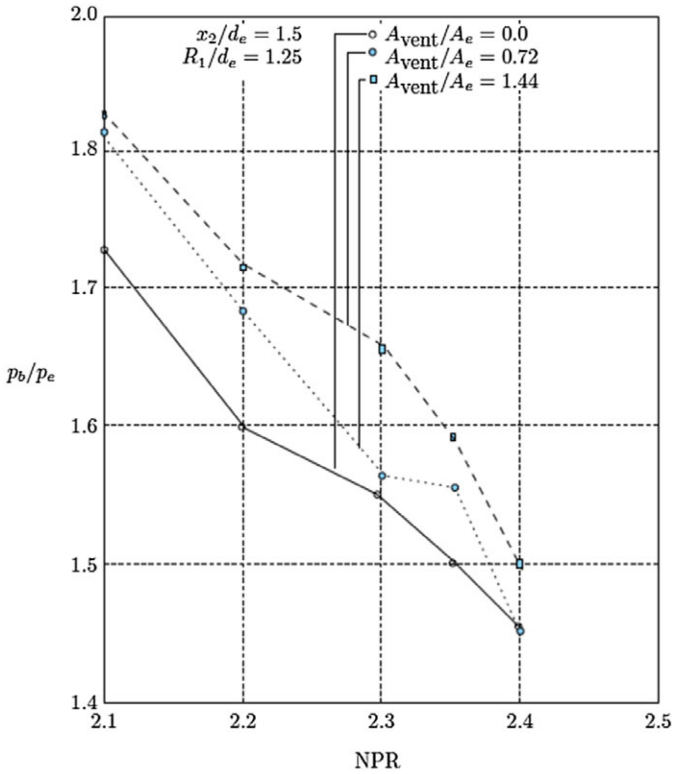

Figure 8. *Base pressure variation with NPR for the vents at x_2/d_e = 1.50, and R_1/d_e = 1.25, for vent area ratio 0.0, 0.72 and 1.44.*

From the results of base pressure tap at $R_1/d_e = 1.25$ and 1.5, for the vent locations $x_1/d_e = 0.5$ and 1.5 and 1.5 (Figs 6, 7, 8 and 9) it is seen that, there is only a marginal difference between the base pressures measured at radial locations 1.25 and 1.5, especially for the vent location $x_1/d_e = 1.5$. This may be because the base vortex entraining the mass from the surrounding interacts with the vortex for this far location of the vents.

Variation of base pressure, for the case of $R_2/d_e = 1.5$ and for vents at $x_1/d_e = 0.5$ and $x_2/d_e = 1.5$, with NPR shown in Fig. 10 shows that the pressure is reasonably uniform over the base region. However, it should be noted that there is a marginal difference between the pressures measured for vents at 0.5 and 1.5 locations. This increased level and fairly uniform nature of the base pressure caused by the vented shroud could be taken as an advantage from the points of view of reduction of base heating and reduction of base drag and diversion of heat flux from the plume to the pyro-layer, compared to the unvented shroud.

Variation of the base pressure (in percentage) caused by the vented shroud as a function of nozzle pressure ratio for the cases of vent area; $A_{vent}/A_e = 0.72$, 1.44, 2.0 and 4.0 is shown in Fig. 11. It is seen that, increase in vent area in the range from 0.72 to 2.0 results in increase of base pressure at all NPR. However, vent area 4 shows a different trend. Though $A_{vent}/A_e = 4.0$ causes the base pressure to increase for NPR less than 2.4, at NPR 2.4 it causes the base pressure to decrease.

Now, the physical reason for the limit on the vent area for achieving the best possible increase of base pressure might be assigned to the combined effect of mass entrainment through the vents and the diversion of the entrained mass to the base region by the suction created by the base vortex (Fig. 2). The low-pressure region formed by the mass-entraining large-scale vortices formed at the base region of the suddenly expanded flow would establish a favorable pressure gradient between the vent and the base region. This pressure gradient being congenial for the mass flow from the surrounding to the base

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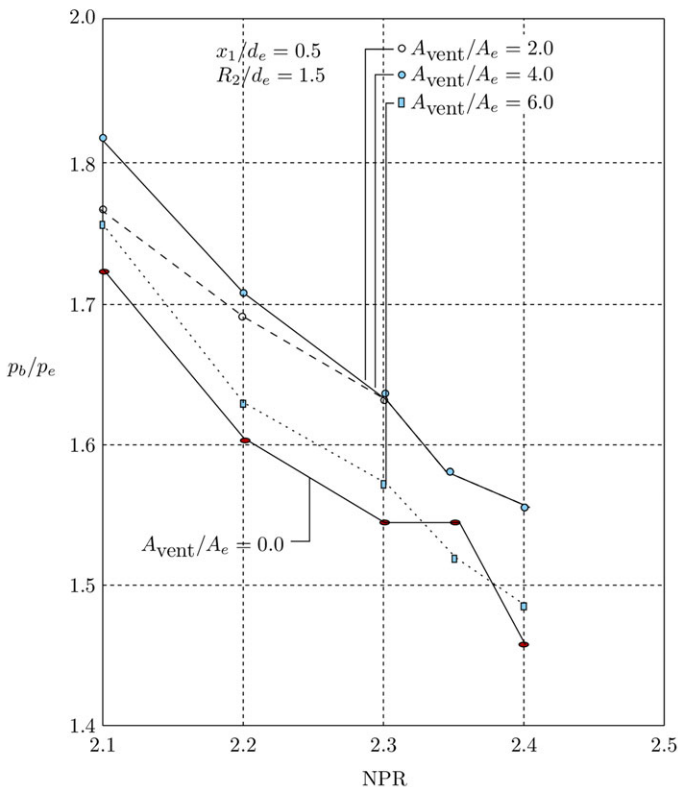

Figure 9. *Base pressure variation with NPR for the vents at $x_1/d_e = 0.5$, $R_2/d_e = 1.5$, for vent area ratio 0.0, 2.0, 4.0 and 6.0.*

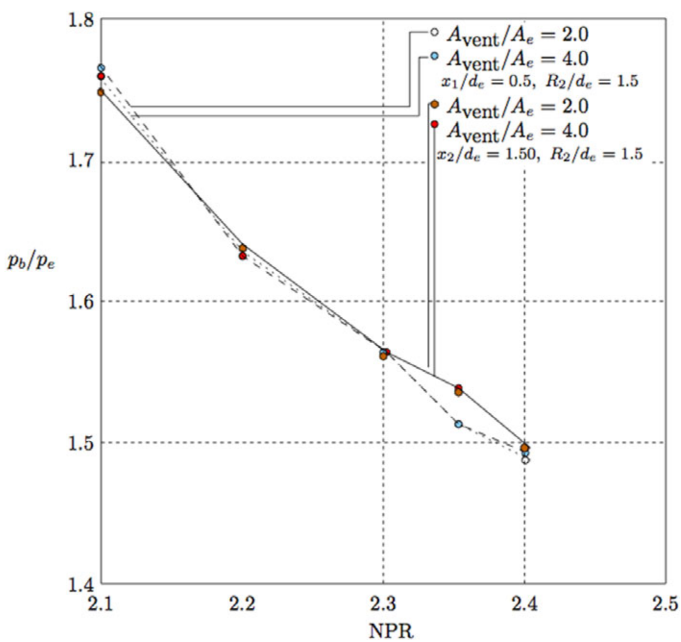

Figure 10. *Comparison of pressure variation for vents at $x_1/d_e = 0.5$ and $x_2/d_e = 1.5$, $R_2/d_e = 1.5$, for vent area ratio 2.0 and 4.0.*

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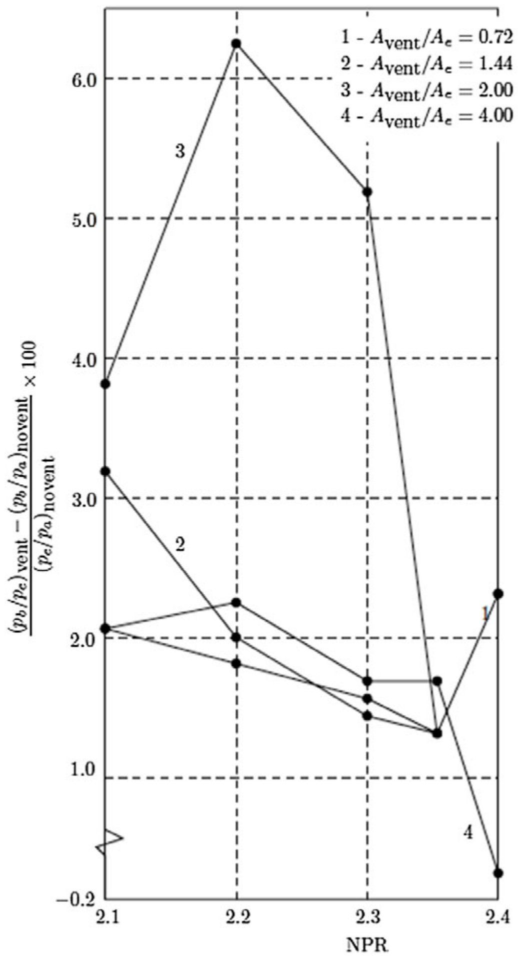

Figure 11. *Percentage variation of base pressure caused by the vents at $x_2/d_e = 0.5$ on the shroud at different NPR.*

would induce mass flow through the vent, termed entrainment. This mass entrained through the vent, being at a higher pressure, would flow to the base region at a lower pressure. This process would result in the mixing of the flow, leading to an increase of base pressure. The entrained mass on its way to the base should negotiate the flow form the base to the downstream direction. This process might be continuous because of the continued emerging of the plume from the nozzle. However, this being the flow from the low-pressure base region moving downstream might reduce the momentum of the entrained fluid mass moving towards the base region, and prevent the flow to the base region. Though this situation is undesirable from base pressure enhancement point of view, cannot be avoided. But if the mass flow rate of the entrainment is increased by increasing the vent area, which might abate the adverse effect that hinders the base pressure increase. Increasing the vent area from 0.72 to 4 addresses this aspect. Also, the vent location at a station nearer to the base and another at a slightly farther are also considered in this study.

To get a better insight into the effect of the vent area in increasing the base pressure, the percentage variation of base pressure is defined as

$$\frac{(p_b/p_a)_{vent} - (p_b/p_a)_{no\ vent}}{(p_b/p_a)_{no\ vent}} \times 100$$

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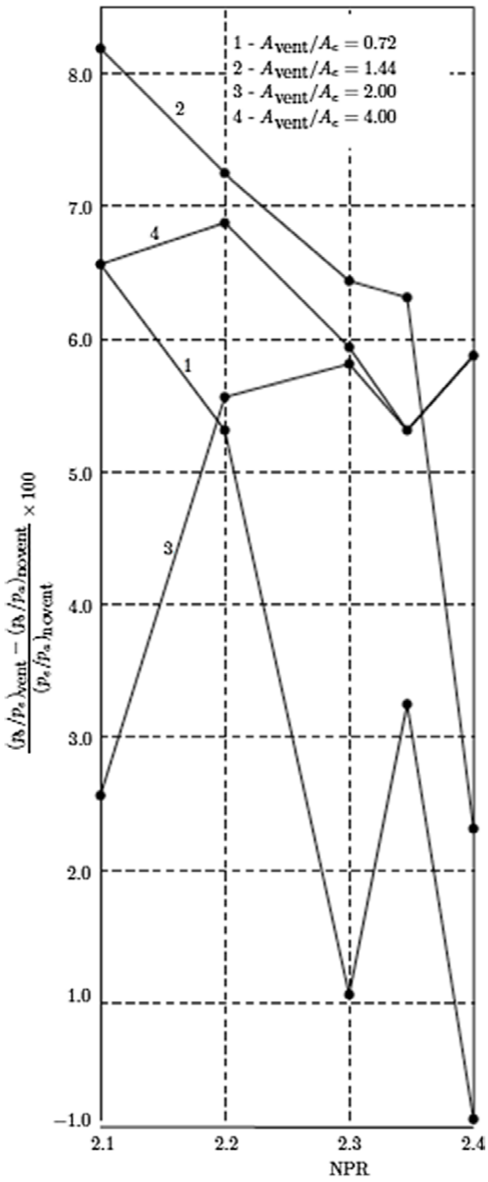

Figure 12. *Percentage variation of base pressure caused by the vents at $x_2/d_e = 1.50$ on the shroud at different NPR.*

Variation of the base pressure (% increase) caused by the mass entrained with $A_{vent}/A_e = 0.72$, 1.44, 2.0 and 4.0, as a function of NPR is shown in Figs 11 and 12, for pressure taps at R_1 and R_2. From these plots it is seen that $A_{vent}/A_e = 2.0$ is the optimum opening for achieving base pressure increase. This vent opening is found to be better than other openings. This superior performance of vent area is found to be independent of nozzle overexpansion level. The highest increase of about 6.25% in base pressure caused by $A_{vent}/A_e = 2.0$ is at the overexpansion level corresponding to NPR 2.3, with an adverse pressure gradient of –64%.

It is worth raising the question, "is the entrainment through the vents on the shroud discussed in this study applicable only for the first stage separation at lower altitude or valid for any stage separation at any altitude?" The answer to this question is the following: the discussions based on this study may be regarded as specific to the first stage separation at lower altitude and hence the outcome of this study is only applicable first stage separation at lower altitudes. For addressing the issue of separation at higher altitudes, the study needs to be conducted by simulating the surrounding pressure around the model as the pressure at the desired altitude. This will ensure that the mass entrained through the events will be appropriate for the altitude at which the separation has to take place.

4.0 Conclusions

The results of this investigation show that, by providing vents on the shroud that separates the two stages of a launch vehicle, the base pressure at the suddenly expanded location can be increased. The surrounding air entrained through the vents is sucked by the suction-creating large-scale vortex formed at the suddenly expanding base region and this process weakens the vortex formed, leading to the reduction of the suction caused by the vortex. Among the vents tested, $A_{\text{vent}}/A_e = 2.0$ is found to be the optimum opening for achieving the best possible base pressure increase, for the parameters considered in this study. The superior performance of vent area 2.0 is found to be independent of nozzle overexpansion level. The highest increase of about 6.25% in base pressure caused by $A_{\text{vent}}/A_e = 2.0$ is at the overexpansion level corresponding to NPR 2.3, which corresponds to an adverse pressure gradient of –64%. The increased level and fairly uniform nature of the base pressure caused by the vented shroud could be taken as an advantage from the points of view of reduction of base heating and base drag, and diverting a higher heat flux from the plume to the pyro-layer surface, compared to the unvented shroud.

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