Gas Density Effects on Dual-Bell Transition Behavior

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Extended Abstract

1. Introduction

The concept of dual-bell nozzle, first proposed by Foster and Cowles in 1949 [1] has received renewed attention in recent years due to its one-step altitude adaptation capability [1-6]. This concept uses two shortened nozzles combined into one with a bump or inflection point between them, as shown in Fig. 1. During ascent it functions first at the lower area-ratio with controlled flow separation occurring at the inflection point, Fig. 1 (a). While the lower area-ratio helps to achieve high sea-level thrust, a controlled and symmetrical flow separation helps avoid dangerous side-loads. As the altitude increases and the gases expand further, the flow undergoes a transition process during which the flow jumps downstream and attaches itself close to the nozzle exit, with the flow filling the full nozzle exit section thereby utilizing the full geometrical area-ratio, Fig. 1 (b). Because of the higher area-ratios that are achievable through this design, a higher vacuum performance is feasible. Despite the losses associated with this design (such as aspiration drag in low altitude mode, non-optimum contour in high altitude mode, etc. [6]), the dual-bell nozzle shows better overall performance than a single bell nozzle of similar area-ratio [2].

In real-flight conditions, since the dual-bell transition will take place at relatively low ambient pressure environment, it becomes mandatory to do tests in ground facilities that can simulate such test environment. Such a high altitude test facility primarily includes an ejector nozzle to evacuate the altitude chamber either singly or in combination with other simulation methods [7-8]. These simulation facilities provide of conducting subscale cold gas tests on topics of basic research. However, it has been recently reported that the test data measured at sea-level conditions can be significantly different from its expected values in low pressure environment [9-10]. These recent studies have shown a strong influence of exhaust flow density in varying the transition NPR of dual-bell nozzle. Further strong transient effects are also observed to occur during engine shut down, especially in facilities with zero secondary flow [7-8].

In order to further validate the effects of flow density on transition NPR, a systematic study was planned. The high altitude simulation chamber (HASC) was evacuated to low ambient pressure and the test nozzle P_0 was reduced from 30bar to 5.3bar in separate test runs. Surprisingly the

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transition NPR for the dual-bell nozzle was observed to increase significantly. To the best of our knowledge, no tests have ever been reported which specifically address flow density effects in nozzles tested in HASC. The present investigation aims at demonstrating these effects by studying the dual-bell transition behavior inside the HASC.

2 Experimental Set up and Procedures

2.1 Test Facility

Figure 2 (a) shows the location of pressure transducers on the test model and the important geometric nozzle parameters, respectively. Tests on this nozzle were carried out in the subscale cold flow test facility P6.2 in DLR Lampoldshausen inside a high altitude simulation chamber (HASC), as shown in Fig. 2. The altitude chamber was evacuated using an additional ejector nozzle. Gaseous nitrogen at ambient temperature is used as the test gas due to its advantage over compressed air. The throat diameter of the sub-scale dual-bell nozzle used for the experimental investigation was 20mm, yielding maximum mass flows in the range of m=4.2kg/s under facility operating limitations. The contour of the dual-bell base nozzle was designed as a truncated ideal contour (TIC) while that of the nozzle extension was designed on the isobar leaving the last point of the base nozzle using method of characteristics featuring a constant pressure profile (CP) [4]. The ejector nozzle used is a thrust optimized parabolic nozzle (M_d = 3.2, NPR for full-expansion 49.5) and supplied with an additional nitrogen feed line with an independent pressure regulating valve.

2.2 Data Acquisition System

The data acquisition system used for the pressure measurements has the capacity of measuring 64 channels at 1kHz and 16 at 50kHz or 8 at 100kHz. A low-pass filter cut-off frequency of 160 Hz is used for 1kHz acquisition and of 8 kHz for high frequency acquisition, respectively. For real-time wall pressure measurements 'Kulite Semi-conductor Inc.' transducers are used (model XT-154-190M). These transducers, with a pressure-sensitive area of 0.4 mm² and an outer case area of 12mm², have a natural frequency of 50 kHz. The accuracy is within 0.5% in the operating pressure range of 0.1 MPa, with a sensitivity of typically 0.97 V/MPa. The transducers are threaded into the nozzle wall. A small orifice connects the transducer to the flow. This configuration has a resonance frequency of 5.4 kHz. The wall pressure data for all the pressure transducer locations was acquired at 25kHz.

Results and Discussions

Usually a high altitude test facility comprises of three major-components; (i) a closed chamber in which low pressure environment is desired, (ii) supersonic ejector nozzle or test-nozzle, and (iii) supersonic exhaust diffuser, Fig. 2 (b). As the ejector/test nozzle is fed with driving pressure, the supersonic exhaust from the nozzle exit begins to evacuate the closed chamber by entraining the air that is driven by (i) the difference in pressure between the nozzle exit and the altitude

chamber, and (ii) momentum transfer by the high-speed nozzle exhaust [7-8]. This initiates a fluid motion in the direction of pressure and momentum gradients established in the test set up. The initial suction during the starting transient evacuates the altitude chamber to low pressures that provides high-altitude environment for nozzle operation, Fig. 3 (a). The diffuser operation is broadly characterized by two distinct operating modes, i.e., diffuser unstart-mode and diffuser start-modes [8]. Figure 3 (b) shows an illustration of a typical chamber pressure history during diffuser operation. In the diffuser un-start mode, the ejector driving pressure (P_0) is not high enough to initiate diffuser starting condition and the nozzle operates in over-expanded condition with the jet exhaust characterized by a Mach disk (mode A). In an intermediate operating condition, the test nozzle reaches full-expansion and a transition from Mach reflection to regular reflection occurs (mode B) but the diffuser is still in un-start condition. And finally, in diffuser-starting mode the ejector nozzle operates in highly under-expanded condition with the jet boundaries impinging on the diffuser inlet wall (mode C). In this condition the altitude chamber gets isolated from the ambient. Once this happens the evacuation process in the altitude chamber is no longer affected by the ambient pressure changes and thus a sudden drop in P_b occurs, Fig. 3 (b). Such an arrangement provides moderate evacuation levels while mimicking low pressure environment at high altitudes.

Figure 4 shows the pressure time-history of one of the two runs made with the present test set up. Initially, the dual-bell nozzle is started and thereafter its P_0 is held constant. Almost 10 seconds later the ejector nozzle is also started and its feeding pressure increased up to 45bar in 4-5seconds during which the diffuser begins to operate in start mode at a certain point of time. During the process of evacuation as the chamber pressure (P_b) decreases, the dual-bell nozzle NPR of operation also increases and at a certain P_b, forward transition occurs, Fig. 4 (a). For different runs, one particular value of P_0 is selected while the ejector nozzle P_{0E} and $\partial P_{0E}/\partial t$ are kept the same. The value of P_0 is reduced in different runs from 30bar (beyond which no change in flow was observed to occur) to a minimum of 5.3bar. Below P_0 of 5.3bar no full transition was observed and so no tests were conducted below this value. Figure 5 shows the NPR versus P_0 while Table 1 shows the respective values from each test campaign. It can be seen that as the dual-bell P_0 is decreased, the NPR of forward transition gets significantly increased. For the minimum value of P_0 tested (5.3bar), transition NPR is increased by approximately 20%. This change is significant and therefore it becomes necessary to further investigate the physical aspect behind the phenomena involved.

Figure 6 shows the pair of images taken from the observation camera movies. The first and the second images show the flow condition before and after transition, respectively. It can be seen that when transition occurs, onset of nitrogen gas condensation occurs and a condensation shock is formed making the exhaust flow visible to the naked eye, Fig. 6 (b). Interestingly it was observed that as feeding pressure P_0 was reduced, the visible intensity of condensation shock

decreased gradually, Fig. 6 (d) and (e), and finally for $P_0 < 22$bar, no condensation shock is visible. Now, it is known that during the onset of condensation, gas molecules begin to nucleate at a certain low temperature and high gas density [11-13]. During the flow acceleration process in a nozzle, the static temperature of the gas also drops and at a certain operating condition can reach values necessary to saturate the gas below 77K as seen from the phase diagram of N_2 (not shown). The present observations in Figs. 5 & 6 suggest that a sufficiently low temperature alone may not be a necessary condition to trigger the onset of condensation process. For a gas to condense a sufficient number of molecules are required to initiate the process of nucleation. In other words, a minimum gas density will be required to initiate the onset of condensation which in turn is a function of nozzle feeding pressure, P_0. Therefore when the feeding pressure is more, higher is the gas density and hence, more gas molecules are available to initiate onset of condensation making the exhaust flow visible better. It is clear therefore that as the nozzle feeding pressure P_0 decreases a drop in gas density and mass flow rate occurs. As a consequence of the latter, the momentum thrust also drops.

The process of flow transition requires a sufficient force to initiate the movement of separation location in the vicinity of wall inflection to the nozzle exit. The observations from Fig. 5 and 6 clearly indicate that as the gas density decreases with decreasing feeding pressure, the process of flow transition also gets delayed which in turn may be related to the delay in movement of separation in the vicinity of wall inflection. For the present test set up, a full transition could be achieved for $P_0 \geq 5.3$bar. Below this value, no full flow transition was achievable and the separation location remained only in the vicinity of wall inflection. Other related flow phenomena such as `sneak' transition, first reported by Genin and Stark [14], also needs to be looked into and will be discussed in the full-length version of this paper.

4. Conclusions

The results discussed in the present paper emphasize that the nozzle tests inside a high altitude test facility should be carefully interpreted especially those caused due to gas density effects. These effects begin to dominate for tests in such facilities in a certain test range. In the present tests, density effects are observed to significantly alter the flow transition NPR of a dual-bell nozzle by as much as 20%. These effects can also alter the flow transition NPR in plug and expansion-deflection nozzles which needs further investigation in each case.

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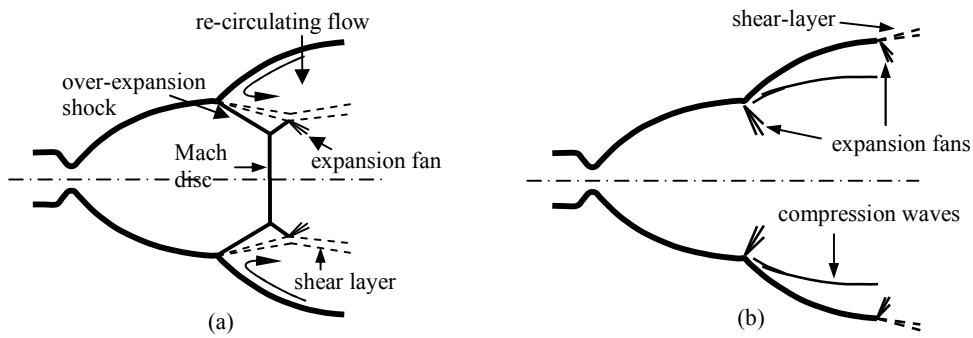
Figure 1: Schematic of the exhaust flow pattern from a dual-bell nozzle in (a) low-altitude mode and, (b) high-altitude mode
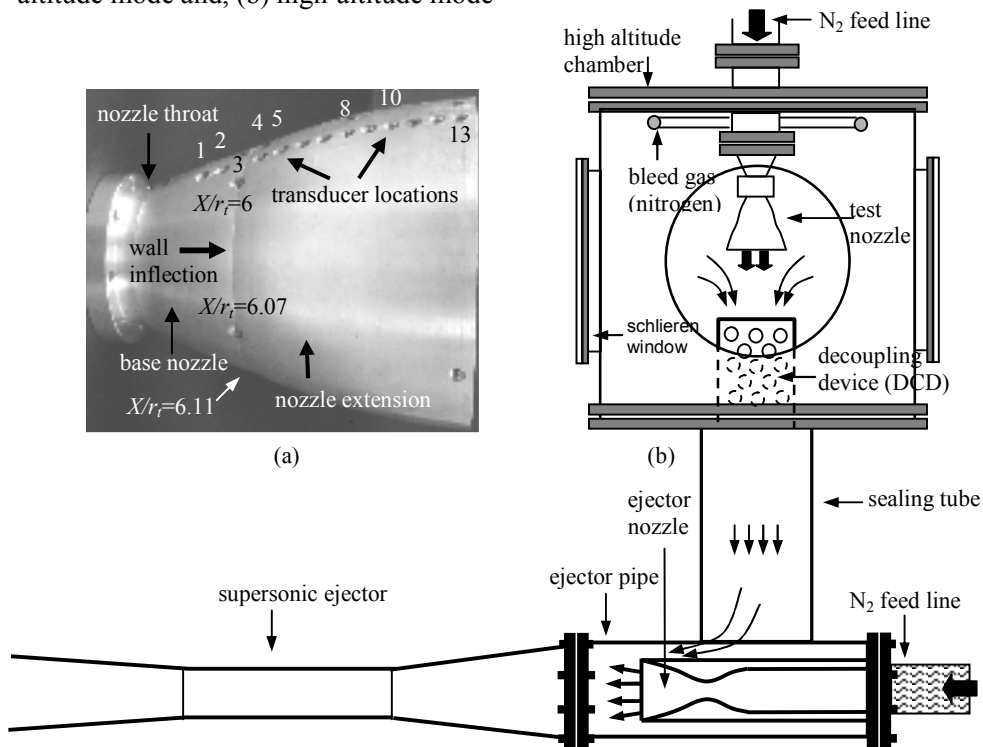

Figure 2: Dual-bell test nozzle showing (a) the pressure transducer locations and, (b) schematic of the high altitude simulation chamber (HASC) nozzle test-facility with nozzle operation in ejector mode
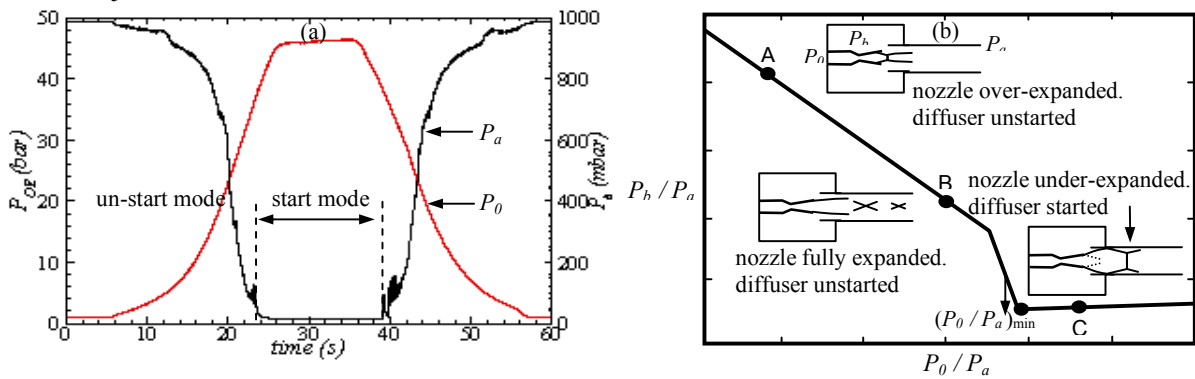

Figure 3: (a) Plot showing the variation in chamber pressure to changes in ejector nozzle pressure and (b) schematic of the diffuser operation inside a high altitude chamber
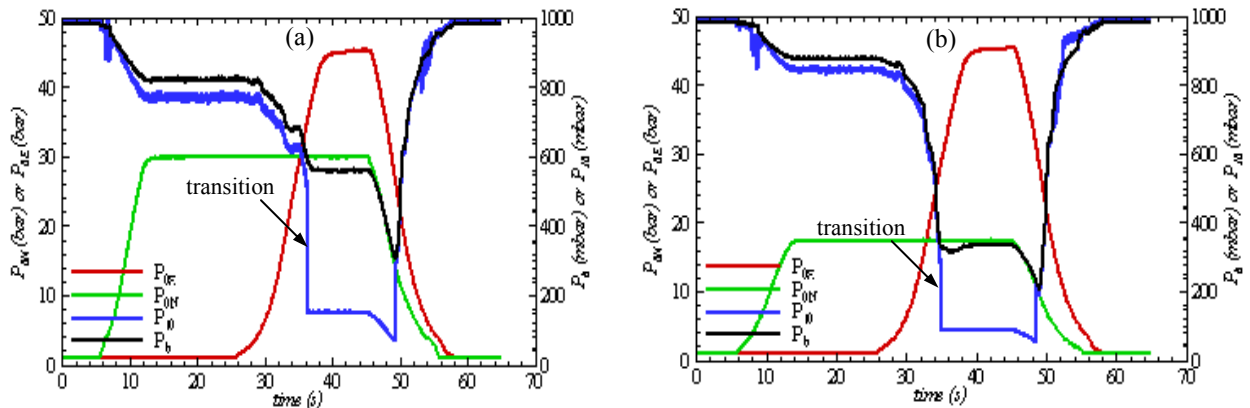
Figure 4: Pressure time history of test nozzle, ejector nozzle, back pressure and wall pressure in the dual-bell extension for (a) P_{0N} = 30bar and, (b) P_{0N} =17.4bar

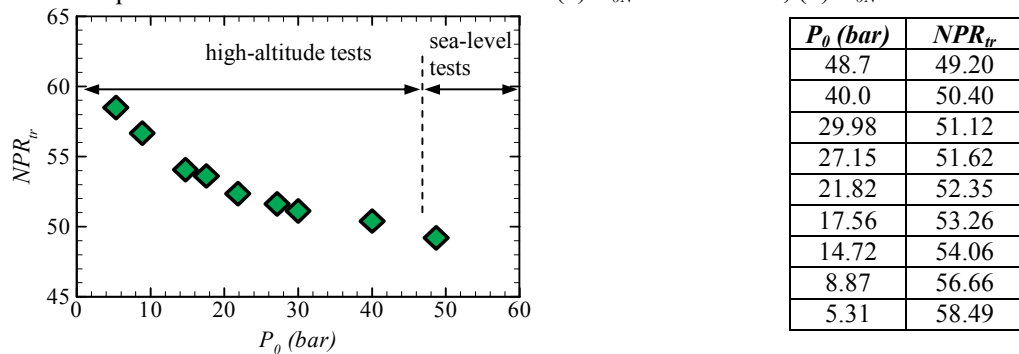| P_0 (bar)	NPR_{tr}
48.7	49.20
40.0	50.40
29.98	51.12
27.15	51.62
21.82	52.35
17.56	53.26
14.72	54.06
8.87	56.66
5.31	58.49

Figure 5: Variation of transition NPR with variation in test nozzle feeding pressure P_0
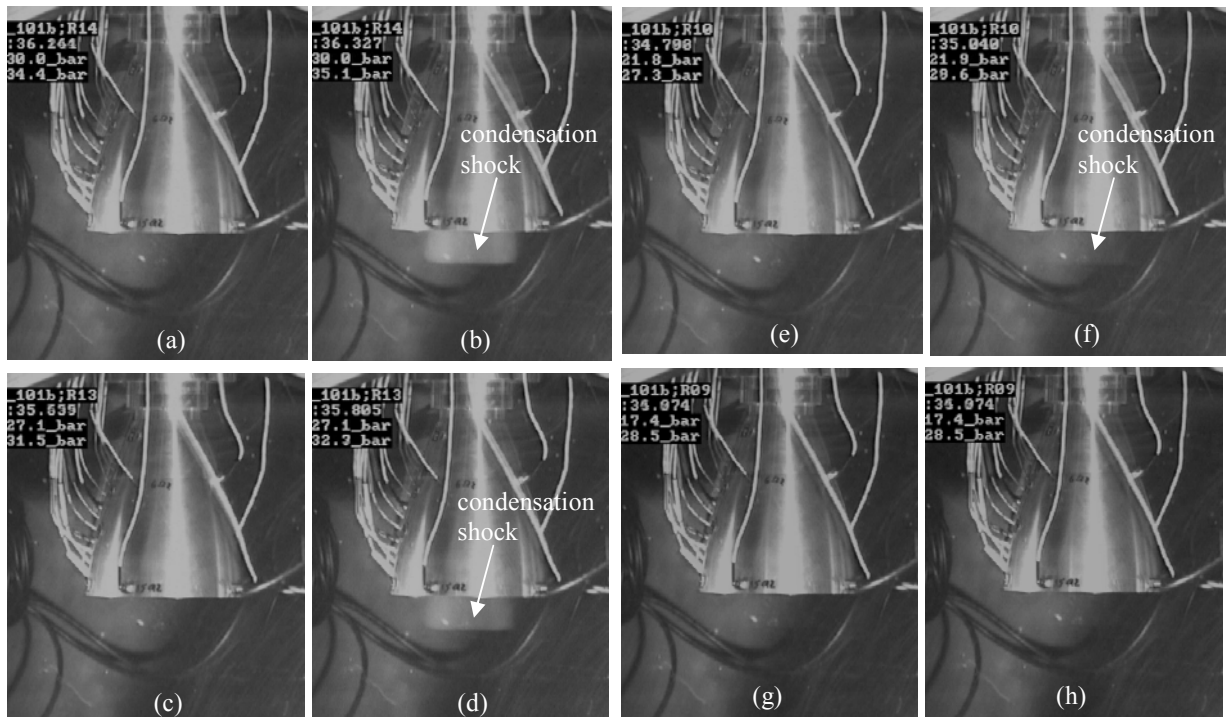

Figure 6: Images showing dual-bell nozzle during tests inside the HASC before and after transition. The first picture (left) in each case shows a test event before transition and the second image (right) shows an event after transition, (a) and (b) P_{0N} = 30bar, (c) and (d) P_{0N} = 27bar, (e) and (f) P_{0N} = 22bar, (g) and (h) P_{0N} =17.4bar