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Experimental investigation of flow through planar double divergent nozzles

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ABSTRACT

Dual bell nozzle is one of the feasible and cost effective techniques for altitude adaptation. Planar double divergent nozzle with a rectangular cross section was designed for two different NPR's to simulate and investigate the flow regimes similar to those inside the dual bell nozzle. Measurements involved flow visualization using Schlieren technique and wall static pressure measurements. The flow transition between the two nozzles at the respective inflection points and the formation of recirculation region due to flow separation was analyzed in detail. Cold flow tests were performed on the double divergent nozzle in the over-expanded conditions to study the shock wave characteristics. The results obtained from the two independent double divergent nozzles were compared with those obtained from a single divergent nozzle of the same area ratio. From the experiments it was observed that inflection angle played a key role in defining the type of shock structures existing inside the double divergent nozzles.

1. Introduction

The dual-bell nozzle concept or altitude–adaptation nozzle concept was first proposed by Cowles [1] in 1949. It gained interest mainly because of its unique feature of altitude adaptation which is achieved only by wall inflection and, thus reduction in weight is achieved due to absence of any moving mechanical assembly. At low altitudes, controlled and symmetric flow separation occurs at the wall inflection which results in a smaller effective area ratio without generating side loads. At higher altitude, the nozzle flow is attached to the extension wall until the exit plane and full area ratio is utilized. During the transition from low altitude to higher altitudes, asymmetric flow separation and complex shock structures exits inside the nozzle and is schematically shown in Fig. 1.

Over the past several years since 1949, flow separation and complex shock structures in CD nozzles have been studied extensively [2–32]. Among the earliest studies Romine [3] proposed an analytical model for flow separation in an over-expanded nozzle. According to the author the proposed separation model mainly depends on the jet mainstream adjustment to the ambient pressure, and the effect of the nozzle boundary layer was considered to be negligible. The model addressed the effects of an incident shock, a reflected shock and a mach stem. In a study of flow separation in the supersonic nozzle by Papamoschou [4] it was found that asymmetric flow separation significantly influenced the mixing enhancement mechanism. His experimental study on planar C–D nozzles showed that asymmetric lambda shock with one foot larger than the other existed in the divergent section. The separation shear layer on the side of larger lambda foot exhibited intense instabilities that developed and propagated as huge eddies downstream of the nozzle whereas the shear layer on the other side of lower lambda foot developed normally. Hagemann [5] carried out experiments to study

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Nomenclature

NPR	Nozzle Pressure Ratio (P_o/P_a)
NPR *wall static*	Nozzle Pressure Ratio wall static (P_w/P_o)
A_{exit}	Area of cross section at the exit (cm^2)
A_{throat}	Area of cross section at the throat (cm^2)
$A_{inflection}$	Area of cross section at the inflection (cm^2)
FFT	Fast Fourier transformation
RSS	Restricted Shock Separation
FSS	Free Shock Separation
DDN1	Double divergent nozzle 1
DDN2	Double divergent nozzle 2
SDN	Single divergent nozzle
P_a	Ambient Pressure
T_a	Ambient Temperature
P_{ref}	Sound Pressure level=20 μPa
CD	Convergent divergent

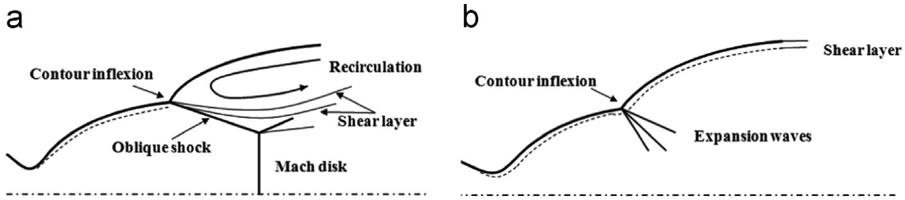

Fig. 1. Operating modes in dual bell nozzle for (a) low altitudes and (b) high altitude mode [2].

the effect of side loads in a parabolic nozzle. These side loads occurred as a result of flow transition from Free shock separation (FSS) where the flow detaches from the wall after separation to Restricted shock separation (RSS) where the flow re-attaches to the wall after separation and vice versa. Reasons for the transition between separations patterns were discussed and among them, the cap-shock pattern was identified to be the cause of this transition and was analyzed in detail. In a study on Advanced Rocket Nozzles by Hagemann [2] the author presented several nozzle concepts that could result in significant gain in the performance by the adaptation of the exhaust conditions to the ambient as compared to the convention nozzle. Dual bell nozzle which has a base nozzle to operate at low altitude and an extension nozzle that works at high altitude was among the first to be discussed and other concepts that were proposed included the plug nozzles for external free stream expansion and dual mode engines such as dual throat and dual expander engines. Frey and Hagemann [6] conducted a critical assessment of dual bell nozzle and presented the design aspects for the contour of base nozzle, the wall inflection and the extension nozzle. The focus was on the transition behavior from sea level to higher altitudes and its dependence on the contour type used for the nozzle extension was highlighted. In addition the losses in the dual-bell nozzle such as thrust loss and aspiration loss were also discussed. The numerical study carried out by them revealed that the additional performance losses caused by the dual-bell contour were lower than expected. Further in an experimental and analytical study on dual bell nozzle by Hagemann [7], the author through a series of hot flow and cold flow tests investigated the effect of nozzle contour on the flow transition, time duration of the transition and the side loads induced due to transition. Three different extension contours producing a negative, zero or positive wall pressure gradient was observed and it lead to different flow behavior. The author further concluded that the hysteresis effects proved better for the dual bell nozzle concept. In an experimental study on flow transition in dual bell nozzle by Genin and Stark [8], the authors investigated the phenomenon of flow transition from sea level mode to high altitude mode on three different geometries of the extension. Their study showed that the dimension of recirculation area at the sea level and the transition NPR is dependent on the length of extension. The intermediate state of the flow between sea level mode and transition to high altitude mode was determined to be the cause of high thermal and structural loads in the vicinity of the inflection region. Based on a cold flow subscale test to measure the side loads on the dual-bell nozzle, Genin and Stark [9] elaborated the reasons for the occurrence of side loads as due to the asymmetrical position and movement of separation point during the transition region. They conducted tests on three different nozzle contours and came to the conclusion that extension length is a critical parameter for the flow stability, transition duration and side load generation. They further laid emphasis on the need for optimizing the dual-bell nozzle in rocket applications. In an experimental study by Verma and Stark [10], the effects of gas density on transition in dual bell nozzle was studied. With a decrease in gas density/reduced mass flow, significant reduction in the amplitude of wall pressure fluctuations was observed in the region of flow separation due to decrease in shock strength. In a recent hot flow experimental study on planar dual-bell nozzle by Genin [11] the effect of contour inflection on the thermal loads and heat flux were studied. Heat flux was found to be increased in the inflection region during both the operational modes. The flow separation near the inflection region during sea-level operating mode further increased the heat fluxes. Genin and Stark [12] conducted an experimental study on the planar dual-bell nozzle. The tests were performed under cold and hot flow conditions. The base nozzle was designed as full length ideal nozzle to limit the three dimensional effects due to the side walls. From their study it was noticed that the extension wall contour resulted in negative pressure gradient at high NPR