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Three dimensional investigation of the shock train structure in a convergent–divergent nozzle

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ABSTRACT

Three-dimensional computational fluid dynamics analyses have been employed to study the compressible and turbulent flow of the shock train in a convergent–divergent nozzle. The primary goal is to determine the behavior, location, and number of shocks. In this context, full multi-grid initialization, Reynolds stress turbulence model (RSM), and the grid adaption techniques in the Fluent software are utilized under the 3D investigation. The results showed that RSM solution matches with the experimental data suitably. The effects of applying heat generation sources and changing inlet flow total temperature have been investigated. Our simulations showed that changes in the heat generation rate and total temperature of the intake flow influence on the starting point of shock, shock strength, minimum pressure, as well as the maximum flow Mach number.

1. Introduction

Shock wave–boundary layer interaction in combination with the flow separation is an important phenomenon in modern aerodynamics. This topic is related to the air flow around supersonic vehicles as well as to nozzle or diffuser flows. The latter plays a major role in the design of supersonic ramjet or scramjet inlets, internal diffusers and supersonic ejectors, supersonic air-breathing engine inlets, internal diffusers, compressor cascades or supersonic ejectors, to name some of them. Most of those applications have convergent–divergent walls or a rectangular cross-section, therefore; the focus of the current investigation lies at the shock train in the convergent–divergent duct. Under certain conditions, even one or more shocks can appear downstream of the first shock (for the Mach number over about 1.5). This series of shocks is also named "shock train". Other names, e.g., 'X-shaped shocks' or 'λ-shaped shocks', can be found in the literature, as well. A typical Schlieren photograph of the shock train is shown in Fig. 1 [1].

In contrast to other shock systems, the supersonic flow is decelerated at first by a shock system that is followed by a mixing area as shown in Fig. 2. At the centerline, the shocks are strong enough to decelerate the flow below $Ma = 1$, whereas the flow remains supersonic between the core flow and the boundary layer. Therefore, the flow undergoes successive changes from supersonic regime to subsonic regime [2]. In this region, the transition from supersonic to subsonic conditions is very gradual. Furthermore, the experiences had shown that the static pressure continues to rise after the shock train over a certain distance along the duct if the duct is long enough. In this case, the static pressure recovery is performed through both the shock train region and the subsequent static pressure recovery region after the shocks.

According to the above discussions, many researchers have investigated the shock train phenomenon experimentally and numerically. In this regards, Katanoda et al. [3] experimentally examined shock train structures in a constant-area passage of the cold spray nozzle. Balu et al. [4] studied the performance of an isolator scramjet engine

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with inlet Mach number 2.0 and found that for length to height ratio of 4 to 5, shock train can be established with maximum static pressure in the isolator. Grzona et al. [5] measured shock train generated turbulence inside an over-expanding rectangular nozzle with a small opening angle of 1.6°. Weiss et al. [2,6] studied the behavior of shock trains in a diverging duct, and then investigated the behavior of a shock train under the influence of boundary-layer suction by a normal slot. Numerical simulation and experiments on the Mach 2 Pseudo-shock wave in a square duct are performed by Sun et al. [7] on the basis of the two-dimensional Navier–Stokes equations, using a Baldwin–Lomax turbulence model, and the Mach 2 supersonic wind tunnel. The numerical results agree well with the experimental results. Based on these investigations, the shock train characteristics, structure, pressure and velocity distributions, and the effect of flow confinement on the interaction are analyzed in detail. Some computational efforts on simulations of the shock train in ducts have been reported. For example, Papamoschou and Johnson [8] numerically and experimentally examined the symmetry and asymmetry of the pseudo-shock system in a planar nozzle. They stated that the separation of the shear layer on the side of the lambda shock foot creates an intense instability that grows into very large eddies at the nozzle exit. Kawatsu et al. [9] numerically simulated the pseudo shock wave in straight and diverging ducts with rectangular cross section and observed the separation of the boundary layer by the first shock wave of pseudo shock wave can be detected only near the corners of the duct. In contrast, in the diverging duct case the large separation region appeared at one corner of the upper wall and did not reattach the wall in the test section. Lin and Tam [10] studied the impact of temperature and heat transfer on the structure of the shock train inside parallel wall isolators both experimentally and numerically. Their study discovered that heat addition to the low Mach number flow can choke the flow and potentially decrease the isolator performance. They showed that heat addition to the supersonic flow increases boundary-layer thickness and decreases the flow Mach number. Allen et al. [11] studied

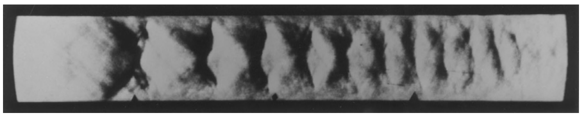

Fig. 1. Schlieren photograph showing shock train in a rectangular duct [1].

the shock train leading edge of a scramjet isolator using RANS and LES numerical models and showed that RANS model provide reasonably suitable agreement with the experimental results. Fotia et al. [12] examined the behavior of a ram-scram transition applying a direct-connect model scramjet experiment along with pressure measurements and high-speed laser interferometry. Their work showed the wall static pressure profile and flame position occurring at the downstream boundary condition suddenly changes when the flow becomes unchoked. Fischer and Olivier [13] experimentally studied the wall and total temperature influence on a shock train. They found that variations of the wall temperature influence on the pressure distribution in the shock train.

Gawehn et al. [14] investigated pseudo-shock systems in a Laval nozzle with parallel side walls, both numerically (steady and unsteady simulation) and experimentally. In the steady case, good agreement is found between the calculated and measured shock structure and pressure distribution along the primary nozzle wall, except for a remaining slight deviation in the shock position. The effects of the divergence angle on the shock train in the scramjet isolator are investigated by Huanga et al. [15]. They discovered that with increasing the divergence angle of the scramjet isolator, the static pressure along the central symmetrical line of the isolator decreases sharply. Grilli et al. [16] analyzed the unsteady behavior in shock wave turbulent boundary layer interaction. Their results supported the assumption that the observed shock-wave turbulent boundary layer interaction phenomena are a consequence of the inherent dynamics between flow separation and shock. Sridhar et al. [17] numerically investigated the effect of geometry on the oscillator performance. They found that the length of the pseudo shock of square configuration is shorter than that of the circular model. Giglmaier et al. [18] numerically and experimentally investigated the pseudo-shock system in a planar nozzle in purpose to examine the impact of bypass mass flow due to narrow gaps. Zhu and Jiang [19] investigated the entrainment performance and the shock wave structures in a 3D ejector investigated by CFD and Schlieren flows visualization. Their results show that the expansion waves in the shock train do not reach the mixing chamber wall when the ejector is working at the sub-critical mode. Mousavi and Roohi [20] numerically investigated the effect of working parameters such as the inlet total pressure, back pressure, nozzle inlet angle, and wall temperature on a 2D shock train in a

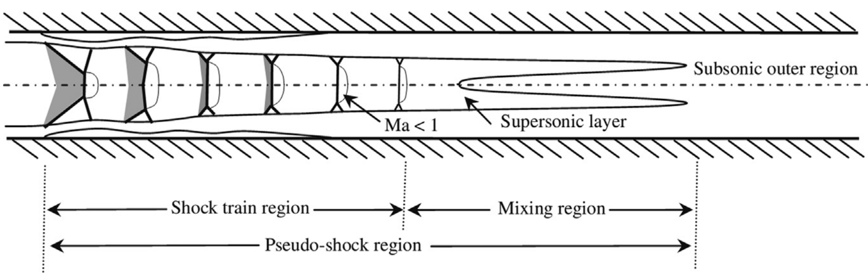

Fig. 2. Sketch of a pseudo shock system [2].