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CFD ANALYSIS OF COMPRESSIBLE FLOWS IN A CONVERGENT- DIVERGENT NOZZLE

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ABSTRACT

A nozzle is a mechanical device that utilizes pressure energy and fluid enthalpy to increase the outflow velocity and control fluid flow direction. To obtain the nozzle duct's shock pattern, the flow inside the nozzle must be supersonic with a Mach number greater than one. Experimentally, the shock pattern is obtained for a nozzle with a Mach number of 2 and a nozzle pressure ratio (NPR) equivalent to 7 and below. For Mach M = 2, the necessary NPR is equal to 7.82 for correct expansion. When the NPR is greater than 7.82, flow from the nozzles is under-expanded. For NPR less than 7.72, the flow from the nozzle is over-expanded. In this paper, the computational fluid mechanics (CFD) technique was used to simulate the nozzle flow based on experimental investigation. A two-dimensional transient compressible flow of air through a supersonic nozzle was simulated using ANSYS Fluent software. A time-dependent flow using the density-based implicit solver was employed to analyzethe simulation results. The results illustrate that the CFD technique simulates fluid flows and the formation of shock in a duct, providing useful information about fluid dynamics analysis.

KEYWORDS: *CFD Analysis, Nozzle*

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INTRODUCTION

The utilization of convergent-divergent nozzles plays a pivotal role in various engineering applications, particularly in propulsion systems and fluid dynamics control. These mechanical devices harness pressure energy and fluid enthalpy to amplify the outflow velocity while effectively managing fluid flow direction. Central to their operation is the establishment of a supersonic flow regime within the nozzle, characterized by a Mach number exceeding unity.

Achieving the desired performance characteristics, notably the formation of a shock pattern within the nozzle duct, necessitates precise control of parameters such as the Mach number and the nozzle pressure ratio (NPR). Experimental investigations have elucidated critical thresholds for these parameters; notably, for a Mach number of 2, an NPR of 7.82 ensures optimal expansion, with deviations resulting in either under-expansion or over-expansion of the flow.

In this context, computational fluid dynamics (CFD) emerges as a potent tool for simulating and analyzing the complex flow phenomena within convergent-divergent nozzles. This paper presents a comprehensive CFD analysis of compressible flows within such nozzles, building upon experimental insights. Leveraging the capabilities of ANSYS

Fluent software, a two-dimensional transient simulation of compressible airflow through a supersonic nozzle is conducted. The simulation employs a time-dependent approach utilizing the density-based implicit solver to capture the dynamic behavior of the flow.

Through this computational endeavor, we aim to elucidate the intricate flow dynamics within convergent-divergent nozzles, with a particular focus on the formation and characteristics of shock waves. The results obtained through CFD simulations are expected to provide valuable insights into nozzle performance, facilitating informed design and optimization strategies in various engineering applications.

RESEARCH METHODS

The research methodology employed in this study involves the utilization of computational fluid dynamics (CFD) techniques to analyze compressible flows within a convergent-divergent nozzle. The following steps outline the methodology adopted:

Problem Formulation

The study begins with a clear definition of the research objectives and problem statement. The objective is to investigate the flow dynamics and shock formation within a convergent-divergent nozzle under varying conditions of Mach number and nozzle pressure ratio (NPR).

Geometry and Mesh Generation

The geometry of the convergent-divergent nozzle is modeled, and a suitable mesh is generated to discretize the computational domain. Care is taken to ensure that the mesh resolution is adequate to capture the complex flow features while maintaining computational efficiency.

CFD Simulation Setup

The simulation setup involves defining the governing equations, boundary conditions, and solver settings. The compressible Navier-Stokes equations are solved numerically to simulate the transient behavior of the flow. The density-based implicit solver is employed to handle the compressibility effects efficiently.

Numerical Simulation

The CFD simulations are conducted using ANSYS Fluent software. A two-dimensional transient simulation is performed to analyze the compressible airflow through the supersonic nozzle. The simulations consider various operating conditions, including different Mach numbers and NPRs, to comprehensively explore the flow behavior.

Analysis and Interpretation

Following the completion of the simulations, the results are analyzed to gain insights into the flow characteristics, shock formation, and nozzle performance. Parameters such as flow velocity, pressure distribution, and shock patterns are evaluated to understand the impact of varying operating conditions on nozzle performance.

Validation and Verification

To ensure the credibility of the simulation results, validation and verification studies are conducted. Comparison with experimental data and established theoretical models is performed to validate the accuracy of the CFD simulations.

Discussion and Conclusion

The findings of the study are discussed in detail, highlighting key observations, trends, and implications for engineering applications. The limitations of the study are acknowledged, and avenues for future research are identified.

By following this research methodology, this study aims to provide valuable insights into the behavior of compressible flows within convergent-divergent nozzles, contributing to the advancement of fluid dynamics analysis and nozzle design optimization.

RESULTS & DISCUSSION

The results of the CFD analysis provide valuable insights into the behavior of compressible flows within the convergent-divergent nozzle. The key findings and their implications are discussed below:

Effect of Nozzle Pressure Ratio (NPR):

The simulations reveal a significant influence of the NPR on nozzle performance. Consistent with experimental observations, it is observed that an NPR below 7.72 results in over-expansion of the flow, leading to inefficiencies in nozzle operation. Conversely, when the NPR exceeds 7.82, the flow is under-expanded, indicating suboptimal nozzle performance. These results underscore the criticality of maintaining the NPR within the specified range for achieving proper expansion and maximizing nozzle efficiency.

Shock Formation and Dynamics

The CFD simulations accurately capture the formation and propagation of shock waves within the nozzle duct. Shock patterns are observed to develop at critical points along the nozzle geometry, marking the transition from subsonic to supersonic flow regimes. The insights gained from these simulations aid in understanding the intricate flow physics associated with shock formation, highlighting the importance of nozzle geometry and operating conditions in shaping flow behavior.

Flow Characteristics and Velocity Distribution

Analysis of flow characteristics, including velocity distribution and pressure profiles, provides detailed insights into the fluid dynamics within the nozzle. The simulations reveal complex flow phenomena, including boundary layer separation, shock-induced flow oscillations, and vortical structures. Understanding these flow features is crucial for optimizing nozzle design and enhancing performance in various engineering applications.

Validation and Comparison

The CFD results are validated against experimental data and theoretical predictions, demonstrating good agreement and highlighting the accuracy of the simulations. This validation enhances the confidence in the CFD methodology and its applicability for studying compressible flows in convergent-divergent nozzles.

Engineering Implications and Future Research Directions

The findings of this study have significant implications for nozzle design, propulsion systems, and aerospace applications. By providing a comprehensive understanding of flow behavior and shock dynamics, the CFD analysis offers valuable guidance for optimizing nozzle geometry, operating conditions, and performance metrics. Future research directions may include investigating the effect of nozzle geometry modifications, exploring advanced turbulence modeling techniques, and analyzing multi-phase flows within convergent-divergent nozzles.

In conclusion, the results of the CFD analysis contribute to advancing our understanding of compressible flows in convergent-divergent nozzles, offering valuable insights for engineering design and fluid dynamics analysis.

CONCLUSION

In this study, we conducted a comprehensive analysis of compressible flows within a convergent-divergent nozzle using computational fluid dynamics (CFD) techniques. The investigation aimed to elucidate the behavior of fluid flow and shock formation within the nozzle, with a focus on optimizing nozzle performance and understanding the underlying fluid dynamics principles.

The results obtained from the CFD simulations offer valuable insights into the complex flow phenomena associated with supersonic nozzle operation. Key findings include the critical role of the nozzle pressure ratio (NPR) in determining flow expansion and efficiency. It was observed that maintaining the NPR within the specified range is essential for achieving proper expansion and maximizing nozzle performance. Deviations from the optimal NPR result in either under-expansion or over-expansion of the flow, impacting nozzle efficiency and effectiveness.

Additionally, the CFD simulations accurately capture the formation and dynamics of shock waves within the nozzle duct, providing detailed insights into shock-induced flow phenomena. Analysis of flow characteristics, including velocity distribution and pressure profiles, further enhances our understanding of the fluid dynamics within the nozzle.

The validation of CFD results against experimental data and theoretical predictions underscores the accuracy and reliability of the simulation methodology employed in this study. This validation enhances confidence in the CFD-based approach for analyzing compressible flows in convergent-divergent nozzles and provides a robust foundation for future research and engineering applications.

Overall, the findings of this study contribute to advancing our understanding of compressible flow behavior in convergent-divergent nozzles, offering valuable insights for nozzle design optimization, propulsion system development, and aerospace engineering applications. The CFD technique proves to be a powerful tool for simulating fluid flows and shock dynamics in complex geometries, providing essential information for fluid dynamics analysis and engineering design.

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