Turbulent supersonic mixing layer: prediction & validation using Machine Learning

TE2502 : Civil engineer thesis topic for game programming students

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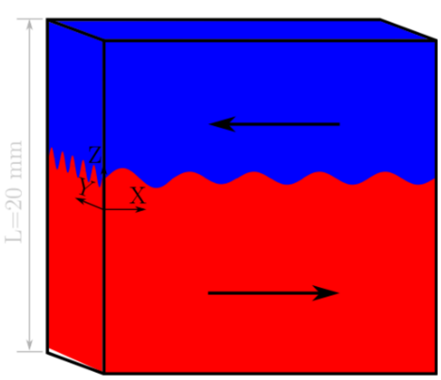
A fundamental understanding of compressible multi-component flows is vital towards advancing our knowledge related to the design of combustion devices operating primarily at high speed. Such flows are not much amenable to experimental studies and thus require advanced numerical tools to analyze them extensively. Direct numerical simulation (DNS) aims to resolve the entire spectrum of length and time scales prevalent in such complex flows.

Recently, at IIT Kanpur, DNS of supersonic reactive mixing layer has been performed using OpenFOAM to obtain insights on the underlying compressibility-turbulence-chemistry interactions. Three-dimensional instantaneous Navier-Stokes equations along with the multi-component species and energy transport equations are solved on very fine grids using Advection Upstream Splitting Method (AUSM) methodology for accurate resolution of discontinuities encountered in such high-speed flows, with minimal numerical diffusion. The domain (as shown in Figure below) under consideration is a cube involving mixing between hydrogen (lower) and air (upper) streams having periodic boundary conditions, signifying a temporally evolving shear layer. Initial perturbations are artificially generated at the air-fuel interface to achieve a rapid transition to a fully turbulent state. The shear-generated instabilities at the fuel-air interface lead to the formation of highly turbulent mixing regions, and as a consequence, the mixture autoignites and product species, water vapor, is formed. A recent DNS of the supersonic mixing layer [1] was used for validation.



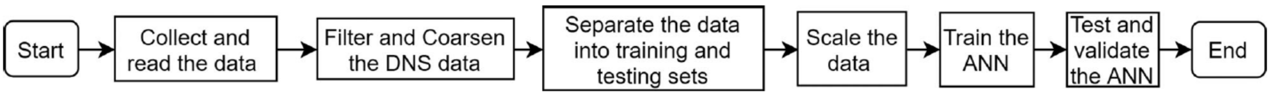
Air:	
p	101,000 (Pa)
T	1,400 (K)
u	-1,168.89 (m/s)
Y_{N_2}	0.767
Y_{O_2}	0.233
Fuel:	
p	101,000 (Pa)
T	1,500 (K)
u	1,665.89 (m/s)
Y_{H_2}	1.0

A. A priori and a-posteriori analysis of DNS/LES of supersonic reactive and non-reactive mixing layers

Here we aim to utilize the vast amount of DNS data available for numerical model development, specifically the subgrid-scale (*sgs*) turbulence model for compressible flows. In an *a priori* testing, the DNS data will be explicitly filtered, and the resulting Large Eddy simulation (LES) quantities will be compared with the DNS output, for a thorough validation and assessment of the turbulence model. In the '*a-posteriori*' testing, a full stand-alone LES of the exact DNS configuration (with the same initial conditions) will be performed, and the numerical results of LES will be compared against the filtered DNS data.

B. Data-Driven sub-grid turbulence and combustion model development

The DNS database generated can serve as a means to train the Artificial Neural Network (ANN), which ultimately would serve the purpose of any conventional sub-grid turbulence model. The ANN output will also be validated against the DNS data, and its performance will also be compared against the predictions from the available sub-grid turbulence model. A flowchart [2] of data processing for the data-driven sub-grid turbulence model development is shown below:



In addition to the Supersonic Mixing Layer DNS data (non-reacting version) shown above, the DNS database [3, 4] could also be used for the ANN training. These mainly include the non-reacting DNS data for forced isotropic turbulence, homogeneous buoyancy-driven turbulence, transitional boundary layer, channel flow, etc.

References:

1. N. Gibbons, V. Wheatley: Combustion Regime Analysis of a Supersonic Turbulent Mixing Layer. Australian Combustion Symposium, 2019.
2. Alvaro Prat, Theophile Sautory & S. Navarro-Martinez (2020): A Priori Subgrid Modelling Using Artificial Neural Networks, International Journal of Computational Fluid Dynamics, DOI: 10.1080/10618562.2020.1789116
3. John Hopkins Turbulence Database, http://turbulence.pha.jhu.edu/datasets.aspx
4. TU Darmstadt Turbulence Database, https://www.fdy.tu-darmstadt.de/fdyresearch/dns/direkte_numerische_simulation.en.jsp