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Thermal and Mechanical Non-equilibrium Effects on Turbulent Flows Fundamental Studies of Energy Exchanges Through Direct Numerical Simulations and Experiments

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The effective life of this grant has been shortened by a superseding BRI, which include more ambitious and challenging research questions. During the six-month period of this grant, we have worked on the tasks and preparations for many of the issues detailed in the BRI. In particular, we have worked on baselines configurations that will serve as point of comparison when thermal non-equilibrium is introduced.

The specific tasks were: (1) lay some of the theoretical framework for baselines flows, (2) develop the infrastructure for non-equilibrium studies, (3) mentor five graduate students, (3) study previous literature on compressible turbulence, turbulence shock interactions and photochemistry of LINE (Laser Induced Non Equilibrium) molecules, and (4) lay down framework to perform equilibrium turbulence interactions studies with a normal shock wave in hypersonic flow.

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1 Table of Contents

1 Summary

The effective life of this grant has been shortened by a superseding BRI, which include more ambitious and challenging research questions. During the six-month period of this grant, we have worked on the tasks and preparations for many of the issues detailed in the BRI. In particular, we have worked on baselines configurations that will serve as point of comparison when thermal non-equilibrium is introduced.

The specific tasks were: (1) lay some of the theoretical framework for baselines flows, (2) develop the infrastructure for non-equilibrium studies, (3) mentor graduate students (Mr. Agustin Maqui, Mr. Chi Mai, Mr. Andrew Leidy, Mr. Wade Eveland and Mr. Nic West), (3) study previous literature on compressible turbulence, turbulence shock interactions and photochemistry of LINE (Laser Induced Non Equilibrium) molecules, and (4) lay down framework to perform equilibrium turbulence interactions studies with a normal shock wave in hypersonic flow.

Simulations

During this first phase of the project, the possibility of applying concentrated momentum lines that resemble photo-dissociation by lasers has been studied. The main objective has been to understand whether and how fully developed turbulence can be achieved with this particular approach. To implement the lines, they are treated as initial conditions with perturbations normal to the direction of the line. In order to satisfy the physics of the problem, these had to be applied in Fourier space and divergence free was met by an additional component of velocity parallel to the lines. The evolution of the flow with lines as initial conditions was studied to determine when the flow became turbulent. Typical results from these flow are shown in the report below for the Taylor Reynolds number and the skewness of velocity gradients for several initial conditions. Two characteristic times scales, dependent only on initial conditions were identified that can capture the transition to a fully turbulent state (where, for example, skewness of the velocity gradient becomes close to -0.5). Other parameters studied involved acceleration statistics, both viscous and pressure acceleration, and radial properties emanating from lines. A self-similar scaling appears to capture the evolution and transfer of energy from LINEs to the rest of the flow. The results have been presented in different venues and a manuscript is currently being written.

Theory

Our efforts in this first stage was focused mainly on baseline configurations as described in the proposal, that is, the scaling of turbulence and shock-turbulence interactions in thermal equilibrium. Continuing our work in [Donzis, Phys. Fluids 24, 011705 (2012)] we have further deepened our understanding of the shock structure when it interacts with turbulence in [Donzis, Phys. Fluids, 24, 126101 (2012)]. In this work we successfully collapsed the available data from simulations on the statistics of the shock thickness and gradients. We have further suggested a new parameter to determine whether the interaction is in the so-called ``wrinkled'' or ``broken''.

In a more recent development [Donzis & Jagannathan, IUTAM Procedia, 2013] we investigate the effect of so-called internal intermittency (through velocity gradients) in shocks as well as their relation in isotropic turbulence. We found that gradients stemming from incompressible turbulence could be as strong as shocks or shocklets in the high-Reynolds number limit.

Understanding the interaction of TNE with turbulence and how to describe its effects and incorporate into engineering models is currently unknown. For example, no mathematical description currently exists to describe the changes to second-order turbulence correlation terms during transit through a shock wave. Therefore, a current objective of ours is to incorporate the mathematics of a shock discontinuity into the transport equations for second-order turbulence correlations, in particular for Reynolds stress and turbulent heat flux. This is an effort that is currently underway.

Experiments

Our goals for the first stage of the research were to (1) lay the transport equation theoretical framework to identify the salient processes and (2) modify our infrastructure to perform the detailed non-equilibrium studies. This work began under the previous AFOSR project and is now continuing under the BRI project.

The overall goal of the proposed experimental work is to acquire detailed turbulence measurements to gain an understanding of how second-order turbulence correlations (Reynolds stress and turbulent heat flux) are altered in homogeneous turbulence interacting with a normal shock wave in hypersonic flows. The experimental methods will include varying degrees of internal non-equilibrium.

During this first phase of the effort, we have designed modification to our Repetitively Pulsed Hypersonic Test (RPHT) Cell (Sanchez-Gonzalez et al 2012) to accomplish the required measurements. The modifications combine the low-disturbance and variable Mach capability of the TAMU Actively Controlled Expansion Tunnel (Semper et al 2012) with the "continuous" pulsed operation of the RPHT cell. The flow pulses are centered on the high-power Q-switched laser diagnostic operation) for both Laser Induced Non-Equilibrium (LINE) turbulence generation and meaningful VENOM statistical studies. The design of the Pulsed Hypersonic Adjustable Contour Expansion Nozzle for Aerothermochemical Test Environments (PHACENATE) is complete and the construction is scheduled for completion by May 15.

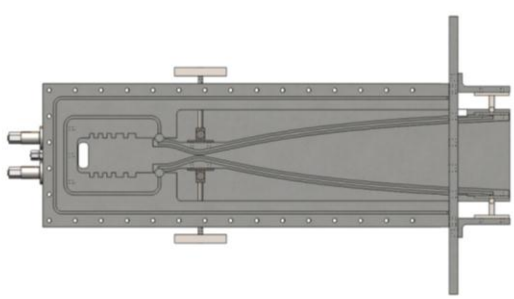


Figure 1. Schematic of PHACENATE ("fascinate").

2 Background

The importance of properly accounting for internal molecular structure of gaseous flow is well established across a number of disciplines including high-temperature aerodynamics and combustion. Utilizing internal energy exchange for intelligent control of basic fluid dynamic processes is of direct relevance to AFOSR scientific objectives is (Schmisseur, 2011). The few studies available demonstrate a clear link between the internal molecular structure and the basic structure of the fluid dynamic processes. They also highlight the extremely limited knowledge about these phenomena which is especially true for strongly non-linear systems like high-Reynolds-number Navier-Stokes turbulence where complexities go beyond any theoretical treatment. The scarce data available has suggested that the interaction mechanisms include both changes in the transport coefficients (e.g. Liao et al., 2010) and coupling of thermal effects into pressure fluctuations (Bowersox & North, 2010). Improving understanding and modeling of these mechanisms are scientific challenges that have the potential to lead to new opportunities to extract fluid energy and to control the basic underlying processes. Providing this knowledge is the objective of this proposal, and will ultimately lead to improved thermal management, combustion efficiency and transport prediction. Thus, the long-term scientific objective of this project (to be achieved under a new BRI project that supersedes this project) is to take advantage of the fundamental understanding of the transfer of energy between turbulence modes (i.e. kinetic or internal energy) and different molecular internal modes (i.e. rotational, vibrational) to control and predict the behavior of turbulence over a range of degrees of thermal and mechanical non-equilibrium.

This project aims at both advancing our understanding of the effect of thermal (rotational, vibrational) and mechanical non-equilibrium on compressible turbulence and proposing new technological advances in the mechanisms to generate and control turbulence. Due to the multidisciplinary nature of the problem, great scientific advances can be expected if multiple approaches are combined. The research team thus comprises expertise in the fields of large-scale simulations of turbulent flows, physics of turbulence, advanced experimental techniques and chemistry of non-equilibrium phenomena. This unique combination will allow us to provide a unified framework in which turbulence under TNE can be understood.

We combine of state-of-the-art massive direct numerical simulations (DNS, on tens or hundreds thousand processors) and novel experimental approaches to explore the detailed physics at levels of fidelity and at a range of parameters not possible before. Specifically, we started working on a new concept to generate turbulence using photo-initiated TNE mechanisms which we will then use to study the specific mechanisms in which TNE modifies turbulence. The basic principle behind this method is to use a high-energy laser to photoexcite seeded molecules along a mesh pattern. Advantages of this technique include the possibility of selecting molecular species to control the degree and mode of TNE, ease of changing grid geometry, and initial perturbation. We have performed preliminary simulations and experiments which shows how this technique can be successfully used to generate turbulence with TNE. Thorough comparisons between this new technique and traditional physical grids will be performed as part of this project.

Studies will be conducted in canonical flows (temporally or spatially decaying turbulence and isotropic turbulence interacting with normal shocks) with special emphasis on discovering venues to control over which modes energy can be stored—this includes characterizing time and length scales associated with those processes. At the same time, to compare with baseline cases, equilibrium turbulence simulations and experiments will be conducted at levels of fidelity not possible before. The results will allow us to solve long standing inconsistencies between experiments and simulations, such as amplification factors across a shock, or the influence of turbulence scales upstream of the interaction.

In the rest of the document, we detail the objectives and tasks accomplished as part of this project and planned for the continuation under the BRI.

3 Effort – Framework and Baseline Studies

Our goals for the first stage of the research were detailed in the corresponding proposal. The effective life of this grant has been shortened by a superseding BRI, which include more ambitious and challenging research questions. During the six-month period of this grant, we have worked on the tasks and preparations for many of the issues detailed in the BRI. In particular, we have worked on baselines configurations that will serve as point of comparison when thermal non-equilibrium is introduced.

The specific tasks were: (1) lay some of the theoretical framework for baselines flows, (2) develop the infrastructure for non-equilibrium studies, (3) mentor graduate students (Mr. Agustin Maqui, Mr. Chi Mai, Mr. Andrew Leidy, Mr. Wade Eveland and Mr. Nic West), (3) study previous literature on compressible turbulence, turbulence shock interactions and photochemistry of LINE molecules, and (4) perform equilibrium turbulence interactions studies with a normal shock wave in hypersonic flow.

4 Background and Previous Research

Research in shock-turbulence interaction, particularly homogeneous turbulence interaction with a normal shock wave, has been previous reviewed by Andreopoulos *et al.* (2000) and partly by Lele (1994). This section is categorized according to theoretical, numerical, and experimental work.

4.1 Theoretical Research

Considering first-order perturbation theory for the Navier-Stokes equations, turbulence in supersonic flow was broken into three separate modes by Kovásznay (1953): acoustic (pressure), entropy (temperature) and vorticity (velocity). Assuming that all state variable disturbances were small compared to the mean properties and that the velocity perturbations are small compared to the speed of sound, these three modes were non-interacting and each described by a linear differential equation. This work was expanded by Chu and Kovásznay (1957). If the noninteracting modes pass through a region of steep gradients, i.e. a shock wave, mode interaction could occur.

Ribner performed the first theoretical treatments of shock-turbulence interaction, which are formally valid in the limit of high Reynolds numbers and low turbulence Mach numbers. His first analysis assumed that only the weak vortical mode in the form of a plane sinusoidal shear wave was present in the upstream turbulence and that the entire upstream flow field could be described by superposition of waves of different orientations and wavelengths (Ribner, 1954a). Ribner’s analytical method, later dubbed as linear interaction analysis ("LIA"), predicted that a shear wave's passage through a shock wave would modify its inclination and amplitude and would activate the acoustic mode in the form of a pressure wave. Thus, the shock wave altered one turbulent mode and generated turbulence in another mode. Ribner, for initially isotropic and axisymmetric turbulence behaviors, would later generalize the upstream turbulent field to include contributions for all three modes (1954b). LIA remains as a standard in shock-turbulence research due to its ease in obtaining results for quantities of interest, and direct numerical simulation results are often compared to LIA predictions. Upstream conditions have been shown to be important to shock-turbulence interaction, but LIA, however, does not account for the effect of upstream conditions (Andreopoulos *et al.* 2000).

Lele averaged the conservation equations with the Rankine-Hugoniot jump conditions to calculate conditions due to a shock wave propagating through a turbulent medium and to compare those values to classical theory (1992). The conservation equations were Favre-averaged, and upstream turbulence was assumed to be axisymmetric. Closure was obtained by appealing to homogeneous rapid distortion theory, which did not include the effects of turbulence on the shock wave itself. To account for the mutual interaction of the turbulence and the shock wave, Zank *et al.*, based on an inviscid form of Burgers' equation, developed a set of self-consistent partial differential equations with jump conditions (2002).

Wouchuk *et al.* developed an exact analytical model for the interaction between a shock wave and a turbulent vorticity field (2009). The vorticity field was decomposed into Fourier modes, and all quantities characteristic of shock-turbulence interaction were reduced to closed-form exact analytical expressions and presented explicitly as functions of the specific heat ratio and the shock Mach number. It was found that turbulent kinetic energy, contrary to most cases, was attenuated after the interaction in cases where the specific heat ratio goes to one and the Mach number goes to infinity. The closed-form expressions lent themselves to the possibility of obtaining exact analytical scaling laws.

Donzis performed scaling analysis and showed that the shock wave thickness in both laminar flow and turbulent flow had incomplete similarity (2012b). This scaling analysis will guide the proposed set of experiments and their counterpart numerical simulations.

4.2 Numerical Research

Much of the numerical work done in shock-turbulence interaction has been done with direct numerical simulations ("DNS") in which the conservation equations are solved directly without resorting to a turbulence model. With rapid advances in computational capabilities, DNS are beginning to solve flow problems at more realistic Reynolds numbers while still resolving the fine turbulent scales.

Lee *et al.* performed one of the first major numerical works for isotropic turbulence interactions with normal shock waves. Weakly compressible, isotropic turbulence (turbulent Mach number of 0.0567 to 0.11) at low turbulent Reynolds numbers interacting with weak shocks (Mach number of 1.05 to 1.20) was studied (1993). Results predicted the amplification of turbulence, turbulent kinetic energy, and transverse vorticity components. Furthermore, at these low Mach and turbulent Mach numbers, the results compared favorably with LIA predictions.

Lee *et al.* extended their analysis to stronger shocks using an essentially non-oscillatory scheme (1997). The Mach numbers in this study were 1.5, 2.0, and 3.0, and the turbulent Mach number for each case was 0.0897, 0.108, and 0.110, respectively. The results indicated that the amplification of turbulent kinetic energy saturated above Mach 3.0. Again, DNS results with available counterpart LIA predictions compared favorably. Fluctuations in thermodynamic variables after the interaction were found to be anisotropic due to the generation of the entropic turbulence mode.

Mahesh *et al.* expanded upon the role of entropy fluctuations by performing DNS of an isotropic turbulent field of vorticity and entropy fluctuations interacting with a normal shock wave (1997). The Mach numbers in this study were 1.29 and 1.80 with LIA predictions ranging from Mach 1 to 3. LIA and DNS both showed no amplification of the turbulent kinetic energy if the upstream correlation between velocity (vorticity) and temperature (entropy) fluctuations is positive. A negative correlation between velocity and temperature fluctuations, however, was observed to enhance the amplification of the turbulent kinetic energy, vorticity, and thermodynamic fluctuations. Thus, the upstream correlation of velocity and temperature fluctuations directly influences turbulent heat flux values downstream of the interaction. Bulk compression and baroclinic torques were found to be the two important contributions to the evolution of fluctuating vorticity across a shock wave, and the velocity-temperature fluctuation correlation determined if the two processes enhanced or opposed each other.

Larsson and Lele pushed the Mach and turbulent Mach number range further than the work cited above for Lee *et al.* (Larsson and Lele 2009). The Mach number in this study ranged from 1.3 to 6.0, and the turbulent Mach number ranged from 0.16 to 0.38. The Kolmogorov length scales decreased during the shock interaction, which implied that the grid resolution needed to properly resolve viscous dissipation is finer than grids used in previous studies. Computational grids coarser than the resolution needed result in rapid increases in downstream streamwise vorticity variance and large anisotropy of the postshock Reynolds stresses. The terms “wrinkled” and “broken” were introduced and used to describe the structure of the shock wave in response to the incoming turbulence. A “wrinkled” shock wave structure locally maintains a distinct shock front whereas a “broken” shock wave structure is where the local flow compresses smoothly. Larsson and Lele expanded their work to include Reynolds- and Mach-number effects with Taylor-microscale Reynolds numbers of 40 and 72 (2013). Those results, like their previous results, indicated that turbulent kinetic energy amplification was described well with linearized dynamics but that the post-shock Reynolds stress anisotropy is qualitatively different than LIA predictions.

Wang and Zhong expanded DNS to Mach 30 simulations and showed new trends in turbulent statistics at higher Mach numbers (2012). Main conclusions from this work is that the upward amplification trend for streamwise vorticity fluctuations through a shock wave reaches a maximum at Mach 2.8 and then decreases as shock strength is increased. On the other hand, the amplification of the streamwise Reynolds stress decreases as the Mach number is increased to Mach 8.8 with a reversal as shock strength is further increased. Current DNS work incorporates a new high-order shock fitting solver for non-equilibrium flow simulations based on 5-species air chemistry with results forthcoming.

Donzis was able to collapse to first order the streamwise velocity amplification factor curves for canonical shock-turbulence interactions from various DNS studies by using a parameter that normalizes shock wave thickness by the Kolmogorov length scale (2012a). This parameter was also shown to assist in understanding the “wrinkled” and “broken” interaction regimes.

4.3 Experimental Research

Experiments in normal shock-turbulence have been carried out in shock tubes and supersonic blowdown wind tunnels.

Experiments in shock tubes generally have a mesh grid or other turbulence generator in the driven tube. The shock wave will pass through the generator and reflect off of the end wall. The reflected shock wave will interact with the incident shock wave’s induced flow that has passed through the generator. Measurement techniques generally utilize hot-wires and fast-response pressure probes.

For blowdown wind tunnels, a variety of options to generate turbulence have been explored. A mesh grid can be installed in the settling chamber, but the resulting turbulence is anisotropic due to the turbulent eddies stretching at the throat. A grid acting a sonic throat has been utilized (Jacquin *et al.* 1991) as well as a multinozzle concept (Barre *et al.* 1996).

Hesselink and Sturtevant studied the propagation of weak shock waves through a statistically uniform random medium in a shock tube with schlieren and shadowgraph methods (1988). Shock Mach numbers in this study were 1.007, 1.03, and 1.10. Images obtained show distorted shock fronts and pressure changes and are interpreted to represent a multiplicity of scattered wave fronts instead of a single highly wrinkled front. The pressure histories of the distorted shock waves reflecting from a normal end wall were seen to be both peaked and rounded, and these are now associated with the “wrinkled” and “broken” shock interaction regimes.

Jacquin *et al.* used a grid that acted as a sonic throat and obtained Mach 1.4 flow (1991). The normal shock position was controlled by a second throat downstream. Measurements were obtained using laser Doppler velocimetry with an unusual observation: the lack of turbulence amplification. Andreopoulos *et al.* cast doubt on the results for the following reasons (2000): 1) review of the data showed that the flow upstream of the interaction was decelerating with the likely cause attributed to Mach waves emanating from the grid; flow deceleration has been shown to augment turbulence, 2) the probe volume was too large to accurately resolve the turbulence, and 3) it has also been shown that laser Doppler velocimetry in compressible flows tend to overestimate turbulence intensities.

Barre *et al.* generated an isotropic turbulent flowfield by using a multinozzle generator and formed a normal shock wave through the intersection of two oblique shock waves of opposite directions (1996). A block with multiple Mach 3 nozzles was placed in a supersonic blowdown wind tunnel, and the shear layers and slip lines between each nozzle decayed into isotropic turbulence a finite downstream of the nozzle exits. The turbulence amplification agreed well with LIA. Diagnostics included hot-wire anemometry and laser Doppler velocimetry. Andreopoulos *et al.* (2000) presented concerns with this study: 1) the shear layers from the shock generators accelerate the flow downstream of the shock wave and are expected to reduce downstream turbulence levels, and 2) the turbulence intensity at the shock wave is extremely low leading to low signal-to-noise ratios.

Xanthos *et al.* studied the interaction of decaying freestream turbulence with a moving shock wave in a shock tube and quantified the pressure field (2002). The induced flow, whose Mach number ranged from 0.32 to 0.62, interacted with reflected shock waves of varying strengths. Hot-wires, pressure transducers, and Rayleigh scattering were used to make measurements. The mutual interaction between the freestream turbulence and the shock wave resulted in 1) shock wave attenuation due to strong viscous effects and 2) substantial changes in turbulence intensity. Finer grids produce turbulence that attenuate the shock wave more than turbulence generated from a coarser grid. The grid spacing also strongly influences the amplification of pressure fluctuations.

Agui *et al.* extended the work of Xanthos *et al.* by quantifying the velocity and vorticity fields (2005). The induced flow was similar to the previous study (Mach 0.3 to 0.6), and reflected shock waves varied from Mach 1.04 to 1.39. Xwires and 3-wire probes were placed at various axial locations along the shock tube to determine the temporal and spatial evolution of turbulent fluctuations and structures. Measured quantities included: longitudinal and lateral velocity gradient fluctuations, longitudinal and lateral vorticity fluctuations, and longitudinal and lateral length scales.

5 Research Objectives and Contributions

The overall goal of the proposed work is to develop a theoretical framework and to conduct detailed simulations and measurements in experimental facilities to gain an understanding of the complex interaction of turbulence in TNE and when it further interacts with a normal shock wave. Knowledge gained from this study will be extended by future studies to include molecular and chemical nonequilibrium effects relevant to hypersonic flows. The current proposed work, therefore, will set a baseline for overall efforts to understand and exploit basic energy processes in hypersonic, nonequilibrium flows and their role in altering the transport properties of turbulence.

The proposed research will be guided by three overall objectives.

5.1 Development of Mathematical Theory

Understanding the interaction of TNE with turbulence and how to describe its effects and incorporate into engineering models is currently unknown. For example, no mathematical description currently exists to describe the changes to second-order turbulence correlation terms during transit through a shock wave. Therefore, an objective of ours is to incorporate the mathematics of a shock discontinuity into the transport equations for second-order turbulence correlations, in particular for Reynolds stress and turbulent heat flux.

5.2 Simulations

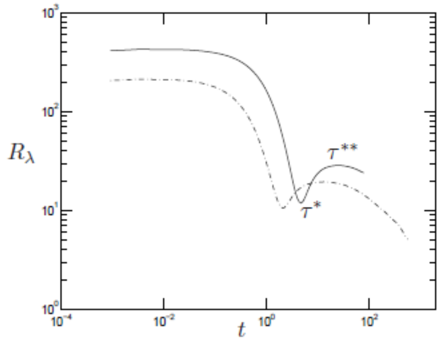
Two main codes are being used: I (incompressible), and II (compressible). CODE I is a mature code whose current implementation was developed mainly by the PI in collaboration with Dr. D. Pekurvosky at the San Diego Supercomputing Center. CODE II is also mature but is currently under continuous development to utilize the latest technology, programing techniques, communication protocols, etc to be able to run efficiently on hundreds of thousands of cores. Thus, we have been working on performance models and paths to more scalable codes that allow for more complex simulations.

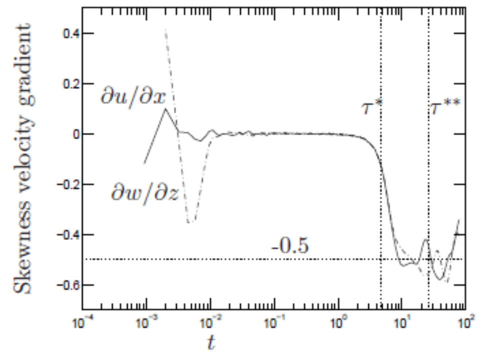
CODE I. Incompressible isotropic turbulence: This code will be used to generate data for incompressible turbulence to (i) study non-equilibrium processes in incompressible flows, (ii) compare with compressible turbulence, (iii) as initial conditions for compressible simulations. The code solves the incompressible Navier-Stokes equations.

Although collective communications to perform the transposes are network bandwidth intensive, extensive benchmarking (Donzis et al., 2008a) has generally shown close to 90% strong scaling over 4X increases of the core count, with the largest test being 81923 on 131072 cores. We are currently using this code for several other projects including a DOE INCITE (Innovative and Novel Computational Impact on Theory and Experiment) to study mixing in non-stratified and stably stratified incompressible and compressible turbulence. A version of this code was also used to generate preliminary results for turbulence generation by means of photo-dissociation.

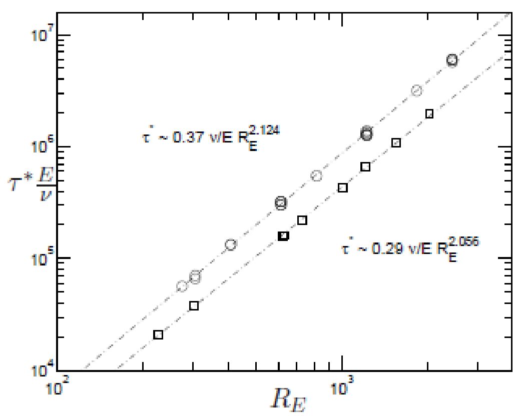
CODE II. Compressible turbulence: This code solves the full compressible Navier-Stokes equations, which represent conservation of mass, momentum and total energy. In addition, equations for different internal modes are solved using advection-diffusion equations for non-equilibrium internal modes. These include a source term representing the exchange of energy between internal modes, which have been implemented, for small departures from equilibrium conditions, following a Landau-Teller model. As a first approximation, standard models for relaxation times and transport coefficients are being used (Vincenti & Kruger, 1975; Park, 1990; Bertolotti, 1998). Due to the additional physics, the computations are several-fold more expensive than incompressible simulations. This is due to the increased number of operations per step and additionally, if a CFL condition is imposed, the number of time steps for a given Reynolds number is larger than in CODE I due to the finite (and large) value of the speed of sound.

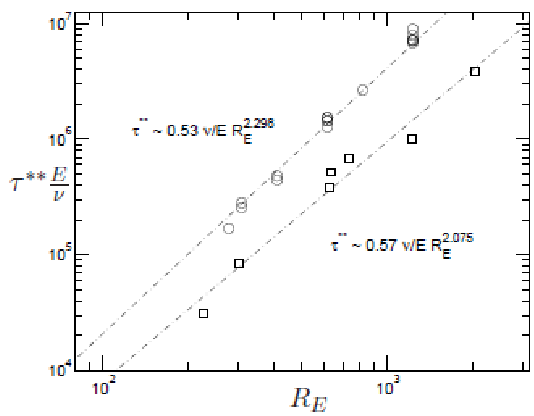
During this first phase of the project, the possibility of applying concentrated momentum lines that resemble photo-dissociation by lasers has been studied. The main objective has been understanding whether fully developed turbulence can be achieved with this particular approach. To implement the lines, they are treated as initial conditions with perturbations normal to the direction of the line. In order to satisfy the physics of the problem, these had to be applied in Fourier space and divergence free was met by an additional component of velocity parallel to the lines. The evolution of the flow with lines as initial conditions was studied to determine when the flow became turbulent. Typical evolution is shown in the figure below for the Taylor Reynolds number and the skewness of velocity gradients for two initial conditions. Two characteristic times scales (□* and □**), dependent only on initial conditions, can capture the transition to a fully turbulent state (where, for example, skewness of the velocity gradient becomes close to -0.5). Other parameters studied involved acceleration statistics, both viscous and pressure acceleration, and radial properties emanating from lines.





The two characteristic times scales has been successfully characterized by the initial conditions given by a new Reynolds numbers R_E based on the initial energy E introduced in the system at the initial time, the size of the "LINEs" and the viscosity. The good collapse of □* and □** is observed for both compressible and incompressible turbulence as seen in the figures below.





This results are allowing us to determine the experimental conditions, such that a realistic turbulent flow in our experimental facilities. In particular, whether the distance from the LINE grid is within the wind tunnel section.

5.3 Experimental work

5.4 <u>Characterization of Pulsed Hypersonic Facility</u>

As mentioned previous, experimental facilities used to study shock-turbulence interactions have been either shock tubes or modified supersonic tunnels. Hotwires have been the measurement technique of choice because of their frequency response and their ease of use. Hotwires, however, only provide point measurements. Laser-based diagnostics offer planar measurements with spatial resolution that can accurately capture turbulent characteristics; these methods are limited by the repetition rate of the laser. Shock tube facilities provide only milliseconds of steady flow, which precludes the use of typical laser diagnostics. Repetitively pulsed facilities have recently been developed to take advantage of the pulsed operation of lasers.

The second objective is to characterize a benchtop, variable Mach number hypersonic facility operating in pulsed mode, which will enable the acquisition of convergent statistics through continuous, synchronized operation with laser systems. Such a facility will operate with relatively inexpensive infrastructure and reduced operating costs compared to typical blowdown facilities. The relevant questions are: How steady is the flow over one pulse? What is the flow uniformity? How repeatable are the flow pulses?

5.5 2D Simultaneous Velocimetry and thermometry

Compared to numerical studies, there have been very few experimental studies of homogeneous turbulence interacting with a normal shock wave. No experimental study has obtained correlated velocity and temperature fluctuation data, and no experiment has been performed for flows above Mach 3. In addition, as mentioned in the previous objective, all previous experiments have used pointmeasurement techniques.

The third research objective is to perform well-resolved, laser-based, 2-D simultaneous velocimetry and thermometry of shock-turbulence interaction at hypersonic Mach number. An important aspect of this objective is to document upstream conditions so that the flow can be accurately emulated in the collaborative DNS work. The relevant research questions are:

- How are the velocity, vorticity, and temperature fluctuations altered?
- How are the integral length scales of turbulence altered?
- How do upstream conditions influence amplification of turbulent quantities?
- How is the degree of anisotropy altered?
- How are second-order turbulence correlations altered?
- Do the results support simplification of second-order transport equations?
- Do the appropriate amplification factors collapse to a universal curve following Donzis (2012a)?

Since hotwires have been used extensively in previous shock-turbulence interaction experiments, hotwire anemometry will be performed to obtain data for comparison to the laser-based methods. Because the laser-based methods are relatively higher risk than hotwire anemometry, hotwires will serve as the primary experimental method in a contingency.

5.6 Future Numerical and Physical Experiments

Numerical and experimental data will also supplement the theoretical work done for the first proposed research objective and the numerical work done by collaborators on the overall project. Experiments will be carried out in four phases.

The primary experimental facility will be the RPHTC equipped with the PHACENATE nozzle; the VENOM diagnostic will provide the bulk of the measurements. The ACE tunnel will serve as an auxiliary experimental facility for preliminary data.

5.6.1 PHACENATE and New RPHTC Characterization

The first experimental phase will be to calibrate the PHACENATE nozzle and characterize its freestream turbulence properties. The nozzle will be operated over its range of Mach numbers and Reynolds numbers, and Pitot probe data gathered from this phase will be compared to data from Semper *et al.* (2012). Since PHACENATE will be a scaled-down version of ACE, it is expected to have its low-noise qualities at low Reynolds numbers and high Mach numbers. Thus, a mesh grid should be necessary to develop decaying turbulence in the freestream. However, if the natural freestream turbulence is high, it may not be necessary to utilize a mesh grid for this study. Based on the Mach- and Reynolds-number sweeps, one operational point will be determined for the remainder of the experimental phases.

5.6.2 NTE Relaxation Studies and LINE Characterization

We have proposed an innovative laser induced photolysis grid concept is proposed to produce turbulence with thermal non-equilibrium. Through variation of the excitation wavelength and identity of the molecular precursor both the magnitude of the energy deposition and the mode-specificity can be tailored. For example, it is possible to produce highly anisotropic velocity distributions in excess of 4000 m/s via the 355 nm photodissociation of seeded Cl_2, or deposit the entire photon energy into molecular vibration via effective internal conversion. Preliminary DNS simulations which include TNE have been conduceted and described above. Experimentally, our initial efforts in the new RPHTC will to measure and model the redistribution of energy following LINE perturbation. We will characterize the collisional energy transfer processes using NO LIF and compare the results to chemical dynamics simulations. The goal is to determine time-resolved energy transfer distributions without explicit determination of state-to-state cross sections.

We will perform experiments to characterize both the magnitude to the excitation and the mode-specificity of the NTE using the LINE technique. We are currently surveying the literature on the photodissociation dynamics of two model systems (i) vibrationally excited C_6F_6, prepared by 266 nm electronic excitation followed by internal conversion to the ground electronic state(i.e., $S_0 + h^o \rightarrow S_1 \rightarrow S_0^*$) and (ii) the nascent NO and O atom fragments arising from NO_2 photodissociation at 355 nm. The first system represents the case of significant vibrational TNE only while the second system involves the dissipation of rotational, vibrational, and translational TNE.

5.6.3 Decaying Mesh/Grid Turbulence Characterization

In simulations, decaying turbulence is easy implemented and simulated and has been a rich playground for scientific experimentation for decades. Experimentally, mesh grids of different grid spacing will be installed into the RPHTC to generate turbulence levels higher than that of the naturally occurring turbulence. The VENOM diagnostic will characterize the grid-generated decaying turbulence over a range of turbulent Mach numbers. It is expected that the turbulent Mach number, influenced by the mesh grid spacing, is the driving parameter for the turbulent decay behavior. Careful measurements of this flowfield, including correlations and spectra, will set the upstream conditions for the experiments characterizing turbulence interaction with a normal shock wave and also provide crucial information for collaborative DNS efforts.

5.6.4 Shock Generator Characterization

For the second experimental phase, shock wave generators will be installed in PHACENATE. Shadowgraph and schlieren optical methods will be used to determine the existence and general characteristics of a Mach stem formed from the intersection of two oblique shock waves similar to that of Barre *et al.* (1996). With expected low freestream noise from PHACENATE and no mesh grid, this phase will serve as the control case. VENOM setup and data analysis processes will be tailored during this period.

5.6.5 Decaying Mesh/Grid Turbulence Interaction with Normal Shock Wave

The fourth experimental phase will investigate decaying mesh/grid turbulence interacting with the normal shock wave formed by the shock generators (Figure). Using VENOM, multiple sets of 2-D velocity and temperature data will be obtained, and a wide field of view can be obtained with a set of cameras. Because VENOM is a planar technique, an image pair will capture the flow both before and after the shock wave. Image pairs will be ensemble averaged, producing mean and fluctuating quantities. Amplification factors can then be determined for velocity, vorticity, and temperature fluctuations. From the basic parameters, Reynolds stresses and turbulent heat flux amplifications can be computed as well as the degree of flow anisotropy. Integral length scales will be deduced through autocorrelation of the velocity fluctuation profiles. Data analysis beyond the scope of the current proposed work will quantify other length scales and the evolution of turbulent structures. The experimental data will be compared against collaborative DNS to verify its results.

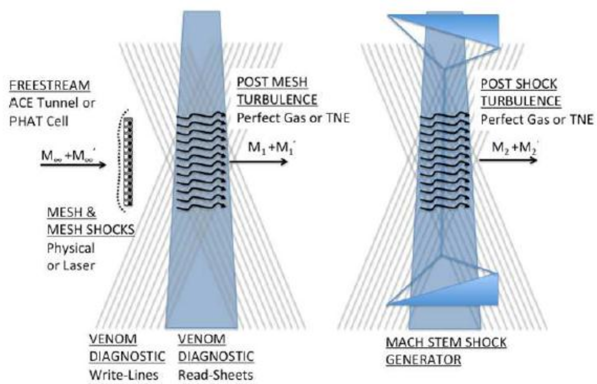


Figure . Schematic of grid-generated turbulence interacting with a normal shock wave created by the intersection of two oblique shock waves (Donzis *et al.*, 2011).

In

Table is a summary of the four Stage 1 experiments.

Table . Summary of proposed experimental phases.

Phase	Mesh	Shock Generator	Characterization	Parameters
1	No	No	PHACENATE nozzle	M, Re
2	No	Yes	Shock wave generator	
3	Yes	No	Decaying mesh/grid turbulence	M_t
4	Yes	Yes	Turbulence interaction with normal shock wave	M_t

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