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FINAL PERFORMANCE REPORT

High Density Turbulent Plasma Processes from a Shock Tube

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Summary

A broad-based set of measurements has begun on high density turbulent plasma processes. This includes determinations of new plasma physics and the initiation of work on new diagnostics for collisional plasmas as follows:

(i) A transient increase is observed in both the spectral energy decay rate and the degree of chaotic complexity at the interface of a shock wave and a turbulent ionized gas. Even though the gas is apparently brought to rest by the shock wave, no evidence is found either of prompt relaminarization or of any systematic influence of end-wall material thermal conductivities on the turbulence parameters.

(ii) Point fluorescence emissions and averaged spectral line evolutions in turbulent plasmas produced in both the primary (high velocity) and the reflected (approximately zero velocity) shock wave flows exhibit ergodicity in the standard turbulence parameters. The data show first evidence of a reverse energy cascade in the collisional turbulent plasma. This suggests that the fully turbulent environment can be described using a stationary state formulation. In these same data, we find compelling evidence for a turbulent Stark effect on neutral emission lines in these data which is associated with evidence (simultaneous) of large coherent structures and dominant modes in the Fourier analyses of the fluctuations in the optical spectra. These results provide additional justification for a molecular based approach to turbulence physics.

(iii) A neutral beam generator has been assembled by coupling a Colutron Ion Gun to a charge exchange chamber. Beam-target collisions of the kind $A+B \rightarrow A+B^* \rightarrow A+B+h\nu$, i.e. where the target species is neutral and the beam is either singly charged or neutral have been performed using argon as the working gas. Spectral analysis of the emission shows specific radiative transitions characteristic of both Ar I and Ar II, indicating that some ionization of the target gas results. Gas and plasma parameters such as density, pressure, temperature and flow velocity and their fluctuations can now be followed in real time by spectroscopic analysis of carefully chosen radiative emissions.

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Interaction of Turbulent Plasma Flow with a Hypersonic Shock Wave

INTRODUCTION

Considerable interest exists in the interactions of shock waves with turbulent gases and plasmas¹ and with turbulent interfaces.² Various theoretical approximations have been used to explore specifically the interactions of shock waves with continuous incompressible turbulent flow systems.^{3,4,5} Generally speaking, thermodynamic, acoustic and pressure fluctuations are all seen as amplified across the shock wave followed by a dramatic decay (relaminarization) usually attributed to a lack of importance of viscosity in the turbulent regions. This decay would be accelerated when the flow speed is also reduced due to the importance usually given to the conventional Reynolds number (which is directly proportional to velocity) as a quality of turbulence index. However, for systems far from equilibrium, the neglect of a role for viscous effects may be generally inappropriate when the relaxation time for the molecular process approaches the local flow time.⁶ Furthermore, for stationary collisional plasmas, the conventional Reynolds number is irrelevant under circumstances where the standard features of turbulence in ordinary gases are observed in the plasma.⁷ In addition, for compressible turbulence, the recent evidence of vanishing triple correlations⁸ suggests that the role of compressive effects ordinarily associated with the shock wave could be significantly muted by the existence of a strongly turbulent local environment. We have therefore explored the influence of a reflected shock wave on the turbulence produced behind an ionizing shock wave of the sort previously reported.⁹

EXPERIMENTAL DETAILS

In our experiments, a hypersonic shock wave is produced by discharging a 14.5 μ F capacitor that has been charged to 18 KV into an argon gas filled cylindrical tube 5 cm in diameter and about 200 cm long. In this arc driven shock tube, the speed of the shock wave depends on the pressure of the gas inside the tube and the charging voltage. The tube is divided into (diaphragmless) driver and driven sections with a test section at the end of the driven section including the end plate where the end-wall materials can be changed.¹⁰ The progress of the shock wave is monitored by three quartz pressure transducers that are located on the wall in the test section. There is also one set of three perpendicularly arranged optical windows in the test section. The position of the optical windows coincides with that of one pressure transducer; the pressure signals are amplified and collected by Tektronix digitizing oscilloscopes with the capability of 2 GHz sampling rates. An x-t diagram showing a typical shock wave evolution is plotted in Fig. 1. Specifically, the shock wave gets reflected back into the tube (toward negative x) and is thereby able to rapidly decelerate the oncoming turbulent plasma flow. The end plate has surfaces of either teflon, stainless steel, or aluminum with thermal conductivities of

1.43, 15, and 190 W/m-K respectively. Our interest is focused on the effects of shock wave-plasma interactions undergone by the reflected shock wave as it reprocesses the turbulent flow produced by the primary shock wave.

As the shock wave propagates down the tube it compresses and heats the gas. We choose operating conditions such that $M_S=19.62$ (M_S is the Mach number of the primary shock wave), based on direct measurements of the primary shock wave's speed (W_S) and the room temperature. We also make a direct measurement of the speed of the reflected shock wave (W_R). Using standard calculational procedures for this kind of flow environment,¹¹ we confirm that the approximate specific heat ratio $\gamma = 1.333$ is obtained as appropriate for a fully ionized plasma. This is shown in Fig. 2; by inference, Fig. 2 also supports the conclusion that the gas behind the reflected shock wave is brought to rest since the behavior in Fig. 2 shows the correct asymptotic trend:

$$W_R / W_S \approx \frac{2(\gamma-1)}{(\gamma+1)} \approx 0.29$$

$M_S \rightarrow \infty$ $\gamma \rightarrow 1.333$

Using this value of γ , we calculate: $T_S=1.89 \times 10^4$ K; $n_S=2.24 \times 10^{22}/m^3$; $T_R=1.02 \times 10^5$ K; $n_R=1.3 \times 10^{23}/m^3$; and the degree of ionization¹² α is $\alpha_S \geq 0.6$, where in all of the above, the subscripts S and R refer respectively to the primary and the reflected shock waves, M is the Mach number, and T and n are temperature and particle number density respectively. Hence the gas behind the shock wave is a high density plasma ($\geq 10^{17}/cc$).

We used laser induced fluorescence (LIF) as our principal diagnostic technique. In the case of ionized argon gas, an excited ion pumped at 488nm emits fluorescence at 488 nm and 422.8 nm wavelengths whenever it decays from $4p^2D_{5/2}$ state to $4s^2$ or $4s^4P_{3/2}$ states respectively.¹³ The results reported here are restricted to fluorescence of 422.8 nm wavelength in order to avoid confusion with the 488 nm pump signal. Specifically, a CW 488 nm 7 Watt laser beam is focused at a point in the test section through one of the test section's optical windows. The fluorescence signal is collected at a 50 MHz sampling rate from a window that is perpendicular to the incoming laser and then focused at the entrance of an adjustable monochromator set at 422.8 nm; the subsequent filtered optical signal is picked up by a photomultiplier tube providing input to the digitizing oscilloscope with a 50K per channel data point storage capacity. The system background is determined by triggering the capacitor with the laser turned off so as to see the strength of any spontaneous emissions due to ionization. These emission are attenuated by using an appropriate number of neutral density filters. Data extraction and computations were done using LabView and Mathematica on a Power Macintosh.

RESULTS

The slope of the power spectrum for the turbulent density fluctuations was computed by fitting the power spectrum to $P \propto \omega^{-n}$ where n is the power spectral index. The fractal dimensions were calculated using the standard Grassberger-Procaccia correlation function to estimate the degree of complexity of our data.¹⁴ The method computes the dimension of N time series data by embedding it in an M -dimensional phase space; the fractal dimensions were calculated as the slope, in a stable regime, of the Grassberger-Procaccia correlation function from the fluorescence data.

Fig. 3a shows a typical pressure signal (with the background removed) as monitored by one of the pressure transducers located at the shock tube's wall; the decay in the pressure reading is an artifact of the external circuitry. The first change in pressure corresponds to the primary shock wave and the next change occurs when the reflected shock wave comes back to the same pressure transducer. In Fig. 3b, we present a subset of the laser induced fluorescence data from the time period after the reflected shock wave from which the background has been extracted. We use these (uncalibrated) voltage fluctuations as a measure of relative local density fluctuations.¹² Fig. 3c shows the power spectrum from these data. As discussed in Ref. 9, the detailed mechanisms providing the source of turbulence are not yet known; however, reaction-diffusion processes arising from the nonequilibrium recombination $\text{Ar}^+ + e^- + X \rightarrow \text{Ar} + X$ (the onset of which increases the dimensionality of the system) have a relaxation time scale appropriate (when compared with the local flow time) for increased chaotic complexity in the system and correspondingly for the development of turbulence.

DISCUSSIONS AND CONCLUSIONS

More than twenty shock tube firings were analyzed for each one of the three end wall materials. No systematic influence of shock tube wall thermal conductivity on the flow environment in the regions of interest for this experiment was found. Specifically, no trends in the evolution in chaotic correlation dimension (D_2) or in the density fluctuation power law spectral index (n in $P \propto \omega^{-n}$) were found in one substance which were not also found in all three cases; no value, at a fixed time either just before or just after the reflected shock wave, was found in the turbulence parameters just cited for one material which was statistically inconsistent with the values found in all three cases. We have therefore chosen to average, without regard for the end-wall conductivity, all values measured for the turbulence parameters.

In Figs. 4 and 5 are presented the evolution of density power law index n and the chaotic correlation dimension for all the experiments averaged over all three end wall materials; the errors indicated include systematic effects arising from shock-to-shock variations in the measured parameters with identical starting conditions. In both cases, the first point in the graph corre-

sponds to data taken when the primary shock wave reached the optical window; each turbulence parameter determination was calculated on 256 data points separated by 25 μ s. In both cases, it is easy to distinguish the regions before and after the reflected shock wave; there is no relaminarization. It is also easy to see that the reflected shock wave causes a transient increase in the two turbulence parameters followed by a period of relaxation toward pre-reflected shock wave values. The higher value of spectral index suggests that interaction of the shock wave with the plasma tends to increase the rate of transfer of energy through the turbulent scales. The higher value of the fractal dimension suggests that the interaction of the shock wave with the plasma tends to increase the degree of complexity of its turbulence. Although there is no theoretical explanation available at present for the slopes of the curves in Figs. 4 and 5, generally stated, these numbers all fall within the expected values for turbulent flows.

However, a distinction can be made in the behaviors shown. Specifically, the rate of change before and after the reflected shock wave is the same for the parameter n ; the rate of change before and after the reflected shock wave is quite different for the parameter D_2 . As previously noted, the temperatures, number densities, and velocities before and after the reflected shock wave are quite different. Therefore one might infer that the chaotic dimension as a turbulence indicator is sensitive to the full range of ordinary macroscopic parameters. By contrast, one might infer that the spectral index n is a fundamental indicator of the turbulent energy transfer processes, dependent only on the microscopic (molecular) constituents.

Collisional Plasmas with Turbulence-Induced Stark Effects from an Arc Driven Shock Tube

Turbulence has been observed in ionizing shock waves in argon gas. The current theoretical understanding of these turbulent phenomenon is inadequate since one cannot reliably distinguish effects which are connected to fundamental and generalizable causes and effects which are simply the byproducts of a particular installation. It is known that the particle concentration behind an ionizing shock front can change not only through the usual compression, convection, and diffusion mechanisms but also through ionization reactions as well; furthermore, the role which might be played by fluctuations on quantum mechanical phenomena is completely unknown. Nonetheless, there is a broad consensus that nonlinear macroscopic phenomena, once understood, should force new options on microscopic phenomena, especially of the sort which might be found in optical spectra. A determination of the role which changing turbulent parameters might play on optical signatures should provide a useful tool for the evolution of theoretical models for turbulence.

To this end, we have applied standard turbulent and spectral analytical procedures to data from our arc driven shock tube. The shock waves are produced in a cylindrical arc discharge shock tube of 5 cm diameter and 250 cm overall length filled with argon. A two piece stainless steel tube of 5 cm diameter and 175 cm overall length is connected to the driver section via an O-ring seal. The discharge is generated by triggering a 14.5 microfarad capacitor charged to 18.5 kV. The blast wave generated by the heating at the arc discharge serves as a piston to create and propel a shock wave in front of it. The principal diagnostic port has four windows arranged at 90° intervals for fluorescence induced resonance radiation, a port for the ion probe and a port for a pressure gauge arranged such that all these measurements are made at the same axial location. Additional pressure gauges are located throughout the tube so that measurements of the local Mach number can be made as appropriate. The resonance radiation is processed at a point by choosing the 422.7 nm line (100,000 measurements at a 50 ns sampling rate) from the 488.0nm CW pump and by a streak camera capable of capturing 1100 full spectra from a 0.5 meter monochrometer at the rate of one every 20 nanoseconds. The shock speed at the test section can be varied from $M = 64$ to $M = 11$ for initial filling pressures of $P_1 = 15$ to 250 mTorr respectively. This corresponds to a range of ionization between 1% and 100%, and typically plasmas of $N(\text{ions})$ approximately $10(E16)/\text{cc}$ and $T(\text{ions})$ approximately 5 eV.

Data processing and analyses are accomplished using an Apple Macintosh IIfx for real time data acquisition from a set of Tektronix 744 Digitizing oscilloscopes ADC's and off-line analyses using a host of Macintosh and Silicon Graphics computers.. The transient recorders provide time histories for: two measurements (at two different sensitivities) of the argon ion fluorescence; the ion probe current; and the wall pressure all at a minimum 100 MHz sampling frequency for at least 0.5ms after the passage of the primary shock wave. This al-

lows us to study the gas processed by the reflected shock wave as well as the primary shock wave on each shock tube firing. In addition to the spectral analyses, phase space trajectories, Lyapunov exponents, chaotic dimensions, power spectra, correlation functions, and dispersion relations can thereby be obtained.

The (relative) ion density fluctuations indicated by the fluorescence emissions and the ion probe voltage readings from the arc discharge shock tube collected on the axis and slightly off axis are used for these investigations. We also use the simultaneously collected optical spectra collected broad band (to search for anomalous emission spectral lines) and narrow band (to look for distortions in individual spectral lines).

We have determined that point fluorescence emissions and averaged spectral line evolutions in turbulent plasmas produced in both the primary (high velocity) and the reflected (approximately zero velocity) shock wave flows exhibit ergodicity in the standard turbulence parameters. We find no evidence of relaminarization and no evidence of conventional turbulent dissipation. The data show first evidence of a reverse energy cascade in the collisional turbulent plasma. This suggests that the fully turbulent environment can be described using a stationary state formulation.

We find compelling evidence for a turbulent Stark effect on neutral emission lines in these data which is associated with evidence (simultaneous) of large coherent structures and dominant modes in the Fourier analyses of the fluctuations in the optical spectra. These results are reminiscent of previous observations in the glow discharge collisional plasmas (in emissions) and is now open to the same type of theoretical interpretation.

We also find a profound insensitivity in the turbulence parameters to the plasma-surface interactions at the end-plate of the shock tube. We especially notice no unique and distinguishable behaviors which can be correlated with the conductivity of the surface material and the extent to which the surfaces are impregnated with small quantities of particulate admixtures.

These results provide additional justification for a molecular based approach to turbulence physics. Specifically, a recent general approach based on reduced molecular chaos with dominant modes connects these data with a variety of other fully turbulent systems in gases and plasmas with clear implications for additional measurements.

Plasma Diagnostics with a Neutral Beam Generator

Progress in gasdynamic research requires the development of specific procedures for the rapid determination of instantaneous parameters in equilibrium or non-equilibrium gases in static and flow situations. The neutral beam fluorescence technique uses optical radiation excited in the gas under study when a beam of energetic neutral particles is passed through the gas. The beam is visible as a thin line of fluorescence and any point along it can be observed by optical means, thus yielding a "point" measurement of the local state of the gas. Gas parameters such as density, pressure, temperature and flow velocity and their fluctuations can then be followed in real time by spectroscopic analysis of the radiative emission. A neutral particle beam generator also provides a means of determining the role of turbulence on the lifetimes of excited atomic and molecular states. A collimated beam of atoms may be targeted onto a glow discharge turbulent plasma. Using a tunable pulsed laser with a sufficiently high repetition rate, definite resonance transitions can be excited in the atom beam and the resulting delayed spontaneous emission monitored together with the exciting laser light. The phase shift between the laser pulse and the atomic emission depends directly on the lifetime of the excited atom and therefore can be studied as a function of standard turbulent parameters.

A neutral beam generator has been assembled by coupling a Colutron Ion Gun to a charge exchange chamber. A collimated ion beam of up to $10\ \mu\text{A}$ and energy variable from a few eV to 10 keV is neutralized through symmetric charge exchange reactions by passage through a ~ 1 mTorr gas cell. Residual ions in the beam are removed by an electric field applied to a pair of plates located at the exit of the gas cell. The resulting neutral beam then passes through a 3 m aperture into a collision chamber positioned directly following the neutralization chamber. Figure 6 shows a schematic of the experimental setup. The three parts of the beam generator i.e. the ion gun, the charge-exchange cell and the collision chamber are held at different pressures using differential pumping techniques. To ensure the absence of impurity atoms or molecules, liquid nitrogen cold traps are used on all three pumping stations. The collision chamber is designed with eight diagnostic ports to allow optical viewing of the collision process from a number of angular orientations. One of the ports also allows a laser pulse to cross the beam path for atomic excitation lifetime studies. The optical emission resulting from beam/gas interaction is collected and analysed by two 0.275 m ARC monochromators with high resolution diffraction gratings. The detector used is a photomultiplier whose output signal is monitored on a digitizing oscilloscope.

Initial beam characterization experiments focused on beam current, divergence and spatial cross-section in the collision chamber. The ion beam current was monitored with a charge collector device located at the extreme port in the beam path. A peak current of up to $3\ \mu\text{A}$ is typical, indicating some loss in beam current due to divergence and the use of limiting apertures required for differen-

tial pumping. The cross-section of the beam and its divergence beyond the last aperture were studied using a beam imaging device which uses a combination of a micro-channel plate and a phosphor. By appropriate control of the electric field profiles in the ion gun velocity filter, a circular cross-section beam is obtained with a typical divergence (dependent on beam current) of ~ 8 mrad. Beam-target collisions of the kind $A+B \rightarrow A+B^* \rightarrow A+B+h\nu$, i.e. where the target species is neutral and the beam is either singly charged or neutral have been performed using argon as the working gas. Spectral analysis of the emission shows specific radiative transitions characteristic of both Ar I and Ar II, indicating that some ionization of the target gas results. In Figure 7, two sample scans are presented, showing a number of spectral lines in the range 4000—4600 Å obtained from a 4 mTorr target gas. The weaker emission from the neutral beam is a result of the lower particle flux. A series of experiments in which the target gas is either oxygen or nitrogen will be performed next with the objective of measuring gas parameters such as density and temperature. Also, using a Nd:YAG-MOPO laser system the influence of turbulent environments on the lifetimes of certain electronic states in excited atoms and molecules will be investigated. These experiments should provide a stringent test for on-going theoretical predictions on atomic/molecular collision dynamics.

Figure 1. An x-t Diagram Showing the Arc Driven Shock Wave Phenomena. A = High Voltage Electrode at the Set-Up Charging Voltage, B = Ground Electrode, D = Blast Wave, E = Ambient Arc Driven Shock Tube Gas, Prior to the Primary Shock Wave at the Set-Up Pressure, G = Post Primary Shock Wave Plasma, S = Primary Shock Wave, R = Reflected Shock Wave, I = Post Reflected Shock Wave Plasma. The fluorescence measurements are made at a point 5.5 cm from the end-wall and 159 cm from the ground electrode.

Figure 2. Changes in the Ratio of Reflected Shock Wave Speed, W_R , to Primary Shock Wave Speed W_S with Primary Shock Wave Mach Number, M_S . The Mach number changes can be made either at constant shock tube pressure (by changing the charging voltage) or at constant charging voltage (by change the shock tube's pressure).

Figure 3. Sample Data. (a) Typical pressure signal of shock wave: The changes in pressure correspond to the primary and reflected shock waves respectively. (b) Fluorescence data history for the time interval after the reflected shock wave using teflon as the end-wall material. (c) Power spectrum for the data in (b) above.

Figure 4. Variation of Spectral Index with Time: All Surfaces. Shown are the logarithms (base e) for the measured spectral indices and the measured elapsed time, in microseconds, since the arrival at the observation port of the primary shock wave.

Figure 5. Variation of Fractal Dimensions with Time: All Surfaces. Shown are the logarithms (base e) for the measured correlation chaotic dimensions (D_2) and the measured elapsed time, in microseconds, since the arrival at the observation port of the primary shock wave.

Figure 6. Schematic illustration of the neutral beam experimental setup

Figure 7. Spectral scans from Ar beam/Ar gas interactions

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