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Mixing of Thermally Stratified Gas in Horizontal Tube Using Shock Waves

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Abstract

A Ludwieg tube can be equipped with a heating system to enable higher Mach number hypersonic wind tunnel tests. However, if axial nonuniformities are present in the temperature distribution, buoyancy effects cause nonuniform temperature distribution in the radial direction making the test conditions suboptimal. To mitigate the problem, it is proposed that the test gas can be pre-mixed by shock waves generated by oscillating a free piston inside the barrel. Two piston oscillation cases were simulated: (1) harmonic oscillation at 10 Hz; and (2) an oscillation in which the stroke is completed in 24 ms, but is repeated only once every second. CFD simulations of pistons oscillating with peak speeds approaching 20 m/s have shown that the shock waves are slightly oblique and have capacity to initiate mixing. Simulations demonstrate that the majority of the mixing occurs within just the first few seconds, although, significant temperature gradients may persist near the walls due to convective heat transfer. Nevertheless, the mixing method has shown promising simulation results and physical experiments are now being planned to assess the practical viability of the method.

1 Introduction

The University of Southern Queensland's hypersonic wind tunnel (TUSQ) uses a Ludwieg tube with free piston compression process to produce test times of the order of hundreds of milliseconds. The long duration allows for investigation of transient effects, hence the tunnel is suitable for a variety of experiments regarding free-flight, shock interaction, aeroelasticity and more. Currently TUSQ is undergoing an upgrade incorporating pre-compression heating of the test gas to enable testing at up to Mach 4 flight enthalpies. Such conditions would extend the tunnel capabilities to supersonic airbreathing engine testing.

TUSQ is a Ludwieg tube with a free piston compression. A schematic of the wind tunnel is shown in figure 1. The principle of operation is as follows. The high pressure air is used to drive the piston down the barrel. The test gas (air) downstream of the piston gets gradually compressed. At a designated pressure a diaphragm located at the end of the barrel ruptures. The test gas accelerates through the nozzle and enters the test section, generating uniform flow conditions for hundreds of milliseconds. Subsequently, the test gas enters the dump tanks preventing shock reflection.

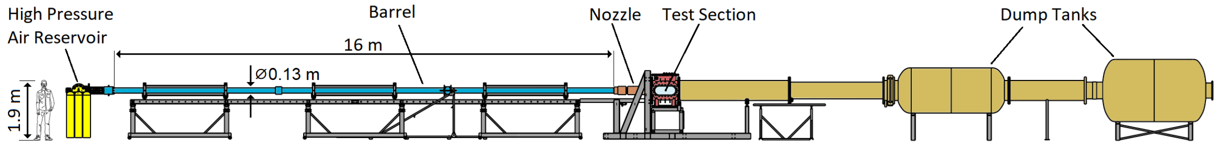

Figure 1. TUSQ wind tunnel schematic.

2 Problem Statement

To provide high quality flows for hypersonic aerodynamic testing or combustion experiments at moderate Mach number conditions, the tunnel must produce flow that is uniform in space and time. The barrel was recently equipped with heaters uniformly distributed around its perimeter at multiple axial locations. The use of multiple heaters enables generation of an axial heating gradient necessary to diminish the temperature variation in time as the test gas passes the nozzle. However, the axial temperature gradient also induces gradients in vertical direction due to buoyancy. As a result, the test flow is non-uniform.

3 Proposed Solution

The problem of flow non-uniformity can be potentially solved without major modifications to the facility by mixing the test gas using free piston motion shortly prior to the run. The piston can be rapidly propelled alternately forward and backward to generate shock waves. When density gradients are present in the gas, there is potential to induce mixing through several mechanisms with such piston motion. The Richtmyer–Meshkov instability, which promotes very efficient mixing, occurs when a shock wave passes through two fluids of different densities (Richtmyer 1954, Meshkov 1969). Our shock generator case is different in that the shock travels normal to the density gradient. The baroclinic instability that arises under such conditions also has the potential to promote mixing.

4 Research Methodology

To first assess the feasibility of the concept, the problem was simulated using Eilmer, which is a Reynolds-Averaged Navier-Stokes CFD open source code specialising in compressible flows. It has been created to aid design of hypersonic wind tunnels (Gibbons *et al.* 2022).

4.1 Computational Domain

The wind tunnel barrel was simulated in 2D as a rectangle with the same dimensions (16 m × 0.13 m), and the simulated domain is shown in figure 2. 10-second laminar flow simulations were initiated with temperature linearly varying from 320 K at the top to 280 K at the bottom. No-slip boundary conditions with a fixed temperature of 300 K at all walls were imposed. The piston motion was modelled by moving the left wall with specified velocity profile using a moving grid. All of the cells are identical with aspect ratio of 2, as shown in figure 2. Gravity effects were modelled using user-defined source terms.

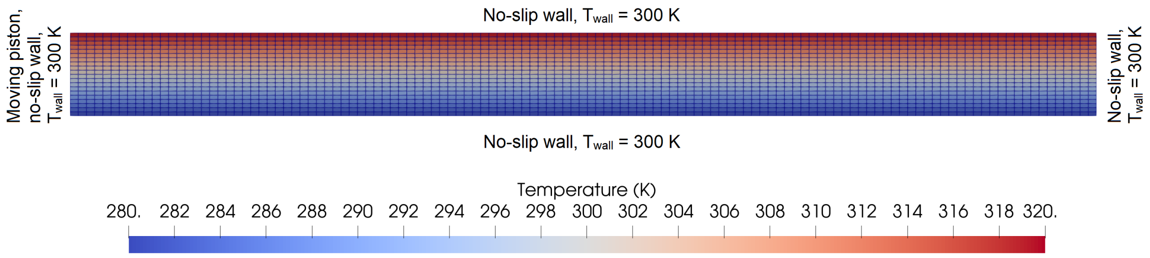

Figure 2. Computational domain. Only 1/10 of the domain length with mesh scale factor of 10 is shown here (2,500 cells shown). Actual domain dimensions used for all simulations are 16 m × 0.13 m with mesh scale factor of 40 (400,000 cells).

4.2 Piston Velocity Profiles

Initially, the piston motion was modelled to be harmonic with 300 mm amplitude and 10 Hz frequency (maximum speed of 19 m/s), shown red in figure 3. Physical experiments have indicated that even though a full piston stroke can be completed in just 24 ms, it can be repeated only once per second in the present experimental arrangement. In this setting the piston velocity was measured and plotted gray in figure 3. Subsequently, it was polynomially interpolated and used for another set of simulations (blue in figure 3). Corresponding amplitude and maximum speed are 240 mm and 17 m/s, respectively. For each of the two velocity profiles, two types of simulations were conducted: one with 10 seconds of mixing, and another one with 5 seconds of mixing and 5 seconds of settling.

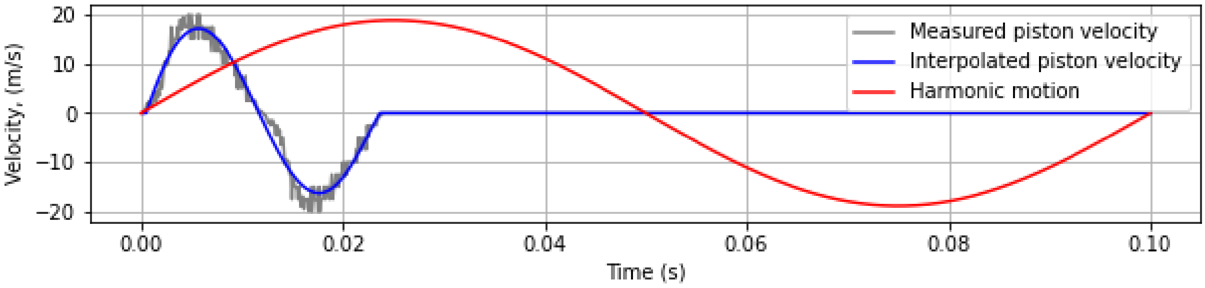

Figure 3. Piston velocity profiles used for the simulations. Harmonic motion at 10 Hz (red), and realistic piston motion - a pulse once per second (blue).

4.3 Mesh Independence

To assess the accuracy of the results a mesh independence study was conducted using 1-second simulations with harmonic piston motion. The mesh scale factor ranged from 10 (25,000 cells) to 60 (900,000 cells). The results are illustrated in the figure 4. The degree of mixing is increasing with the mesh scale factor. Even though the simulations at mesh scale factor of 40 are not yet mesh independent, 40 was the one selected due to limited RAM and long processing time. Using a single node with 128 processors of the USQ Fawkes HPC facility, each 10-second simulation took about 6 days to compute.

5 Results and Discussion

Figure 5 presents selected time steps of the 10-second mixing simulation with realistic piston velocity profile (blue continuous line in figures 3 and 7). A shock wave forms early in the simulation (around $t = 0.1$ s), followed by a reflected shock that can be clearly seen in figure 5 b. At $t = 0.5$ s an effect similar to Richtmyer–Meshkov instability emerges, with spikes of hot gas penetrating the cold regions and vice versa, predominantly in the middle of the domain. This phenomenon most likely is a result of higher speed of sound in the hotter regions, as indicated in figure 6 a. Hence the shock wave is inclined forward at about 5° from vertical, according to the CFD simulations. When a shock wave processes the flow, it generates a velocity vector that has a downward component (figure 6 b). The horizontal velocity components cancel out as the reflected shock sweeps the entire domain, as indicated by figure 6 c, but the downward component gets amplified over time near the middle of the tube, forming the spikes. As the spikes grow, eventually they turn around as they collide with top and bottom walls (figure 5 d), and coalesce with each other (figure 5 e). Simultaneously, a series of vortices emerge at the left and the right ends of the domain about $t = 3.5$ s, promoting diffusion in those regions. The majority of the mixing occurs within the first 4 seconds. For the rest of the time, the mixing progresses slowly. The main goal of the process is to attenuate the vertical temperature gradients, which has been accomplished.

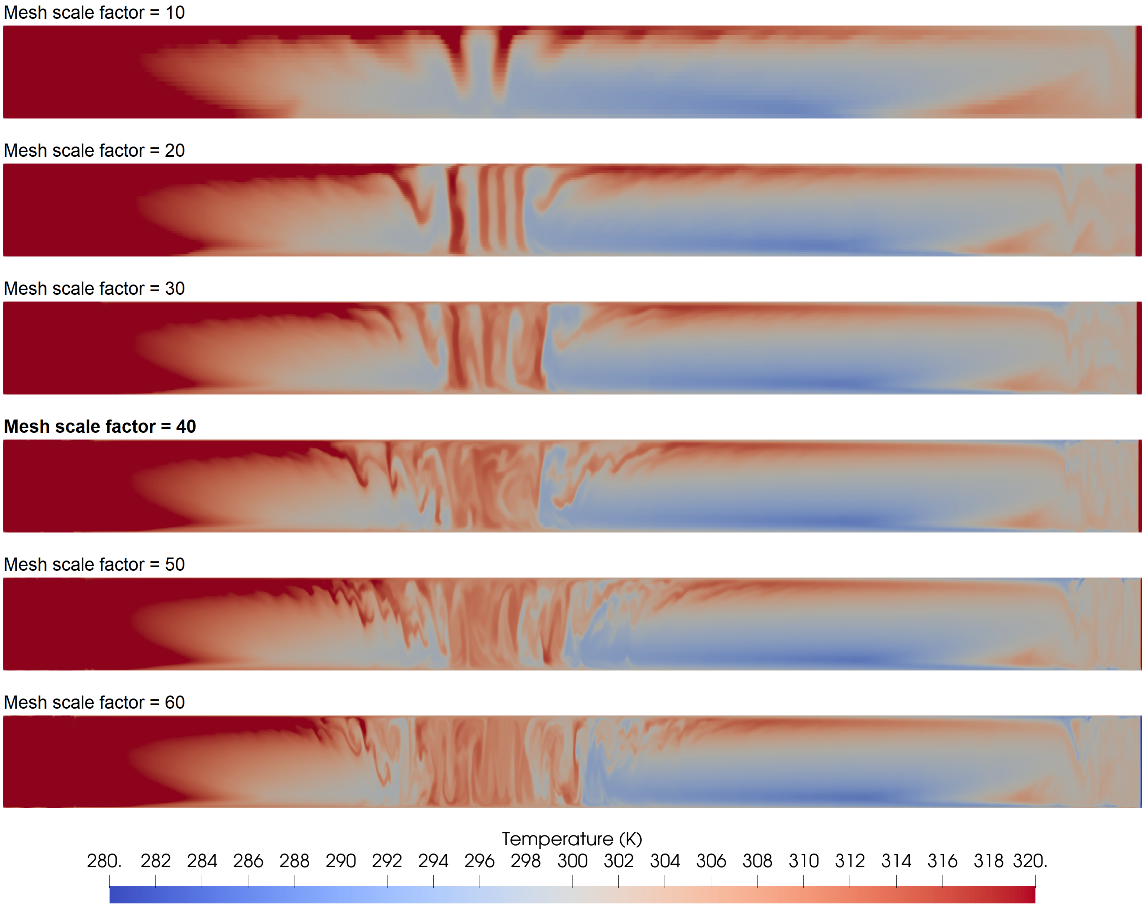

Figure 4. The results of the mesh independence study. Entire domain shown (16 m × 0.13 m), but stretched vertically 10 times.

The standard deviation of the temperature across the entire computational domain was used as a metric to assess the degree of mixing. Figure 7 presents the standard deviation for four different simulations. In the case of the realistic piston motion, significant mixing occurs within the first 4 piston pulses (which reconfirms the observations from the temperature plots). For the rest of the simulation the mixing progresses at much slower rate. The blue dashed line in figure 7 denotes settling. It is evident, that the air will continue to mix when the piston stops and the shock waves dissipate. However, at $t = 5s$ the air is insufficiently mixed and at this point it is more effective to proceed with piston mixing.

On the other hand, the harmonic mixing is very different. Due to 10 times higher frequency the mixing occurs much faster, but also much more energy is supplied by the piston. Within 10 seconds of mixing the average temperature has increased by 20.4 K (whereas for realistic motion only by 1.4 K). As a result, from about $t = 1.5$ s the convective heat transfer overpowers the mixing process near the walls. Even though the air continues to mix very well away from the walls, the standard deviation of temperature across the entire domain increases. The effect is exacerbated during settling.

6 Future Work

Evidently, 10 seconds is not enough to achieve sufficient mixing at the current (experimental) piston settings. Nevertheless, piston mixing for even a few minutes is feasible, and prolonging the process could yield satisfactory results. The future work would incorporate 1-minute-long simulations at increased mesh scale factor with additional time allowed for settling. Also, the turbulent effects in the boundary layers could be examined to increase fidelity of the simulations. In this study they were omitted due to computational cost.

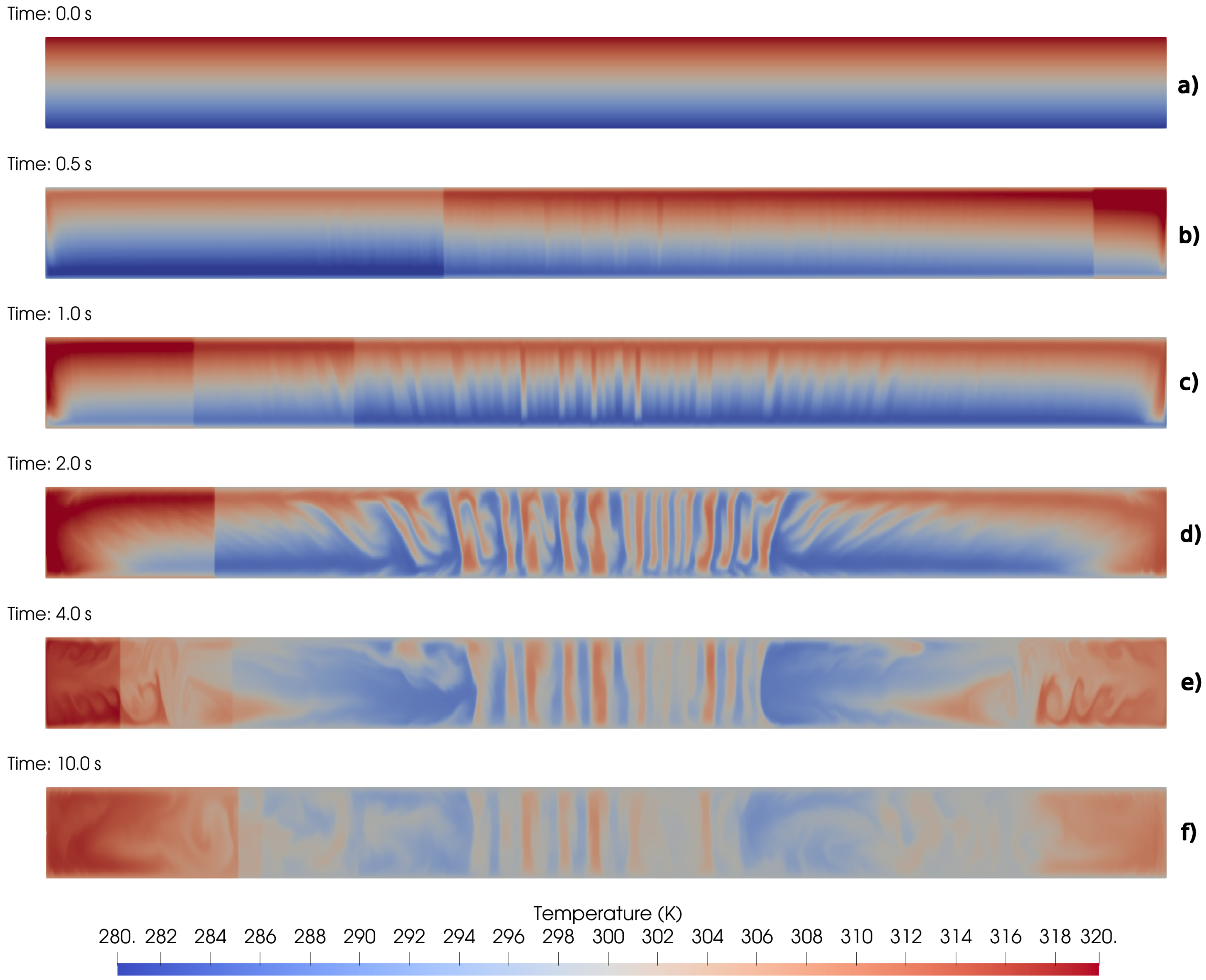

Figure 5. 10-second CFD simulation of shock-induced mixing. Temperature distribution variation with time within the heated barrel. Piston velocity profile based on measurements of experimental setup. Gravity source terms included. Entire domain shown (16 m × 0.13 m), but stretched vertically 10 times.

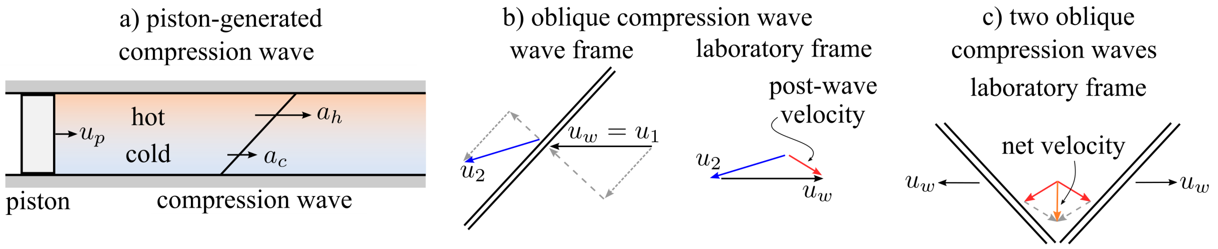

Figure 6. Initiation of the mixing process. When an oblique shock wave processes stationary gas, it generates a velocity vector that has a downward component (red arrows). With time, as shock waves pass in alternate directions, the horizontal velocity components cancel out, but the vertical ones add up.

Although the experimental work is still ongoing, we have already seen promising visual results using smoke generator. Moreover, the data from thermocouples is consistent with conclusions drawn from the simulations. The next step is to integrate the testing rig with the wind tunnel barrel and conduct tests with axial temperature gradient.

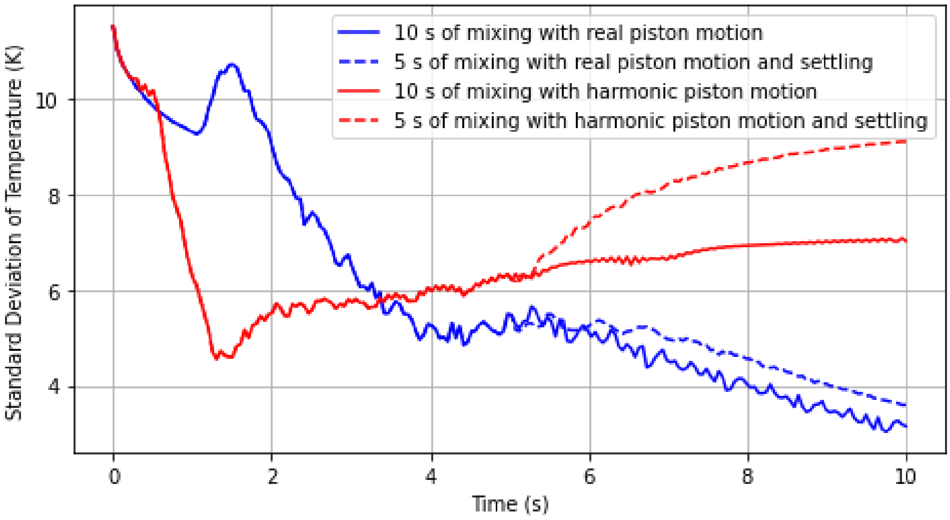

Figure 7. Standard deviation of temperature across the entire domain for four different simulations.

7 Conclusions

A series of CFD simulations was conducted to prove the feasibility of the piston-generated shock wave mixing concept. It was found that a piston travelling at 19 m/s can generate a shock wave strong enough to initiate the mixing of thermally stratified gas. The mixing near the mid-point of the tube appears to be driven by the generation of higher temperature spikes that are forced downward into lower temperature gas. It was found that temperature gradients can persist near the walls due to convection, if the piston motion significantly heats up the test gas, although, this can be mitigated by appropriate wall temperature control. Even though the most recent experiments have generated weaker shock waves than expected, there is still potential to achieve sufficient mixing within a longer time frame, which will be validated with further simulations and experiments. Upon successful integration of the piston mixing with the existing facility, TUSQ will be ready for a new range of experiments, including supersonic airbreathing engine testing.

Acknowledgements

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