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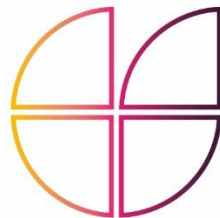


**13th September
2024
Oxford**

International Workshop of Shock Tube Technology

Workshop Booklet

Hosted by the University of Oxford



DEPARTMENT OF
**ENGINEERING
SCIENCE**



International Workshop of Shock Tube Technology 2024



Welcome

Dear Participants,

It is with great pleasure that we welcome you to the International Workshop on Shock Tube Technology here in the historic University of Oxford. This gathering brings together leading experts, researchers, and practitioners from around the globe to share knowledge, discuss advancements, and explore the future directions of shock tube technology.

We extend our gratitude to our organizing committee, and all participants for making this event possible. Your dedication and enthusiasm are what drive the continued advancement of this field.

We wish you a productive and enjoyable time.

Sincerely,

Professor Matthew McGilvray

Chair, International Workshop on Shock Tube Technology

The Organising Committee:

Professor Matthew McGilvray, Dr Luke Doherty, Dr Tobias Hermann, Dr Eric Chang, Ms Vicky Green, Ms Julie Meikle, Ms Kathryn Scott

International Workshop of Shock Tube Technology 2024

Essential Information

Transport

The Oxford e-Research Centre is in Keble Road on the northern edge of Oxford city centre, just off Banbury Road and the northern end of St Giles and near to Keble College. We are a 15-minute walk from the city centre. Oxford suffers from traffic congestion and limited parking so we recommend using public transport when visiting the city. If you are driving we recommend using one of the [Park and Ride](#) facilities around the city.

Parking

Please note that parking at the Oxford e-Research Centre is by prior arrangement only and limited to a single space. Limited paid public parking is available in Keble Road.

Travelling by rail

Taxi services are available outside the Station entrance.

For rail travel information [visit the National Rail website](#).

Walking directions from the station

The Oxford e-Research Centre is approximately 18 minutes' walk from the railway station. For a map showing the best walking route from the station, click [here](#).

Travelling by coach

Coach services run between Oxford and London, and other destinations nationwide.

The Coach Station at Gloucester Green is approximately 15 minutes' walk from the Oxford e-Research Centre. Alternatively there is a Taxi rank at Gloucester Green.

For coach travel information contact:

[The Oxford Bus Company](#)

[Stagecoach, Oxford](#)

[Oxford Tube](#)

[National Express](#)

Travelling by air

There is a frequent coach service from Heathrow and Gatwick airports to Oxford. [See here for details](#). Alternatively, there are a range of [local taxi/car firms](#) who offer an airport transfer service.

Presentation Instructions

Talks: As per the programme, contributed talk slots are 30 minutes long which should include time for questions. We advise speakers to plan for 20-minute talks.

Catering

Refreshments will be provided during the morning and afternoon sessions. Lunch is not provided – cafés, sandwich shops and bakeries are located a short distance from the venue on Woodstock Road and Little Clarendon Street. Or you can walk down St Giles into the town where you will find a range of supermarkets and food outlets.

WI-Fi access

There is no public Wi-Fi available at the venue, guest Wi-Fi is available upon request but is set up for each individual so may take time to be accessible.

Contacts

Any further enquires can be sent by email to events@eng.ox.ac.uk or victoria.green@eng.ox.ac.uk

Programme

08:30	COFFEE & WELCOME Note		
09:00	Kohei Shimamura	Microwave diagnostics technique for free-piston driven expansion tube	Diagnostic Development
09:30	Ronald Hanson	Laser Absorption Spectroscopy for Non-Equilibrium Flow Experiments in the T5 Reflected Shock Tunnel	Diagnostic Development
10:00	Toby J. van den Herik	Modelling Free-piston Driven Impulse Facilities with the Method of Characteristics	Modelling
10:30	COFFEE		
11:00	Joseph Steer	LASTA 2.0: Modelling of real tunnel effects using experimental data as an input	Modelling
11:30	Janardhanraj Subburaj	Predicting the non-ideal effects due to the diaphragm rupture process in shock tubes	Modelling
12:00	Timothy Aiken	Sensitivity Analysis for the Development and Shock-Tube Validation of Highly Parametrized Kinetic Models	Modelling
12:30	LUNCH		
14:00	Omar Valeinis	Design and Commissioning of the Cold-Driven Expansion Tube CXT	New Facility
14:30	Eric Won Keun Chang	Development of the Arc-jet Preheating System in an Expansion Tube	New Facility
15:00	david buttsworth	Reciprocating-Piston-Compression Shock Tunnel	New Facility
15:30	COFFEE		
16:00	Lukas Jakobs	Test Condition Design for the HELM Shock Tunnel	Facility investigation
16:30	Touqeer Anwar Kashif	An overview of the gas dynamic investigations in diverse shock tube operation modes	Facility investigation
17:00	Wrap up		

Sensitivity Analysis for the Development and Shock -Tube Validation of Highly Parametrized Kinetic Models

Timothy T. Aiken and Iain D. Boyd

Background

Existing models for the electronic excitation and ionization of air, key processes in the shock-heated gas surrounding hypersonic vehicles, have yet to be conclusively validated at suborbital velocities. These models were designed primarily using data from shock speeds in excess of Earth's orbital velocity¹. Recently, Boyd and Josyula² have shown that the ionization processes which dominate at suborbital velocities, namely, associative ionization, are significantly affected by the degree of electronic excitation in the gas. These findings suggest that an electronic state-resolved model is required to provide a full description of the ionization process at suborbital speeds. However, one challenge inherent in such a model is that the predicted ionization dynamics become a function of many more rate parameters than in a typical multitemperature model.

With such a highly-parametrized model, it is important to identify the subset of model parameters that most strongly influence the primary quantities of interest. In the case of ionization modeling, the principal quantity of interest is the electron number density. Once the model parameters most affecting the chosen quantity have been identified, the next problem is the identification of suitable experimental datasets to validate these key parameters.

Both of these needs can be addressed using formal sensitivity analysis techniques, which quantify the contribution of the uncertainty in each model parameter to the total variance in a given model prediction. In the case of the electronic state-resolved model which is the focus of this work, sensitivity analysis enables the identification of reaction rate and relaxation parameters that most significantly affect predicted ionization levels. It then follows that these are the parameters which should receive the most attention in any effort to improve the modeling of plasma formation in hypersonic flows. In the case of an experiment, sensitivity analysis of model predictions for a given measured quantity can offer insight into the model components that can be meaningfully validated through comparisons with the measured data. If done in the design phase of an experiment, sensitivity analysis can also help guide the experimental design toward measurements whose prediction is maximally dependent on the model parameters of greatest interest.

Methodology

The electronic state-resolved model investigated in the present work involves hundreds of potentially important parameters. Traditional sensitivity analysis techniques are not computationally tractable at such a scale – advanced methods are needed. In the present work, the method chosen by West and Hosder³ is adopted. This technique involves constructing a polynomial chaos expansion (PCE) surrogate that approximates the input-output mapping between uncertain parameters and model predictions for each quantity of interest. Total Sobol' indices are chosen as the metric for quantifying sensitivity. The coefficients of the orthogonal polynomials in the PCE surrogate are efficiently determined using sparse sampling techniques borrowed from compressed sensing. The computational efficiency of the method is underpinned by the "sparsity of effects" heuristic, which states that the bulk of the variance in

any given model prediction can be attributed to uncertainty in only a small number of model parameters.

1 Chul Park. "Review of Chemical-Kinetic Problems of Future NASA Missions, I: Earth Entries". In: Journal of Thermophysics and Heat Transfer 7.3 (Sept. 1993), pp. 385–398.

2 Iain D. Boyd and Eswar Josyula. "Analysis of Associative Ionization Rates for Hypersonic Flows". In: Journal of Thermophysics and Heat Transfer (May 2021). DOI: 10.2514/1.T6109.

3 Thomas K. West and Serhat Hosder. "Uncertainty Quantification of Hypersonic Reentry Flows with Sparse Sampling and Stochastic Expansions". In: Journal of Spacecraft and Rockets 52.1 (Jan. 2015), pp. 120–133. ISSN: 0022-4650, 1533-6794. DOI: 10.2514/1.A32947.

Results

Two classes of sensitivity analyses are performed. First, sensitivity analyses of post-shock electron number density predictions by an electronic state-resolved model are described. The conditions correspond to normal shock waves with velocities of 5, 7, and 9 km/s propagating into air with freestream temperature and pressure corresponding to 60 km standard altitude. Next, the sensitivities of model predictions for atomic excited state populations corresponding to several experimental measurements are analyzed.

Behind the 5 km/s shock in air, the sensitive processes primarily involve ground-state species; in particular, the dissociation of O₂ and the first Zel'dovich reaction ($\text{N}_2 + \text{O} \rightleftharpoons \text{NO} + \text{N}$). One exception is the formation of NO⁺ via the collision of metastable N(2D) with ground state oxygen atoms. At 7 km/s, the sensitivities become more complex as there is more energy available to activate a greater number of processes. In addition to the processes that showed sensitivity at 5 km/s, a number of interactions producing N₂(A) and N(2D) show marked sensitivity. These results indicate that improved characterization of N(2D) and N₂(A) kinetics can yield improvements in ionization predictions. When the speed is increased to 9 km/s, a number of atom-atom and electron-atom excitation rate coefficients become sensitive; continuing the trend of increasing importance for excited state chemistry at elevated shock speeds.

A second group of sensitivity analyses are then described which analyze atomic excited state measurements recently taken at Stanford University in a reflected shock tube⁴. The measured electronic states correspond to N and O atoms with excitation energies between 9 and 11 eV, denoted here as N* and O*, respectively. The populations of these highly excited states are influenced by a large number of collisional and radiative processes. By performing sensitivity analysis of model predictions for the population time histories, it is possible to clearly isolate the parameters being assessed through comparison with the measured data.

Both the N* and O* measurements were taken in highly dilute mixtures of N₂ and O₂, respectively, in argon. Sensitivities for the N* measurements show a dominance of N+Ar collisional processes in the 1% and 2% mixtures of N₂ in argon; however, N+N₂ and N+N collisional processes begin to exert a much more significant effect on the predicted N* population as the initial N₂ concentration is increased to 5% and 13%⁵. These results highlight the value of follow-on experiments with decreased N₂ dilution and show that even modest decreases in the argon dilution can allow a much wider range of air-relevant processes to be studied using the N* diagnostic.

In both sets of experiments, the O* and N* populations are sensitive to a large number of excitation processes, not just the excitation from the ground to measured states⁶. Such complex sensitivities motivate the interpretation of the experimental data using a more complete electronic state-specific model, as opposed to the highly simplified models used previously.

Conclusion

Sensitivity analysis of a collisional-radiative model is performed to identify the parameters most influencing predictive uncertainty for the electron number density behind strong shocks. Then, a sensitivity analysis of several experimental measurements of electronically excited atomic oxygen and nitrogen is described. The value of such analyses to the development and validation of highly parametrized kinetic models is discussed. Sensitivities for key quantities of interest can help inform experimental and computational efforts to more accurately characterize important model parameters, while the sensitivities of model predictions that correspond to experimental measurements can help to quantify the utility of a given dataset and guide the design of future validation experiments.

4 P. M. Finch et al. “Shock-Tube Measurements of Atomic Nitrogen Collisional Excitation in 8000–12000 K Partially Ionized Nitrogen–Argon Mixtures”. In: The Journal of Physical Chemistry A 127.6 (Feb. 2023), acs.jpca.2c07839. Doi: 10.1021/acs.jpca.2c07839; Y. Li et al. “Collisional Excitation Kinetics for O(3s5So) and O(3p5P3) States Using Laser Absorption Spectroscopy in Shock-Heated Weakly Ionized O₂-Ar Mixture”. In: Physical Review E 103.6 (June 2021), p. 063211. Doi: 10.1103/PhysRevE.103.063211.

5 Timothy T. Aiken and Iain D. Boyd. “Collisional-Radiative Modeling of Shock-Heated Nitrogen Mixtures”. In: Journal of Applied Physics 135.9 (2024), p. 093301. Doi: 10.1063/5.0179577.

6 Timothy T Aiken and Iain D Boyd. “State-Resolved Modeling of Electronic Excitation in Weakly Ionized Oxygen Mixtures”. In: Physical Review E 109.4 (Apr. 2024), p. 045203. Doi: 10.1103/PhysRevE.109.045203.

Reciprocating-Piston-Compression Shock Tunnel

David Buttsworth, Ray Malpress

Background

We have been exploring methods to generate repetitive, strong acoustic waves to mix-out thermal stratification in our hypersonic facility prior to applying free piston compression. One encouraging approach that we have developed uses a motored reciprocating diesel engine to draw-in and expel a mass of test gas in a repetitive manner, generating expansion and compression waves within the manifold. Leveraging acoustic effects in engine manifold design to enhance performance is a well-established technique, but in our case, the engine is motored, being driven by an external electric motor and the piston acts as an agitator to draws-in and expel air through the exhaust port only. With an appropriate length of pipe connected to the exhaust manifold, modest strength shocks can be generated in a repetitive and repeatable manner. This presentation explores several laboratory-based applications of this technique.

Methodology and Results

The volumetric compression ratio being achieved with the motored diesel engine is many times smaller than is typically achieved in high enthalpy free piston compression shock tunnels compressors, so only modest strength shock waves are generated, with $M_s = 1.4$ being a typical value. However, the high repetition rate and good repeatability of the shock generation process is conducive to resonant-enhancement and phase-locked measurement techniques.

The presentation will provide an overview of the apparatus and illustrate results achieved through its application in several configurations:

- (1) A shock generator for mixing of thermal inhomogeneities;
- (2) A shock tube for instrument calibration leveraging the step-input characteristics; and
- (3) A resonantly-excited shock tunnel.

Conclusion

We expect to conclude the presentation with several ideas for other applications of the technique in the near future.

Development of the Arc-jet Preheating System in an Expansion Tube

Eric Won Keun Chang, Omar Valeinis, Matthew McGilvray, Tobias A. Hermann

Abstract

Ground testing of hypervelocity flows during atmospheric re-entry typically employs plasma wind tunnels and impulse facilities, each capturing partial aspects of the flow environment. This presentation will outline the development and construction of an integrated facility at the University of Oxford. In this facility, the OPG2 plasma generator is used as a preheating device within the CXT expansion tube. This novel setup will preheat a test model to flight-representative surface temperatures and expose it to hypervelocity test flows, replicating both aerodynamic and thermal conditions experienced by ablating spacecraft heat shields during atmospheric entry. This talk will detail the status of the physical integration of the dual-facility system, presenting static testing results of the model movement mechanism, along with flow data from the commissioning experiments of the CXT facility.

1. Introduction

Atmospheric entry is a critical phase of a space-return mission, where a spacecraft encounters high thermal loads at hypersonic speeds. This phase involves complex phenomena such as the formation of high-temperature shock layers, as well as the ablation and spallation of heat shields. High-enthalpy ground test facilities [1], including plasma wind tunnels and impulse facilities, can replicate only certain aspects of the flow environment. Although impulse facilities can simulate flight-representative densities and velocities, their short quasi-steady test times require the implementation of model preheating methods to attain flight-representative surface temperatures on the model. Recent works from the Oxford Hypersonic Group have explored the technical challenges associated with dual-facility systems [2], characterised the OPG2 plasma generator [3], and evaluated the capabilities of an integrated facility [4]. As the main phase of this research, this work aims to present the current construction status of the integrated facility.

2. Experimental Details

The integrated facility features the OPG2 plasma generator, a small-scale thermal arc-jet plasma generator specifically designed to preheat sub-scale test models for use in impulse facilities [3]. Its compact size facilitates straightforward installation within the expansion tube facility. The OPG2 has been thoroughly characterised across various settings, including different mass flow rates and electric currents. This characterisation ensures its reliable operation and suitability for generating relevant hypervelocity flight total enthalpies.

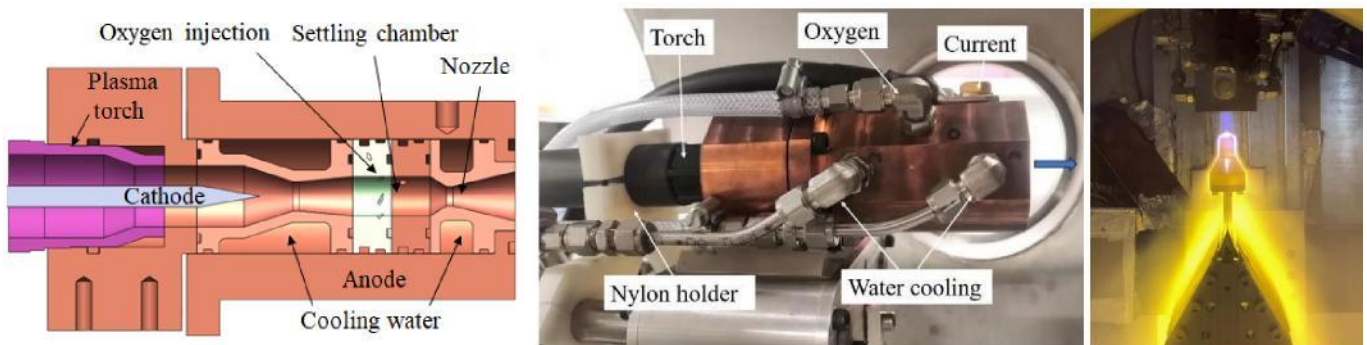


Figure 1: Schematic of the OPG2 plasma generator and its flow characterisation run [3].

The CXT is an expansion tube facility currently under construction at the University of Oxford [5], scheduled for completion in August 2024. As illustrated in Figure 2, the tubes are filled with different pressures (p_4 , p_1 , and p_5), which generate hypervelocity test flows ranging from 3 to 6

km/s. Prior to hypersonic testing, preheating is performed using an. Subsequently, a pneumatic actuator moves the heated model assembly vertically towards the exit of the expansion tube. Then, the CXT facility is fired, enabling the experimental investigation of hypervelocity flow over an ablating test model.

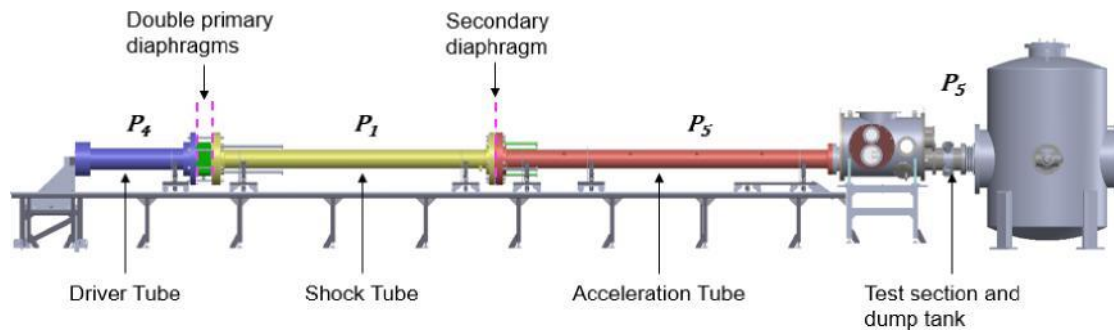


Figure 2: Schematic of the CXT facility, with labelled sections and fill pressures [5].

Figure 3 depicts a CAD schematic of the arc-jet preheating system. A critical parameter for the expansion tube testing is maintaining the acceleration tube/test section pressure (p_5) to generate the correct freestream flow. Since the arc-jet preheating increases the chamber pressure, a dedicated channel for arc-jet flow has been constructed, equipped with the trap doors to minimise pressure leakage into the test section. This must be ensured by maximising the speed of the model traverse, with proper shock absorbers at the bottom to protect the test model assembly. The traversed test model must remain stationary during the steady test-time the expansion tube flow.

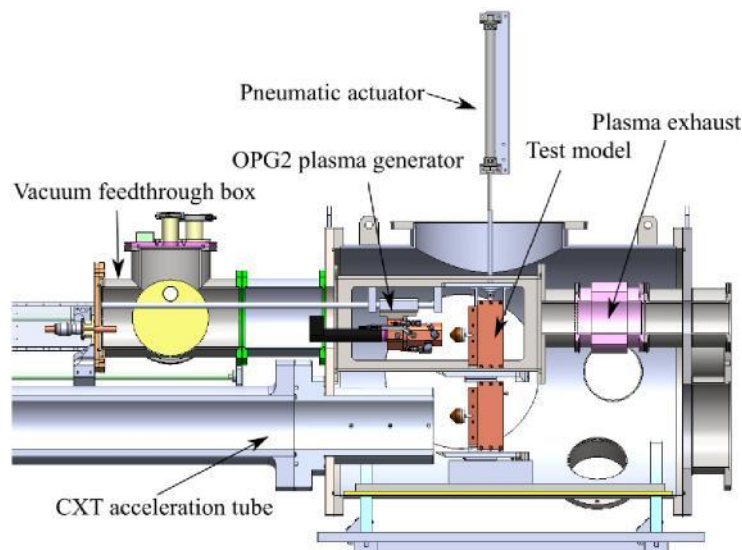


Figure 3: Schematic of the arc-jet preheating system in the CXT test section.

Currently, major components of the system are being delivered and the final design is in place. The assembly process will ensure correct integration of components, leading up to the static testing phase. The sub-atmospheric static testing within the CXT test section will address the technical challenges. This will involve recording the chamber pressure changes within the test section after the model has been traversed. Following the static testing phase, initial experimental testing will commence concurrently with the commissioning experiment of the CXT facility [5]. The experimental phase will include fundamental geometries and re-entry capsule models to validate the performance and capabilities of the integrated facility in simulating realistic re-entry conditions.

References

- [1] Lu. F. and Marren. D.E., Advanced hypersonic test facilities, Vol. 198, American Institute of Aeronautics and Astronautics, 2002. <https://doi.org/10.2514/4.866678>
- [2] Chang, E. W. K., Hermann, T. Integration of Arc-jet in Impulse Facility for Hypervelocity Aerothermal Testing with Ablation. *AIAA SciTech 2023 Forum (2023)*. <https://doi.org/10.2514/6.2023-2334>
- [3] Chang, E. W. K., Valeinis, O., Buquet, M. T., Hermann, T. Development and Flow Characterization of a Small-Scale Thermal Arc-jet Plasma Wind Tunnel. *Aerospace Science and Technology*, in preparation.
- [4] Chang, E. W. K., Hermann, T. System study of an integrated facility with arc-jet and expansion tube for hypervelocity testing with ablating spacecraft models. *AIAA Journal*, in preparation
- [5] Valeinis, O., Chang, E. W. K., McGilvray, M., Hermann, T. Design and Commissioning of the Cold-Driven Expansion Tube CXT. *IWSTT (2024)*

LASER ABSORPTION SPECTROSCOPY FOR NON-EQUILIBRIUM FLOW EXPERIMENTS IN THE T5 REFLECTED SHOCK TUNNEL

Ronald Hanson, Christopher Strand, Peter Finch, Julian Girard, Tal Schwartz, Spencer Barnes, & Dylan Drescher - Stanford University

Wesley Yu, Ying Luo, Joanna Austin, & Hans Hornung - California Institute of Technology
Thomas Gross, Tom Schwartzenruber, Graham Candler, & Don Truhlar - University of Minnesota

BACKGROUND

New flight vehicle concepts are being developed that involve flight at high speeds in the atmosphere where nonequilibrium effects become important. To support this endeavor, new nonequilibrium chemistry models for high-temperature air are under development using results from computational chemistry. However, the validation of kinetic models for flight applications is hampered by the lack of experimental data that directly probe molecular interactions in hypersonic flows. To address this deficiency, a research collaboration between Caltech, Stanford, and the University of Minnesota has applied spectroscopic measurement techniques to probe molecular and atomic states in hypervelocity, nonequilibrium air flows directly.

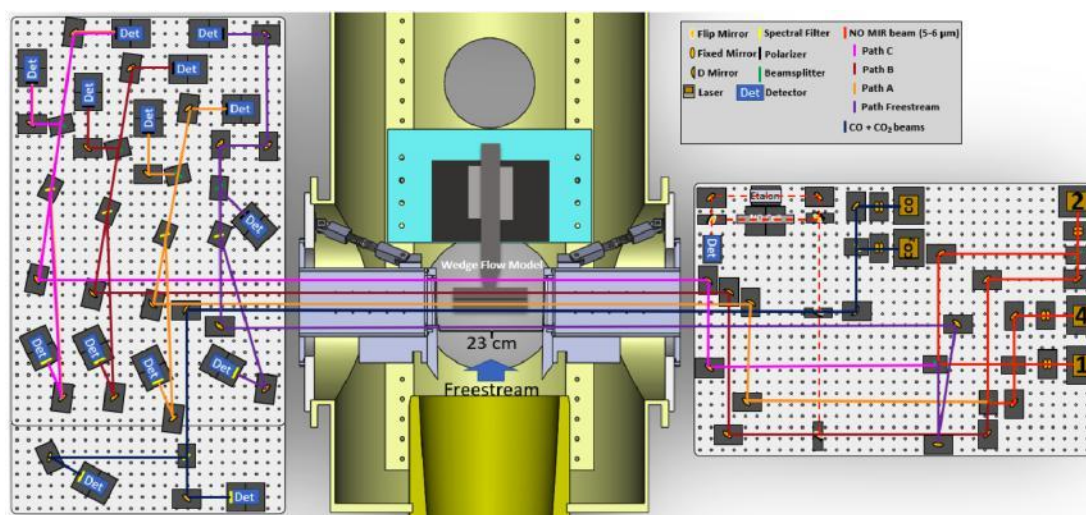


Figure 1: Optical schematic for T5 wedge flow LAS experiments. Five lasers on the pitch side (right) were directed through the test section core, avoiding the boundary layer by passing through the optical arms. A wedge was mounted in between the arms. Lasers 1, 2, and 4 (in red) were co-aligned and then split onto several paths. The freestream path (purple) traveled through the test section in front of the flow model. Paths A, B, and C (in orange, maroon, and pink respectively) traversed the test section through the post-shock region. Lasers denoted as CO and CO₂ are also co-aligned and directed through the flow. On the catch side (left), the beams were caught and directed towards high-bandwidth photovoltaic detectors (labeled 'Det').

METHODOLOGY

Laser absorption spectroscopy (LAS) has been employed to measure the rotational and vibrational temperatures, composition (NO, CO, CO₂, H₂O, O₂, O*, N*, & N₂(A)), and velocity of flows with flight-relevant enthalpies (8-18 MJ/kg) generated by the Caltech T5 Reflected Shock Tunnel. As illustrated by the schematic of the LAS sensor system presented in Figure 1, a multi-wavelength, multi-beam approach has been adopted to simultaneously measure a subset of these parameters in the freestream, for concurrent inflow characterization, and at multiple locations in the near-body post-shock region.

A range of canonical test article geometries have been investigated including cylinders, wedges, and mach-stem-generating opposing wedges. Experiment design is performed as a collaborative and iterative procedure using kinetic models, CFD flow simulations, and

spectroscopic modeling to select test article geometries, run conditions, absorption transition selections, and beam positions to optimize for measurable and differentiable outcomes as predicted by competing aerothermochemistry models.

RESULTS

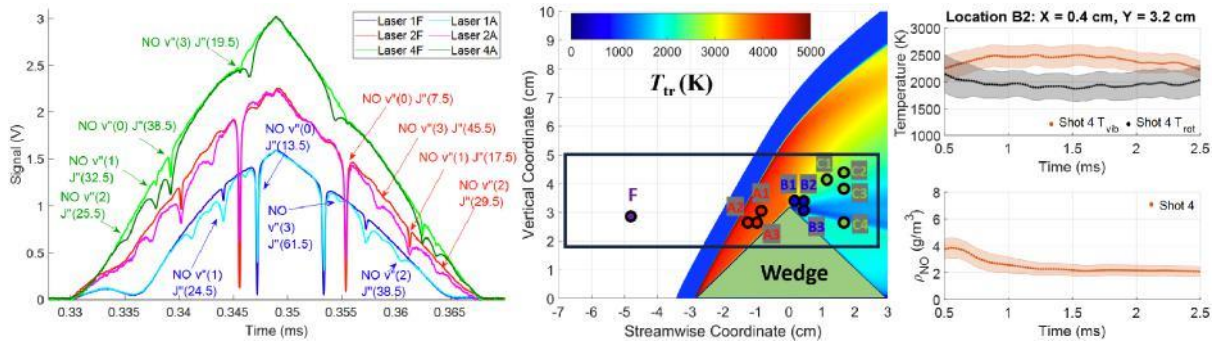


Figure 2: (Left) Raw single scan detector signals for three lasers superimposing the traces for the freestream (F) beam and a post-shock beam from wedge experiments. (Center) Beam positions for the 48° wedge test article. (Right) Sample rotational temperature, vibrational temperature, and NO mass density measurements in the expansion near the tip of the wedge.

A comprehensive set of measurements have been performed over a series of repeated facility entries. Results comprise a detailed aerothermochemical characterization of the temporally evolving freestream conditions, multi-point measurements of post-shock flows, and a demonstration of novel measurement capabilities presently under development. Figure 2 provides a representative subset of results showing typical signal characteristics, the extent to which the model flows were probed, and final measurements with attendant uncertainty.

CONCLUSION

Closely coordinated experiment design, involving modelling & simulation, laser spectroscopy, and wind tunnel researchers, has employed predictive aerothermochemistry CFD models to optimize test conditions, model geometries, and diagnostic designs to interrogate hypersonic flow physics (thermal/chemical nonequilibrium, dissociation, and recombination). The resulting datasets aim to differentiate historic and state-of-the-art aerothermochemistry models, validate predictive air chemistry CFD, improve understanding of reflected shock tunnel operation, and create high-fidelity archival experimental datasets for the hypersonics community.

An overview of the gas dynamic investigations in diverse shock tube operation modes

Touqeer Anwar Kashif *, Janardhanraj Subburaj, Aamir Farooq

Clean Combustion Research Center (CCRC), King Abdullah University of Science & Technology (KAUST), Thuwal 23955, Saudi Arabia

Background

For over five decades, shock tubes have been used for various applications in aerospace engineering, chemical kinetics studies, and material science. A basic shock tube consists of a driver section and a driven section separated by a diaphragm. Ideally, instantaneous removal of the diaphragm generates a shock wave that compresses the driven gas as it travels through it. The shock velocity is calculated using the Rankine-Hugoniot equations, assuming one-dimensional, inviscid, and adiabatic flow conditions. However, shock tube operation often deviates from this ideal behavior, partly due to the finite time required for diaphragm opening in practical scenarios. Factors such as diaphragm material, operating conditions, and facility characteristics can lead to asymmetric or partial diaphragm openings, affecting shock strength and profile. Double diaphragm shock tubes, commonly used in the chemical kinetics community, are particularly complex and understudied. Additionally, shock attenuation due to boundary layer growth causes non-uniform compression of the fuel/air mixture, resulting in axial gradients of temperature, pressure, and density, which violate the 0-D homogeneous assumption of shock tube experiments. This study aims to evaluate shock wave dynamics and their effects on the heated slug in various shock tube operation modes, including a newly developed diaphragmless shock tube.

Methodology

Shock tube experiments were conducted at KAUST's high-pressure shock tube (HPST) facility, which has driver and driven sections of 2.6 m and 6.6 m, respectively, with a cross-sectional diameter of 0.1016 m. The HPST can operate in single or double diaphragm modes and can be modified to be diaphragmless mode using a fast-acting valve. Shock velocity, a key efficiency parameter, was measured using 12 pressure transducers placed from 10.48 mm to 6.636 m from the end wall. Helium and Argon were used as driver and driven gases. An optical section with a high-speed camera (150,000 frames per second) visualized the diaphragm opening process, with MATLAB used for image processing. More facility details are in our previous works [1], [2], [3].

To study the impact of slow diaphragm opening on the flow field, 2D and 3D numerical simulations were performed using CONVERGE CFD software. These simulations incorporated experimental inputs like driver and driven pressures and diaphragm opening profiles. The 2D simulations used a rectangular domain matching the shock tube diameter, while the 3D simulations used a 45-degree sector of the shock tube. The simulations also captured the effects of shock deceleration due to boundary layer growth.

Results

The experimental shock velocity profiles from three different modes of operation are shown in Fig. 1. In single diaphragm mode (Fig. 1a), the expected trend of initial acceleration of the shock wave is observed in the shock formation region. Later, the shock exhibits a consistent linear deceleration due to boundary layer growth. In double diaphragm mode, a mid-section (~10 cm in length) is added between the driver and driven sections. In this mode, the shock profiles vary significantly with changes in mid-section pressure, despite similar driver and driven pressures (Fig. 1b). More details on the reasons for the observed trends can be found in our previous work [4]. In diaphragmless mode, the shock acceleration continues for a longer duration, indicating lower efficiency due to the slow opening of the valve (Fig. 1c). After 40 X/D, the shock shows consistent deceleration. Despite the lower efficiency, the diaphragmless shock tube offers

advantages such as automation of the shock tube process, debris-free runs, and repeatable valve opening.

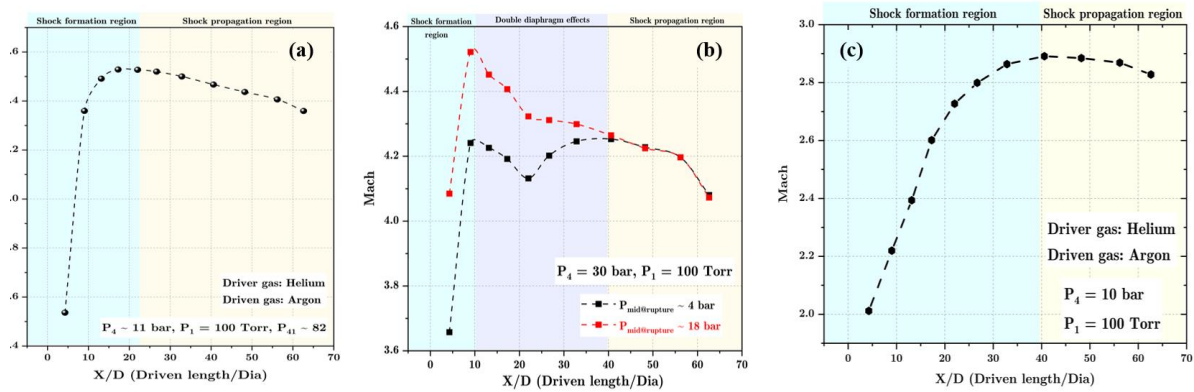


Figure 1. Experimental shock velocity profiles measured in three different modes (a) single diaphragm (b) double diaphragm mode and (c) Diaphragmless mode

The flow evolution as the diaphragm ruptures is shown in Fig. 2 using numerical schlieren from a 2D simulation. In addition to the leading shock wave, multiple lateral discontinuities occur. Complex interactions between different waves eventually lead to the primary shock becoming planar. The flow within the contact surface is highly inhomogeneous, with vortex and localized recirculation regions. Additionally, discontinuities are present in the contact surface due to the sudden expansion of the driver gas. Classical shock diamond structures also form near the diaphragm interface later. This work aims to investigate the after-effects of such a slow diaphragm opening.

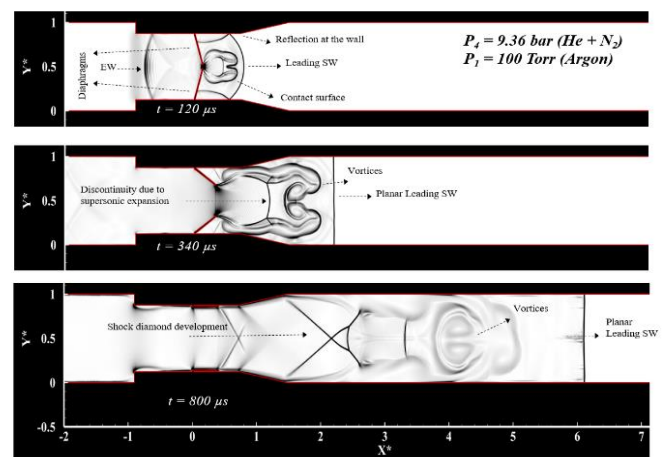


Figure 2 Synthetic schlieren of flow near the diaphragm

Conclusions

This study aims to understand and characterize the differences in flow, shock strength, and various thermodynamic parameters for shock tubes operated in different modes. The experimental aspect involves measuring the shock velocity along the length of the shock tube and recording the opening times of diaphragms in diaphragm mode and the valve opening speed in diaphragmless mode. The numerical aspect involves simulating the shock tube process to understand the flow field and its inhomogeneities.

References:

- [1] S. Janardhanraj, K. Abhishek, and G. Jagadeesh, "Insights into the shockwave attenuation in miniature shock tubes," *J. Fluid Mech.*, vol. 910, p. A3, Mar. 2021, doi: 10.1017/jfm.2020.914.
- [2] M. Figueroa-Labastida, J. Badra, and A. Farooq, "Dual-camera high-speed imaging of the ignition modes of ethanol, methanol and n-hexane in a shock tube," *Combust. Flame*, vol. 224, pp. 33–42, Feb. 2021, doi: 10.1016/j.combustflame.2020.07.002.
- [3] T. A. Kashif *et al.*, "Effect of oxygen enrichment on methane ignition," *Combust. Flame*, vol. 258, p. 113073, 2023.
- [4] T. A. Kashif, J. Subburaj, M. Z. A. Khan, and A. Farooq, "Insights into shock velocity variation in double-diaphragm shock tubes," *Phys. Fluids*, vol. 36, no. 5, 2024, Accessed: Jun. 30, 2024. [Online]. Available: <https://pubs.aip.org/aip/pof/article/36/5/056124/3294585>

Title: Microwave Interferometry Shock Velocity Measurements in the X2 and X3 Expansion Tubes.

Authors: Christopher M. James, Henry G. Straede, Toby J. van den Herik, Isaac Jenkinson

The measurement of shock velocity with distance is important for quantifying the test flows generated in shock tubes, shock tunnel and expansion tubes. Generally, this is done with high-frequency pressure transducers mounted every several metres down the length of a facility or more tightly spaced in important measurement locations. Recent simulation results have shown a need to perform more shock velocity measurements down the whole tube of a facility to allow flow conditions to be fully quantified. In expansion tube facilities where the test flow interacts with a secondary diaphragm, the measurement of shock speed locally in this area is also important.

Microwave interferometry is a technique which allows shock velocity to be measured with this desired level of accuracy. It uses a microwave source and an antenna at a specified frequency to form a standing wave in the tube which is reflected back to the antenna at a Doppler shifted frequency by the ionised flow behind the shock wave generated by the facility. The Doppler shifted frequency is mixed with the original source frequency and can be used to calculate shock velocity every half wavelength down the tube, which is roughly every tube diameter.

This technique has recently been successfully implemented in UQ's X2 expansion tube and due to its power, it was decided that it should also be implemented in UQ's larger X3 expansion tube facility as part of a recommissioning campaign for X3's acceleration tube with a new diameter of 200 mm.

This presentation will report on these results which included measurements of shock velocity in the X2 and X3 facilities over a distance of 10 and 35 metres respectively over a range of important shock velocities.

Predicting the non-ideal effects due to the diaphragm rupture process in shock tubes

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Background

Shock tubes are common facilities in aerospace and reaction chemistry research, designed to rapidly elevate the thermodynamic conditions of a test gas mixture and maintain these conditions for a desired duration. Ideally, the temperature and pressure behind the reflected shock in a shock tube is constant and not varying in location or time and can be predicted using classical gas-dynamics theory. However, deviations from these ideal conditions, known as non-ideal effects, can significantly influence the system, leading to a reduction in shock strength, temporal and spatial variations in thermodynamic conditions. Several factors, such as the diaphragm opening process, viscous effects, and the three-dimensional nature of the flow, etc. [1,2] have been attributed to the non-ideal effects. It is well established that the flow in a shock tube is influenced by the diaphragm opening effects during the initial stages of the flow (shock formation region) and the boundary layer effects dominate the later stages of the flow close to the end wall (shock propagation region) [3]. Most of the previous models developed predict either the early or latter stages of the shock tube flows influenced by the diaphragm opening or the shock attenuation, respectively. In the present work, the diaphragm opening influence on the shock parameters has been studied. The existing models in literature do not cover irregular ruptures and only account for the boundary layer effects [4]. The main objective of this work is to visualize the diaphragm opening process in shock tube experiments, develop predictive models for diaphragm opening, and use the derived parameters to predict the variation of shock attenuation and post-shock pressure rise in the reflected shock region.

Methodology

Experiments were performed in the Low-Pressure Shock Tube (LPST) facility at the Clean Combustion research Center (CCRC) in King Abdullah University of Science and Technology (KAUST). The driver and driven sections of this facility are each 9.1 m long and have an inner diameter of 14.2 cm. A diaphragm cutter is employed to puncture the polycarbonate diaphragms used for shock generation. Two optical sections were used at the end of the driver and driven section to visualize the rupture process of the diaphragm. A Photron Fastcam SA-X2 camera was used to capture images at 81,000 frames per second. The pressure rise from the incident shock wave was used as a trigger to record the camera signals. The incident shock speed was measured by the time-of-flight method using a series of five piezoelectric PCB pressure transducers over the last 1.5 m of the shock tube. The attenuation of incident shock was estimated for each experiment and the shock velocity at the end wall was obtained through a linear extrapolation. The post-reflected-shock pressure rise in the reflected shock region was measured following the procedure used in previous studies.

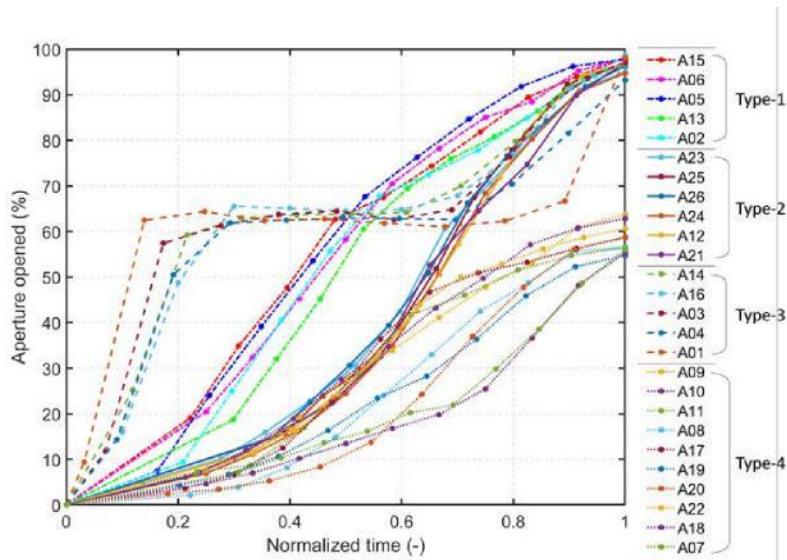


Figure 1. Plot showing the percentage of opening as a function of normalized time. The tests are grouped based on the type of opening.

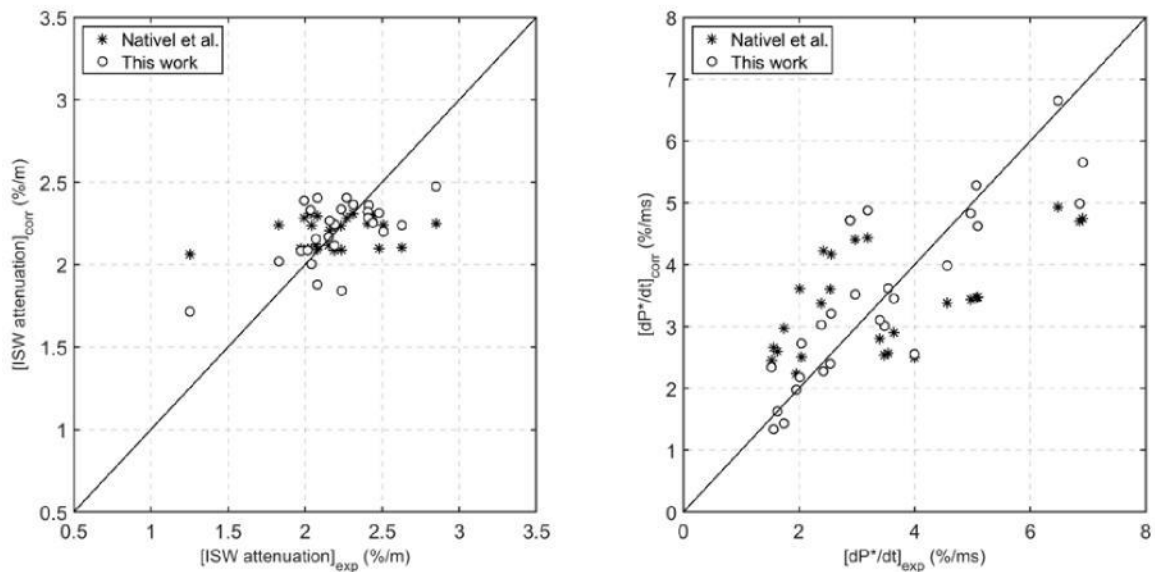


Figure 2. Plots showing predicted incident shock attenuation (left) and the post-shock pressure rise (right) in this work as compared to a previous model reported in literature.

Results

Figure 1 presents a detailed depiction of the diaphragm aperture opening as a function of time, showing four distinct patterns of diaphragm ruptures in the experiments. The vertical axis of the plot is normalized against the shock tube's cross-sectional area and the time is normalized against the total diaphragm opening time. A sigmoid function is employed to characterize the diaphragm opening profiles shown in the figure. Using the sigmoidal fit parameters, initial driven gas pressure, incident shock Mach number, and diaphragm opening time, new correlations were developed to predict the incident shock attenuation and post-shock pressure rise. Figures 2 shows a comparison between correlations developed in this work and that reported in literature for incident shock attenuation and post-shock pressure rise.

Conclusions

Using high-speed imaging, different diaphragm opening profiles were captured in shock tube experiments. New correlations developed using the diaphragm opening profiles, thermodynamic and shock parameters predicted the non-ideal effects better than previous models described in literature. Detailed analysis and discussions will be presented at the workshop.

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Microwave diagnostics technique for free-piston driven expansion tube

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Keywords:

Microwave, millimeter-wave, expansion tube, interferometry

Research on shock tubes using microwaves, primarily conducted during the 1950s and 1960s, focused on measuring the velocities of detonation waves and shock waves. In recent years, microwaves have found extensive applications in automotive radar and communications. However, their compatibility with shock tubes, which can be viewed similarly to waveguides, makes them highly suitable for this purpose.

The principle involves the reflection of microwaves by the high-dielectric chemical reaction layer, enabling the measurement of shock wave velocities. This method has been adopted by several facilities in recent years.[1,2] Additionally, microwaves are utilized in plasma diagnostics through interferometry. Unlike lasers, the lower frequency of electromagnetic waves results in a lower cut-off frequency, allowing the measurement of electron number densities in the range of 10^{17} - 10^{18} , m^{-3} using microwaves or millimeter waves.

We have employed microwave interferometry for plasma diagnostics and piston motion measurement in free-piston drivers. Demonstrations have been conducted on expansion tubes ranging from less than 10 meters [3] to large-size expansion tubes exceeding 20 meters in total length. This paper reports the findings from these demonstrations.

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Design and Commissioning of the Cold-Driven Expansion Tube CXT

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Introduction

A new cold-driven hypersonic wind tunnel named CXT is currently being built at the University of Oxford. Once complete, the facility will allow the creation of test flows up to 6 km/s velocity, by using a helium cold driver section pressurised up to 8 MPa. Current work has been focused on the design and construction of the facility, with commissioning experiments currently due to commence in August 2024.

Facility overview

CXT is an expansion tube facility, consisting of three tube sections: a driver tube, shock tube and acceleration tube. The facility also features a primary diaphragm station between the driver and shock tubes, and secondary diaphragm station between the shock and acceleration tubes. The acceleration tube is connected to the cylindrical test section and a dump tank, as shown in Figure 1.

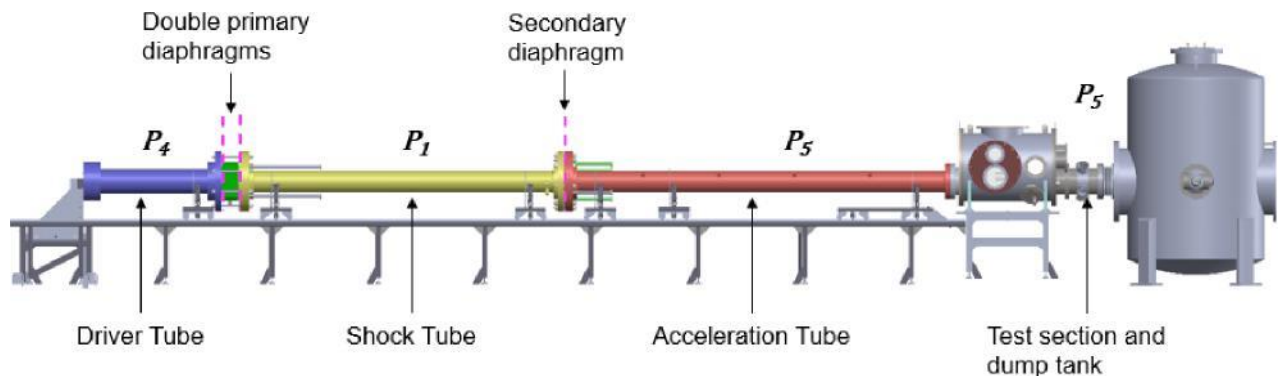


Figure 1: Design of the CXT facility, with each section highlighted and corresponding fill pressures indicated.

During facility operation the shock tube will be filled with the test gas of interest, such as a synthetic air mixture, to a sub-atmospheric pressure p_1 . The shock tube is isolated from the driver tube by the two diaphragms clamped within the primary diaphragm station, as shown in Figure 2a; it is similarly isolated from the acceleration tube by a thin secondary diaphragm as shown in Figure 2b. The driver tube is filled with laboratory air or helium and pressurised to its initial pressure p_4 , between 0.5 and 8 MPa. The acceleration tube is also evacuated, then is filled with helium to a pressure p_5 on the order of 10 to 100 Pa. To achieve simultaneous rupture of both primary diaphragms, the primary diaphragm station features a midsection, which is initially filled to an intermediate pressure around half of p_4 . At the beginning of a shot, the midsection is vented, increasing the pressure difference between the driver and midsection. Once this pressure difference is sufficient to rupture the primary diaphragms, both burst in quick succession, generating a shockwave that propagates downstream. After passing through the shock tube, this shockwave will burst the thin secondary diaphragm allowing for the unsteady expansion of the shocked test gas into the acceleration tube.

Flow condition survey

Previous work has been focused on numerical simulation of the exit conditions using the PITOT3 development tool [1, 2]. To experimentally characterise the flow exiting the acceleration tube, a

Pitot-static rake has recently been designed, shown in Figure 3. This includes a linear array of Pitot probes with high-speed pressure transducers to accurately measure the radial pitot pressure distribution of the exit flow, allowing for determination of the usable core flow region. The design also features a flush-mounted pressure transducer oriented perpendicular to the incoming flow, which will determine the static pressure of the core flow region. From these data, it is possible to determine relevant flow parameters, such as the exit Mach number, velocity and mass density. These properties are important for experimentation with subscale models, as replicating flight-equivalent conditions in an impulse facility such as CXT requires a matched total enthalpy (derived from

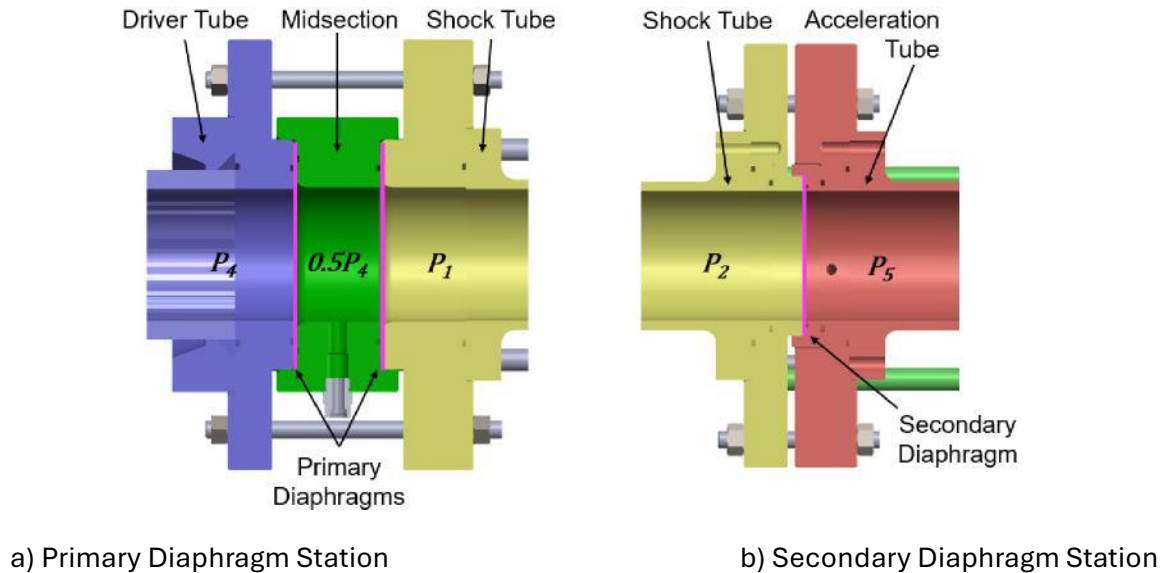


Figure 2: Cross-section view of the diaphragm stations, with relevant pressures indicated.

velocity) and an appropriate model length scale to capture the post-shock thermochemistry, in accordance with either binary (p - L product) or ternary (p^2 - L product) scaling [1]. The Pitot rake design will capture 88.5% of the total exit flow, based on a similar design used in the T6 facility [3].

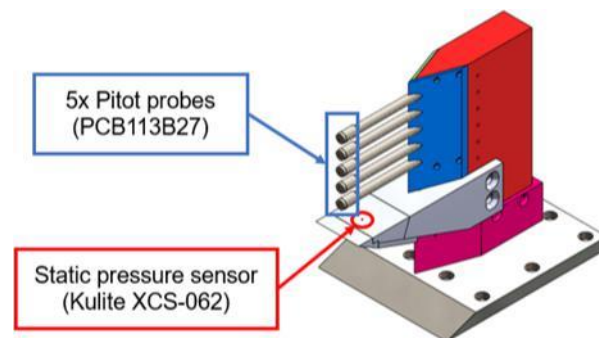


Figure 3: CAD model of the CXT Pitot-static rake.

CXT can be operated as a standalone facility but is primarily designed to operate as part of a new hybrid facility, which will combine the hypervelocity impulsive flows produced by CXT with the hot model capabilities of the arc-jet plasma generator OPG [1, 4, 5]. As of writing, the construction process is entering its final stage, with current work focused on the final installation of all sections. The target for completion is August 2024, with a series of Pitot rake experiments commencing after construction is finished.

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