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Deduction of Temperature Fluctuations in Transient Compression Wind Tunnels Using Incompressible Turbulent Flow Data

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Abstract— **Wind tunnels and other aero-thermal experimental facilities are likely to make a contribution to the optimisation of energy and propulsion systems for the foreseeable future. Short duration wind tunnels such as shock tunnels and gun tunnels rely on a transient compression process and are likely to generate significant turbulent fluctuations in the nozzle reservoir region. In the present study, the magnitude of likely stagnation temperature fluctuations in two such facilities is inferred from incompressible temperature fluctuations data obtained by other workers. The friction velocity Reynolds numbers for the gun tunnel and shock tunnel cases considered presently were Re_τ = 31,579 and 24,975 respectively. The RMS stagnation temperature fluctuations, when averaged over the pipe flow diameter, are estimated to be 15.3 and 291 K for the gun tunnel and shock tunnel cases respectively. The estimated RMS value in the case of the gun tunnel is significantly larger than the experimental value previously measured on the centre line of the gun tunnel nozzle of 2.3 K. The difference observed between the inferred and measured temperature fluctuations in the gun tunnel case may be related to spatial variations in the temperature fluctuations. In the case of the shock tunnel, the magnitude of the fluctuations is demonstrated to be significant for supersonic combustion experiments. The present approach for estimating the magnitude temperature fluctuations should be refined, but more detailed measurements of temperature fluctuations in such facilities are also required.**

Keywords- temperature fluctuations; aerodynamic facilities; combustion; gun tunnel; shock tunnel

I. INTRODUCTION

Fluctuations present in the free stream of ground test facilities can have a level much higher than in flight [1]. Typically wind tunnel fluctuations can be one or two orders of magnitude larger than in flight. Fluctuations within the free stream flow conditions produced by wind tunnels can have a significant effect on the data produced during the ground tests. The level and distribution of the disturbances in the free stream can be particularly significant in shear layer transition [2].

Fluctuations in wind tunnel test sections can be of three different types as identified by Kovasznay [3]: vorticity, entropy spottiness, and acoustic waves. The three modes can be treated as independent when intensities of fluctuation are small, however coupling between the modes must be considered at larger intensities.

Laufer [4] investigated free stream vorticity fluctuations at Mach numbers from 1.7 to 4 by varying the turbulence level in the settling chamber from 0.6 % to 7 %. The results showed that transition on a sharp cone in the test section was independent of the settling chamber fluctuations for free stream Mach numbers above 2.5. Morkovin [5] determined that the source of entropy fluctuations is traceable to the settling chamber and farther upstream in blow-down types of wind tunnels. Entropy fluctuations can arise if there are temperature gradients in the settling chamber or stagnation region of the nozzle. It is usually the case that vorticity and entropy fluctuations in conventional wind tunnel facilities can be minimized by a carefully design of the settling chamber. At Mach numbers higher than 2.5, acoustic waves become the primary source of free stream disturbance in conventional (blow down) wind tunnels. Acoustic waves can be generated upstream of the nozzle by elements such as control valves and through careful design and operation, such effects can be minimized. However the primary source of acoustic fluctuations is the turbulent boundary layer on the nozzle wall [6].

Fluctuations in conventional wind tunnels and in some hypersonic facilities can be identified by means of hot-wire anemometry. The hot-wire anemometer responds to two fluctuating variables: the mass flow and the stagnation temperature. Each of the three types of disturbance can contribute to both of these variables. The preferred technique used to determine the three modes of disturbance is through the use of the hot-wire anemometer in combination with the fluctuation diagram (modal analysis) as adopted by Kovasznay [3] and Morkovin [7]. This technique appears rather time consuming due to the fact that the hot-wire must be successively used at different temperatures.

In addition to affecting shear layer development and transition, fluctuations and in particular, temperature fluctuations can have a crucial influence on supersonic combustion ramjet (scramjet) experiments. Transient compression wind tunnels are commonly used for aerodynamics and combustion experiments relating to scramjet propulsion. However, due to the very short testing time available and difficulties associated with the impulsive loading of the instrumentation in such facilities, direct measurement of the level of free stream fluctuations has rarely been achieved in shock tunnel facilities [8].

Experiments which reveal temperature fluctuations within the hypersonic flow generated by a gun tunnel have been performed by Buttsworth and Jones [9]. RMS stagnation temperature fluctuations during a 12 ms flow period were determined to be 2.3 K for a stagnation temperature of about 610 ± 10 K. This data was obtained at one location at the exit of the hypersonic nozzle. It was concluded the measured temperature fluctuations were primarily due to fluctuations in entropy.

The primary aim of the present work is to report a method for deducing stagnation temperature fluctuations at the nozzle exit of two different transient wind tunnel facilities: (1) a gun tunnel facility; and (2) a shock tunnel facility. The first case we consider is that of a gun tunnel in which a piston is used to compress the test gas up to about 600 K – the test gas is carbon dioxide. The second case we consider is that of a free piston shock tunnel in which the stagnation temperature of the test gas (air) is around 6000 K.

II. ANALYSIS BASED ON INCOMPRESSIBLE DATA

A. *Brief Review of Existing Data*

Many numerical and experimental investigations of temperature fluctuations in low speed boundary layers and fully developed pipe flow have been reported.

Abe et al. [10] investigated surface heat-flux fluctuations in turbulent channel flow for Re_τ = 180, 395, 640 and 1020 and with Prandtl numbers of 0.025 and 0.71. In this case, the length scale used in the Reynolds number was half the width of channel. The large scale structures were observed to affect the heat flux – fluctuations increased with increasing Reynolds number in the expected manner. Redjem-Saad et al. [11] investigated the effect of Prandtl number on heat transfer of fully developed turbulent pipe flow with uniform heat-flux imposed at the wall. Redjem-Saad et al. performed simulations for a Reynolds number based on pipe radius of 5500. The results showed that RMS temperature fluctuations and turbulent heat fluxes increased when the Prandtl number increased. Numerical simulations [10, 11] generally indicate that RMS values of temperature and Q_w increase when the Prandtl number increases, however for the Reynolds number $\mathrm{Re}_\tau >> 1000$, [10] found that RMS values were lower for Pr = 0.71 than for Pr = 0.025. Redjem-Saad et al. [11] observed that slightly more intense temperature fluctuations occurred in their simulated pipe flow configuration compare to that of available simulations with a channel flow configuration.

Subramanian and Antonia [12] obtained temperature fluctuation measurements in a turbulent boundary layer on a slightly heated smooth plate. Zero pressure gradients applied in this experiment. The results showed that for both momentum and thermal fields, the law of the wall does not vary with Reynolds number. Spatial profiles of RMS temperature fluctuation data normalized by the friction temperature were found to vary with Reynolds number for y^+ greater than about 10.

B. *Approach*

To deduce temperature fluctuations in the nozzle exit flows of the gun tunnel and shock tunnel, we have adopted the experimental results of Subramanian and Antonia [12], see Fig. 1. The original data of [12] was presented in terms of Reynolds numbers based on the boundary layer momentum thickness. However, for convenience, we have assumed fully developed turbulent pipe flow in the gun and shock tunnel nozzle reservoir regions. We apply the results of [12] to our assumed fully developed turbulent pipe flows by converting the momentum thickness Reynolds number to a friction velocity Reynolds numbers (Re_τ) based on the velocity boundary layer thickness as reported in data of [12]. When converted to Re_τ, the Subramanian and Antonia data corresponds to friction velocity Reynolds numbers of Re_τ = 371, 559, 1055, 1441, 1986, and 2273. We then apply the data of [12] results in the two cases of interest (gun and shock tunnel flows) by extrapolating their data to the appropriate pipe flow Re_τ value (based on the pipe radius) for the nozzle reservoir region.

The flow within the nozzle reservoir region of each facility is assumed to be fully developed turbulent pipe flow. A constant time averaged heat flux is assumed at the pipe internal surface. Variables relating to the conservation of momentum and energy equations are normalized by friction velocity $u_\tau = (\tau_w/\rho)^{1/2}$, and the friction temperature $T_\tau = Q_w/\rho c_p u_\tau$ where Q_w is average surface heat flux.

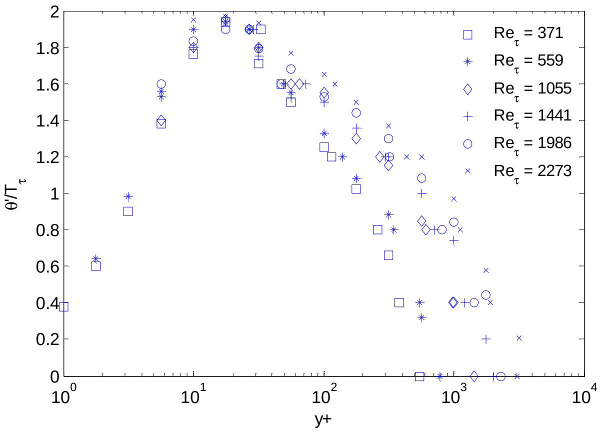

Figure 1. Distribution of normalised RMS temperature fluctuations for different friction velocity Reynolds numbers (Re_τ) from [12].

In the present deduction of stagnation temperature fluctuations, the heat flux at the wall Q_w is obtained by using the convective heat transfer equation defined as:

$$Q_w = h(T_0 - T_w) \qquad (1)$$

where h is convective heat transfer coefficient, T_0 is initial stagnation temperature and T_w is wall temperature. The convective heat transfer coefficient is obtained from the pipe-flow correlation:

$$h = \frac{\mathrm{Nu}k}{D} \qquad (2)$$

where Nu is the Nusselt number, k is the thermal conductivity, and D is diameter of gun tunnel. For thermally fully developed flow in a smooth tube with Prandtl number Pr > 0.5, Gnielinski's formula is recommended by Mills [13] for calculation of the Nusselt number

$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3} - 1)} \qquad (3)$$

which can be applied for $3000 < \mathrm{Re} < 10^6$. This in turn, depends on the friction factor, which can be obtained from Petukhov's formula

$$f = \frac{1}{(0.790 \ln(\mathrm{Re}) \ \text{-}1.64)^{\text{-}2}} \qquad (4)$$

which applies for $10^4 < \mathrm{Re} \le 5 \times 10^6$.

The pipe flow Reynolds number required in the above correlations is based on the pipe diameter and the flow velocity which is the bulk flow velocity deduced from the stagnation conditions and the nozzle throat area.

To approximate the velocity distribution across the assumed fully developed turbulent pipe flow, a power-law velocity profile is used

$$\frac{\bar{u}}{V_c} = \left(1 - \frac{r}{R}\right)^{1/n} \qquad (5)$$

where $\bar{u}$ and V_c are the mean velocity and centre line velocity of pipe flow respectively, and n = 7 is used as a reasonable approximation.

To approximate the temperature distribution, expressions presented by Mills [13] have been adopted.

$$T^+ = \mathrm{Pr}\, y^+ \ \text{ if } 0 < y^+ \le 5 \qquad (6a)$$

$$T^+ = 5\,\mathrm{Pr} + 5 \ln\left[\mathrm{Pr}\left(\frac{y^+}{5} - 1\right) + 1\right] \ \text{ if } 5 < y^+ \le 30 \qquad (6b)$$

$$T^+ - T^+\Big|_{y^+=30} = \frac{\mathrm{Pr}_t}{0.4}\left[\ln\left(\frac{y^+}{30}\right) - \left(\frac{y^+ - 30}{R^+}\right)\right] \ \text{ if } y^+ > 30 \qquad (6c)$$

where $R^+ = u_\tau R/\nu$, Pr_t is turbulent Prandtl number. T^+ is a dimensionless variable defined as

$$T^+ = \frac{(T_w \text{ - } T)\rho\, c_p u_\tau}{Q_w} \qquad (7)$$

For the gun tunnel, the stagnation region pressure and temperature were taken as P_0 = 6.36 MPa, and T_0 = 610 K; for the shock tunnel, values were taken as P_0 = 36.5 MPa, and T_0 = 6187 K. Profiles of velocity and temperature were used to generate the variation of ρu with radius which was in turn integrated to determine the mass flow rate through the pipe. An adjustment was made to the velocity profile because the initial velocity profile was determined without reference to the density which varied across the radius of the pipe. A factor of 1.37 was applied to the velocity profile in the case of the gun tunnel flow, and a factor of 1.31 was used in the case of the shock tunnel flow so that the mass flow rate in the pipe matched the sonic discharge values for the given stagnation pressure and temperature conditions. A similar adjustment was made to the temperature profile so that the bulk temperature calculated for the gun and shock tunnel cases matched the assumed stagnation region values. A factor of 1.05 was applied to the temperature profile in the gun tunnel case, and a factor of 1.10 was applied in the shock tunnel case.

III. RESULTS AND DISCUSSION

A. *Result for Gun Tunnel Case*

The Oxford University Gun Tunnel (OUGT) is a short duration hypersonic facility producing useful test flows with a duration of less than 100 ms. OUGT has been used in diverse experiments such as scramjet testing, hypersonic mixing studies, aerodynamics experiments, and hypersonic boundary layer studies. The barrel of the OUGT has a length of 9 m and an internal of 96.3 mm. An illustration of the OUGT is presented in Fig 2. The conditions in the nozzle reservoir region considered in this work are P_0 = 6.36 MPa, T_0 = 610 K, and the wall temperature of the barrel was taken as T_w = 300 K. The test gas considered was carbon dioxide. The nozzle throat diameter was 19.1 mm giving a mass flow rate of 3.57 kg/s from which the mean flow velocity in the pipe was found to be 8.89 m/s and Re_τ = 31,579.

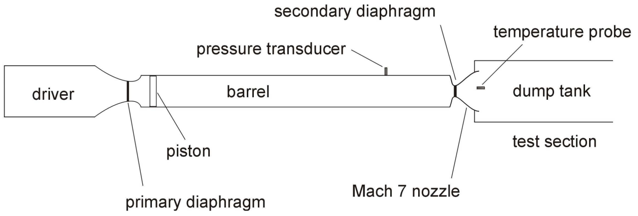

Figure 2. Schematic illustration of gun tunnel facility.

The extrapolation of the data of [12] to the present gun tunnel condition is illustrated by the broken line in Fig. 3 and this figure also presents the original data of [12]. The RMS stagnation temperature fluctuation deduced from the extrapolation is plotted versus radius of the pipe in Fig. 4. The peak of RMS stagnation temperature fluctuation is located at $r \approx 0.047$ m and has a value ≈ 25 K. The RMS stagnation temperature fluctuations are intense near the wall and decay towards the centre line of the pipe, reaching a minimum value ≈ 5.3 K. The mean RMS stagnation temperature fluctuation was obtained by integrating the mass-flux-averaged stagnation temperature fluctuation profile across the pipe. The average stagnation temperature fluctuation obtained in this manner was 15.3 K.

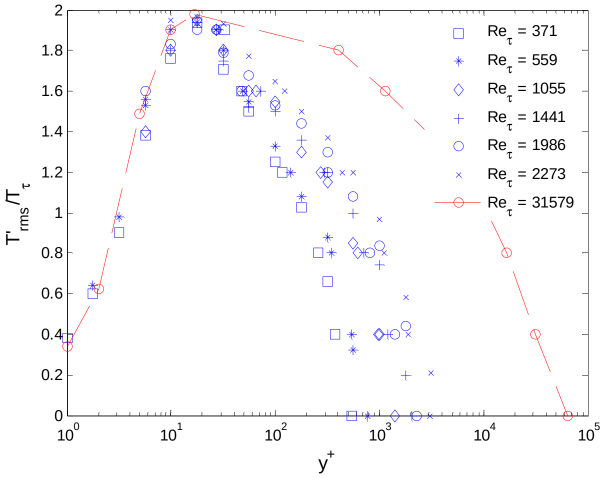

Figure 3. Normalised temperature fluctuation data from [12] (symbols) and extrapolated profile relevant to the gun tunnel case (broken line).

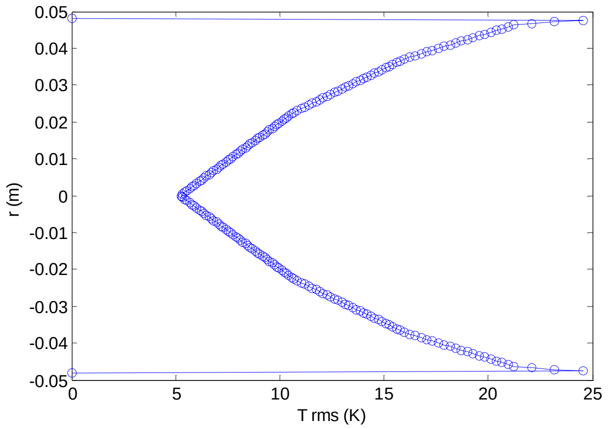

Figure 4. Variation of RMS stagnation temperature fluctuations with pipe radius in the gun tunnel case.

The RMS stagnation temperature fluctuations deduced in this gun tunnel case can be directly compared with the previous result obtained by Buttsworth and Jones [9]. The experimental result of [9] gives the magnitude of RMS stagnation temperature fluctuation of 2.3 K at a location close to the centre line of the hypersonic nozzle exit. This is about half the magnitude of the centre line fluctuation value deduced from the data of [12] in the present work.

B. *Results for Shock Tunnel Case*

The T4 shock tunnel is a type of impulse facility, located at University of Queensland. It is typically used to produce high enthalpy flows for high speed aerodynamic and scramjet experiments. T4 shock tunnel is capable of producing flows with total enthalpies in the range 2.5 - 15 MJ/kg. A schematic illustration of the apparatus is presented in Fig. 5. The conditions in the nozzle reservoir region considered in this work are P_0 = 36.5 MPa, T_0 = 6187 K, and wall temperature of the shock tube was taken as T_w = 300 K. The test gas considered in this work is air, and the nozzle throat diameter was 25 mm. These conditions give a mass flow rate of 9.05 kg/s from which the bulk flow velocity in the pipe was found to be 100.44 m/s and Re_τ = 24,975.

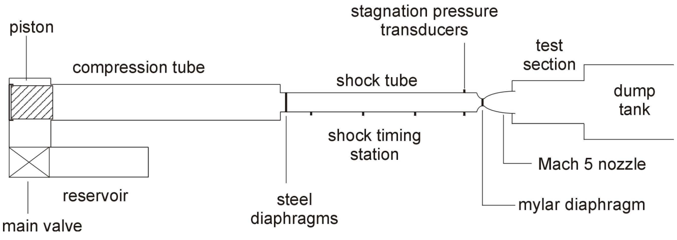

Figure 5. Schematic illustration of shock tunnel facility

The results from extrapolation of the data of [12] to the present shock tunnel condition is illustrated Fig. 6 as the broken line. Included on this figure is also the original data of [12]. Fig. 7 presents the profile of the RMS stagnation temperature fluctuation deduced from the extrapolation. The peak of RMS stagnation temperature fluctuation is located at $r \approx 0.038$ m and has a value ≈ 463.9 K. The RMS stagnation temperature fluctuations are intense near the wall and decay towards the centre line of the pipe, reaching a minimum value ≈ 99.53 K. The mean RMS stagnation temperature fluctuation was obtained by integrating the mass-flux-averaged stagnation temperature profile across the pipe. The average stagnation temperature fluctuation obtained in this manner was 291 K. This represents a relative RMS stagnation temperature fluctuation of about 5 %.

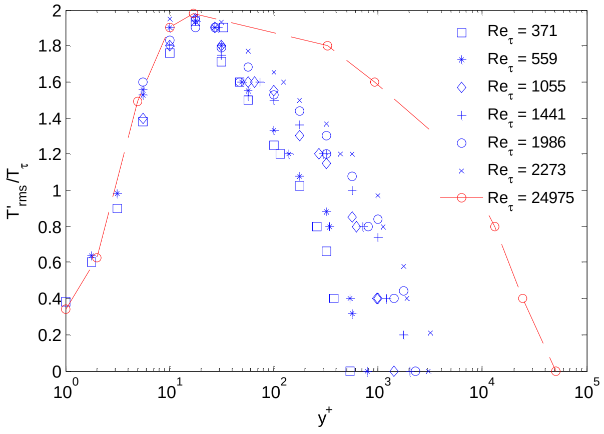

Figure 6. Normalised temperature fluctuation data from [12] (symbols) and extrapolated profile relevant to the shock tunnel case (broken line).

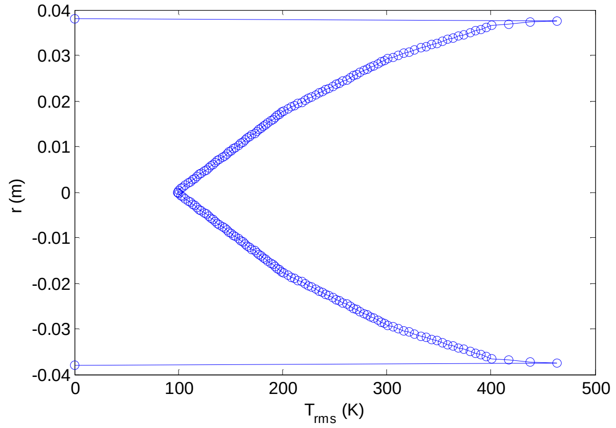

Figure 7. Variation of RMS stagnation temperature fluctuations with pipe radius in the shock tunnel case.

C. *Ignition delay and reaction time for shock tunnel case*

The T4 shock tunnel is regularly used for scramjet combustion experiments. To assess the possible significance of the temperature fluctuations in the shock tunnel case, combustion characteristics of hydrogen-air mixtures are assessed using a correlation for ignition delay and reaction times. Because the residence time of fuel and air mixtures in model scramjet engines tested in T4 can be as short as several milliseconds, ignition delay and reaction times can be very important at some conditions. There are three parameters that must be within reasonable limits for self-ignition of the hydrogen-air mixture within the scramjet. These are: the static pressure, the fuel-air equivalence ratio, and the static temperature. Under the assumption that the fuel air-mixture is stoichiometric and the static pressure remains constant, the effect of different static temperatures on the ignition and reaction times can be estimated using global approximations.

Ignition is considered accomplished when the temperature rises by 5 % of the complete reaction temperature rise [14]. Ignition delay time τ_i and reaction time τ_r can be calculated by using the equations

$$\tau_i = \frac{8\times10^{-9} e^{9600/T}}{P} \tag{8}$$

$$\tau_r = \frac{0.000105 e^{-1.12T/1000}}{P^{1.7}} \tag{9}$$

where T is the static temperature (K) and P is the static pressure (expressed in atm). This equation is reported as being valid for the range P = 0.2 to 1.0 atm and T = 1000 to 2000 K [15].

Static temperature at the T4 shock tunnel nozzle exit for the particular test condition of interest was obtained from [16] as 1440 K. On the assumption that the magnitude of the static temperature fluctuations at the nozzle exit scale with the magnitude of the stagnation temperature fluctuations in the nozzle reservoir region, the expected value of RMS static temperature fluctuation at the nozzle exit is 72 K (corresponding to 5 % of 1440 K).

In Figs. 8 and 9, the ignition delay time and the reaction time characteristics for the shock tunnel case are presented. Ignition delay and reaction times for two static pressures (20 and 100 kPa) are presented as a function of static temperature. For both pressures, two different lines are presented: the RMS static temperature fluctuation at the representative maximum temperature (T + T_{rms}) and the other at the representative minimum temperature (T – T_{rms}). At each temperature, the value of the RMS fluctuation is determined using T_{rms} = 0.045T.

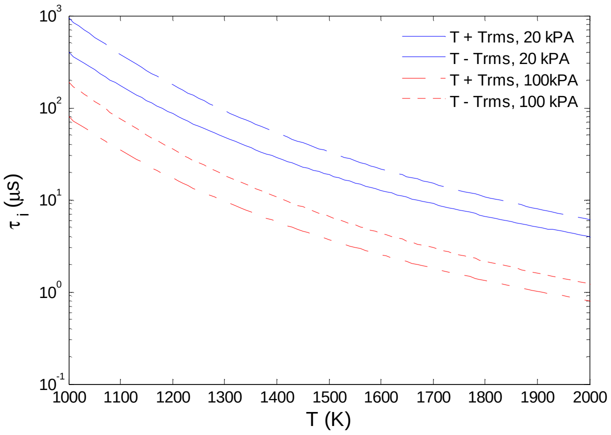

Figure 8. Igniton delay time characteristics for the shock tunnel case.

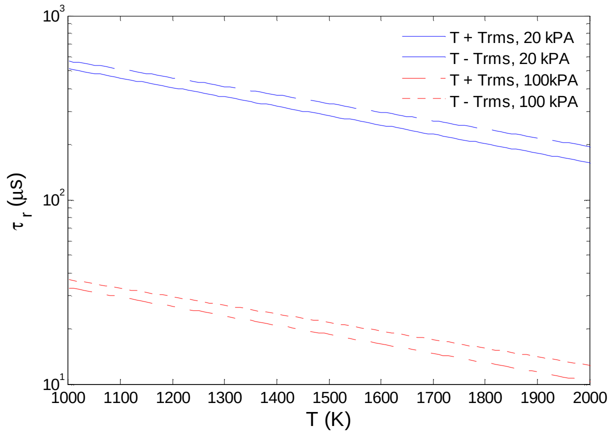

Figure 9. Reaction time characteristics for the shock tunnel case.

Results indicate that the static temperature fluctuation can have a significant influence on the combustion process for hydrogen-air mixtures. For example, consider Fig. 8 and the pressure of 20 kPa. Over the representative peak-to-peak variation in the static temperature fluctuations (a magnitude of 2T_{rms}), the ignition time delay will vary by around 600 µs for a mean static temperature of 1000 K. For a static pressure of 100 kPa and a mean static temperature of 1000 K, the corresponding difference in ignition delay times is somewhat shorter, at around 100 µs. The reaction time (Fig. 9) for a mean static temperature of 1000 K varies by about 70 μs at 20 kPa and 5 μs at 100 kPa for the assumed peak-to-peak fluctuation in the nozzle exit static temperature.

Scramjet combustors must be sized to accommodate mixing, ignition and reaction times for the fuel and air. The nozzle exit flow velocity was 4020 m/s for this shock tunnel condition [16]. Assuming a representative scramjet model combustor length on the order of 1 m, the residence time will only be around 250 μs. Clearly an ignition time fluctuation of 600 μs is very significant.

CONCLUSIONS

In the present work, we assess the significance of temperature fluctuations by analysing existing temperature fluctuation data and relating it to conditions in two specific transient compression wind tunnel cases. The first case we consider is that of a gun tunnel in which a piston is used to compress the test gas up to about 610 K – the test gas is carbon dioxide. The second case we consider is that of a shock tunnel in which driver gas is used to directly compress the test gas up to about 6187 K – the test gas considered in this case is air.

Using the suggested approach, we found that the mean value of root-mean-square stagnation temperature fluctuations to be 15.3 K and 291 K for the gun tunnel and shock tunnel cases respectively. The estimated RMS value in the case of the gun tunnel is significantly larger than the experimental value previously measured on the centre line of the gun tunnel nozzle of 2.3 K. The difference observed between the inferred and measured temperature fluctuations in the gun tunnel case may be related to spatial variations in the temperature fluctuations. In the case of the shock tunnel, the magnitude of the fluctuations is demonstrated to be significant for supersonic combustion experiments.

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