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MODELLING OF A SCRAMJET FLOW USING VARIOUS TURBULENCE MODELS

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ABSTRACT

Three turbulence models of varying sophistication are compared in a high-Mach-number reacting flow field which is typical of many shock-tunnel scramjet experiments. The simulations confirm that there are some significant differences in the predictions obtained with the different models. A comparison with experimental data shows that none of the models give completely satisfactory results over the entire length of the scramjet engine, however, all models indicate that the fuel/air mixing rate is insufficient to achieve complete mixing within the given engine length.

NOTATION

$C_{\varepsilon1}, C_{\varepsilon2}, C_{\mu}$	constant coefficients in turbulence models
H_j	injector step height
k	kinetic energy of turbulence
ℓ_m	mixing length
ℓ_ε	dissipation length scale
p	pressure
p_i	inlet pressure
St	Stanton number based on inlet conditions
u	axial velocity
v	transverse velocity
x	axial distance measured from injector
y	transverse distance
y_G	characteristic width
ε	rate of turbulence dissipation
η_{mix}	*mixing efficiency*
η_{RR}	*reaction-rate efficiency*
λ	constant in mixing-length model
μ_t	turbulent viscosity
ρ	density
σ	"Prandtl" number

INTRODUCTION

The sophisticated instruments required to measure detailed profiles, such as velocity, temperature, composition, etc., in hypervelocity, short-duration flows created by a shock-tunnel, are only in the development stage. As a consequence, heavy reliance must be placed upon current CFD (Computational Fluid Dynamics) to extract detailed information from a shock-tunnel scramjet experiment. However, a large amount of uncertainty is attached to present-day CFD, particularly if the flows being modelled are turbulent, since the turbulence and combustion models used are unlikely to have been validated in hypervelocity flows.

Turbulence models are usually developed from reference to simple, incompressible, low-speed flows. However, it is well known that these models can give poor predictions if they are extended to flows which contain (a) compressibility effects, (b) pressure gradients, (c) wall-damping effects, and (d) combustion. A scramjet, unfortunately, can suffer from all of these complications simultaneously. Several methods have been suggested in the literature for improving these models in "complex" flows, eg. by incorporating algebraic Reynolds stresses and also by incorporating multiple-time-scale effects. However, the complexity of the turbulence models increase substantially with these modifications, and it is not clear whether these modifications will have a substantial effect on the predictions in a scramjet flow, or even if the effects will be beneficial. In this current study, a series of numerical scramjet experiments were performed using different turbulence models to see how the predictions were affected by the different turbulence models. The test conditions chosen for the study correspond to a particular flow condition produced by the T4 shock tunnel at the University of Queensland, and hence, some experimental data was also available for comparison.

TURBULENCE MODELS

Three turbulence models were chosen for the present study. The first was Prandtl's (1925) *Mixing Length Hypothesis* (MLH). The model assumes that the turbulent viscosity may be evaluated from the formula

$$\mu_t = \rho \ell_m^2 \left|\frac{\partial u}{\partial y}\right| \qquad (1)$$

where the mixing length, ℓ_m, is determined from the relation

$$\ell_m = \lambda y_G \qquad (2)$$

where λ is a constant, and y_G is a characteristic width in the flow. For the current study, the flow field was divided into several regions with different characteristic widths. The method used to determine the characteristic widths was that suggested by Spalding (1977). A value of $\lambda = 0.118$ was chosen for the present scramjet computations. This value is slightly higher that the value of 0.09 suggested by Spalding, however, it is slightly lower that the value of 0.125 used by

Launder et al. (1973). A value of 0.118 was found to give satisfactory predictions for the spreading rates of single-stream, incompressible, free shear layers.

The second model chosen was the well-known k-ε model (see eg. Launder and Spalding, 1974). The *high-Reynolds-number* version of the model evaluates the turbulent viscosity from the formula

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \qquad (3)$$

where the values of k and ε are determined from solving the following transport equations

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial y} = \frac{\partial}{\partial y}\left[\frac{\mu}{\sigma_k}\frac{\partial k}{\partial y}\right] + \mu_t\left[\frac{\partial u}{\partial y}\right]^2 - \rho\varepsilon \qquad (4)$$

and

$$\rho u \frac{\partial \varepsilon}{\partial x} + \rho v \frac{\partial \varepsilon}{\partial y} = \frac{\partial}{\partial y}\left[\frac{\mu}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right] + C_{\varepsilon 1}\left[\frac{\varepsilon}{k}\right]\mu_t\left[\frac{\partial u}{\partial y}\right]^2 - C_{\varepsilon 2}\left[\frac{\varepsilon}{k}\right]\rho\varepsilon \qquad (5)$$

The k-ε model is generally applicable in a larger range of flows than the simpler MLH model. The "standard" model constants recommended by Launder and Spalding (1974) where used during the computations.

For simple, parabolic flows, both the MLH and k-ε models are usually reliable (although the MLH model usually requires an adjustment of λ from one flow geometry to another). However, it is well documented that the predictions from these models can break down under certain "complex flow" conditions. One of the shortcomings of the k-ε model is that it does not allow for the transport effects on the Reynolds stresses (eg. $\overline{uv}$). Rodi (1976) proposed an extension to the k-ε model to help introduce these transport effects. The extension proposed by Rodi effectively converts the k-ε model into an *Algebraic-Reynolds-Stress* (ARS) model. Experiments have also indicated that the Reynolds stresses $\overline{uv}$ and $\overline{v^2}$ may be decreased in the proximity of walls, and that this can decrease the spreading rate of wall jets. Ljuboja and Rodi (1980) have proposed a similar ARS model which allows these wall-damping effects to be predicted.

Another significant advance in turbulence modelling has been the development of *Multiple-Time-Scale* (MTS) models (Hanjalić, Launder, and Schiestel, 1979). MTS models are similar to the k-ε model, except that they require the solutions of four transport equations, rather than the customary two associated with the standard k-ε model (i.e. Eqs. 4 and 5). The MTS model proposed by Hanjalić et al. also included a dissipation equation which was *sensitized to irrotational strains*. Such a modification is often beneficial in flows with adverse pressure gradients. Fabris, Harsha and Edelman (1981) have indicated that MTS models are probably the best available for scramjet-combustor calculations.

The third model tested (which will be referred to as the ARS-MTS model) was effectively a hybrid model which incorporated the ARS and MTS ideas together. Full details of this model, and the model constants used, are available in Brescianini (1992).

Because all three models were being used in highly-compressible flows, compressibility corrections were also applied to each model. For the MLH model, the compressibility correction suggested by Kim (1990) was adopted. For both the k-ε and ARS-MTS models the correction suggested by Brescianini (1991) was adopted. Predictions obtained with these "corrected" models have been found to agree well with compressible-free-shear-layer data taken in conventional wind tunnels, however, their performance in high-enthalpy flows remains relatively unexplored.

The fluxes of heat and shear-stress to the walls of the scramjet were evaluated using *wall functions*. The wall functions used were similar to those developed by Spalding (1977), except that they were extended to account for the compressible flow.

TEST CONDITIONS

The scramjet test condition used corresponded to an actual scramjet experiment performed in the T4 shock tunnel at the University of Queensland, and reported in Brescianini and Morgan (1992). In this earlier scramjet study, four numerical/experimental test cases were examined, with the numerical simulations being based on a k-ε model. Three of the test cases were found to give quite satisfactory agreement, however, a fourth condition (namely Run 697) was not predicted so well. As a result, it was decided to concentrate on Run 697 for this current study to see if the predictions were substantially altered or improved by using different turbulence models.

A schematic of the constant-area scramjet engine used to perform the experiment is shown in Fig. 1. The main-stream flow within the combustion chamber consisted of a Mach 3.6 air stream, with a static temperature of 1500 K, and static pressure of 40 kPa. Hydrogen fuel was injected from a step along the wall of the model with a stagnation pressure of 357 kPa, stagnation temperature of 300 K, and a fuel/air equivalence ratio of 1.5. The model was essentially two-dimensional, with a duct height of 25 mm and a fuel-injector step height of 5 mm. A lip of 2.25 mm was present on the wall injector. This lip could not be modelled with the Parabolic Navier-Stokes (PNS) code used in the current study, and as a result, the initial hydrogen fuel was assumed to expand to the full hydrogen step height. In view of the modeling assumptions required near the thick lip, the initial boundary layer on the injector was also ignored. The two-dimensional, supersonic-combustion program developed by Brescianini (1992) was used to compute the flow field, and the finite-rate hydrogen/air chemistry was modelled using the *basic hydrogen/air mechanism* and the *nitrogen-oxides supplement* recommended by Oldenborg et al. (1990). The effects of turbulence on the chemical reaction rates were not considered.

RESULTS

Figure 2 compares the numerically predicted pressure distributions along the wall of the model which contains the fuel injector. None of the models predict the experimentally noted wave structure correctly, however, a large part of this discrepancy may be due to the thick lip on the injector. Flow visualisation was not available during the experiments, and hence the true source of the waves within the scramjet was difficult to identify. The large wave structure present in the numerical results is due to the initial mismatch in the hydrogen/air static pressures ($p_{H2}/p_{AIR} = 0.2$) at the injector step.

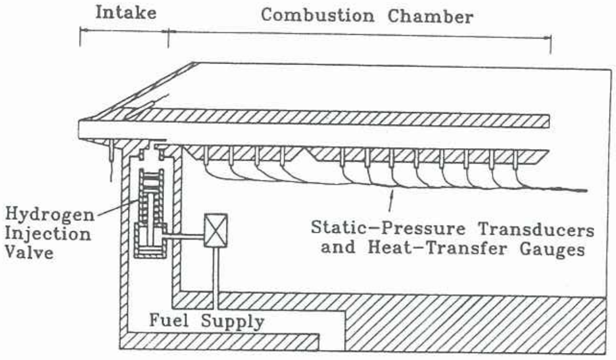

Fig. 1 Schematic of scramjet model.

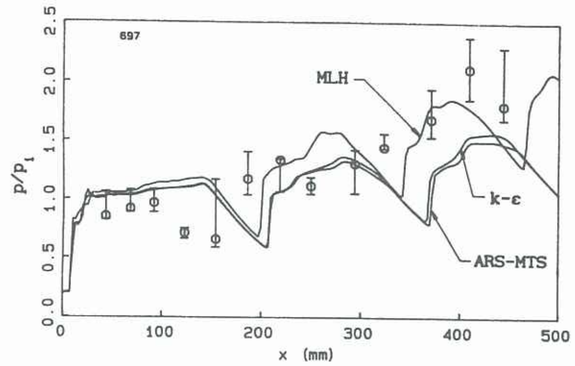

Fig. 2 Pressure variation along wall of scramjet.

The MLH model clearly predicts a significantly higher pressure rise than either the k-ε model or the ARS-MTS models. Between x = 200-300 mm, the MLH model over-predicts the experimental pressures, however, towards the rear of the duct the MLH predictions are in quite good agreement with the experiments.

The k-ε and ARS-MTS predictions are very similar. The pressure rises predicted in the centre of the duct are in good agreement with the experiments, however, towards the rear of the duct the predicted pressures fall short of the experimental pressures.

The Stanton-number predictions obtained with the three models are shown in Fig. 3. The MLH model clearly predicts the highest heat-transfer rate, with the heat-transfer rate near the injector being significantly larger than the experimental measurements. Around the x=200 mm position, however, the numerical and experimental heat-transfer rates are quite similar. In comparison, the k-ε model predicts the initial heat-transfer rate, and the film-cooling length, quite successfully, however, further downstream the heat-transfer rate is significantly under-predicted.

It should be noted that the predicted heat-transfer rate obtained with the k-ε model near the injector is quite sensitive to the initial turbulent length scale ($\ell_\varepsilon \equiv C_\mu\, k^{3/2}/\varepsilon$). It is possible to improve the heat-transfer prediction at the x = 200 mm station by increasing the initial value of ℓ_ε, but only at the expense of the film-cooling-length prediction. The value of ℓ_ε/H_j which was adopted here (namely, 0.002), as well as the initial turbulence levels, were the same as those used in Brescianini and Morgan (1992). In a similar fashion, the film-cooling length predicted by the MLH model could be improved by decreasing λ, but only at the expense of the downstream heat-transfer and pressure predictions.

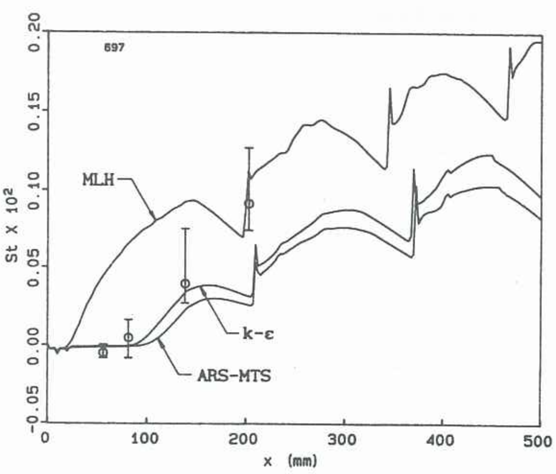

Fig. 3 Stanton-number variation along wall of scramjet.

For the ARS-MTS model, an initial length scale was chosen which was identical to the k-ε model. It can be seen that the Stanton number predictions obtained with the ARS-MTS and k-ε models are very similar, with the ARS-MTS predictions being only slightly lower.

Two of the major parameters of interest in the scramjet, namely the *mixing* and *reaction-rate efficiencies*, are shown in Fig. 4. (The mixing efficiency is defined here as the amount of reacted hydrogen if all mixed hydrogen reacted completely, divided by the same quantity if mixing had been complete. The reaction-rate efficiency is defined as the reacted hydrogen, divided by the amount of reacted hydrogen if the hydrogen which has mixed with oxygen reacted completely). It can be seen that the MLH model has predicted a significantly larger amount of mixing than either the k-ε model or the ARS-MTS models. However, what is also important is the fact that all three models predict the fuel/air mixing to be far from complete by the time the flow has reached the end of the duct. This is in general agreement with the results obtained by Brescianini and Morgan (1992). In comparison to the mixing efficiencies, the reaction-rate efficiencies shown in Fig. 4 are virtually identical for all the turbulence models. This shows that a change in the fuel/air mixing rate has not affected the overall reaction rate.

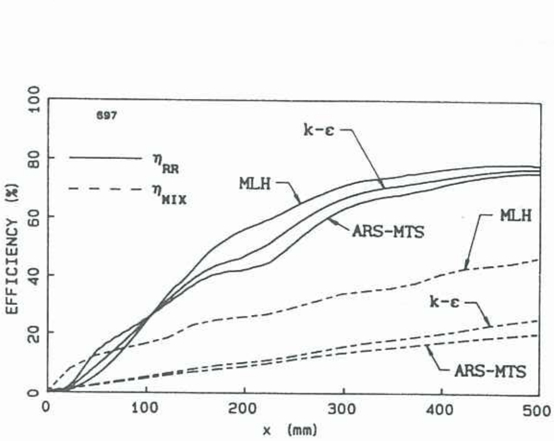

Fig. 4 Mixing and reaction-rate efficiencies along length of scramjet.

CONCLUDING REMARKS

Three turbulence models of varying sophistication were compared in a supersonic scramjet flow. A significant difference between the MLH model and the k-ε model was noted. The k-ε results and the ARS-MTS results also differed, but by a much smaller extent. The MLH model predicted the highest mixing rate, while the ARS-MTS model predicted the lowest. All models showed that the fuel/air mixing rate was insufficient to produce complete mixing within the given length of combustion chamber. None of the models appeared to predict the experimental results accurately over the entire length of model. The k-ε and ARS-MTS models appeared to give the best results near the injector, however, further downstream the MLH model appeared to perform better. The reasons why none of the models appears to be completely satisfactory over the entire model length is uncertain at this stage, although transition-to-turbulence effects, and also the injector's thick lip, are possible explanations.

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