Effect of Turbulence Models on Steam Condensation in Transonic Flows

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Abstract: Turbulence modelling plays an important role in the numerical prediction of nonequilibrium condensations in transonic flows. The present study evaluates the effect of four different turbulence models, namely, $k - \varepsilon$ standard, RNG, realizable, and $k - \omega$ SST, on the condensation behaviour in transonic flows considering shock waves. The numerical simulation is compared to experimental data, which demonstrates that the $k - \omega$ SST model shows better performance than $k - \omega$ turbulence models in predicting the nonequilibrium condensation and shock waves in transonic flows.

Keywords: Turbulence modelling, Transonic flow, Shock wave, Nonequilibrium condensation

1 Introduction

Steam condensation in transonic flows is a common issue in various industries, such as Laval nozzles, ejectors, turbines, thermo-compressors and supersonic separators [1, 2, 3, 4, 5]. Various turbulence models have been used in wet steam flow simulations, from $k-\varepsilon$ models to SST $k-\omega$ model. Simpson and White [6] numerically calculated the steam nucleation and condensation in a converging–diverging nozzle using the standard $k-\varepsilon$ model. Ariafar et al. [7] employed the realizable $k-\varepsilon$ model to perform the numerical simulation on steam condensations in a primary nozzle used for an ejector. Wang et al. [8] adopted the RNG $k-\varepsilon$ model to predict the homogeneous condensation in a primary nozzle for the steam ejector. Mazzelli et al. [9] numerically studied the non-equilibrium condensation in a steam ejector by employing the $k-\omega$ shear stress transport (SST) model. In the present study, an assessment of the turnulence model on the steam condensation in transonic flows is performed using computational fluid dynamics (CFD) modelling.

2 Numerical Model

The fundamental equations governing the non-equilibrium condensation under supersonic conditions are the compressible Navier–Stokes equations. Two transport equations are utilized to describe the phase change process during the steam condensation, including the liquid fraction (Y) and droplet number per volume (N):

$$\frac{\partial(\rho Y)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho Y u_j\right)=\Gamma \tag{1}$$

$$\frac{\partial(\rho N)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho N u_j\right)=\rho J \tag{2}$$

where J is the nucleation rate [10], N is the number of droplets per volume. Γ is the condensation mass due to phase changes:

$$\Gamma = \frac{4\pi r_c^{3}}{3}\rho_l J + 4\pi r^2 \rho_l N \frac{dr}{dt} \tag{3}$$

$$J = \frac{q_c}{1+\phi}\frac{\rho_v^{2}}{\rho_l}\sqrt{\frac{2\sigma}{\pi m_v^{3}}}\exp\left(-\frac{4\pi\sigma}{3k_B T_v}r_c^{2}\right) \tag{4}$$

The growth rate of droplets due to evaporation and condensation, dr/dt, is calculated by Young's model [11].

$$\frac{dr}{dt} = \frac{\lambda_v\left(T_s - T_v\right)}{\rho_l h_{lv} r}\frac{\left(1-r_c/r\right)}{\left(\frac{1}{1+2\beta \mathrm{Kn}} + 3.78(1-\nu)\frac{\mathrm{Kn}}{\mathrm{Pr}}\right)} \tag{5}$$

For the numerical implementation, the mass, momentum and energy conservation equations are directly solved by the ANSYS FLUENT 18 [12], while the User-Defined-Scalar (UDS) and User-Defined-Function (UDF) interfaces are used to solve two scalar equations and source terms. The pressure inlet and pressure outlet conditions are assigned for the entrance and exit of the supersonic nozzle. The computational simulation employs a structured mesh of 22,800 cells based on a mesh convergence test using 7920, 22,800 and 40,000 cells [13].

3 Results

Four turbulence models ($k-\varepsilon$ Standard, $k-\varepsilon$ RNG, $k-\varepsilon$ Realizable and $k-\omega$ SST) are evaluated against experimental data presented by Binnie and Green in a Laval nozzle [14] to evaluate the influence of the turbulence modelling both considering the steam condensation and shock waves in supersonic flows. Figure 1 displays the static pressure profile along the flow direction of the Laval nozzle clearly showing the occurrence of shock waves in supersonic flows. By comparing the numerical result and experimental data, it is shown that all of four turbulence models capture almost the same onset of the steam condensation and agree well with the experiments. However, the shock wave position differs significantly among four turbulence models. The shock wave appears in the downstream end of the Laval nozzle, around $x = 0.19$ m for the $k-\omega$ SST model. The $k-\varepsilon$ turbulence models predict the position of the shock waves further downstream, around $x = 0.21$ m for the standard $k-\varepsilon$ model and $x = 0.20$ m for the RNG and realizable $k-\varepsilon$ models. For this case, both the standard $k-\varepsilon$ model and the $k-\omega$ SST model capture the experimental static pressures.

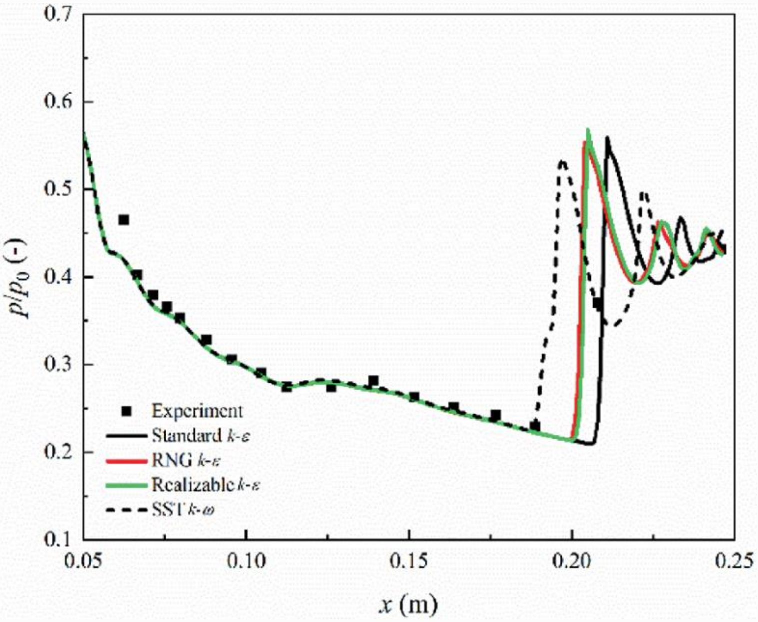

Fig. 1 Pressure profiles at the central line of the Laval nozzle [14]

To further investigate the $k-\varepsilon$ standard and $k-\omega$ SST turbulence models capabilities to predict the shock structure in supersonic flows, we consider experimental data in [15] which focused on the flow separation in a convergent-divergent nozzle without considering the nucleation behaviour. Figure 2 describes the comparisons between the computed and experimental pressure profiles along the nozzle. The results show that the $k-\omega$ SST turbulence model accurately captures the shock position inside the convergent-divergent nozzle, while the standard $k-\varepsilon$ model predicts a later shock position. Hence, the standard $k-\varepsilon$ model is slow to respond to the flow separation in supersonic flows.

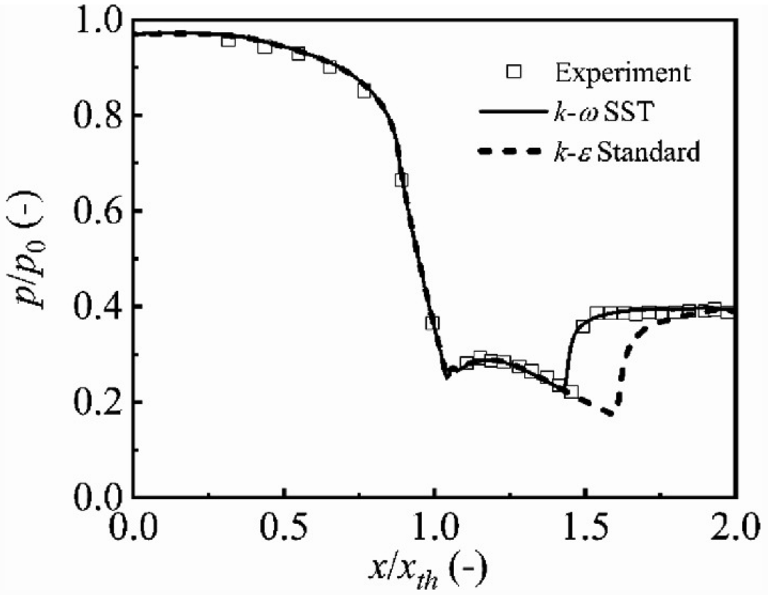

Fig. 2 Static pressure between computation and experiment

In general, by comparing the numerical results with experimental data from Binnie and Green Laval nozzle [14] and Hunter convergent-divergent nozzle [15], the $k-\omega$ SST turbulence model shows better performance on the prediction of the supersonic flow with non-equilibrium condensation and shock waves.

4 Conclusions

A computational fluid dynamics model is developed to evaluate the effect of turbulence models on steam condensation behaviour in transonic flows considering shock waves. The $k-\omega$ SST turbulence model shows good agreement with experimental measurements, which is recommended for the numerical simulation of the wet steam flows concerning both steam condensations and shock waves.

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