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# Evaluation of Turbulence Models Performance in Predicting Incipient Cavitation in an Enlarged Step-Nozzle

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**Abstract.** Predictive capability of RANS and LES models to calculate incipient cavitation of water in a step nozzle is assessed. The RANS models namely, Realizable k-ε, SST k-ω and Reynolds Stress Model did not predict any cavitation, due to the limitation of RANS models to predict the low pressure vortex cores. LES WALE model was able to predict the cavitation by capturing the shear layer instability and vortex shedding. The performance of a barotropic cavitation model and Rayleigh-Plesset-based cavitation models was compared using WALE model. Although the phase change formulation is different in these models, the predicted cavitation and flow field were not significantly different.

## 1. Introduction

Formation of vapour due to cavitation affects the fluid flow and a two-way interaction exists between the bubbles and the turbulent oscillations. Chahine [1] has developed a cavitation model to account for the two-way interaction of bubbles and the flow field. Okabayashi and Kajishima [2] investigated the two-way interaction between cavitation and turbulence using Direct Numerical Simulation (DNS). They reported the modulation of turbulence by cavitation which can form a basis for a Sub Grid Scale (SGS) model for cavitation in Large Eddy Simulation (LES). Iyer and Ceccio [3] used Fluorescent Particle Image Velocimetry (PIV) to assess the effect of cavitation on shear layer instabilities and flow turbulence downstream the shear layer, using a sharp edged plate in a cavitation channel. The importance of accurately capturing the turbulence pressure fluctuations in cavitating flows is highlighted in Wilfried *et al*. [4]. They have compared Reynolds Averaged Navier-Stokes (RANS) and LES simulations of a cavitating throttle flow and show the situational applicability of the RANS model. They conclude that RANS can predict cavitation with a reasonably acceptable accuracy in an operating condition with high pressure difference, whereas it fails to predict the cavitation at a low pressure difference. Grid requirements and therefore the computational cost of RANS simulations is lower than LES, and in some studies [5] they proved to predict cavitation accurately, however their applicability varies from case to case.

Cavitation can be modelled using the Rayleigh-Plesset equation for bubble dynamics [6], which has been implemented in cavitation models of Singhal *et al*. [7], Schnerr and Sauer [8] and Zwart *et al*. [9]. Another approach to model cavitation is based on the assumption of thermodynamic equilibrium using an equation of state, such as the cavitation model of Schmidt *et al*. [10].

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In the current study CFD solver FLUENT V15.0 is used to compare the performance of a number of turbulence models and cavitation models for modelling incipient cavitation in a step nozzle geometry, based on the experimental study of Sou *et al.* [11].

## 2. Test Cases and Simulation Setup

The experimental setup is extensively reported in the reference study [11], so in the present report the operating conditions and geometry are only briefly presented. Water is discharged into a rectangular nozzle with 4.8 ml/s flow rate and the outlet is subjected to atmospheric pressure. Schematic of the nozzle is shown in figure 1.

A coarse mesh is systematically refined to perform a grid independency test. Simulations are done using Shear Stress Transport (SST) k-ω model. Inlet pressure of 2.42 bar and atmospheric outlet pressure is set as boundary conditions. After the grid independency test, performance of three RANS models, namely the Realizable k-ε, SST k-ω and Reynolds Stress Model (RSM) is assessed and compared to Wall Adaptive Local Eddy Viscosity (WALE) LES simulation for incipient cavitation. WALE is used to compare three different cavitation models, namely a barotropic model (see Koukouvinis *et al.* paper [12]), Zwart-Gerber-Belamri (ZGB) and Schnerr-Sauer (SS) cavitation models, and one simulation is set-up using ZGB model with modification. The ZGB model is modified by increasing the evaporation and condensation rate equation constants. Table 1 reports the summary of CFD test cases.

**Table 1.** Summary of Test Cases.

| | Test Case | Run 1 | Run 2 | Run 3 | Run 4 |
|---|---|---|---|---|---|
| **1** | Grid Independency | Coarse | Medium | Fine | - |
| **2** | RANS Models | Realizable k-ε | SST k-ω | RSM | - |
| **3** | Cavitation Models | Barotropic | ZGB | Modified ZGB | SS |

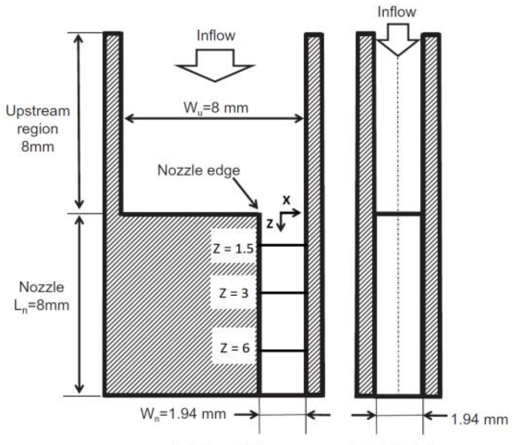
## 3. Results and Discussion

Grid independency test results are reported in table 2 along with effect of grids on the flow rate. A consistent trend is achieved in the predicted velocities and it can be concluded that no significant improvement is reached by further refinement of the grid.

**Table 2.** Grid parameters and their effect on flowrate.

| Grid | Cells | Max $y^+$ | Min $y^+$ | Flowrate (ml/s) |
|---|---|---|---|---|
| **Coarse** | 1M | 55 | 1 | 4.7 |
| **Medium** | 2.3M | 45 | 0.5 | 4.7 |
| **Fine** | 6.8M | 37 | 0.2 | 4.8 |

Mean streamwise velocities calculated by Realizable k-ε, SST k-ω and RSM model and the LES WALE model at z = 1.5 mm are presented in figure 2. The minimum $y^+$ for the RANS models is ~1 and for the LES it is ~ 0.2. The Realizable k-ε and SST k-ω have less than 1% difference in the majority of the flow section. The most significant disparity between this two models is at the region between the recirculating flow and the bulk flow moving above it, where the SST k-ω over-predicts the velocity by ~24% and Realizable k-ε by ~20%. On average the two-equation models have ~30% discrepancy with experiment in mean streamwise velocity at z = 1.5 mm. The RSM results over-predicts the velocity at the recirculation region and on average RSM results have ~20% more discrepancy with experiment velocities compared to two-equation models.



(a) Front View (b) Side View

**Figure 1.** Nozzle geometry [11]

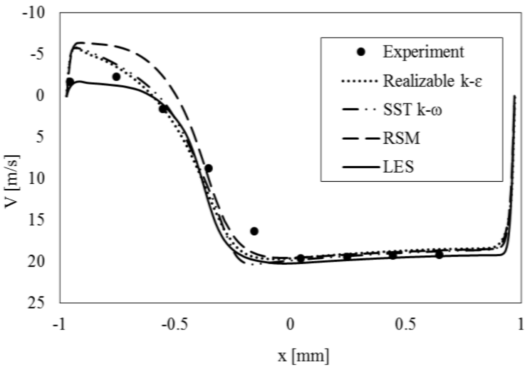
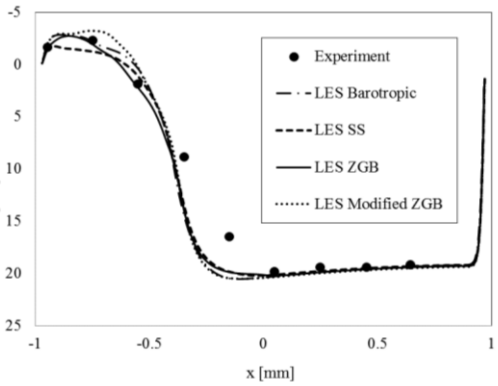


**Figure 2.** Mean streamwise velocity at z = 1.5 mm calculated by different turbulence models

No cavitation is predicted by the RANS models and using higher order discretization schemes does not improve this result. RANS models are not designed to capture the shedding of small vortices, instead the effect of these vortices is modelled by artificially increasing the local viscosity. LES can predict vortex shedding and pressure fluctuations in the shear layer. LES can predict the cavitation and the results significantly improve in the near wall and the recirculation region. On average the LES velocity profile was ~10% closer to experiment result compared to two-equation models predictions.



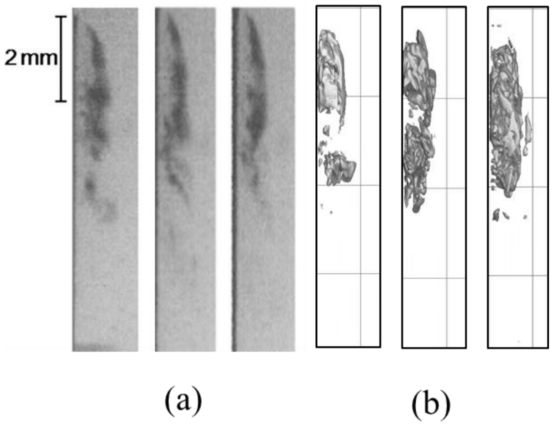


**Figure 3.** Mean streamwise velocity at z = 1.5 mm calculated using different cavitation models

**Figure 4.** Cavitation in experiment [(a) and CFD (b)

It is evident from figure 3 that changing the cavitation model, only affects the streamwise velocity in the region of cavitation and the bulk flow remains unaffected. This result has also been observed at positions z = 3 mm and z = 6 mm. Furthermore the velocity predictions by the barotropic and the ZGB model are nearly identical, and have the best match with experiment velocity measurements. The minimum mean pressure in the flow field for the barotropic and the modified ZGB model are ~10,000 Pa and for the default SS and ZGB models it is ~8,000 Pa. Negative pressures indicates regions of mechanical tension. The lower minimum mean pressure predicted by default models can be because these models predict regions of negative pressure as low as -13,000 pa. The minimum pressure calculated with modified ZGB is close to zero, and the barotropic model does not predict any region of negative pressure. Figure 4 shows instantaneous isosurface of 50% vapour volume fraction predicted by the default ZGB model and the experiment images.

## 4. Conclusion

This paper evaluates the predictive capability of two-equation and 7-equation RANS models to simulate incipient cavitation in a rectangular step nozzle, and compares the results with WALE model predictions. The LES model is then used to further investigate the performance of barotropic and non-equilibrium cavitation models.

This test case shows the situational applicability of RANS model for predicting cavitation. All the RANS models used for this study, i.e. the Realizable k-ε, SST k-ω and RSM model failed to predict pressures below the saturation pressure. RANS is a useful tool for many cavitation problems as seen in the literature [5], but its limited capability has also been reported for cases with small amounts of cavitation [4]. For problems such as incipient cavitation in a nozzle where the pressure drop from inlet to outlet is low, small vortices are formed that act as nucleation cites for bubbles. In order to capture these flow structures, more rigorous turbulence models such as LES are required.

The average minimum pressure predicted by the barotropic and the non-equilibrium cavitation models is above the saturation pressure of water. This result further justifies the minimum pressure predicted by RANS models, which is above saturation pressure. Furthermore, changing the cavitation model did not significantly affect the streamwise velocity outside the cavitation region. The predicted shape of the cavity was in agreement with experimental images, however quantitative measurements inside the vapour volume is required to judge the accuracy of the calculated cavitation.

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