Application of two turbulence models for computation of cavitating flows in a centrifugal pump

M He¹, Q Guo¹, L J Zhou¹, Z W Wang² and X Wang¹

¹ College of Water Conservancy and Civil Engineering, China Agricultural university, Haidian District, Beijing, 100083, China.
² Department of Thermal Engineering, Tsinghua University Qinghuayuan, Haidian District, Beijing, 100084, China.

E-mail: zlj09@263.net

Abstract. To seek a better numerical method to simulate the cavitating flow field in a centrifugal pump, the applications between RNG \( k-\varepsilon \) and LES turbulence model were compared by using the Zwart-Gerber-Belamri cavitation model. It was found that both the models give almost the same results with respect to pump performance and cavitation evolutions including growth, local contraction, stability and separation in the impeller passage. But the LES model can not only capture the pump suction recirculation and the low frequency fluctuation caused by it, but also combine the changes of the shaft frequency amplitude acting on the impeller with the cavitation unstable characteristics. Thus the LES model has more advantages than RNG \( k-\varepsilon \) model in calculating the unsteady cavitating flow in a centrifugal pump.

1. Introduction
Cavitation is a very complex vapour-liquid two-phase flow including phase changes and viscous effects cavitation [1]. Therefore, its simulation presents significant modelling difficulties due to the consideration of the multiphase model, the cavitation model as well as the turbulence model. For a long time, researchers have done more works to study the influence of turbulence models on the cavitating flow field and found that the RNG model could obtain successful results around the foil or the hydrofoil. Such as: Li et.al [2] successfully predicted the unsteady characteristics of cavitation region around a hydrofoil using this model. Tan et al.[4] exactly simulated the periodic evolution of the unsteady cavitation including the incipit, development, rupture and take off for a two-dimensional NACA66 airfoil. Qian et al.[3] also found that the accuracy of the RNG model is relative higher than others according to the calculation results. In recent years, the LES model is applied gradually with an advantage of capturing the unsteady cavity collapse characteristic. Zhang et al.[6] and Yu et al. [7] observed the obvious unsteady cloud cavitation characteristic for the Clark-y foil by combining the LES method with the RNG model. Besides, Wang and Starzewsk [5] obtained the periodical shedding details of cavitation cloud for the NACA0015 foil.

In spite of above researches, the influence of turbulence models on the cavitating flow field for a centrifugal pump is still less studied, in which the computational results present large differences with various turbulence models. In this paper, the RNG and the LES turbulence model were compared...
for a centrifugal pump with respect to the pump performance, cavity unsteady feature and pressure fluctuation, aimed to give out the reasonable suggestions on selecting the turbulence model in the pump cavitating flow field.

2. The calculation model

2.1. computational domain and grids
The calculation model is a single stage centrifugal pump with specific speed 97.1, impeller diameter 180mm, and rotating speed 2900rpm.

Two sets of mesh schemes were used here due to different grid accuracy requirement in near wall region for both the RNG and the LES model. One is that the unstructured grids were adopted in the impeller mainly suitable for the RNG model, as shown in figure 2(a); another is that the boundary layer meshes were added in blade near wall zone mainly suitable for the LES model, as shown in figure 2(b). Besides, the unstructured hybrid grids were used for rest components, and the whole calculation domain grids were shown in figure 1.

![Figure 1. Calculation domain and mesh.](image)

![Figure 2. Comparison of meshes in the impeller.](image)

Grid independence tests have been done and no major influence of grid size was observed on the global performances. Finally, the meshes for the RNG and LES turbulence model were 1.42 and 2.45 million respectively. Here, one blade named “Blade 1” is marked out in convenient for the later analysis, as shown in figure 1.

2.2. Boundary condition
The boundary conditions were specified with a velocity inlet and a pressure outlet. At the solid wall, no-slip condition was adopted and wall function was applied in near wall computation zone. In order to improve the rapidity of convergence and stability of calculation, the calculation results of single phase and steady flow were initialed for cavitating flow.

2.3. Cavitation model
A homogeneous multiphase model was applied for the cavitation model [8]. The Zwart-Gerber-Belamri cavitation model was employed to describe the growth of a gas bubble[9], and the saturated vapor pressure was 3574Pa. The total calculation time is about ten revolution times (T is one revolution time), the time-step used was of $\Delta t = 1/120T$.

2.4. Turbulence model
The RNG model[10] is based on the analysis theory of Navier-Stokes equations renormalization group, in which the turbulence generated and dissipative term is the same with the standard model.
except for the different model constants. This model has been selected based on its ability to accurately predict the high strain rate and large streamline curvature flow with considering the large scale separation effect on the wall, so it can obtain good results in predicting the three-dimensional unsteady flow in rotating machinery.

For the LES model, the big three-dimensional eddies which are dictated by the geometry and boundary conditions of the flow involved are directly resolved, whereas the small eddies which tend to be more isotropic and less dependent on the geometry are modeled. Two constant sub-grid-scale models, namely the Smagorinsky–Lilly model and the dynamic eddy viscosity model are widely used as well as the latter is more convenient in the practical application.

3. Results analysis
The unsteady flow simulation was performed using Zwart-Gerbe-Belamri cavitation model with the RNG and LES turbulence model for a centrifugal pump under 0.7Qo. Meanwhile, the comparisons were conducted with respect to the energy characteristic, cavity unsteady feature and pressure fluctuation.

3.1. Influence of turbulence model on the pump performance

![Figure 3(a). Comparison of NPSH-H curves.](image)

![Figure 3(b). Comparison of NPSH-η curves.](image)

Convergence criteria of cavitating flow calculations were based on the comparisons between inlet and outlet mass-flow rates (allowed maximum error<0.4%). It is worth noting that each calculated unsteady state solution was carefully converged. The calculated performance curves with the two models were compared in figure 3, where the head difference is limited in 2% before the head dropped significantly (Cond. A and B), and the difference is continue narrowing when the cavitation is more serious(Cond. C, D and E), indicating both the two turbulence models have a certain precision in calculating the cavitating flow. The pump efficiency obtained by using the LES model is slightly lower than that from the RNG model as shown in figure 3(b).

Some typical conditions (A,B,C D and E) were selected for the following analysis, in which Cond. A corresponds to non-cavitation case. Cond. B and C are the inception and developed of the cavities, Cond. E corresponds to the serious cavitation stage; D is a condition just before the sudden head drop.

3.2. Influence of turbulence model on the cavity evolution characteristics
For this centrifugal pump, cavities first appear on the suction side of blades (Cond. B); then the cavities grow toward the flow passage center accompanied with a significant unstable characteristic including cavity growth and contraction as a lower NPSH (Cond. C), and this unsteady feature is relatively weakened when the cavities reach the throat between the two adjacent blades(Cond. D and E). It can obviously found that the cavity unsteady feature is significant in condition C, in which the difference of cavity separation for each turbulence model can better be reflected. Thus, the cavity evolution and streamline distribution on “Blade 1” at 6 special positions (θ=0°, 60°, 120°, 180°, 240°, and 300°) were compared with the RNG and LES methods for this cavitation stage, as shown in figure 4. Define the angle θ=0° is the location where the blade front, blade rotation center and tongue in a straight line, as shown in figure.1 for “Blade 1”.

6th International Conference on Pumps and Fans with Compressors and Wind Turbines IOP Publishing
IOP Conf. Series: Materials Science and Engineering 52 (2013) 062015 doi:10.1088/1757-899X/52/6/062015
\[ \theta = 0^\circ, t = 0 \]
\[ \theta = 60^\circ, t = 1/T \]
\[ \theta = 120^\circ, t = 2/T \]
\[ \theta = 180^\circ, t = 3/T \]
\[ \theta = 240^\circ, t = 4/T \]
\[ \theta = 300^\circ, t = 5/T \]

**Figure 4(a).** Cavity evolution and streamline distribution in Z=0 section (Cond. C, RNG \(k-\varepsilon\) model)

\[ \theta = 0^\circ, t = 0 \]
\[ \theta = 60^\circ, t = 1/T \]
\[ \theta = 120^\circ, t = 2/T \]
\[ \theta = 180^\circ, t = 3/T \]
\[ \theta = 240^\circ, t = 4/T \]
\[ \theta = 300^\circ, t = 5/T \]

**Figure 4(b).** Cavity evolution and streamline distribution in Z=0 section (Cond. C, LES model).
The two-phase areas appear in yellow (the surface drawn corresponds to a 5% void ratio); the “Blade 1” and its passage are colored by red curve. The unsteady cavity process predicted by the RNG model can be divided into four stages: Firstly, a small attached cavity around the blade head is observed together with a large separated cavity in the flow channel at 0° position. Then the separated cavity grows and combines with the small cavity on blade head into a narrow cavity as the blade moving out of the volute tongue in cavity growth stage (60°-120°). This cavity has a small length but an extreme thickness in local contraction stage (120°-180°). Barely change of the cavity shape in the steady stage (180°-240°). But when the blade newly arriving the tongue in the separation stage (240°-0°-60°), this cavity contracts and eventually falls off from the roots of cavity due to the high pressure on volute tongue. Therefore the cavity completes the evolution of one cycle. It can also be found that the cavity evolution process in other passages are not only the same with passage 1, but also the cavity shape is basically identical in the same blade-tongue position, reflecting an obvious periodical unsteady cavitation characteristic with a frequency corresponding to the impeller passing frequency.

The unsteady cavity process obtained by the LES model also has four stages including cavity growth, local contraction, stable and separation in one rotating period with the similar cavity shape on each blade in spite of the slightly difference in cavity closure region shape. As a whole, both the two models can well simulate the unsteady cavity evolution characteristics.

3.3. Influence of turbulence model on the pressure fluctuation
The low frequency fluctuation is a typical feature of the cavitating flow field [12]. In order to further discuss the difference of each turbulence models, the pressure fluctuation was analyzed and the monitor points were shown in figure 5. In which the monitor point P0 is located in the interface center between the inlet pipe and impeller, monitor point PS1 and SS1 are located in impeller import region.

![Figure 5. monitor points.](image)

3.3.1. pressure fluctuation for pump inlet

![RNG model](image)
The pressure fluctuation and frequency spectrum predicted by these two methods for point P01 were shown in figure 6. In which the horizontal coordinate $f/f_r$ indicates the ratio of frequency and axial frequency; the vertical coordinate is the pressure amplitude.

The following typical frequencies mainly exist in the flow field: shaft Frequency $f_s = n/60 = 48.8 \text{Hz}$, blade passing frequency $f_b = Z/60 = 290 \text{Hz}$. The dominant frequency on pump inlet is $6f_r$ and the amplitude on which is decreased with the development of cavitation calculated by the RNG $k-\varepsilon$ model. While the results from the LES model indicate that the dominant frequency is still $6f_r$ with some low frequency components occurred ahead of the blade passing frequency in condition A; then the blade passing frequency amplitude is reduced but the low frequency components is added in condition B; and each frequency amplitudes are quickly reduced from condition C to E. Therefore, the biggest difference for each turbulence model is the ability to capture the low frequency components on pump inlet.

For better explain this low frequency, the vorticity contours in the impeller passage predicted by these two models were shown in figure 7. Clearly be seen that a certain intensity of vorticity near the shroud in the impeller inlet is captured by the LES model, as labeled by black circle, while the RNG $k-\varepsilon$ model cannot predict this phenomenon. Therefore, the low frequency component has more relation with the pump suction recirculation, and the LES model has some advantages in capturing this flow characteristic.

3.3.2. Pressure fluctuation for impeller passage

**Figure 6.** Pressure fluctuations and frequency spectrums at different cavitation stage.

**Figure 7.** Comparison of the vorticity in the impeller channel (Cond.A).
The frequency spectrums for point SS1 and point SS2 at different cavitation conditions were compared with the two models. As shown in figure 8, the dominant frequency at all the conditions is the same value of $f_r$, which is approximate to the shaft frequency. The results from the RNG $k-\varepsilon$ model indicate that the amplitude of the dominant frequency is continuing decrease with the development of cavitation. However, the shaft frequency amplitude first increased and then decreased in this cavitation process by the LES model with the maximum amplitude appeared in condition C, which is corresponding to the changes of cavity instability characteristics according to the above analysis.

LES model uses the dynamic grid stress model in the turbulent core zone with a good ability to capture the fluctuation of the small scale vortex movement; therefore the calculated results can obtain the strong gas-liquid exchange in detail and effectively combine the unsteady characteristics of cavitation with the pressure pulsation. While, the RNG model treats the different scale vortex as the same in the flow field and neglects the spatial and temporal variations of fluctuation according to the average computation, thus the calculated pulsation cannot accurately reflect the pressure fluctuation characteristics in cavitation sensitive region, and therefore this model is superior than LES model in simulating the pressure pulsation of the cavitating flow field.

4. Conclusion
In this paper, the unsteady flow simulation was performed using Zwart-Gerbe-Belamri cavitation model combining the RNG $k-\varepsilon$ and LES turbulence model for the centrifugal pump under $0.7Q_0$. The comparisons were conducted with respect to the pump characteristic, cavity unsteady feature and pressure fluctuation.

1) Both the two models give almost the same results with respect to pump performance and cavitation evolutions including growth, local contraction, stability and separation in the impeller passage.
2) The LES model can not only capture the pump suction recirculation and its corresponding low frequency component but also combine the changes of the shaft frequency amplitude acting on the impeller with the cavitation unstable characteristics. Thus the LES model has more advantages than RNG model in calculating the unsteady cavitating flow in a centrifugal pump.

Nomenclature:

\[ NPSH = \frac{P_{in} - P_v}{\rho g} + \frac{v_{in}^2}{2g} \]

- \( P_{in} \): Inlet total pressure (Pa)
- \( P_v \): Saturated vapor pressure (Pa)
- \( v_{in} \): Inlet velocity (m/s)

Acknowledgments

The authors gratefully acknowledge the support from the National Natural Science Foundation of China (No. 51279205) and the Open Research Fund Program of State Key Laboratory of Hydroscience and Engineering (No. sklhse-2012-E-01).

References

[1] Huang B and Wang G Y 2010 China Mechanical Engineering 21(1) 85-88 (in Chinese)
[2] Li X B, Wang G Y Zhang B and Yu Z Y 2008 Transactions of Beijing Institute of Technology 28(11) 975-978 (in Chinese)
[3] Tan L and Cao S L 2010 Journal of Jiangsu University 31(6) 683-686 (in Chinese)
[4] Qian Z D and Huang S H 2006 Advances in Water Science 17(2)203-208 (in Chinese)
[5] Zhang M, Tan J J Yi W J Chen Z H and Cai X W 2012 Journal of Nanjing University of Science and Technology 36(2) 314-319 (in Chinese)
[6] Yu Z L, Gu L Y Li X B and Wang G Y 2008 Transactions of Beijing Institute of Technology 28(1) 32-36 (in Chinese)
[7] Wang G and Ostoja-Starzewski M 2007 Applied Mathematical Modelling 31(3) 417-447 (in Chinese)
[8] Li Z 2011 Doctor Dissertation (Jiangsu University, China) (in Chinese)
[9] Zwart P, Gerber A G and Belamri T 2004 A Proceedings of ICMF 2004 International Conference on Multiphase Flow, Yokohama, Japan 1－11 (in Chinese)
[10] Launder B E and Spalding D B 1974 Computer Methods in Applied Mechanics and Engineering 3(2) 269-289 (in Chinese)
[11] Mi Z L and Jiang M 2004 Journal of Shaoyang University 3(1) 88-91 (in Chinese)
[12] Wang Z J and Zhang Y X 1994 Journal of Shandong Mining Institute (13) 1-5 (in Chinese)