Liquid-solid steady and unsteady flow analyses in a Francis turbine using Eulerian-Lagrangian Modified Partially Average Navier-Stokes

Edgar Cando, Department of Thermal Engineering, Tsinghua University, Beijing, China,
XianWu Luo, Department of Thermal Engineering, Tsinghua University, Beijing, China,
Esteban Valencia, Departmento de Ingeniería Mecánica, Escuela Politecnica Nacional, Quito, Ecuador

Long Abstract

Introduction

Hydropower plays an important role in the contribution of global electricity supply, whose tapping has been increased in the last years. Despite of numerous hydropower plants in operation, South America and Asia continue to have many untapped hydro resource and their demand energy is the highest due to the industry development and population growing [1]. However their rivers show a presence high concentration of fine solid particles due to heavy precipitation in weak geological formations and ash expulsed from volcanos activation. This characteristic leads to the problems like head and efficiency drop produced by liquid-solid flow behavior and intense wear of the flow components in Francis turbines [2]. Thus, it is necessary to understand the features of liquid-solid two phase flows so as to improve the operation of hydraulic machines and to predict the solid particle erosion in the flow passage components [3]. Although numerous scholars have been devoted to study of solid particle flow prediction in Francis turbines with CFD method, rather less attention has been paid to study the proper turbulent diffusion and dispersion characteristics of particle motions using non-conventional turbulence models. Guangjie et al. [4], Koirala et al.[5], Eltvik [6], Neopane [7] predict solid particle erosion in Francis turbine based on liquid-solid two phase flow simulation. On other side, Huang et al.[8], Wu et al. [9], Zhang et al. [10] carried out unsteady numerical simulation for liquid-solid flow in hydraulic machines. However, they used conventional turbulence model as standard k-ε, RNG k-ε SST k-ω. These turbulence models show limitations to predict the flow in Francis turbines [11][12], which according previous studies over-estimate the viscosity [13][14], therefore the instantaneous fluid velocity of the continuous used to calculate motion of particles.
The purpose of the present work is to use the modified Partially-Averaged Navier-Stokes model to investigate the unsteady liquid-solid two phase flow using Eulerian-Lagrangian, in the whole passage of a model Francis turbine, which includes the spiral casing with stay and guide vanes, the runner and the draft tube. Attention is focused on the internal flow to better understand the liquid-solid flow characteristic. Finally, the liquid and solid velocities, particle distribution are analyzed due to strongly correlated with turbulence flow behavior.

1. Methods

The numerical simulation is carried out using modified Partially-Averaged Navier-Stokes model (MPANS) based on the Eulerian approach, coupled with dispersed phase with Lagrangian approach. The mesh of CFD computation domain is established on design point operation (head H=30.07 m and rotation speed 872 rpm) and consists of a spiral casting, stay vanes and guide vanes, a runner and a draft tube. The parameters fo the model turbine are: runner diameter i.e. D_1= 420 mm, runner blade number Z_b=17, relatively heigh of the guide vane b_0=0.18257.
A commercial CFD code, ANSYS FLUENT 14.0, is used to solve the equations. The modified Partially-Averaged Navier-Stokes model has been implemented via user defined functions (UDF). The solid particle injection is applied using the disperse particle method (DPM) at the inlet boundary condition. The main features of the turbulence solver are given bellow.

The MPANS mode proposed by Huang [13] treats the standard k-ε model as parent RANS model as follow

$$\frac{\partial(\rho_q k_u)}{\partial t}+\frac{\partial(\rho_q u_i k_u)}{\partial x_i}=-\rho_q\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j}-\rho_q\varepsilon_u+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_{ut}}{\sigma_{ku}})\left(\frac{\partial k_u}{\partial x_j}\right)\right] \quad (1)$$

$$\frac{\partial(\rho_q\varepsilon_u)}{\partial t}+\frac{\partial(\rho_q u_i\varepsilon_u)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_{ut}}{\sigma_{\varepsilon u}})\left(\frac{\partial\varepsilon_u}{\partial x_j}\right)\right]+C_{1\varepsilon}\left(\rho_q\overline{u'_i u'_j}\frac{\partial u_i}{\partial x_j}\right)\frac{\varepsilon_u}{k_u}-C^*_{2\varepsilon}\frac{\varepsilon_u^{\,2}}{k_u} \quad (2)$$

where k_u and ε_u are the turbulence kinetic energy and dissipation rate, respectively. The model coefficients σ_{ku}, $\sigma_{\varepsilon u}$ *and* $C^*_{\varepsilon 2}$ are different from the parent standard k-ε model.

$$\sigma_{ku}=\sigma_{k_k}\frac{f_k^2}{f_\varepsilon},\sigma_{\varepsilon u}=\sigma_\varepsilon\frac{f_k^2}{f_\varepsilon},C^*_{2_\varepsilon}=C_{\varepsilon 1}+\frac{f_k}{f_\varepsilon}(C_{\varepsilon 2}-C_{\varepsilon 1})$$

The unresolved ratio f_ε is set to 1.0 and f_k is given by

$$f_k=\min(1,3(\Delta/l)^{1.5})$$

where l is the turbulence length scale ($l=k^{1.5}/\varepsilon$), and Δ is the local grid size ($\Delta=\Delta x.\Delta y.\Delta z)^{1/3}$.

Finally, the eddy kinematic viscosity is given by

$$\mu_{ut}=C_\mu\rho_q\frac{k_u^{\,2}}{\varepsilon_u}$$

Reference

[1] B. S. Thapa, O. G. Dahlhaug, and B. Thapa, “Sediment erosion in hydro turbines and its effect on the flow around guide vanes of Francis turbine,” *Renew. Sustain. Energy Rev.*, vol. 49, pp. 1100–1113, 2015.

[2] B. Singh, O. Gunnar, and B. Thapa, “Sediment erosion in hydro turbines and its effect on the fl ow around guide vanes of Francis turbine,” *Renew. Sustain. Energy Rev.*, vol. 49, pp. 1100–1113, 2015.

[3] Y. Zhang, E. P. Reuterfors, B. S. McLaury, S. a. Shirazi, and E. F. Rybicki, “Comparison of computed and measured particle velocities and erosion in water and air flows,” *Wear*, vol. 263, no. 1–6, pp. 330–338, Sep. 2007.

[4] P. Guangjie, W. Zhengwei, X. Yexiang, and L. Yongyao, “Abrasion predictions for Francis turbines based on liquid-solid two-phase fluid simulations,” *Eng. Fail. Anal.*, vol. 33, pp. 327–335, 2013.

[5] R. Koirala, B. Thapa, H. P. Neopane, B. Zhu, and B. Chhetry, “Sediment erosion in guide vanes of Francis turbine: A case study of Kaligandaki Hydropower Plant, Nepal,” *Wear*, vol. 362–363, pp. 53–60, 2016.

[6] Eltvik Mette, “Sediment erosion in Francis turbines,” *Ph.D. thesis*, 2013.

[7] H. Neopane, “Sediment erosion in hydro turbines,” *Ph.D. thesis*, no. March, p. 201, 2010.

[8] S. Huang, X. Su, and G. Qiu, “Transient numerical simulation for solid-liquid flow in a centrifugal pump by DEM-CFD coupling,” *Eng. Appl. Comput. Fluid Mech.*, vol. 9, no. 1, pp. 411–418, 2015.

[9] B. Wu, X. Wang, H. Liu, and H. Xu, “Numerical simulation and analysis of solid-liquid two-phase three-dimensional unsteady flow in centrifugal slurry pump,” *J. Cent. South Univ.*, vol. 22, no. 8, pp. 3008–3016, Aug. 2015.

[10] Y. Zhang, Y. Li, B. Cui, Z. Zhu, and H. Dou, “Numerical simulation and analysis of solid-liquid two-phase flow in centrifugal pump,” *Chinese J. Mech. Eng.*, vol. 26, no. 1, pp. 53–60, 2013.

[11] A. V Minakov, A. V Sentyabov, D. V Platonov, A. A. Dekterev, and A. A. Gavrilov, “Numerical modeling of flow in the Francis-99 turbine with Reynolds stress model and detached eddy simulation method,” *J. Phys. Conf. Ser.*, vol. 579, no. 1, p. 012004, 2015.

[12] Z. Yaping, L. Weili, R. Hui, L. Xingqi, and H. Engineering, “Performance study for

Francis-99 by using different turbulence models," *Fr. Work.*, vol. 012012, 2014.

[13] R. Huang, X. Luo, B. Ji, and Q. Ji, "Turbulent flows over a backward facing step simulated using a modified Partially-Averaged Navier-Stokes model," *J. Fluids Eng.*, no. c, 2016.

[14] Anwar-ul-Haque, F. Ahmad, S. Yamada, and S. R. Chaudhry, "Assessment of Turbulence Models for Turbulent Flow over Backward Facing Step," in *World Congress on Engineering 2007 Vol II*, 2007, vol. II, pp. 1–6.