การศึกษาการไหลของอากาศผ่านเนินเขาเปรียบเทียบระหว่างภูมิประเทศและรูปทรงเลขาคณิตโดยกระบวนการจำลองทางพลศาสตร์ของไหล

CFD Evaluation of Wind Flow Over Hill: A Comparison of Trapezoid Hill Shape and Relative Geometry

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บทคัดย่อ

บทความนี้อาศัยกระบวนการทางอุตุนิยมวิทยาและการจำลองทางพลศาสตร์ของไหลเพื่อศึกษารูปแบบการไหลของมวลอากาศที่ไหลผ่านเนินเขา โดยการเปรียบเทียบผลที่ได้รับจากแต่ละวิธีการเพื่อหาแบบจำลองความปั่นป่วนและวิธีการกำหนดเงื่อนไขขอบเขตของแบบจำลองที่เหมาะสมสำหรับใช้กับการจำลองเพื่อนำมาทดแทนการเก็บข้อมูลในพื้นที่จริงในอนาคต ส่วนแรกของบทความนำเสนอตำแหน่งที่เหมาะสมสำหรับการติดตั้งกังหันลมผลจากการจำลองแสดงว่าแบบจำลองความปั่นป่วน Standard k-ε ให้ผลการจำลองแม่นยำที่สุดบริเวณด้านหน้าเนินเขา ขณะที่แบบจำลอง Reynolds Stress Model แสดงผลที่ใกล้เคียงกับการทดลองมากที่สุดเมื่อผ่ายจุดยอดของเนินเขาไป 1.0 เท่าของความสูงเนินเขา ส่วนแบบจำลอง Standard k-ε และ Standard k-ω แสดงค่าที่ต่ำกว่าการทดลองมาก ส่วนหลังของบทความนำเสนอตำแหน่งศักยภาพลมเปรียบเทียบระหว่างภูมิประเทศจริงและรูปทรงเลขาคณิตที่มีเงื่อนไขขอบเขตคล้ายคลึงกันเพื่อเป็นข้อมูลสำหรับสร้างกราฟความสัมพันธ์ระหว่างมุมของเนินเขา ความเร็วลม ความหยาบของพื้นผิวและแสดงตำแหน่งศักยภาพลมของเนินเขานั้น ๆ ซึ่งจะช่วยลดขั้นตอนสำหรับการศึกษาตำแหน่งติดตั้งกังหันลมต่อไปในอนาคต

คำสำคัญ: การจำลองทางพลศาสตร์ของไหล แบบจำลองความปั่นป่วน ตำแหน่งศักยภาพลม

Abstract

Computational fluid dynamics is used to explore new aspects of wind flow over a hill. This analysis focuses on flow dependency and comparison of results from measurements and simulations to show the optimum turbulance model and the possibility of replacing measurements with simulations. The first half of the paper investigates a suitable turbulence model for the suitable site of a wind turbine. Results of the standard k-ε model are compared precisely with the measures in front of the hill top; while the Reynolds Stress Model showed exact results after 1.0 times of hill steep ness, but the standard k-ε model and standard k-ω model showed more of an underestimation. In addition, velocity flow over Pha Taem hill topography and reference geometry shape are compared to find a suitable site for a turbine in case the actual hill structure is associated with geometric shape. Further study of the geometry shape of the hill and its suitable site will be reported elsewhere.

Keywords*:* computational fluid dynamics, turbulent model, suitable site

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Introduction

World energy consumption has increased significantly in the last decade However, the use of fossil fuels creates serious environmental problems, including acid emissions, air pollution and climate change Many countries provide renewable energy such as solar, wave, geothermal or wind energy. Today, the use of wind energy technology has been developing very fast[1-5] given that wind power is a local resource and that it is a clean and environmentally friendly resource.

The Energy Policy and Planning Office of Thailand (EPPO) showed electricity consumption of the year 2009 of 134,729.89 GWh, which 2,460.09 was imported from neighboring countries. The cumulative electricity energy increased by an average of 10.5% and 39.9% from year 2005 and 1999, respectively. Mainly, the energy resources of Thailand are crude oil, coal and natural gas. The reports of EPPO showed in December 31, 2008 reserved raw energies were 183 MMBBL of crude oil and 12,003 BCF of natural gas[6]. So, wind energy is an alternative energy which reduces electrical energy imported and environmental friendly.

The Ubonratchathani region has 16,112 square kilometers and a 1.8 million population[7] on the plateau in southeastern of Thailand. The average region is situated at approximately 123 m from the sea level.The 51.07% of region are farm land and 78% of electricity is used in household and agricultures [6].

Pha Taem national park is located at the eastern edge of Ubonratchathani district near the Khong river. Figure 1 showed that the hill top is 240 m above from ground level with 20.06° slope. The terrain behind the hill top is a 1.66° rockbound slope with few obstacles, while the front of the hill is farmland and river. The hill structure is located perpendicular to one fourth of the wind impact direction.

Nowadays computational fluid dynamics techniques are used worldwide to investigate suitable site for turbines. The effect of a rough surface, wall function problem, turbulent model et al. were simulated to adopt most energy from the wind[7-11]. The Fluent commercial codes with turbulent models were used in this article because of their ready availability well developed interface and broad verification and validation.

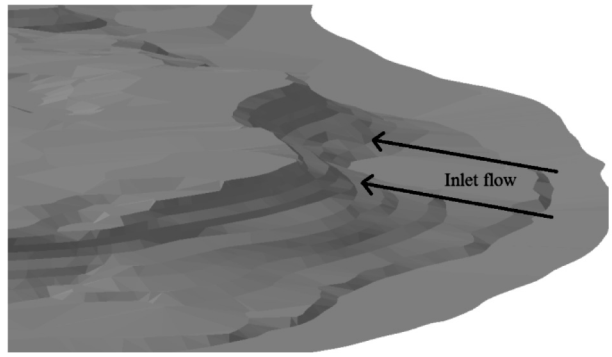


Figure 1 Geographic Information System of geometry with 1:50,000 resolutions

The case chosen in this analysis was measured March 11, 2011 at 9:00 - 11:00. The ambiant was generally found at 27.2°C of mean tempreature and the mean pressure was 1009.43 pascal. The mean wind speed at 10 m height of reference station was 2.728 m/s and direction was 2.4 ° vertical with 10.8 ° turning.

Turbulence model description

Turbulence of flow is difficult to define precisely, and is most often described by its properties. The first property of turbulence described by Panofsky and Dutton[5], states that the fluid velocity is a chaotic and apparently random function of both space and time. This means that the turbulent information is contained in the velocity fluctuations. The only expression containing the velocity fluctuations is the Reynolds stresses, which therefore represent the turbulence of the flow. Another property of the turbulence is non-linearity. The Reynolds stresses are also non-linear terms, in accordance with its property are in the Reynolds Averaged Navier-Stokes equations:

$$P\frac{\partial U_i}{\partial t} + U_j\frac{\partial U_i}{\partial x_j} = -\frac{1}{p}\frac{\partial p}{\partial x_i} - \frac{\partial \overline{U_i U_j}}{\partial x_j}, \quad (1)$$

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (2)$$

where U_j are the Reynolds averaged components of the mean flow, P is the pressure and ρ is the density and $u_i u_j$ with an overbar are turbulent stresses. This formulation includes both vertical and horizontal turbulent flux divergence. Equations for each of the six Reynolds stresses and dissipation are solved at each time step to close the mean equations. The model equations are solved using a fractional step method in which the equation for pressure is derived in such a way that it ensures a divergence-free momentum field.

The standard k-ε model is an industrial standard turbulence model in engineering practice. In this case, the transport equations of momentum, potential temperature, mixing ratio of water vapors and turbulence energy are adopt, while near-wall treatment are enhanced[6]. Because of their computational robustness and efficiency, the two-equation k-ε turbulence model and its variants are most commonly used in wind energy researches[12-13]. In particular, they have been extensively validated and calibrated for engineering application flows around bluff bodies and structures[14].

k-model

The standard k-ε model[15] is a semi-empirical model based on model transport equations for the turbulence kinetic energy (*k*) and its dissipation rate (ε). The model transport equation for *k* is derived from the exact equation, while the model transport equation for ε was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart. In the derivation of the k-ε model, it was assumed that the flow is fully turbulent, and the effects of molecular viscosity are negligible. The standard k-ε model is therefore valid only for fully turbulent flows, so that

$$\mu_{eff} = \mu + \mu_t \qquad (3)$$

where μ_t is the turbulence viscosity. The *k*-ε model assumes that the turbulence viscosity is linked to the turbulence kinetic energy and dissipation via the relation

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \qquad (4)$$

k-model

The standard k-ω model is an empirical model based on model transport equations for the turbulence kinetic energy (*k*) and the specific dissipation rate (ω), which can also be thought of as the ratio of ε to *k*[16].

One of the advantages of the *k*-ω formulation is the near wall treatment for low-Reynolds number computations. The model does not involve the complex non-linear damping functions required for the *k*-ω model and is therefore more accurate and more robust. A low-Reynolds *k*-ω model would typically require a near wall resolution of $y^+<0.2$, while a low-Reynolds number *k*-ω model would require at least $y^+< 2$. In industrial flows, even $y^+< 2$ cannot be guaranteed in most applications and for this reason, a new near wall treatment was developed for the *k*-ω models. It allows for smooth shift from a low-Reynolds number form to a wall function formulation.

The *k*-ω models assumes that the turbulence viscosity is linked to the turbulence kinetic energy and turbulent frequency via the relation

$$\mu_t = \rho \frac{k}{\omega} \qquad (5)$$

Reynolds Stress Model

The Reynolds stress model[17-19]involves calculation of the individual Reynolds stresses, , using differential transport equations. The individual Reynolds stresses are then used to obtain closure of the Reynolds-averaged momentum equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'}) \qquad (6)$$

The exact form of the Reynolds stress transport equations may be derived by taking moments of the exact momentum equation. This is a process wherein the exact momentum equations are multiplied by a fluctuating property, the product then being Reynolds averaged. Unfortunately, several of the terms in the exact equation are unknown and modeling assumptions are required in order to close the equations. In this section, the Reynolds stress transport equations are presented together with the modeling assumptions required to attain closure.

Simulation

Experimental basis

Pha Taem national park is located in the eastern edge of Ubonratchathani district far from the Khong river The hill is 240 m height from the bottom ground with 20 degree slope. The wind data for this analysis was measured to compare with the simulation. The ambient temperature was generally found at 27.2°C of mean tempreature and the mean pressure was 1009.43 pascal. The mean wind speed at 10 m height of reference station was 2.728 m/s and direction was 2.4°with 10.8° turning.

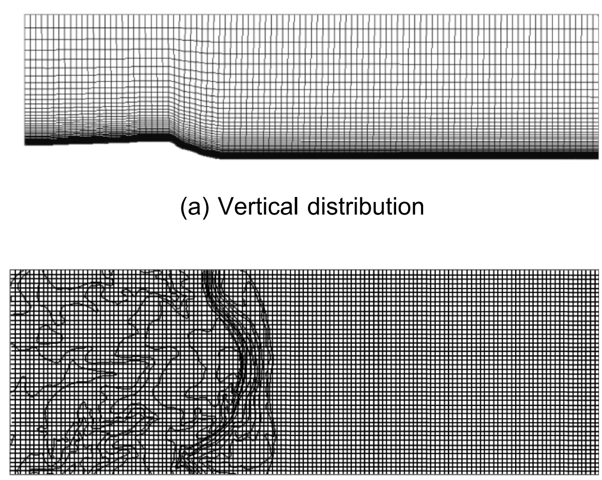
A cup anemometer and wind vane with 0.1 m/s and 1.0°accreted were used to measure wind speed and direction at 10 m height, respectively. The measurement sites in front of hill top were at -1.0 and -1.5 time of front hill distance while behind the hill top were measure at 0.0, 0.5, 1.0, 1.5 and 2.0 time of front hill distance.

The mean wind speed at -2.0 time of front hill distance which is the reference station was 2.728m/s and the direction was 2.4°with 10.8° turning, while mean temperature and pressure was 27.2°C and 1009.43Pascal, respectively.

Grid arrangements and boundary conditions

Figure 2 illustrated the grid used in the simulations highly influences the results. Both the grid resolution and accuracy of the terrain data are important. The simulation domain is chosen to include the neighboring hills behind the Pha Taem hill, and the grid used in the simulations has a horizontal extension from 1 km in front of the hilltop, to 1 km behind the hilltop. The width of the domain is about 1 km, and the height of the domain is 1 km. The horizontal and vertical distribution of the grid cells is visualized in Figure 3.8(a) and 3.8(b), respectively. The resolution in the center is Δx = 1.0 m and Δy = 1.0 m This is constant in a central square of 500m x 500m, with a linear increase of 11% in the x-direction and 9% in the y-direction outside this square. The largest cell is109.53 m in the x-direction and 27.69 m in the y-direction. The height of the first grid cell is Δz = 1.0 m. With a vertical stretching of 10%, the largest vertical extension is 108.54 m. The total amount of grid cells is 590x564x45.

A one-dimensional simulation is done to establish a profile over homogeneous conditions. With the roughness length z_0=0.04 m, the simulated velocity 10 m above ground level becomes 2.728 m/s. This profile is used as whole inflow boundary condition and initial condition for the entire domain. At the side boundaries there are periodic boundary conditions, and at the outflow boundary there is a zero-gradient condition. The surface boundary condition is expressed by wall functions, connecting the velocity in the first cell to the roughness and the log law assumption. The top boundary is as a zero-gradient surface in all variables except the vertical velocity, which is defined not to allow any material transports through the boundary. This means a vertical velocity equal to zero at the top boundary.



(a) Vertical distribution

(b) Horizontal distribution

Figure 2 Distribution of grids cells used in the simulations

Results

General results

3 showed the Comparison of wind profile at reference station from standard k-ε model, standard k-ω model, RSM, and measurements were compared at the vertical velocity along -1.0 time of front hill distance in front of hill top. The simulations and measurements were compared at 5m, 10m, 15m and 20m height. The comparison showed the measures was related with standard k-ε model. Since, some results data from the standard k-ε model were in uncertainty range of the measured, while trend line of standard k-ω model and RSM was dissimilar. The standard k-εmodel has been shown to be useful for free-shear layer flows with relatively small pressure gradients. Similarly, for wall-bounded and internal flows, the model gives good results only in cases where mean pressure gradients are small; accuracy has been shown experimentally to be reduced for flows containing large adverse pressure gradients.

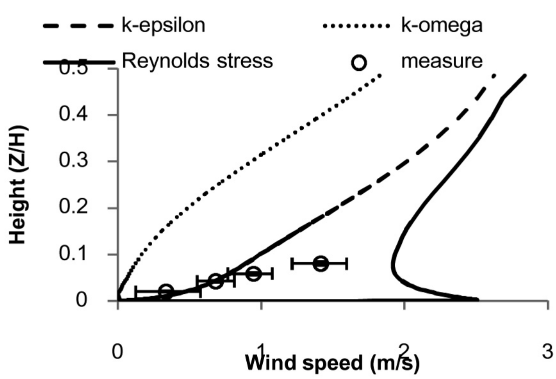


Figure 3 Wind velocity profile at reference station

Comparison of velocity

The horizontal velocity comparison showed increased velocity in RSM while k-ε model and k-ω model showed similar results. In Figure 4 is the velocity increase of each model of RSM, k-ε model and k-ω model occurred 16.45%,8.42%and 7.76%, respectively. And the maximum velocity in simulation appeared in turn at 2.36, 2.11and 1.73 times of hill height.

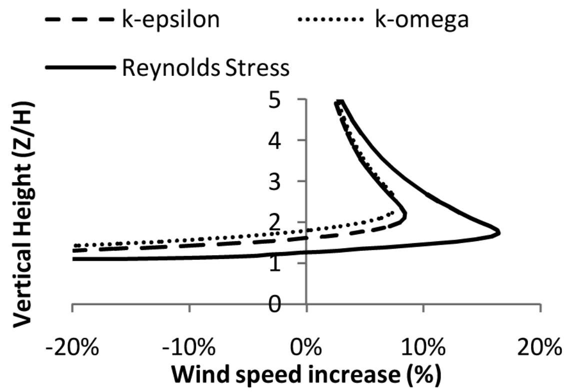


Figure 4 Comparison of increasing speed at hill top

Figure 5 showed the comparison of velocity and uncertainty limits at 10 m height from ground of measured and the simulated. The results separated in three phase, in the initial phase standard k-ε model showed similar results with the measured. In the second phase along the hill top to 1.0 times of hill steep the simulation showed that results from standard k-ε model and standard k-ω model was an underestimation while RSM showed overestimation. The final phase, after 1.0 times of hill steep, the RSM showed the exact result but the standard k-ε model and standard k-ω model showed more underestimation, because RSM naturally includes the effects of streamline curvature, sudden changes in the strain rate, secondary flows or buoyancy compared to turbulence models using the eddy-viscosity approximation.

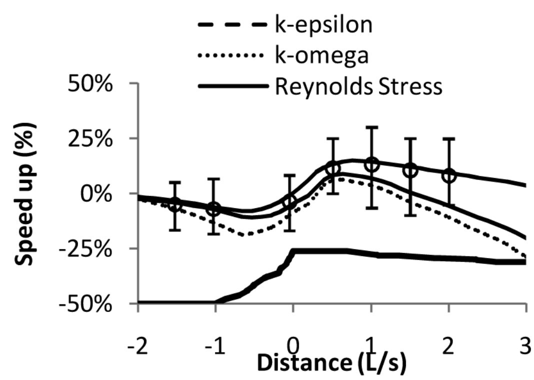


Figure 5 Comparison of velocity at 10m height from ground along the hill

Comparison of turbulence kinetic energy

Figure 6 illustrated turbulence kinetic energy along wind direction, comparison of measured and simulated. After the distance 0.5 L/s the complete simulation appeared as an underestimation of TKE at 10 m height.

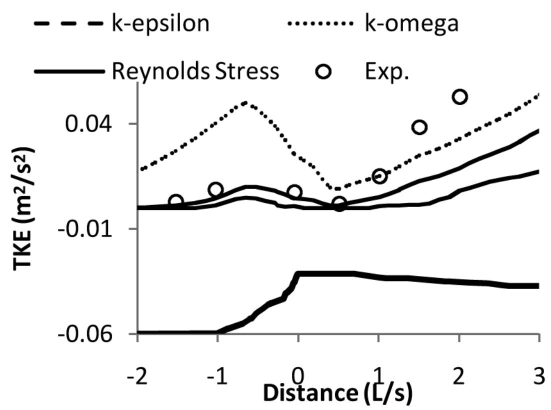


Figure 6 Comparison of turbulence kinetic energy along wind direction at 10m height

Figure 7 showed the turbulence kinetic energy at distance 0.5 L/s, its maximum peak was at a little height from flat terrain, but RSM greatly overestimated around the ground. On the other hand, the k-Ɛ model and k-ω model showed underestimated with a wide gap. The peak value of turbulence kinetic energy for the RSM, k-Ɛ model and k-ω model appeared 0.288, 0.190and 0.166 m^2/s^2, respectively.

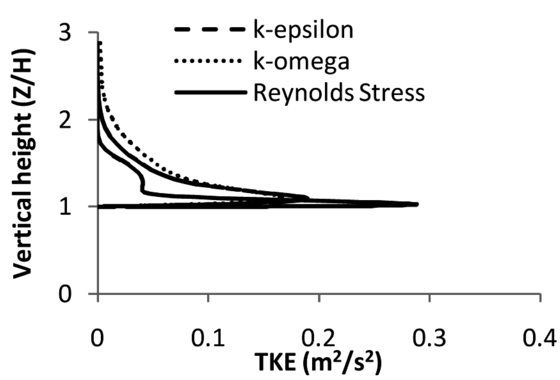


Figure 7 Comparison of turbulence kinetic energy at distance 0.5 L/s

Mean velocity component in the longitudinal

Velocities profiled were used to investigate suitable sites for turbines; hill height H and steep distance L are procedure to be implied. Simulations were made at different distances along the hill from -6L to 3L for two cases, that is, inflow profile before impact (-6L and -3L) and velocity profile after impact (0L to 3L). The mean velocities in vertical direction around the hill are shown in Figure 8. The inlet profile flow from -6L to -3L are steady, illustrated that the profile model is appropriate. After the impact line (0L) the simulation showed the velocity profiles change along the distance. The results from RSM indicated further velocity than k-Ɛ model and k-ω model along the ground to 2 times of hill height, while k-Ɛ model and k-ω model demonstrated rather similar results.

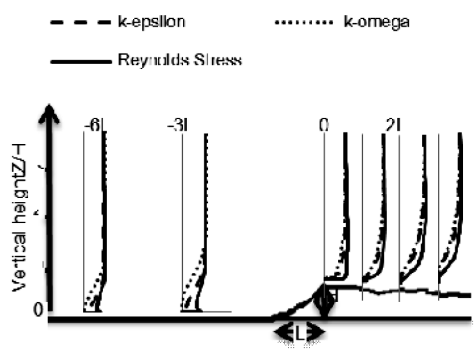


Figure 8 Mean velocity component in the longitudinal direction

Comparison of hill shape and geometry shape

The Pha Taem hill topography is quite similar with the geometry. To investigate a suitable site for wind turbines matching with real topography, reference geometry shapes were used to associate with the actual hill structure as shown in Figure 9. The hill shape can be separated into two parts, the hill with 20.06°slope and the flat rocky plate with 1.66° slopes to the backside and a few fences. The trapezoid geometry with 20.0 ° slope and the flat plate 1.7°slopes to the backside with 0.04m roughness is used to examine for this case.

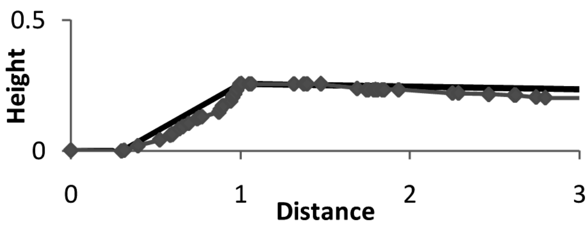


Figure 9 Pha Taem topography associate with reference trapezoid geometry

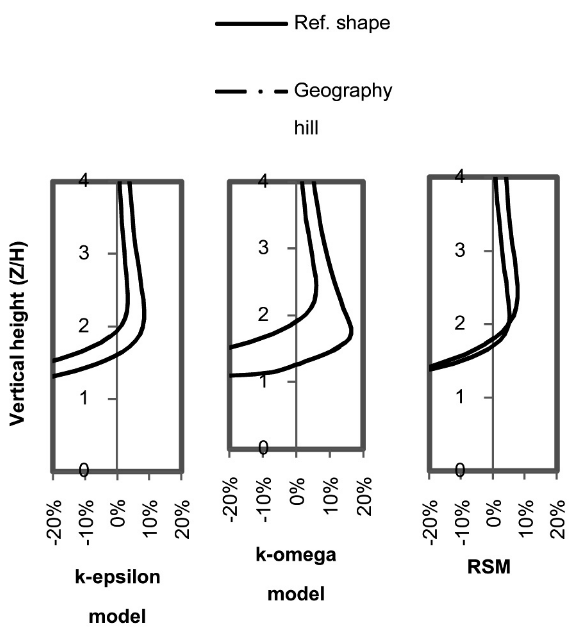


Figure 10 Increasing of velocity comparison of Pha Taem hill topography and reference geometry shape.

Figure 10 showed increasing velocity at 0.5 L/s from the hill top. The RSM simulations indicated that results from Pha Taem hill topography provide similar velocity with the reference geometry shape from ground to 2 Z/H in vertical height, but in the higher region the RSM showed further results at 2.63% in this region. The simulations the from k-ε model and k-ω model illustrated similar tendency, which Pha Taem hill topography always had additional results at 5.02% and 10.53%. Since, rocky plate roughness surface from topography compose more turbulent intensity.

Investigation of the turbulent kinetic energy, comparison of the flow over Pha Taem hill topography and reference geometry shape is shown in figure 11. The simulations results from k-ω model showed mostly neighbor at 2.97% difference, while the k-ε model showed 8.02% difference. The RSM result demonstrated two times more of turbulent kinetic energy. Figure 12 indicates a turbulence intensity comparison of the flow. The result tendency was in harmony with results of the turbulence kinetic energy.

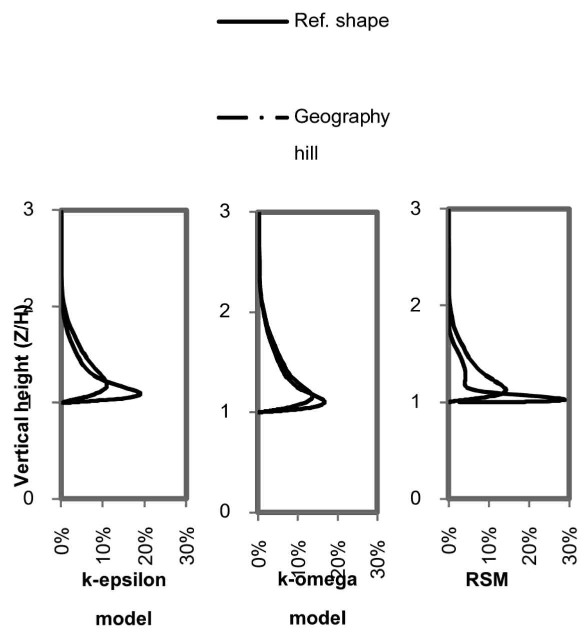


Figure 11 Comparison of turbulence kinetic energy increasing of the flow over Pha Taem hill topography and reference geometry shape

Conclusions

Computational fluid dynamics was used to analyze the Pha Taem hill flow which can be separated into two parts, the hill with 20.06°slope and the flat rocky plate with 1.66° slopes to the backside and a few fences. The standard k-ε model, standard k-ω model and RSM were used to compare with the measure. mento, wind speed and direction, pressure and temperature were collected at 5m, 10m, 15m and 20m height for 7 stations.

The mean wind velocity at 10m height on the measured date is 2.728 m/s and wind velocity 3.014 m/s at 40 m height. Investigation of wind velocity and uncertainty limits at 10 m height from ground of measured and simulated. The results illustrated standard k-ε model showed similar results with those measured in front of the hill top. After 1.0 times of hill slope the RSM showed exact results but the standard k-ε model and standard k-ω model showed more underestimation. The turbulent kinetic energy in the simulations showed great approach with the measured since earlier to distance 0.5 L/s after impacted, after the distance 0.5 L/s the completely simulation appeared underestimation of TKE at 10 m height.

Comparison of the Pha Taem hill topography is similar to trapezoid geometry in which 20.0 ° slope and the flat plate 1.7°slopes to backside with 0.04m roughness. The coefficient of determination of Pha Taem hill and trapezoid is 0.9546. The RSM simulations indicated that results from Pha Taem hill provide similar velocity with trapezoid from ground to 2 Z/H in vertical height, but in the higher region the RSM showed further resulted at 2.63% in this region.

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Reference

1. Coelingh JP, van Wijk AJM, Holtslag AAM. (1996) Analysis of wind speed observation sover the North Sea. *J Wind Eng Indus Aerodynam*, 61, pp: 51–69.
2. Sahin AZ, Aksakal A. (1998) Wind power energy potential at the northeastern region of Saudi Arabia. *Renew Energy*, 14, pp: 435–40.
3. Vogiatzis N, Kotti K, Spanomitsios S, Stoukides M. (2004) Analysis of wind potential and characteristics in North Aegean Greece. *Renew Energy*, 29, pp: 1193–208.
4. Naif M. Al-Abbadi, (2005) Wind energy resource assessment for five locations in Saudi Arabia. *Renew Energy*, 30, pp: 1489–99.
5. Al Nassar W, Alhajraf S, Al-Enizi A, Al-Awadhi L. (2005) Potential wind power generation in the State of Kuwait. *Renew Energy*, 30, pp: 2149–61.
6. Department of Alternative Energy Development and Efficiency, Ministry of Energy, Thailand (2004). *Statistic Data*, URL: http://www.eppo.go.th/index-E.html, access on 12/12/2011.
7. Takahashi T. et al. (2002) Turbulence characteristics of wind over a hill with a rough surface. Journal of Wind Engineering and Industrial Aerodynamics, 90, pp: 1697-1706
8. Bert Blocken. (2007) CFD simulation of the atmospheric boundary layer : wall function problems. Atmospheric Environment 41.pp: 238–252
9. Hargreaves D.M., Wright N.G. (2007) On the use of the k–ε model in commercial CFD software to model the neutral atmospheric boundary layer. Journal of Wind Engineering and Industrial Aerodynamics 95.pp: 355–369
10. Undheim O., (2005) 2D simulations of terrain effects on atmospheric flow. *Conference proceedings MekIT'05*.
11. OveUndheim., (2003) Comparison of turbulence models for wind evaluation in complex terrain, *Conference proceedings EWEC 2003*
12. The Ministry of Interior. (2010) http://www.dopa.go.th/stat/y_stat.html.
13. Feregh GM. (1993) Wind energy potential for Bahrain. *Energy Conv Manage*, 34(6), 499–506.
14. Celik AN. (2003) A statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey. *Renew Energy*, 29, pp: 593–604.
15. B. E. Launder and D. B. Spalding.(1972) Lectures in Mathematical Models of Turbulence.*Academic Press*, London, England.
16. D. C. Wilcox. (1998) Turbulence Modeling for CFD. DCW *Industries, Inc*. La Canada, California.
17. M. M. Gibson and B. E. Launder. (1978) Ground Ejects on Pressure Fluctuations in the Atmospheric Boundary Layer. *J. Fluid Mech*., 86, pp: 491- 511.
18. B. E. Launder. (1989) Second-Moment Closure, *Inter. J. Heat Fluid Flow*, 10(4), pp: 282-300.

19. B. E. Launder, G. J. Reece, and W. Rodi.(1975) Progress in the Development of a Reynolds-Stress Turbulence Closure.*J. Fluid Mech*, 68(3), pp: 537-566.