

## Application of $k-\omega$ -SST Turbulence Model for Separated Particle-Laden Flows

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### Abstract

Two-phase turbulent flows of dilute concentration of discrete particles occur in many industrial and natural processes such as the combustion of liquid and fuels, cyclone separators, pneumatic transport of particulate material, and environmental particulate transport. In these applications, turbulence modulation will occur. Turbulence modulation refers to the fluid turbulence flows can be affected by the presence of the particles.

Two-equation Eddy Viscosity Models (EVM) such as  $k-\varepsilon$  models are widely employed models for computational fluid dynamics (CFD). Their major advantage is the simplicity and suitability for an easy incorporation into the Navier-Stokes numerical codes. Computation of a variety of flows has shown agreement with experimental measurements in some simple classes of flows. However, many results are misleading and wrong especially in complex flows (e.g. separation and recirculation) because of limitations of the linear two-equation models. Recent advanced eddy-viscosity models (e.g.  $k-\omega$  SST model) that represent an intermediate closure level between the linear eddy-viscosity and second-moment closures are especially worth considering because of demonstrated successful performance in a number of more complex flows.

The objective of this article is to review particle-laden characteristics which affect the turbulence and to simulate the particle-laden turbulent flow over a 2D backward-facing step using  $k-\omega$  SST model. The backward-facing step is a basic geometry which has many important flow features such as flow separation, flow reattachment, and free shear jet phenomena. The simulation results are validated against experimental data obtained by Ruck and Makiola [1]. The reviewed information is combined and will be used to modify the turbulence model to include the effect of particles on carrier phase (fluid phase).

**Keywords:** Turbulence model, Particle-laden flows, Backward-facing step

### 1. Introduction

Particle-laden flows are commonly found in both engineering and in nature. Although they are commonly found, they are not well understood. Nowadays, the numerical models used for particle-laden flows in engineering analysis have two categories. The first category is called 'Lagrangian approach' which treats the

dispersed phase (particle phase) by tracking a large number of particles in Lagrangian frame. The second category is called 'Eulerian approach' which is also known as the 'two-fluid' approach because the particle-phase is described by fluid-like equation such as, Reynolds averaged Navier-Stokes (RANS). This work focuses only in the Eulerian approach, RANS, which concentrates in the particle effect on turbulence not the behavior of particles. The numerical models for engineering analysis are based on the solution of RANS equations for the carrier phase. The models have been improved such that they can produce good prediction of the carrier phase. This has led to the modification of increasingly accurate particle dispersion models because gas-particle flows are characterized by the coupling between phases. The common model used for turbulent flows is the classical  $k-\varepsilon$  model. Tian et al. [2] investigated the performance of Lagrangian and Eulerian approach of dilute gas-particle flow over a backward-facing step. The numerical results agreed well with the experimental data of Ruck and Makiola [1]. The turbulence models in Eulerian approach were standard  $k-\varepsilon$ , RNG  $k-\varepsilon$  and realizable  $k-\varepsilon$  models. The two successful models were RNG  $k-\varepsilon$  and realizable  $k-\varepsilon$  models because the good agreement was achieved between the model results and measurement data. Moreover, the advantage of the Eulerian approach was not only less computational time but also gave the better performance than the Lagrangian approach.

The backward-facing step (Figure 1) is a simple geometry which has many complex flows such as separation, reattachment and recirculation. For particle-laden flows, the particles make the flows more complex. To make sure that the result of the developed particle model is accurate, the simple geometry is used to reduce the effect from its body. Yu et al. [3] used large eddy simulation (LES) for the fluid phase while particle's motion was traced by a particle track model in a backward-facing step. Their work could predict a small anti-clockwise circulation region near the corner between the step and the lower wall which had not been reported in the experimental work of Fessler and Eaton [4] nor predicted by the simulation using Reynolds-averaged equations of Chan et al. [5]. Tian et al. [2] found that the RNG  $k-\varepsilon$  and realizable  $k-\varepsilon$  models could simulate a secondary recirculation at the corner of the step but the standard  $k-\varepsilon$  model could not predict.

Recently, there is more advanced turbulence model than the  $k-\varepsilon$  model that can predict the complex flows more successfully. The  $k-\omega$  SST model is the turbulence model that can capture the separated flows better than the  $k-\varepsilon$  model (Hanjalic [6]). Thus there is the possibility that the  $k-\omega$  SST model is appropriate to simulate separated particle-laden flows. A number of particles are modeled by the species transport equation which the particle diffusivity ( $D$ ) is an important parameter. However, Soo [7] found that the particle diffusion of the dispersed phase was smaller than the carrier phase. This result shows that the particle diffusivity can be neglected while the turbulent diffusivity ( $D_t = \mu_t / Sc$ ) still remains. The turbulent diffusivity is modeled through a Schmidt number ( $Sc$ ). This article evaluates the Schmidt number for a backward-facing step by defining  $Sc = 0.35, 0.5,$  and  $0.7$ . It is found in this paper that the numerical results are unchanged with varying Schmidt number. Then the paper uses the  $k-\omega$  SST model to simulate a separated particle-laden flow. The numerical results are compared with the experimental data of Ruck and Makiola [1] for the particle-laden turbulent flow over a backward-facing step. Particles diameter of  $1 \mu m$  ( $\rho_s = 810 \text{ kg/m}^3$ ) is simulated under the Reynolds numbers (based on the step height,  $h$ ):  $Re=64000$ . This work is in the turbulence attenuation case because the flow is dilute where mass loading is  $0.2$  and Stokes number is smaller than unity.

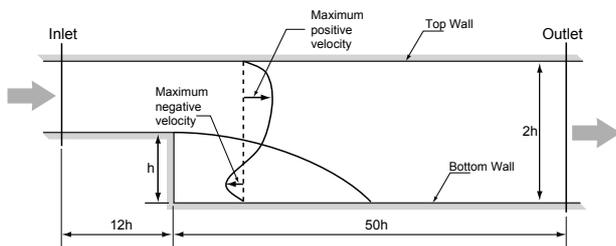


Figure 1. The backward-facing step geometry ( $h=0.025 \text{ m}$ ).

### Characteristic of Particle-Laden Flows

The complexity of momentum coupling in a particle-laden flow depends on a number of parameters. The volume and mass of mixture are quantified by the volume fraction and bulk density. The volume fraction is the volume of a phase per unit volume of mixture. The bulk density is the mass of a phase per unit volume of mixture. The volume fractions of each phase sum to unity while the sum of the bulk density yields the density of the mixture (Crowe [8]). The ratio of the mass of dispersed phase to the mass of the carrier phase is called “loading,  $w$ ”.

A dilute dispersed phase flow is one which the particle motion is controlled by the fluid forces (drag and lift). A dense flow is one in which the particle motion is controlled by collisions. The nature of dilute and dense flows can be compared by the ratio of the particle’s inertia, given by particle time constant ( $\tau_p$ ), and the time between collisions ( $\tau_c$ ). The particle time constant is the time it takes for a particle at rest in flowing stream to

accelerate to  $1 - e^{-1}$  of the freestream velocity ( $U_0$ ). Thus the flow can be considered *dilute*, if  $\tau_p / \tau_c < 1$ . It means that the particle has sufficient time to respond to the local fluid dynamics forces before the next collision so its motion is dominated by the carrier phase. On the other hand, if  $\tau_p / \tau_c > 1$ , the particle has no time to respond to fluid forces before next collision and the flow is *dense*. The particles’ responsiveness to the carrier phase is determined by the ratio of the particle time constant to the fluid time scale ( $\tau_f$ ). This ratio is a very important parameter in gas-particle flows called “Stoke number,  $St$ ”.

$$St = \tau_p / \tau_f; \quad \tau_p = \frac{\rho_p d_p^2}{18\mu_f}$$

For backward-facing step [5]

$$\tau_f = 5H / U_0, \text{ where } H \text{ is the step height}$$

### Particles Interaction with Turbulence

The effect of the turbulence on the turbulence of the carrier phase is important in the development of numerical models for two-phase flows. There has been a continuing interest concerning the effect of particles on the turbulence of the carrier phase. In Figure 2, the dilute and dense dispersed phase can be separated by the inter-particle spacing or the volume fraction. Gore and Crowe [9] indicated that small particles will attenuate the turbulence while large particles will generate turbulence. From Figure 3, the data suggested that the transition occurs when the particle size was about  $1/10$  of the integral length scale (the characteristic length of the most energetic eddy). Elghobashi [10] has proposed the map shown in Figure 4 for the effect of particles on carrier-phase turbulence. For volume fraction less than  $10^{-6}$  the presence of the particles would have no effect on turbulence. For volume fractions between  $10^{-6}$  and  $10^{-3}$ , the particles can augment the turbulence, if the ratio of particle response time to the turbulence time scale is greater than unity, or attenuate turbulence, if the ratio is less than unity. For volume fractions greater than  $10^{-3}$ , particle-particle collisions become important, and the turbulence of the carrier phase can be affected by the oscillatory motion due to particle collisions. This effect is called four-way coupling.

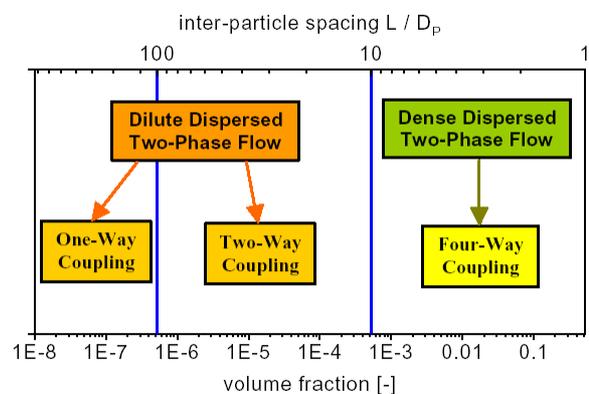


Figure 2. Regimes of dispersed two-phase flow as a function of particle volume fraction [11].

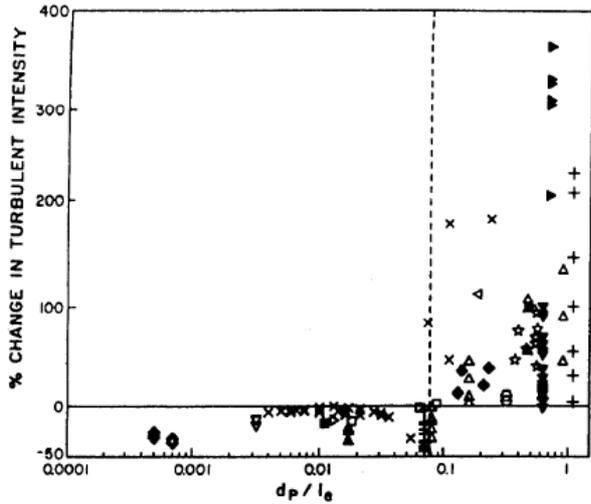


Figure 3. A summary of experimental data on the effect of the particle diameter/turbulence length scale on the turbulence intensity of the carrier phase [9].

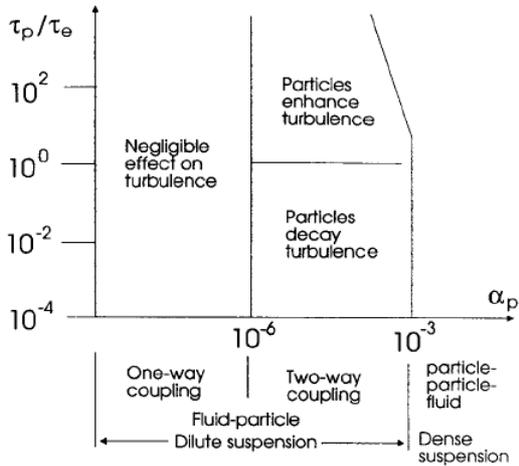


Figure 4. Proposed map for particle-modulation.  $\tau_p / \tau_e$  is the ratio of the particle response time to the turbulence time scale;  $\alpha_p$  is the particulate phase volume fraction [10].

There are many flow and particle parameters that determine the particle's effect on the turbulence such as Stokes number, Particle diameter, Particle concentration

( $\alpha$ ), Particle mass loading, and Particle Reynolds number. Values of the parameter define particle's influence on turbulence, as conclude in Table 1.

Table 1 The comparison of the particle parameter effect on turbulence.

Turbulence Attenuation
$St < 1$
Particle diameter is smaller than the Kolmogorov scale ( $d_p < \eta$ )
Particle is smaller than 10% of the fluid scale ( $d_p/l_e < 0.1$ )
Low concentration ( $\alpha_p \leq O(10^{-6})$ )
Particle Reynolds number ( $Re_p \leq 110$ )

Turbulence Augmentation
$St > 10$
Particle diameter is larger than the Kolmogorov scale ( $d_p > \eta$ )
Particle is larger than 10% of the fluid scale ( $d_p/l_e > 0.1$ )
High concentration ( $\alpha_p \geq O(10^{-3})$ )
Particle Reynolds number ( $Re_p \leq 400$ )

$$Re_p = \frac{|U_x - V_x| d_p}{\nu}$$

where  $U_x$  = fluid velocity

$$V_x = U \left( 1 - e^{-1/\tau_f} \right) = \text{particle velocity}$$

Turbulence attenuation happens because the energy of the carrier phase transfers to the particles. The particles are still at first, and then, starting moving by using energy from the carrier phase until they reach the same velocity. On the other hand, turbulence augmentation results from the turbulence wake behind the particle, and thus the turbulence increases as the particle size increase.

**Investigated Models for Turbulence Modulation**

The various turbulence modulation models found in the survey on the  $k-\epsilon$  model are concluded in Table 2. To modify the turbulence model which has the particle effect, the added source terms are proposed. This added source terms in the turbulent kinetic energy ( $k$ ) and dissipation rate of turbulent kinetic energy ( $\epsilon$ ) equations were modeled to predict the particle effect on turbulence.

Table 2 Comparison of the added source term in  $k$  and  $\epsilon$  equations.

Model	$S_k$	$S_\epsilon$	Comment
Chen and Wood [12]	$\frac{1}{\rho_f} \frac{2k}{\tau_p} \alpha \left[ 1 - \exp\left(-\frac{0.5\epsilon\tau_p}{k}\right) \right]$	$-\frac{1}{\rho_f} \frac{2}{\tau_p} \alpha \epsilon$	
Motafa and Mongia [13]	$\frac{1}{\rho_f} \frac{2k}{\tau_p} \alpha \left( 1 - \frac{\tau_{LI}}{\tau_{LI} + \tau_p} \right)$	$-\frac{1}{\rho_f} C_{\epsilon 3} \frac{2\epsilon}{\tau_p} \alpha \left( 1 - \frac{\tau_{LI}}{\tau_{LI} + \tau_p} \right)$	$\tau_{LI} = 0.35k / \epsilon$ $C_{\epsilon 3} = 1.0$
Tu and Fletcher [14]	$\frac{1}{\rho_f} \frac{2k}{\tau_p} \alpha \left[ 1 - \exp\left(-\frac{B_k \tau_p}{w^n \tau_f}\right) \right]$	$-\frac{1}{\rho_f} \frac{2\epsilon}{\tau_p} \alpha \left[ 1 - \exp\left(-\frac{B_\epsilon \tau_p}{w^n \tau_f}\right) \right]$	$n = 0, w \leq 1 \quad B_k = 0.09$ $n = 1, w > 1 \quad B_\epsilon = 0.4$

Lightstone and Hodgson [15]	$\frac{2k\alpha}{\rho_f \tau_p} \left(1 - \frac{\tau^*}{\tau^* + \tau_p}\right)$	$-\frac{2\varepsilon\alpha}{\rho_f \tau_p} \left(1 - \frac{\tau^*}{\tau^* + \tau_p}\right)$	$\frac{1}{\tau^*} = \frac{u_{REL}}{L_I} + \frac{1}{\tau_{LI}}$ $\tau_{LI} = 0.135k / \varepsilon$ $L_I = 2\tau_{LI}\sqrt{2k/3}$
Garcia and Crespo [16]	$-\rho\varepsilon_p$	$C_{\varepsilon 3} \frac{\varepsilon}{k} \varepsilon_p$	$\varepsilon_p = (3/2)C_0\varepsilon\phi_p$ $C_0 = 3, C_{\varepsilon 3} = 0.9$

## 2. Governing Equations

Menter [17] proposed to combine the two models in such a way that the model reduce to the  $k-\omega$  model close to the solid wall, and the  $k-\varepsilon$  model away from the wall. The combination of the two models has been accomplished using a blending function.

### The Shear-Stress Transport (SST) $k-\omega$ model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega$$

where (2)

$G_k$  represents the generation of turbulence kinetic energy due to mean velocity gradients.

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} = \mu_i S^2, \quad S \equiv \sqrt{2S_{ij}S_{ij}}$$

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) = \text{strain rate tensor}$$

$$G_\omega = \frac{\alpha}{V_t} G_k = \text{the generation of } \omega$$

$$\alpha = \frac{\alpha_\infty}{\alpha^*} \left( \frac{\alpha_0 + Re_t / R_\omega}{1 + Re_t / R_\omega} \right), \quad Re_t = \rho k / \mu \omega$$

$$\alpha_\infty = F_1 \alpha_{\infty,1} + (1 - F_1) \alpha_{\infty,2}$$

$$\alpha_{\infty,1} = \frac{\beta_{i,1}}{\beta_\infty^*} - \frac{\kappa^2}{\sigma_{\omega,1} \sqrt{\beta_\infty^*}}, \quad \alpha_{\infty,2} = \frac{\beta_{i,2}}{\beta_\infty^*} - \frac{\kappa^2}{\sigma_{\omega,2} \sqrt{\beta_\infty^*}}$$

$Y_k$  and  $Y_\omega$  represent the dissipation of  $k$  and  $\omega$  due to turbulence

$$Y_k = \rho \beta^* k \omega, \quad Y_\omega = \rho \beta_i \omega^2,$$

$$\beta_i = F_1 \beta_{i,1} + (1 - F_1) \beta_{i,2}$$

$D_\omega$  represents the cross-diffusion term

$$D_\omega = 2(1 - F_1) \rho \sigma_{\omega,2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

$\Gamma_k$  and  $\Gamma_\omega$  represent the effective diffusivity of  $k$  and  $\omega$

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k}, \quad \Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega}$$

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left[ \frac{1}{\alpha^* a_1 \omega}, \Omega \right]}, \quad \Omega \equiv \sqrt{2\Omega_{ij}\Omega_{ij}}$$

$$\Omega_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) = \text{rate of rotation tensor}$$

$$\sigma_k = \frac{1}{F_1 / \sigma_{k,1} + (1 - F_1) / \sigma_{k,2}}$$

$$\sigma_\omega = \frac{1}{F_1 / \sigma_{\omega,1} + (1 - F_1) / \sigma_{\omega,2}}$$

$$F_1 = \tanh(\Phi_1^4), \quad F_2 = \tanh(\Phi_2^2)$$

$$\Phi_1 = \min \left[ \max \left( \frac{\sqrt{k}}{0.09\omega y}, \frac{500\mu}{\rho y^2 \omega} \right), \frac{4\rho k}{\sigma_{\omega,2} D_\omega^+ y^2} \right]$$

$$D_\omega^+ = \max \left[ 2\rho \frac{1}{\sigma_{\omega,2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-20} \right]$$

$$\Phi_2 = \max \left[ 2 \frac{\sqrt{k}}{0.09\omega y}, \frac{500\mu}{\rho y^2 \omega} \right]$$

where  $y$  is the distance to the next surface

### Model constants

$$a_1 = 0.31, \quad \alpha^* = 1, \quad \sigma_{k,1} = 1.176, \quad \sigma_{k,2} = 1.0, \quad \sigma_{\omega,1} = 2.0,$$

$$\sigma_{\omega,2} = 1.168, \quad \alpha_0 = 1/9, \quad R_\omega = 2.95, \quad \kappa = 0.41,$$

$$\beta^* = \beta_\infty^* = 0.09, \quad \beta_{i,1} = 0.075, \quad \beta_{i,2} = 0.0828$$

### Mass fraction equation

$$\frac{\partial}{\partial x_j}(\rho u_i \phi_p) = \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi_p}{\partial x_j} \right) \quad (3)$$

where  $\phi_p$  is the mass fraction of particles

$\Gamma_\phi$  represents the effective diffusivity of mass

$$\Gamma_\phi = \rho D + \frac{\mu_t}{Sc}, \quad Sc = 0.7$$

where  $Sc$  is the turbulent Schmidt number

Table 3 The Schmidt number comparison.

Researcher	Schmidt Number
Laslandes and Sacré [18]	0.35 (backward-facing step)
Launder and Spalding [19]	0.7 (round jet)
	0.5 (plane jets, mixing layers)

The governing transport equations are discretized by using the finite-volume approach. QUICK scheme is used to approximate the convective terms. The pressure-

velocity coupling is computed by the SIMPLE method. The simulation is in the steady state. Grid spacing is 0.5 mm. The convergence criteria for the properties (velocity, pressure,  $k$ , and  $\omega$ ) were achieved when the iteration residual reduced by six orders of magnitude.

### 3. Results and Discussion

Figure 5. presents the particle velocity profile against measurements for a Reynolds number of 64,000 at location of  $x/H = 0, 1, 3, 5, 7,$  and  $9$  behind the step. The velocity profiles are normalized by the free stream velocity,  $U_0$ . The acceptable results were found at the  $x/H = 5, 7,$  and  $9$ .

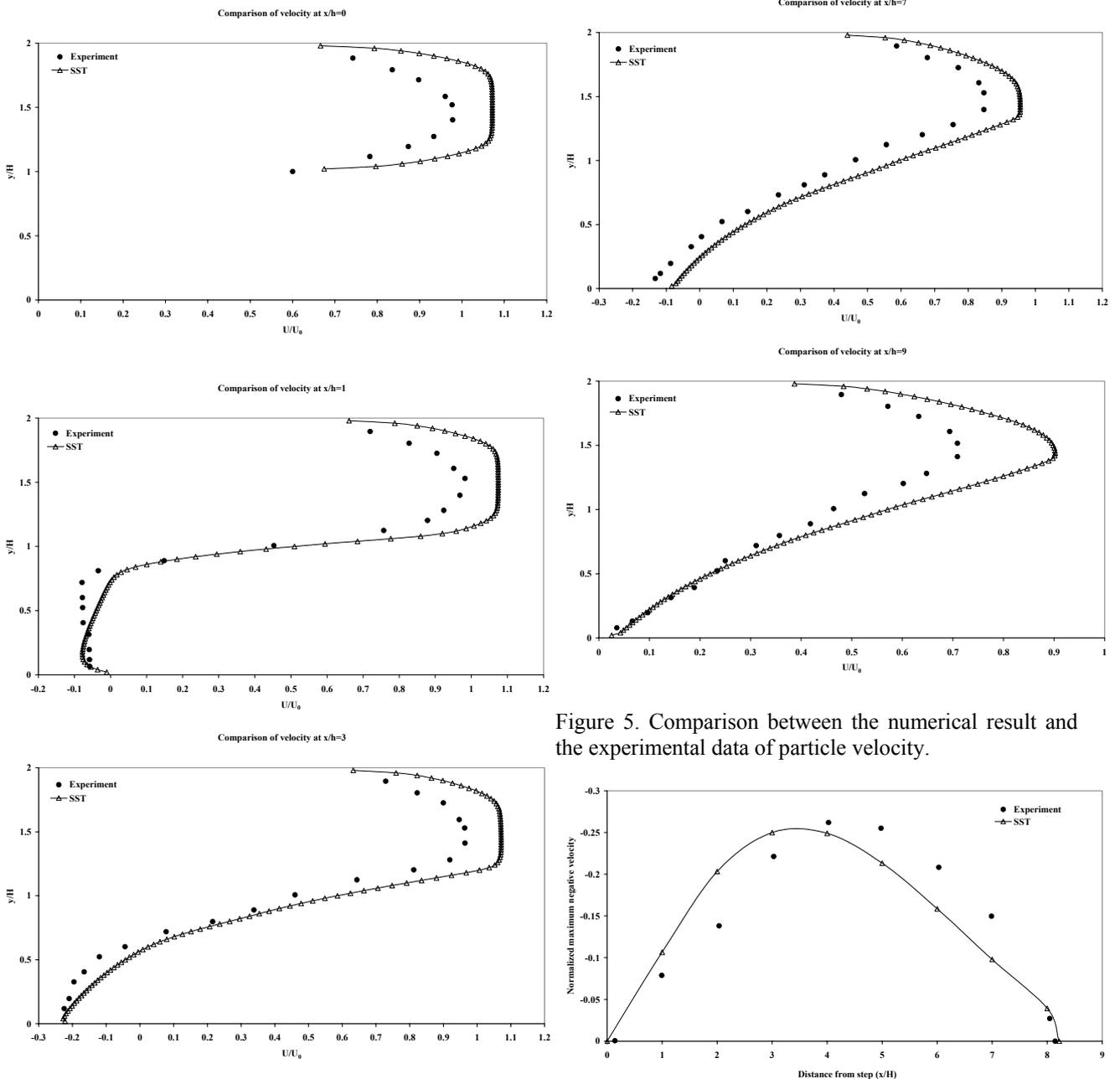


Figure 5. Comparison between the numerical result and the experimental data of particle velocity.

Figure 6. Maximum negative x-direction velocity (normalized with free stream velocity,  $U_0$ ).

In Figure 6, the maximum negative velocity profile of particles in the recirculation zone is shown. The reattachment length of the  $k-\omega$  SST model is  $x/H = 8.2$  compared to the measures value of  $x/H = 8.1$ .

#### 4. Conclusion

Eventhough the particle-laden turbulent flows are common nature. The understanding of the behavior of the particle is still unclear in many situations. This paper presents the characteristics of particles and their behavior on the turbulence. The  $k-\omega$  SST model can demonstrate the nature of the particle-laden separated flows not only the particle behavior but also the reattachment length. The second recirculation at the corner of the step can be found in the simulation. The numerical results can predict the flow behavior similar to the experimental data. In the future work, the turbulence models need to be further modified in order to give a better prediction by considering the particle effect on the turbulence.

#### 5. Acknowledgements

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