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CFD Simulation of Particle Residence Time in Small and Industrial Scale Spray Dryer

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***Abstract*—This paper presents a CFD study of short and tall spray dryers. The simulations were performed using turbulent model; standard k-ε (SKE), realizable k-ε (RKE) and the Detached Eddy Simulation (DES). The predicted axial velocity, temperature and humidity profile inside the spray drying chamber were found to be in fair agreement to the experimental data adapted from literature for model tested in this work. The Detached Eddy Simulation provides more accurate prediction of fluid flow in a co-current spray dryer. Moreover, particle tracking has been included using the source-in-cell method to enable calculation of particle residence time (RTD) and their impact positions in the drying chamber. This study suggests that the tall spray dryer has less overall residence time than the shorter one due to lesser recirculation.**

Keywords*—*spray drying, particle velocity and temperature, residence time.

I. Introduction

Spray drying is a dehydration process to convert liquid feed materials into dry powder forms through the hot gas medium. Spray drying is widely used to produce foods, pharmaceutical products and other products such as fertilizers, detergent soap and dyestuffs. Spray dryer enabled a continuous production of dry powder, granulated or agglomerated with low moisture content [1-3].

The detail hydrodynamics of the spray dryer chamber are widely studied experimentally and numerically by several researchers in the past, such as Kieviet et al [4,5], Anandkharamakrishnan et al. [6], Southwell and Langrish [7], Langrish and Zbincinski [8], Zbicinski et al. [9], Harvie et al. [10] and Huang et al. [11]. Most of the previous work deals with a common co-current flow spray drying and reported vast comparison between experimental measurement and CFD simulation. The turbulence modelling was realised using a RANS i.e., the standard k-ε (SKE) model in their work, and it seems to give a fair prediction of the multiphase flow inside the drying chamber. However, there is a still discrepancy, especially in the prediction of gas axial velocity and the temperature profile. Therefore, this work aims to evaluate the performance of various turbulent models, i.e., standard k-ε (SKE) and Detached Eddy Simulation (DES) with the unsteady condition for predicting the flow pattern in a co-current spray dryer [12]. The DES is a relatively new development in turbulence modelling belongs to a hybrid turbulence model, which blends Large Eddy Simulation (LES) away from the boundary layer and RANS near the wall. This model was introduced by Spalart et al. [13] in an effort to reduce the overall computational effort of LES modelling by allowing a coarser grid within the boundary layers. The DES employed for the turbulence modelling in this work is based on Spalart-Allmaras model and has never been previously used for modelling of spray drying. The following sub-sections explain the spray drying simulation methodology, followed by results and discussions of two different case studies as follows:

Study Case A : Short-form spray dryer

Study Case B : Industrial scale tall spray dryer

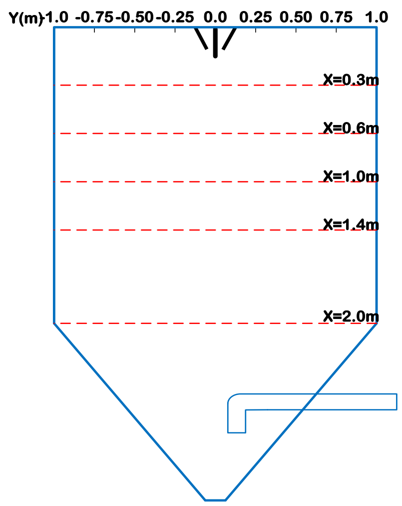

Fig. 1. Axial positions for comparisons of measurements and simulations

II. COMPUTATIONAL APPROACH

The commercial CFD code, FLUENT 6.3, was used to simulate the three-dimensional configuration of a co-current spray dryer. GAMBIT was used to draw the spray dryer tower diagram illustrated in Fig. 1, which has the same dimension to the one studied by Keiviet [14]. The simulation was performed using a grid consisting of about (420K) for both of spray dryer. The SIMPLE method was used for the pressure-velocity coupling and the 2nd order differencing for momentum terms for the SKE modelling, whereas the bounded central differencing was used for the DES simulation with unsteady solver. Particles were assumed as spherical for discrete phase modelling with 20,000 discrete phase integration used to obtain the final solution.

III. RESULTS AND DISCUSSION

A. Case A: Short-form spray dryer

In this work, CFD model predictions were compared with experimental results [2]. The airflow pattern was measured using a hot-wire anemometer while the temperature and humidity were measured using an array of a micro-separator [2]. The results obtained from the CFD model are presented in the following sub-sections in terms of velocity magnitude, temperature and humidity profiles. The simulations are performed using unsteady solver as it was found to be superior to a steady solver [17]. The axial positions for comparison of measurements and simulation are shown in Fig. 1.

B. Comparison Of Gas Velocity Profile Without The Spray Injection

Fig. 2 shows the predicted velocity profiles at various positions in the drying chamber. The predicted velocities by all three turbulence models show good agreement with experiment measurement [2]. Figure 4.2 also showed a non-uniform velocity distribution in the core region of the chamber. It is also found that the air flow patterns are nearly symmetric at the upstream of the 0.3m and 0.6m level but asymmetric velocity profiles were found at the 1.0m. This may be due to the bent outlet pipe which reduces the area for the gas to go through at one side of the drying chamber.

The highest velocity magnitude is 8.8 m/s as the 0.3m level. The velocity magnitude is reduced as the air goes into the chamber further due to the expanding area. At position Z = 0.3, prediction by the standard k-ε is somewhat better than DES at the centre region of the drying chamber, however, there are minimal differences in CFD predictions at other radial positions where the experimental data are available. At position Z = 0.6, predictions of all three models are again showing minimal differences except the peaks for DES is higher than those of SKE. All three turbulence models predict the axial velocity well at all radial positions where the experimental data are available except in the central region. At this position, all three models slightly underpredicts the axial velocity in the central region. Interestingly, the velocities in the central region of the chamber are predicted well by both the SKE and DES away from the nozzle at Z = 1.0. Differences between all three turbulence models tested in this work for the prediction of axial velocity is minimal, with all models capable of predicting the velocity profile very well. This is due to lack of swirling flow in the chamber, hence it is not critical to use a sophisticated turbulence model to predict the flow field in a co-current spray dryer.

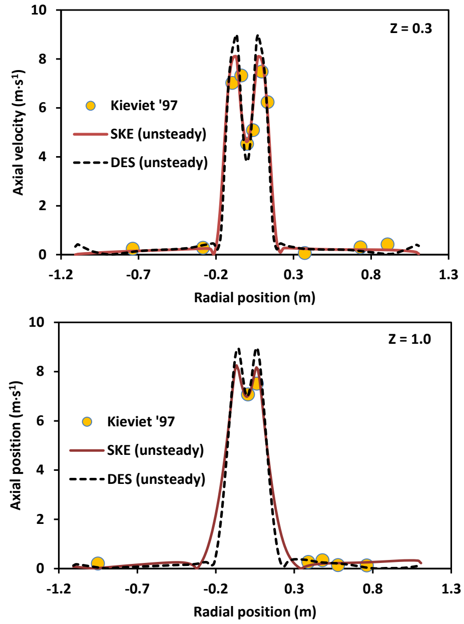

Fig. 2. Comparison of axial velocity between different turbulence models with experimental measurement by Kieviet [2]

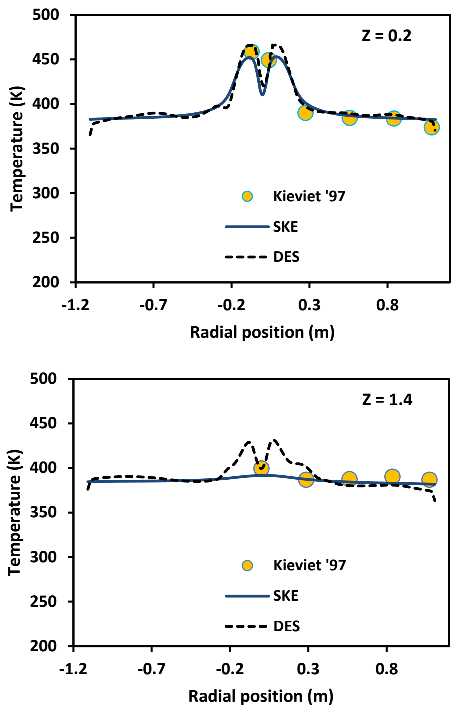

Fig. 3. Comparison of temperature between different turbulence models with experimental measurement by Kieviet [14]

C. Prediction of Temperature Profile

Fig. 3 shows the radial profiles of the gas temperature under the spray condition, the predicted temperature and measures by data by experimental [2] at various axial positions. Fig. 3 shows that the temperatures are much higher, closer to the nozzle at Z = 0.2 and much lower away from the nozzle at position Z = 1.4. This is due to very high heat and mass transfer rates in the nozzle zone due to high relative velocities between the gas and droplets coupled with large temperature driving forces. The predicted temperature profile by SKE and DES turbulence model are in good agreement with Keiviet's [14] measurement. The predictions from the DES turbulence model show better agreement with the experimental data compared to the predictions by SKE.

D. Particle Residence Time Distribution

The particle trajectories are calculated in Fluent by integrating the equation of motion over time; assuming gravity and drag to be the only significant terms. Particle residence time distributions were extracted from the simulation data by using the in-house-developed post-processor as these options are also not available in the present commercial CFD codes.

The primary particle residence time distribution (RTD) was calculated by tracking a large number of particles through the flow domain and recording the time taken each particle leaving the atomizer to when it terminates on a wall or leaves the product outlet. The time a particle spends in the drying chamber is determined by its trajectory, which in turn depends on the air flow pattern.

The residence time (RT) can be divided into two parts, namely, primary and secondary residence times. The primary RT is calculated from the time taken for droplets leaving the nozzle until the particles impacts on the wall or leave by the outlet. For the particles that hit the wall a secondary residence time can be defined as the time taken for a for a particle to slide along the wall from the impact position to the exit. This is based on an assumption that the particles move with constant velocity along the wall from the impact position. This constant sliding velocity is calculated based on the experimental measurements [2]. However, this sliding velocity measurement may not be accurate, as sliding behaviour of powder differs at various positions. The layer of the powder on the wall grows with intermittent detachment of pieces of the layer. Moreover, two mechanical hammers are also often used to tumble the powder, so it is very difficult to calculate a representative constant sliding velocities of the particles. Hence, only primary RT results are given in this study.

The overall primary residence time distribution (over all particle diameters) is shown in Fig. 4. The observed minimum and maximum particle RTs are 0.24 s and 124.32 s. The RTD curve shows a sharp peak between 6.4 s to 31.2 s also shows some of the particles having long RT, due to re-circulation of the particles. The average RT is 6.97 s. This RTD was calculated for the primary residence time and the particle travel with high velocity for a short period after leaving the atomiser. Zbiciski *et al* [15] also concluded from their experimental results that there is no simple relation between gas and particle mean residence times.

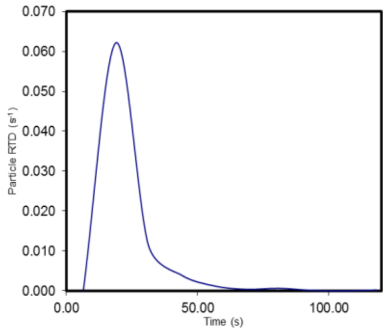

Fig. 4. Particle overall primary RTD of short spray dryer

E. Particle Impact Positions

Knowledge of the particle impact positions is important for the design and operation of spray dryers and also influences the quality of the products. Particles impact positions on wall results were extracted from the simulation data using the in-house-developed post-processor written in Visual Basic program.

The predicted particle impact positions on the walls are depicted in Fig. 5 which show the top and front cross-sectional views of the simulated results. Fig. 5 indicate that a large fraction of the particles (61.47%) strike on the conical part of the spray dryer chamber and 1.32% of the particles hit the cylindrical part of the wall, and the small proportion (35.21%) comes out of the outlet pipeline (the intended destination). A very small 0.06% of the particles hit the ceiling.

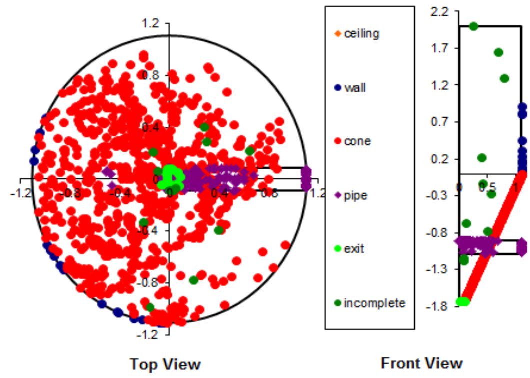

Fig. 5. Particle Impact Position of short spray dryer

F. Case B: Industrial Scale Spray Dryer

Case B is concerned with the CFD simulations relating to the tall-form industrial scale spray dryer (about twice the height of Case A). The simulation methodologies used were the same for Cases A and B since the methodology had been validated with Case A and hence should be applied with confidence to study the Case B. The main industrial spray dryer process and the geometric dimensions of spray dryer was illustrated in Fig. 6. The hot air is blown from the top of drying chamber. The pressure nozzle is located at the centre of drying chamber. There is an exit tube for the exhaust air conveying the dried particles at the centre of the cone. In the 3D-model the hexahedral grid was used with 428749 grid cells. The grid geometry is shown in Fig. 6.

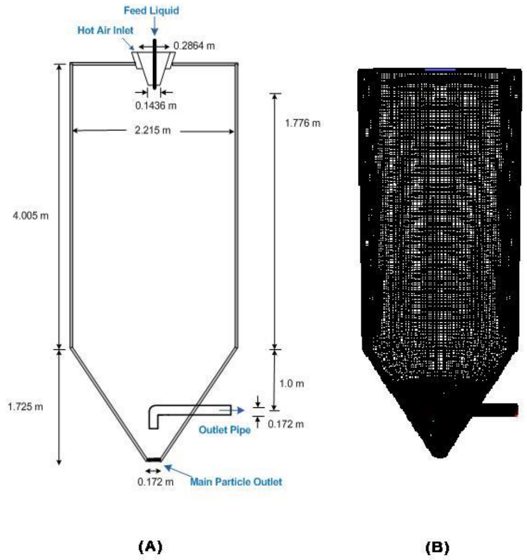

Fig. 6. A) Industrial Spray Dryer Geometry, B) Surface Mesh

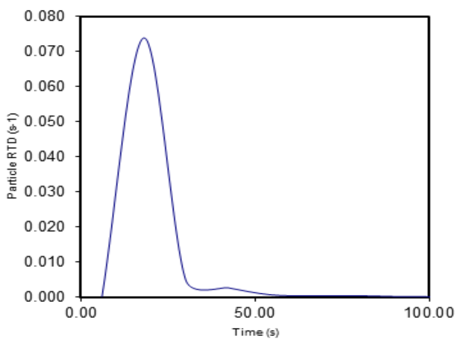

Fig. 7. Particle overall primary RTD of tall spray dryer

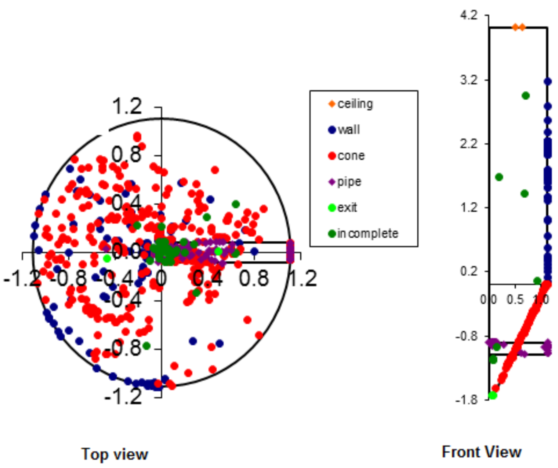

Fig. 8. Particle Impact Position of tall spray dryer

The simulated particle residence time distributions and particle impact positions on the wall were extracted on wall extracted from the simulation results by using the in-house-developed post-processing visual basic computer program. The particle residence time distribution was calculated based on the particle trajectories. The overall primary residence time distribution of all particles is shown in Fig. 7 which indicates the wide range of RT. The minimum and maximum RT was 0.06 s and 120.37 s respectively. The average RT is 4.12 s.

In this simulation, the particle impact positions on the walls are depicted in Figure 1.8. It shows the top and front view of the simulated results for the particle impact on the chamber. These figures indicate that 40.05% of the particles strike on the cylinder part of the wall and 42.58% of the particle hit the conical part of the wall. Hence 15% of the particles comes out from the outlet pipeline. No particles impact the ceiling, as recirculation of gas only took place on a large scale at the bottom of the chamber. This tall-form spray drying simulation study indicates that most of the particle (42.58%) impact on the cylindrical wall position and which increases the particle residence time inside the chamber. However, this will affect the product quality, especially for heat sensitive compound.

G. *Comparison of Short-Form And Industrial Scale Spray Dryer B*

Dimension and size of the spray dryer play an important role in their performance. There is, however, limited published knowledge available in the literature on this issue. Anandharamakrishnan *et al*. [16] has carried out a simulation concerning the tall and short spray dryer, and they found out that the mean residence time is not much affected by chamber height. In this section, detail comparison between the flow field and particle residence time for both short and tall type spray dryer were discussed. Comparison was made by extracting data from equivalent position, i.e., identical Z/H as shown in Fig. 9.

Fig. 10 shows radial profiles of axial velocity at ratio distance Z_V/H =0.1496 below the nozzle (see Fig. 9). There is a little difference between the peak of the axial velocity, which is about 9 m/s but there is a significant difference on the velocity in the central region. The tall spray dryer has over twice as higher axial velocity in the central region compared to the short type ones. This may be attributed by intense recirculation for the short type spray dryer which in turn may disturb the velocity profile inside the chamber. Meanwhile, flow for the tall type spray dryer is straightforward and has a fewer recirculation near the top of the chamber, thus promoting higher central region velocity.

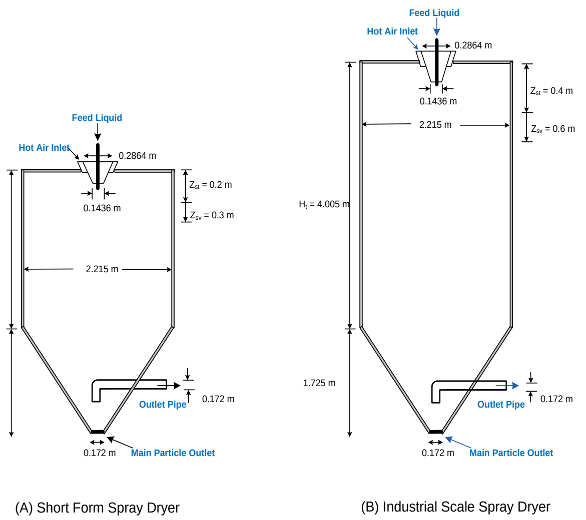

Fig. 9 Ratio of Z/H for velocity (Z_v) and temperature profile (Z_t)

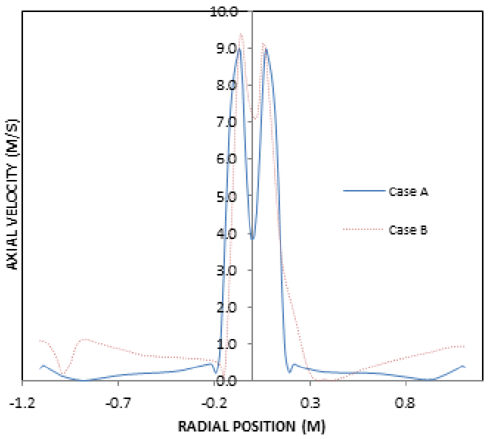

Fig 10. CFD simulated particle axial velocity at the same ratio position

Fig. 11 shows radial profiles of temperature at equivalent distances below the nozzle (see Fig. 9). The result suggests the overall temperature profile for the tall type spray dryer is much higher than the short type ones. This may be attributed to the back mixing of colder air in the short type dryer, and as we understood the tall type dryer do not have many recirculation near the top of the chamber. This is because the recirculation is mainly due to the conical shape of the drying chamber which is far away down in the case of the tall spray dryer. This higher temperature is not always desirable for drying of a heat-sensitive product such as protein because they can increase the denaturation rate of the product.

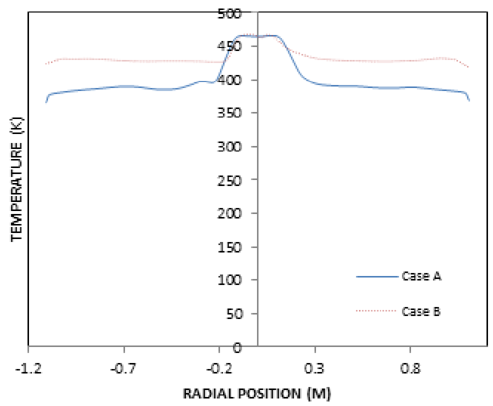

Figure 11 CFD simulated temperature at the same ratio position

Particle residence time distribution for both tall and short dryer is shown in Fig. 12. The result suggests the tall type spray dryer has a shorter overall residence time than the shorter ones with most particles has less than 30 seconds residence time for the tall type dryer. Meanwhile, there is a significant amount of particles having residence time over 40 seconds for the short type dryer. As mentioned earlier, this is attributed by intense recirculation in the short type spray dryer. A significantly higher amount of particles with about 20 seconds was observed for both dryer types.

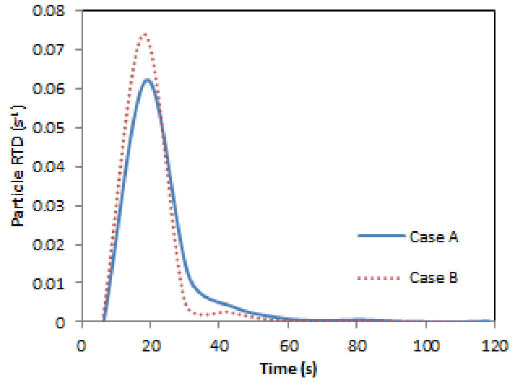

Fig 12 Comparison of short-form and industrial spray particles overall primary RTD.

IV. CONCLUSIONS

A three dimensional CFD model for a short-form spray was developed and compared with published experimental results and predictions. The results obtained from the CFD simulation were presented in terms of axial gas velocity, temperature and humidity profiles. The comparison study shows good agreement between the model and published experimental by Kieviet [16] . This work has uncovered a great potential of DES for modelling the flow field of the co-current spray dryer. A study on the tall type spray dryer suggests that they have much higher temperature and velocity profile compared to the shorter type dryer. A study on the tall type spray dryer suggests that they have much higher temperature and velocity profile compared to the shorter type dryer. However, they also have slightly shorter particle residence time due to fewer recirculation. The tall type dryer is good for heat the sensitive products due to shorter residence time. However, this benefit is balanced up by the higher temperature and hence the advantage of using a taller spray dryer may not be significant in terms of minimising the product damage due to denaturation. However, the tall type spray dryer is a good choice if a shorter residence time and a higher temperature are desirable.

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