Investigating the Effect of Inlet Velocity on Temperature Distribution and Solid Volume Fraction in Fluidized Bed Dryer using CFD

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Abstract: Tea leaves drying is a process to stop polyphenol oxidation and reduce the humidity of the leaves by roasting technique. The roasting techniques uses heat which generated from wood burning. The roasting must be monitored carefully so that the leaves are not too dry or even singed. The process of roasting from wood burning (organic material) increasing the levels of Polycyclic Aromatic Hydrocarbon (PAH) of the tea because of the fume from its combustion. Polycyclic Aromatic Hydrocarbon (PAH) is a member of Hydrocarbon which consisting of two or more close aromatic ring structures. Each of structure consist of benzo[a]pyrene. Benzo[a]pyrene formed from the imperfect combustion which are carcinogenic and mutagenic which can cause cancer. One of the ways that can be done to reduce the negative impact of drying with a wood burning is using a fluidized bed dryer (FBD). Fluidized bed dryer is a drying technique by reducing and eliminating humidity on the solid particle and change the humidity to gas (evaporation), in another word, this technique is called convective drying. On the drying technique, water has a role as evaporating fluid (evaporated) and air as gas cleaner. This research aims to analyze the effect of velocity variation on temperature and solid volume fraction distribution. This research uses Computational Fluid Dynamics (CFD) software in 2D modelling with a constant temperature at 130 ˚C and varying velocity at 1.152 m/s, 1.536 m/s, 1.728 m/s and 1.8 m/s to get the average particle temperature distribution. Simulation results obtained error on temperature distribution of particles with an average error of 0.67625%. Solid volume fraction contour, velocity contour, and temperature distribution contour show that the optimum velocity of fluidization and particle temperature distribution optimum velocity is 1.728 m/s.

1 INTRODUCTION

Development of tea business in Indonesia is located at North Sumatra region, however, tea estates in Indonesia lately are on declining condition. Development of tea plants area in Indonesia has declined since 2002, so there is 126.251 Ha left in 2009. Indonesia's tea agro-industries have recorded as the biggest earning of foreign exchange in the national economy at the time. Declining of the cast of planting area causes the tea production in Indonesia declined too. Tea production in 2008 was recorded as many as 137.499 tons, however, in 2010 the production became 129.200 tons (Sudjarmoko, 2014). Indonesia's tea agro-industries are currently undergoing declined because it has not been able to overcome the problems which were faced by tea producers in Indonesia, like the low crop productivity because it has not used superior seeds, the limit of technology to make a product, and farmers' inability to use technology in GMP standard (Good Manufacture Process), GAP (Good Agriculture Practice), and quality product standards such as ISO standards (Sudjarmoko, 2014). The desired standard product condition can be reached by increasing the quality of tea production. Tea companies in Indonesia commonly do the drying process by using a roasting technique. The roasting technique uses heat which produced by burnt wood (organic material) for triggering and increasing the levels of Polycyclic Aromatic Hydrocarbon (PAH) of the tea because of the smoke from its combustion. Polycyclic Aromatic Hydrocarbon (PAH) is a member of hydrocarbon which consists of two or more close aromatic ring structures, where each of structure is consisting of benzo[a]pyrene.

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Benzo[a]pyrene is formed by completing burn which is carcinogenic and mutagenic, those characteristic is believed to contribute to forming of cancer cells (Philips, 1999). In this research, the drying process has a role to stop the fermentation process and to decline the water content on tea leaves with fluidized bed dryer technique. Fluidized bed dryer is one of a few drying techniques that used in industry to produce the dried particulate product. Particle or object is dried by fluidized bed dryer has to size about 50-2000 μm. The using of a fluidized bed dryer has several advantages such as simple construction and low maintenance cost. Fluidization is the key of the success of the fluidized bed dryer. Figure 1 shows the scheme from several fluidized bed characteristics. The characteristics are affected by two factors that are gas velocity and pressure drop (ΔPb). Bed or place of particle support in which used as insulation between water distributor with the particle is made from holey slabs (distributor).

Basically, the higher velocity of the gas, the higher pressure drop. they both have a linear relation. At the particular velocity, called a minimum of fluidization (umf), and pressure drop along the area of the object (particle) will equally as the weight of particles per area (ΔPmf). The particle in this condition will levitate in the air and spread out. Increasing of the gas velocity would make the particle spread out easily, it is caused by the forming of bubble gas and (ΔPb) would be constant at (ΔPmf). Minimum point of fluidization can be clearly identified when the gas velocity decreasing (Bahu, 1997).

This research is focused on temperature distribution condition and fluidization effect by varying inlet velocity on fluidized bed dryer. The analysis is necessary to do because the temperature condition and fluidization effect (seeing from solid volume fraction) from the fluidized bed dryer during the drying process of tea leaves will be seen. To get the temperature distribution and fluidization effect of solid volume fraction, a mathematical model of computational fluid dynamics (CFD) is used (Versteeg and Malalasekera, 2007).

2 RESEARCH METHOD

The research on the fluidized bed dryer is done with aiming to compare the experimental result and the research (Ngoh and Lim, 2016). Invalidation, modeling corresponding to the paper is used to analyze temperature distribution and fluidization effect. CFD is used for analyzing hydrodynamics phenomena and heat transfer in the 2D modeling of solid-gas fluidized bed dryer. Modeling by using "Eulerian-eulerian (gas-solid) model multiphase" and turbulent model k-omega are used to analyze hydrodynamics phenomena and heat transfer in fluidized bed dryer. On the Eulerian-eulerian modeling, gas phase and solid phase are modeled by a mathematical model which continue and conservative so that could be written for each phase. CFD software, Ansys Fluent, is used to solve mass equation, momentum equation, and energy conservation equation simultaneously. Kinetic energy theory is used to get phase characteristic on granular flow, the equation which used to solve the model is written as follows (Ngoh and Lim, 2016):

Continuity equation for gas phase (g) and solid phase (s):

$$\frac{\partial}{\partial_t}\left(\alpha_g \rho_g\right) + \nabla.\left(\alpha_g \rho_g \vec{v}_g\right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial_t}\left(\alpha_s \rho_s\right) + \nabla.\left(\alpha_s \rho_s \vec{v}_s\right) = 0 \qquad (2)$$

Momentum equation for gas phase and solid phase:

$$\frac{\partial}{\partial_t}\left(\alpha_g\rho_g\vec{v}_g\right)+\nabla.\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right)=-\alpha_g\nabla p_g+\nabla.\overline{\overline{\tau}}_g+\alpha_g\rho_g\vec{g}+K_{gs}\left(\vec{v}_s-\vec{v}_g\right) \qquad (3)$$

$$\frac{\partial}{\partial_t}\left(\alpha_s\rho_s\vec{v}_s\right)+\nabla.\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right)=-\alpha_s\nabla p_g-\nabla p_s+\nabla.\overline{\overline{\tau}}_s+\alpha_s\rho_s\vec{g}+K_{gs}(\vec{v}_g-\vec{v}_s) \qquad (4)$$

In momentum equation, τ is Reynold tensor stress, g is gravity acceleration, and interaction force (tension and buoyant) describes momentum displacement between a gas phase and solid phase (solid) which shown with the following equation

$$\left[-\alpha_s\nabla p_g + K_{gs}\left(\vec{v}_g - \vec{v}_s\right)\right]$$

The fluctuating conservative energy equation for solid particle is as follows:

$$\frac{3}{2}\left[\frac{\partial}{\partial_t}\left(\alpha_s\rho_s\theta_s\right)+\nabla.\left(\alpha_s\rho_s\vec{v}_s\theta_s\right)\right]=\left(-\rho_s\overline{\overline{I}}+\overline{\overline{\tau}}_s\right):\nabla\vec{v}_s+\nabla.\left(k_{\theta s}\nabla\theta_s\right)-\gamma_{\theta s} \qquad (5)$$

Drag model from (Gidaspow, 1994) is used to evaluate the changing on momentum coefficient. The change in momentum coefficient based on drag model from Gidaspow is as follows:

$$K_{gs} = \frac{3}{4}C_D\frac{\alpha_s\alpha_g\rho_g\left|\vec{v}_s-\vec{v}_g\right|}{d_s}\alpha_g^{-2.65}\; for\,\alpha_g > 0.8 \qquad (6)$$

$$K_{gs} = 150\frac{\alpha_s^2\mu_g}{\alpha_g d_s^2} + 1.75\frac{\alpha_s\rho_g\left|\vec{v}_g-\vec{v}_s\right|}{d_s}\; for\,\alpha_g \le 0.8 \qquad (7)$$

where,

$$C_D = \frac{24}{\alpha_g Re_s}\left[1+0.15(\alpha_g Re_s)^{0.687}\right] for\ Re_s < 1000 \quad (8)$$

$$C_D = 0.44\ for\ Re_s \geq 1000 \quad (9)$$

Reynold number for particle (solid), Re_s, is as below

$$Re_s = \frac{\rho_g d_s \left|\vec{v}_s - \vec{v}_g\right|}{\mu_g} \quad (10)$$

Constitutive equation is used to completing the equations relation. Solid phase tensor stress (solid), τ_s, is given as follows

$$\bar{\bar{\tau}}_s = \alpha_s \mu_s \left(\nabla \vec{v}_s + \nabla \vec{v}_g^T\right) + \alpha_s (\lambda_s - \frac{2}{3}\mu_s)\nabla.\vec{v}_s \bar{\bar{I}} \quad (11)$$

Where shear stress on solid phase, μ_s, is given as follows

$$\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr} \quad (12)$$

Viscosity of particle collision, $\mu_{s,col}$, is given below

$$\mu_{s,col} = \frac{4}{5}\alpha_s \rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (13)$$

Kinetic viscosity (Gidaspow model), $\mu_{s,col}$, is

$$\pi_{s,kin} = \frac{10 d_s \rho_s \sqrt{\theta_s \cdot \pi}}{96\alpha_s (1+e_{ss}) g_{0,ss}} \times \left[1+\frac{4}{5} g_{0,ss}\alpha_s (1+e_{ss})\right]^2 \quad (14)$$

And shear viscosity of particle (solid), $\mu_{s,col}$, is

$$\mu_{s,fr} = \frac{p_s \sin\phi}{2\sqrt{I_{2D}}} \quad (15)$$

Shear viscosity of particle ($\mu_{s,col}$), p_s shows the particle pressure, ϕ shows the inner shear angle, and I_{2D} shows both variation from stress tensor deviator.
Particle pressure, ps, is determined as follows

$$p_s = \alpha_s \rho_s \theta_s + 2\rho_s (1+e_{ss})\alpha_s^2 g_{0,ss}\theta_s \quad (16)$$

Particle pressure (solid pressure) or termed as kinetic time (α_s ρ_s θ_s) while $\left[2\rho_s(1+e_{ss})\alpha_s^2 g_{0,ss}\theta_s\right]$ stated the particle collision effect. On the granular flow case, particle pressure can be calculated separately (itself). e_{ss} as restitution coefficient for particle which collide, while $g_{0,ss}$ as function of radial distribution and can be written as follows

$$g_{0,ss} = \left[1-\left(\frac{\alpha_s}{\alpha_{s,max}}\right)^{1/3}\right]^{-1} \quad (17)$$

Viscosity of solids, λ_s, can be written

$$\lambda_s = \frac{4}{3}\alpha_s \rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (18)$$

Solid viscosity (λ_s) calculates resistance of particle granules to tension and pressure. Diffusion coefficient from particle temperature based on Gidaspow's drag model is

$$k_{\theta s} = \frac{150\rho_s d_s\sqrt{\theta_s\pi}}{384(1+e_{ss})g_{0,ss}}\left[1+\frac{6}{5}\alpha_s g_{0,ss}(1+e_{ss})\right]^2 + 2\rho_s d_s \alpha_s^2 g_{0,ss}(1+e_{ss})\sqrt{\frac{\theta_s}{\pi}} \quad (19)$$

Energy equation is written as below

$$\frac{\partial}{\partial_t}(\rho E) + \nabla\cdot\left(\vec{v}(\rho E + p)\right) = \nabla\cdot\left(k_{eff}\nabla T - \sum_f h_j \vec{J}_j + \left(\bar{\bar{\tau}}_{eff}\cdot\vec{v}\right)\right) + S_h \quad (20)$$

Where k_{eff} is the effective and combined of $k + k_t$, where k_t is turbulent conductivity which is determined on turbulent model. J_j as diffusion flows from object "j". Equation on the right side shows energy transfer in conduction, diffused object, and dissipation of each viscosity. S_h shows the heat which occurs because of chemical reaction.
Heat transfer convection equation

$$Nu_{sph} = \frac{hD}{k} = 2 + \left[0.4Re^{1/2} + 0.06Re^{2/3}\right]Pr^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4} \quad (21)$$

Where $3.5 \leq Re \leq 80.000$ and $0.7 \leq Pr \leq 380$.
Heating of particle based on time

$$\frac{T_{(t)} - T_\infty}{T_i - T_\infty} = e^{-bt} \quad (22)$$

Where

$$b = \frac{hA_s}{\rho V C_p} \quad (23)$$

3 RESULT AND ANALYSIS

3.1 Validation with Previous Research

In this research, ANSYS fluent using 2D with 3 boundary condition, that is the inlet, outlet, and the wall is used. Be height shows how tall or vast will be modeled as a particle (solid) which has material properties and operating parameter as shown in Table 1. The first step, drawing the geometry in ANSYS Fluent, as shown in Figure 1.

CFD program do analysis on obsject by deviding the volume into small parts (mesh), meshing process is shown below.

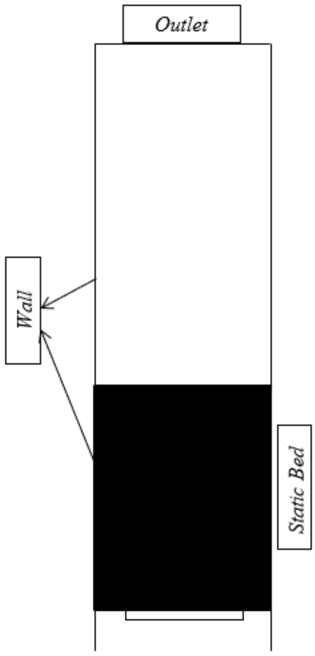


Figure 1: Fluidized bed dryer sketch.

Table 1: Operational Condition.

Parameter	value
Bed height	500 mm
Bed widht	90 mm
Static bed height	176 mm
Bed thickness	24 mm
Time step	10^{-4}s

Table 2: Mesh details.

Number of divisons	*Skewnees*	*Max Skewnees*	*Max Skewnees on Fluent*
400x800	7.75E-004	1.77E-003	0.85

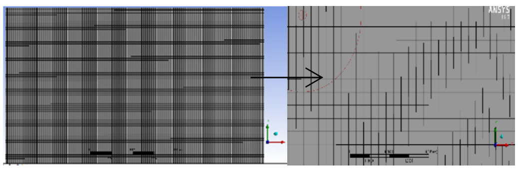


Figure 2: Generating mesh.

Geometry manufacture and mesh processing is the pre-processing stage. In the processing, the stage is using the Fluent software.a Set-up or variable value uses set-up according to the previous research (Ngoh and Lim, 2016). In post-processing stage is getting the result of temperature distribution result and fluidization effect on fluidized bed dryer. Fig 3a, 3b, and 3c show the fluidization effect, air dynamic pressure, and air temperature distribution.

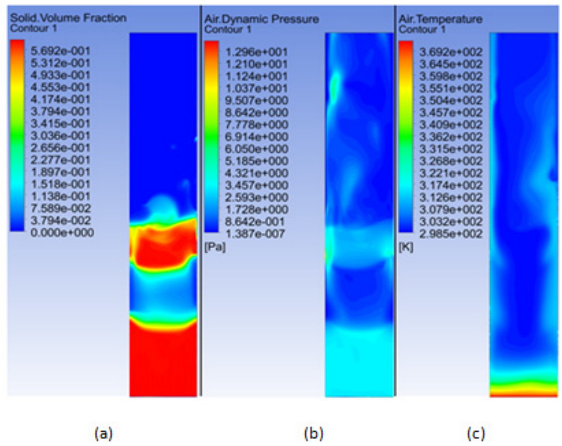


Figure 3: Contour of (a) Solid volume fraction, (b) Dynamics pressure, dan (c) Air temperature distribution.

Fluidization and heat transfer can be seen from solid volume fraction and temperature distribution by using Eulerian-eulerian model. Fig 3 shows temperature distribution which can be seen at low part (approaching inlet) has the temperature at 100°C, this is in corresponding to the simulation previously (Ngoh and Lim, 2016).

Table 3: Material properties.

Particle density, ρ_p	640 kg/m^3
Gas density, ρ_g	1.225 kg/m^3
Initial solid packing, e_{s0}	0.6
Particle diameter, d_p	5 mm
Superficial gas velocity, U	1.152-1.728 m/s
Gas temperature fluidization, T_f	130 °C
Initial particle temperature, T_p	25 °C
Particle thermal conductivity, k_p	0.17 W/(m K)
Particle specific heat, c_p	1780 J/(kg K)
Air thermal conductivity, k_g	0.0242 W/(m K)
Air specific heat, c_g	1006.43 J/(kg K)

Table 4: Simulation settings.

Time step	10^{-4}s
Number of iteration	30000
Multiphase	*Eularian-eularian*
Pressure	SIMPLE
Momentum	First order upwind
Turbulent	*K-omega*

Simulation result which interpreted as temperature distribution chart can be seen in Fig 4. Charts from the simulation are compared with reference paper. From the compared result which has done is got the average error 0.67625%, with the highest and the lowest value is 1.226% and 0.033% respectively. An error got from validation is under 10%, then the method can be applied in this research.

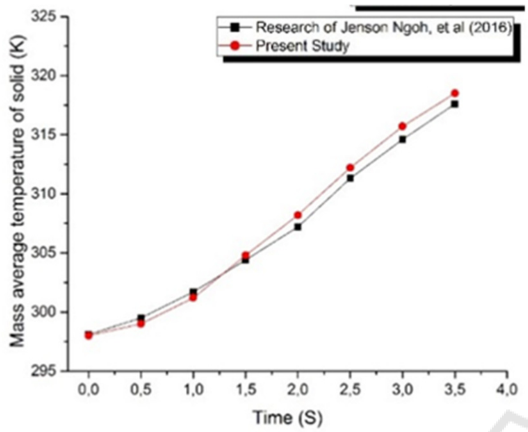


Figure 4: Particle average temperature vs fluidization time chart.

3.2 Gas Inlet Velocity Effect

Heat transfer which occurs on fluidization effect can be investigated with different operation condi-tions, the simulation is done repeatedly by varying inlet air velocity as well as the keeping of operation parameters and constant material proper-ties. The fluidized bed is heated by flowing hot air constantly at temperature 130 oC and particle initial temperature is 25 oC. Particle size used is 5 mm and the air velocity used is 1.152 m/s, 1.536 m/s, dan 1.728 m/s.

Analyses were done on solid volume fraction profile, temperature profile, and velocity profile explain the heat transfer that occurred. Figure 5 shows solid volume fraction contour (solid volume fraction) at a velocity of 1.152 m/s, where air bubblethat is formed is lifting the particle (bed) as initial fluidization's step.

Particle concentration at the bottom tends to lift uniformly, this thing indicates gas inlet velocity uniform according to the characteristic of a fluidized bed dryer. Contour profile of solid volume fraction showing bubble which created near the bottom has the smaller size and will get bigger as it moves upward as seen in the second 1.5s to 2s, this statement corresponds to simulation (Ngoh and Lim, 2016). The contour profile shows that the particle tends to fix and will move downward again when gas inlet velocity is small as shown at time 2s. The solid particle will have a good heat transfer when they contact each other. However, in the case of a fluidized bed dryer, the convection heat transfer more concerned than conduction heat transfer. This research is done to analyze optimum velocity that makes a particle of tea which later undergoes a drying process with fluidiszed bed dryer does not leap out of the fluidized bed chamber. Figure 6 and figure 7 show the velocity contour profile at 1.536 m/s and 1.728 m/s.

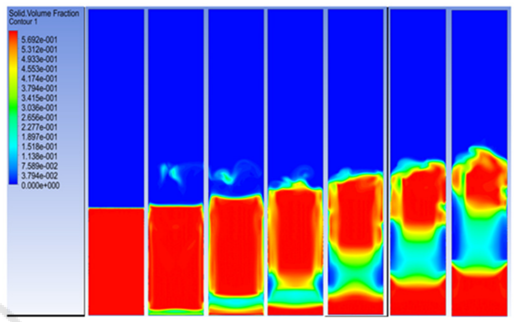


Figure 5: Contour of solid volume fraction at velocity 1.152 m/s.

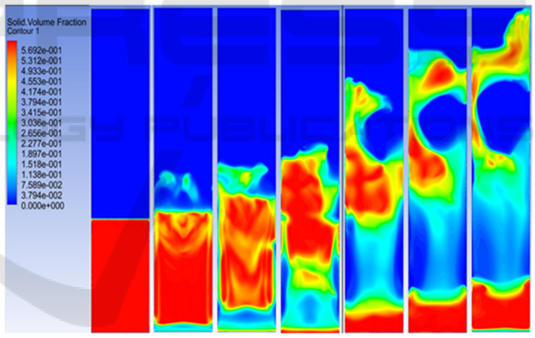


Figure 6: Velocity contour of solid volume fraction velocity at 1.536 m/s.

Figure 6 shows inlet velocity variation at 1.536 m/s. Compared to the velocity at 1.152 m/s as shown at Figure 5, it shows that the increasing of velocity makes the bubble which produced becomes bigger and so does separation effect, this phenomenon be seen at time 1s. From Figure 6, it is seen that the contour at 2s shows the particle moving downward, but the bubble will begin to reform at a time 3s. At 3s, it shows that the particle got the highest point of the chamber, this is not same as the purpose of research, where it was originally intend to get optimum velocity so that the particle does not leap out of the chamber. In Figure 7, it shows the variation speed at 1.728 m/s, from the figure, it can be seen that the particle is steady until 3s when comparing with previous speed and the particles that come back down look less than the previous speed.

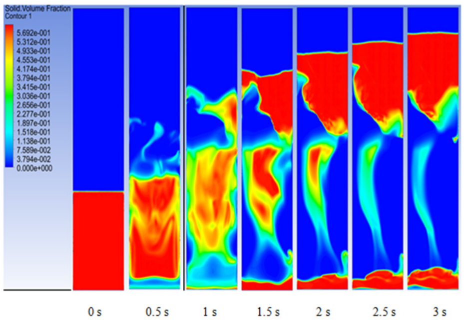


Figure 7: Velocity contour of solid volume fraction at 1.728 m/s.

(Bahu, 1997), his book, explaining, basically, the increasing of gas inlet velocity that occurs on fluidized bed dryer was causing an increase in pressure drop (ΔPb) and it is linear with gas velocity (u). In particular gas velocity, it is called as the optimum velocity of fluidization (umf), and pressure drop along with object area (particles) would be equi-valent to the weight of particles per area (ΔPmf). The particle at this condition will fly out freely and it will begin to expand as shown in figure 7 (Bahu, 1997).

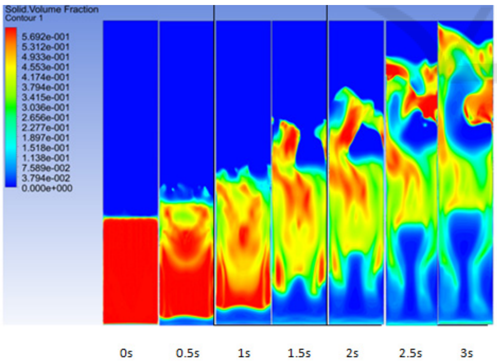


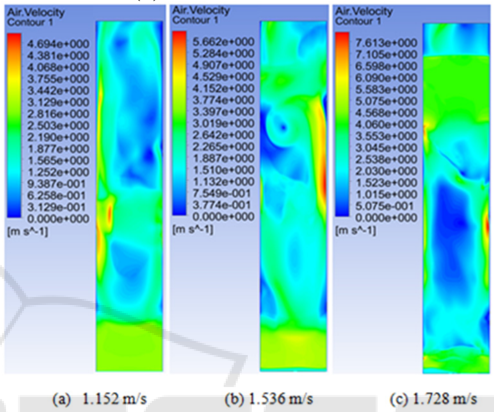
Figure 8: Velocity contour of solid volume fraction at 1.8 m/s.

The contour at 1.8 m/s shows that there is a high enough fluctuation at 2s, and it increases until 3s. Tea particles at 3s reach the highest point of the chamber and make the possibility of the particle to leap out of the chamber, although in this velocity does not any precipitation of the particles at the bottom of the chamber.

3.3 Temperature Distribution

Temperature distribution and heat transfer effect on the particle can be seen from gas inlet velocity and gas temperature distribution, which will have an effect on particle temperature. Gas inlet velocity will influence particles speed and vector speed of the particle. The small gas inlet speed will cause the vector speed of the particles becomes low, the low speed of the particles makes the convection heat transfer becomes slow.

Figure 9: Contour of gas velocity (a) 1.152 m/s, (b) 1.536 m/s, dan (c) 1.728 m/s



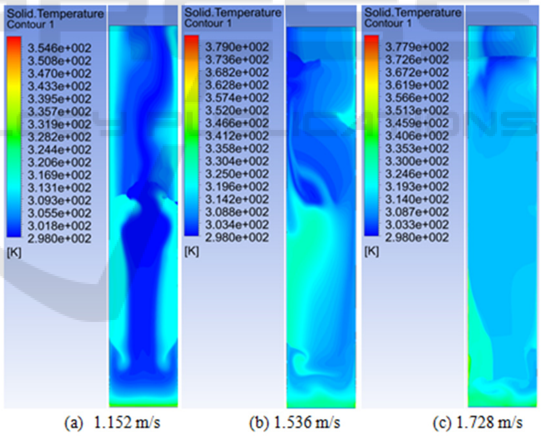
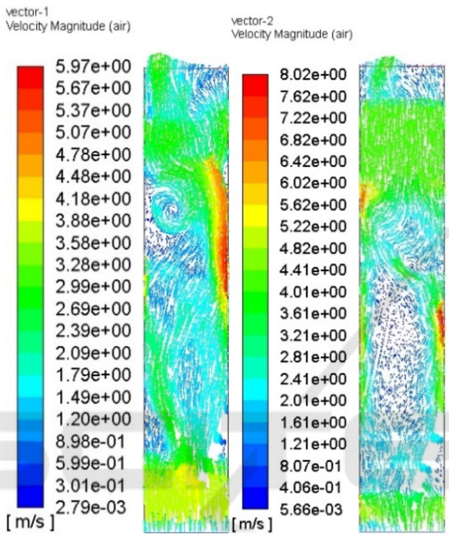


Figure 10: Contour of particle temperature (a) 1.152 m/s, (b) 1.536 m/s, dan (c) 1.728 m/s.

Figure 9.c which velocity at 1.728 m/s shows the gas velocity value of particle 4.568 m/s, where it is higher than gas velocity on the particle with inlet velocity 1.152 m/s and 1.536 m/s. This value shows that the gas velocity is linear with velocity vector of particle. Figure 9.c has a high particle velocity vector, so it causes good convection heat transfer. This result is proportional to contour of temperature distribution of particle, it is seen at Figure 10.

Figure 10 shows contour of particle temperature with variation speed at 3s. At Figure 10, the increasing of temperature is proportional to its velocity, but the temperature distribution at 1.728 m/s looks more evenly. The uniform of temperature distribution is in accordance with opinion of (Ngoh and Lim, 2016). which says that the higher particle velocity vector, the better convection heat transfer.convection heat transfer in simulation can be seen from its gas velocity vector. Figure 11 shows gas velocity vector at 1.536 m/s and 1.728 m/s at time 3s.



(a) (b)

Figure 11: Velocity vector at (a) 1.536 m/s and (b) z1.728 m/s.

Convection heat transfer is strongly influencedby velocity fluid flows when passing or pounding an object. Figure 11 shows gas velocity vector when passing the tea particle, Figure 11.b shows velocity vector which is passing the tea particle is bigger than that velocity vector that happens on the particle, Figure 11.b shows the velocity vector passing the particle is bigger than the velocity vector at Figure 11.a. The value of the velocity vector when passing the particle will influence the heat transfer happening on the particle.

The higher velocity vector, the better heat transfer, because the higher velocity vector passing the particle then the higher Nusselt number of the fluid. Optimum velocity at 1.728 m/s has the highest Nusselt number 10.5 (equation 21). Nusselt number influence the convection heat transfer coefficient value which is linear with the convection heat transfer value (Cengel, 2003).

Figure 12 shows the temperature distribution chart with various velocity from 0s to 3s and increase of gas inlet velocity will influence the particle average temperature. The increasing of temperature is influenced by Nusselt number, and Figure 12 shows that longer fluidization time, the higher temperature (Cengel, 2004) mentioned that heat transfer on the object along time “t” is same as the energy increase on the object along time “t” (equation 22) (Cengel, 2004).

4 CONCLUSIONS

Analysis of fluidization effect and heat transfer on this research is using software Computational Fluid Dynamics (CFD). Simulation is done by varying of gas inlet velocity at 1.152 m/s, 1.536 m/s, 1.728 m/s and 1.8 m/s and keeping the temperature operation constant at 130 oC to determine optimum fluidization velocity and optimum temperature distribution velocity. The results show that optimum fluidization velocity by assuming no tea particle leap out from the chamber is 1.728 m/s, it is seen in Figure 7. Heat transfer becomes one of the essential

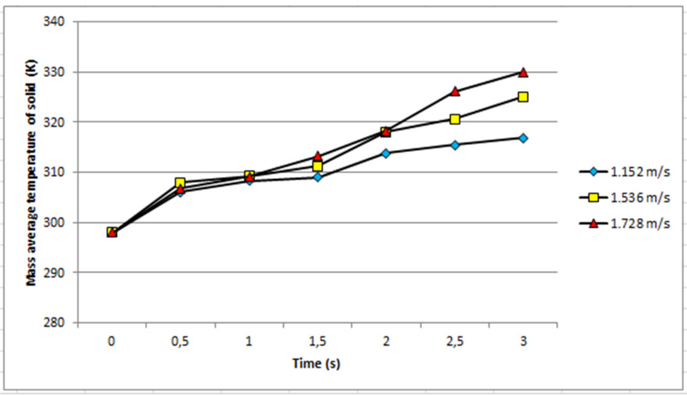


Figure12: Particle average temperature vs fluidization time with various velocity chart.

things of a fluidized bed dryer because the key of drying is the heat transfer. The heat transfer that occurs is convection heat transfer. According to the simulation, convection heat transfer can be seen from the particle velocity vector, it means the optimum heat transfer occurring at 1.728 m/s. The optimum heat transfer is proven by the contour of the temperature distribution of the particle (Figure 10), the optimum temperature distribution is influenced by gas inlet velocity which is linear particle velocity vector. Particle temperature distribution is increased linearly with the gas inlet. And it is proven by Nusselt number with a value 10.5 at optimum velocity 1.728 m/s affection convection heat transfer, it is seen at temperature distribution chart (Figure 12).

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