The Power Consumption Performance of an Orbiting Screw Solid-Solid Mixer

Semuel Pati Senda[1], Renanto[1], Achmad Roesyadi[1], Wahono Sumaryono[2] & Yazid Bindar[3]

[1]Department of Chemical Engineering, Sepuluh November Institute of Technology, Kampus ITS Keputih, Sukolilo, Surabaya, Jawa Timur 60111, Indonesia
[2]Deputy of Agroindustry and Biotechnology, Agency for the Assessment and Application of Technology, Jalan M.H. Thamrin No. 8 Jakarta 10340, Indonesia
[3]Research Group on Energy and Chemical Engineering Processing System Faculty of Industrial Technology, Institut Teknologi Bandung, Jalan Ganesa No. 10 Bandung, Jawa Barat 40132, Indonesia
Email: sps_24@yahoo.co.id

Abstract. In this work we have investigated mixing in a modified orbiting screw mixer (MOSM) designed for solid-solid mixing. Mixing was carried out using urea powder and natural zeolite powder (UZ) of three varying particle sizes (50-60, 60-80 and 80 mesh). Power consumption was calculated from the measured torque of orbit and screw, obtained from computerized records. It was found that the mixing process in the modified orbiting screw mixer with air injection required a lower power consumption for each particle-size group when compared to mixing without air injection. With UZ mixing in MOSM with air injection, the lowest *E* was obtained for the 60-80 mesh particle-size group (4,297 Joule/kg^{-1}), whereas when mixing without air injection, the value was 10,296 J/kg. The best mixing operation in this experiment was achieved at $N_{Fr} = 1.18 \times 10^{-3}$ and in the range of values $N_{Re} \approx 8.77 \times 10^{7}$ to 2.63×10^{8}. Moreover, in this study, we have developed an equation to estimate the power consumption required for mixing and determined its correlation with dimensionless numbers.

Keywords: *air injection; modified orbiting screw mixer; power consumption; power number; solid-solid mixing; urea-natural zeolite.*

1 Introduction

Mixing is an important process that is performed before granulation in order to achieve bulk homogeneity. Mixing and agitating vessels are widely used in the chemical, biochemical, food and other industries. Mixing urea and zeolite powder for the manufacture of SRF (Slow Release Fertilizers) aims to reduce the loss of urea due to its high solubility. In addition to increasing the efficiency of urea usage, natural zeolite employed as the matrix can serve as a conditioner. Natural materials, such as zeolite or clay, are attractive for use as a matrix. The development of SRF using clay has previously been explored, as clay is

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abundant in various regions in Indonesia. However, recently zeolite has come up as an alternative matrix. The natural properties of zeolite give it advantages when used as a matrix support, including its good hygroscopic properties, large surface area, high action exchange capacity and capability (CEC) and good adsorption-desorption ability.

Power consumption is the most important parameter to use for estimating mixing performance. To estimate the power consumption, a power correlation was developed for an orbiting screw mixer. The correlation of power consumption to particle size variations for the mixing of powdered urea-natural zeolite has not been previously reported. For paddle impellers in spherical and cylindrical agitated vessels, a new correlation of power consumption has been developed [1-2], which is more accurate than Nagata's correlation [3]. However, the new correlation cannot calculate the power consumption of other types of stirrers, such as the orbiting screw. Specifically mixing powdered urea-natural zeolite with particle size variations no one has reported to date.

Orbiting screws are used for mixing cohesive solids, and this type of screw is widely used in vessels ranging in size from portable to large tanks. Currently, there are no correlations for this type of stirrer. Therefore, we have developed a new correlation of power consumption for the orbiting screw. An orbiting screw mixer consists of a vessel in which the screw travels around the wall of the cone as it simultaneously rotates around its own axis, setting up strong circulation currents throughout the powder. A performance characteristic that must be considered in any mixing process is the power requirement, as sufficient power must be provided during the mixing process [4]. The power consumption required for the mixing process is one of the most important factors affecting the cost of the process. Therefore, energy consumption is expected to be as low as possible. The difference in density of the components that will be mixed may increase both the mixing time and power consumption. Denser material will sink through less dense material, leaving less dense particles on top [5]. If denser particles are present in the lower layer at the start of the mixing, the degree of mixing will increase gradually until equilibrium is attained. If denser particles are present in the upper layer, the denser components fall through the lighter components, leading to segregation instead of mixing.

In this study, orbital and rotation speeds of the screw were varied in combination with the air flow rate, and their effects on mixing with three particle-size groups were investigated. The decreased power consumption of the mixing process results from the decreased load torque caused by the intrusion of air between the grains, creating a gap that reduces friction loss. Load friction may occur between particles, between particles and the chamber wall, and between particles and the surface of the screw mixer. An air flow rate that is too low will not be effective because the air will not penetrate the gap; a flow rate that is too high will also be ineffective because the air flow through the middle of the chamber is not served by the screw mixer. This is due to the dome-shaped profile of the material surface, ensuring that the center makes the smallest obstacles go through the air. Thus, there is a correlation between the size of the particles and the optimum air flow rate, which decreases the power consumption of the mixing.

The aim of this work was to examine the influence of rotation and orbital velocity, particle size and velocity of air flow on the power consumption of mixing urea-natural zeolite powder. The results will allow an estimation of the power required to rotate the screw and orbit at a specified speed, and determine the lowest energy-consuming configuration of the screw agitator. The criterion for selection was the mixing energy. The interaction between the power consumption, the mixing time and the geometric parameters of the orbiting screw mixer was also investigated.

The performances of the mixing process are quantified by the specific energy E, mechanical power W_m, the electrical power W_l and torque τ_m. The involved mixing operational parameters are mass of solid m, angular velocity ω_r mixing power P_m, mixing time t_{mx}, rotational speed N, electrical voltage V and current I. Those variables are defined as follows

$$E = (\eta \, x P_m \text{ x } t_{mx})/m, \quad (1)$$

$$W_m = \tau_m \text{ x } N \quad (2)$$

$$W_l = V \text{ x } I] \quad (3)$$

$$\tau_m = F \text{ x } L \quad (4)$$

2 Experiment

A schematic diagram of the orbiting screw mixer used in this work was adapted from the typically used powder mixer in the pharmaceutical industry. The size of this mixer was scaled-down to 1:10 with an effective height of 6 m (Figure 1). The mixer's wall was made of flexi glass. The conical diameter at the top and the bottom of the mixer was 50-600 mm and 100 mm, respectively. The angle of the screw conveyor from the vertical axis was approximately 18°. The mixer used a three-phase motor as the driver, with a speed range of 150-600 rpm. The mixer was equipped with a gear reducer and a speed controller.

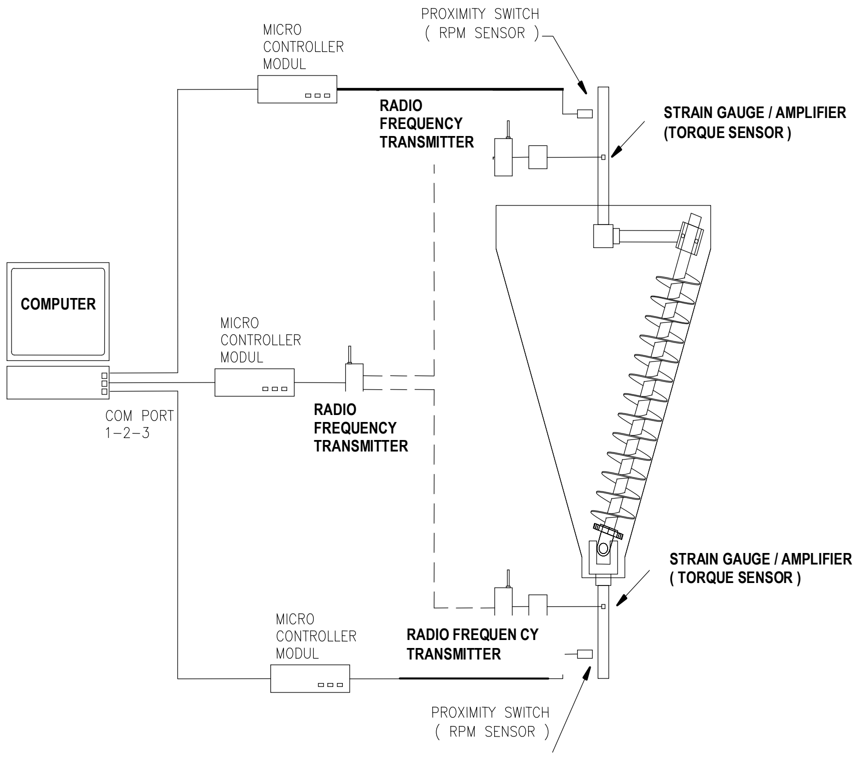

Figure 1 Schematic diagram of the experimental apparatus.

To minimize the occurrence of segregation, mixtures weighing 16 kg with a 1:1 ratio of urea to zeolite with the same particle sizes were mixed in the vessel. The orbital and rotation speed should be sufficient to ensure homogeneity. From visual observation, the position of the zeolite at the lower part resulted in a better mixing performance compared to positioning it within the upper part. The experiment was conducted for orbital speeds of 5, 10, and 15 rpm and rotation speeds of 30, 50, and 67.5 rpm to achieve effective material movement within the bulk mass. Therefore, these speeds were selected for further tests. Based on previous experiments for batch mixing, the mixings were conducted for 15 minutes [4]. The mixing experiments were performed in duplicate throughout the study.

Data acquisition in the system was carried out using an instrumentation device and data acquisition program. The data obtained were torque transferred to the computer program by radio transmission. Figure 1 depicts the design layout of the equipment for the mixing experiments and data acquisition. This system has the capability to record data for time intervals in seconds. The data on the test system were collected in real time with the instruments and the data acquisition program. The data recorded were the torque load on the stirring and rotation or the screw axis of the orbit.

Sensors were used to measure the strain-gage torque. Load measurements were conducted during the mixing process, so the use of radio transmission was necessary to send the data to the computer. Velocity measurements were performed using a proximity sensor. The data were processed first with a micro-controller during data acquisition. Samples were taken manually from a specific point at the top of the mixtures every 24 seconds during the mixing process. After the mixing process ended, samples were also taken from different heights within the conical chamber.

3 Results and Discussion

Mixing urea-natural zeolite powder using a modified orbiting screw mixer with three particle-size groups (50-60, 60-80 and 80 mesh) with variations in rotation and orbital speeds has been previously conducted and evaluated [6]. It was reported that the lowest energy consumption is obtained at an orbital speed of 5 rpm, a rotation speed of 50 rpm, and a particle size of 50-60 mesh.

3.1 The Effect of Particle Size on Power Consumption

Figures 2, 3 and 4 show that the power consumption for mixing with the three particle sizes, 50-60 mesh, 60-80 mesh and 80 mesh, without air injection was higher than that with air injection. These figures show that the power consumption for the 60-80 mesh particle size tended to decrease, except for the orbital speed of 10 rpm. At this speed, the power consumption tended to increase upon increasing the rotation speed. For the 80 mesh particle size, the power consumption also tended to increase, except for the orbital speed of 15 rpm. At a constant orbital speed, a higher rotation speed yields a higher power consumption. Likewise, a higher rotation speed gives a higher power consumption.

These figures also demonstrate the effects of air injection on power consumption for the various particle sizes. Figure 2 shows that the energy consumption of mixing without air injection is higher when compared to mixing with air injection for all variations of air flow rate, except for the power fluctuation in the 50-60 mesh particle size at air flow rates of 5 and 10 l/min.

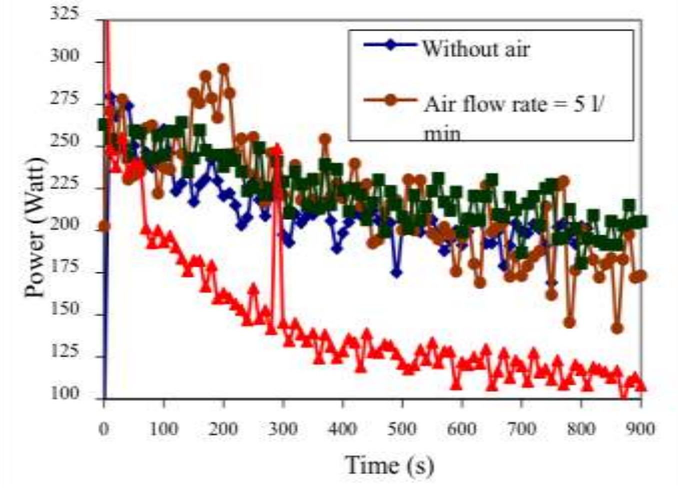

Figure 2 Power consumption for PS = 50-60 mesh at n_r/n_o = 67.5/5 rpm.

Figure 3 shows that the power consumption for mixing the 60-80 mesh particle size tended to decrease at air flow speeds of 10 and 15 l/min, but not at 5 l/min. At this lower speed, power consumption was almost constant over the mixing time. This result may be due to the air flow not being large enough to penetrate the gaps, so the mixture showed constant power consumption over the mixing time.

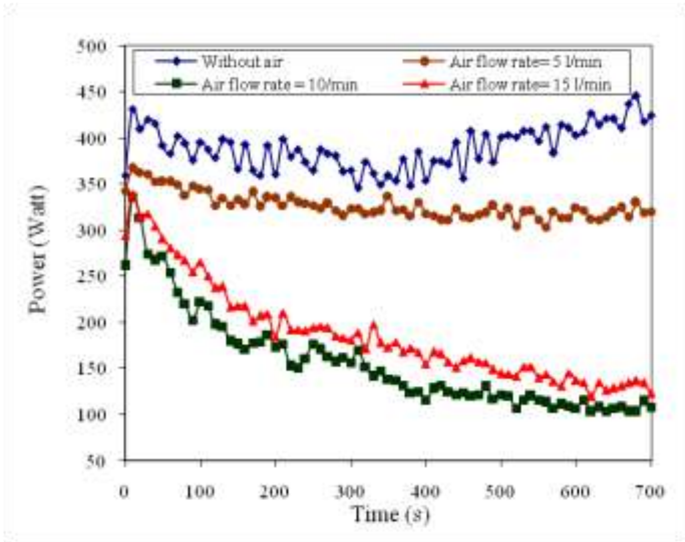

Figure 3 Power consumption for 60-80 mesh PS at n_r/n_o = 67.5/10 rpm.

For the 80 mesh particle size, the power consumption also tended to decrease until it reached a value of 150 watts at mixing times above 600 seconds, as shown in Figure 4. The mixing of the 80 mesh particle size with an air flow rate of 5 l/min showed a higher power consumption that is relatively constant until the mixing time reached 700 seconds. The largest decline in power consumption was observed when mixing the powdered urea-natural zeolite of 60-80 mesh at an air flow rate of 10 l/min. This air flow rate was very effective because of the flow through the gap around the screw mixer, reducing the burden of friction during stirring. Power consumption for UZ mixing with the 60-80 mesh particle size was 150 watt at an air flow rate of 10 l/min.

At an air flow rate of 15 l/min, the air speed was too high to be able to lift or break through the center of the dome surface of the material. With the opening of a gap in the dome, the majority of the air will flow out, and air in cracks around the screw mixer will be reduced. This reduced amount of air will reduce the effectiveness of the stirring and thus increase the power consumption. An air flow rate of 5 l/min is not effective enough to reduce the friction that occurs in the tank. However, the 60-80 mesh particle size reduced the power consumption when compared with the 50-60 mesh particle size, because the smaller sizes are lighter. The power consumption for mixing the UZ 80 mesh particle size was 168 watt at an air flow rate of 10 l/min.

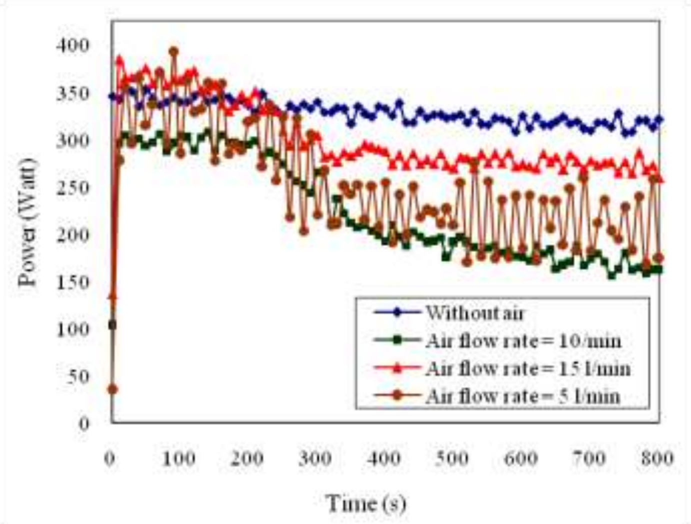

Figure 4 Power consumption for PS = 80 mesh at n_r/n_o = 67.5/5 rpm.

The mechanical requirements of the orbiting screw mixer established for operating performance demonstrate that an increased ratio of orbital and rotation speed yielded increased power consumption for all particle sizes studied.

3.2 Energy Consumption

Energy consumption required for the mixing process is one of the most important factors affecting the process costs. Therefore, energy consumption is expected to be as low as possible. Figure 5 describes the specific energy consumption required for mixing the urea-natural zeolite powder at the three different particle size variations (50-60 mesh, 60-80 mesh, and 80 mesh). This figure shows that the specific energy consumption with air injection for particle sizes of 50-60 and 80 mesh was higher than that of the 60-80 mesh particles. Moreover, the specific energy consumption decreased as the air flow rate increased. As previously mentioned, fine particles are more cohesive than coarse particles, leading to a higher force required to break down aggregates formed during the mixing process. Therefore, the mixing time for fine particles is longer than that for coarse particles, and there is a trade-off between power consumption and mixing time. The optimum specific energy consumption is achieved by considering both of these parameters [6].

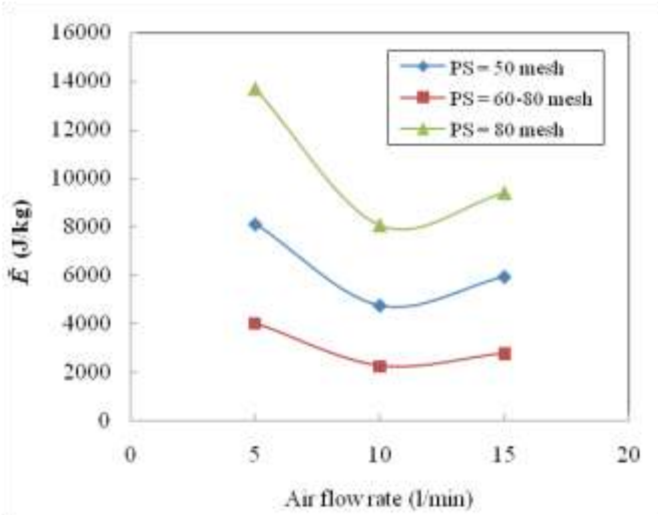

Figure 5 Variation in specific energy consumption with air flow rate.

Figure 5 also shows that for the three particle-size groups, the 60-80 mesh group has the lowest specific energy consumption given by the combination of an orbital speed of 5 rpm and a rotation speed of 67.5 rpm at an air flow rate of 10 l/min. For the particle sizes of 50-60 and 80 mesh, the lowest values were obtained by the combinations of an orbital speed of 5 rpm and a rotation speed of 50-60 rpm with an air flow rate of 15 l/min, and an orbital speed of 5 rpm and a rotation speed of 30 rpm with an air flow rate of 10 l/min, respectively. Among all the variations, the lowest specific energy consumptions was obtained by the combination of orbital and rotation speeds of 5 and 67.5 rpm and an air flow rate of 10 l/min with a 60-80 mesh particle size.

Figure 6 shows that the optimum specific energy consumption was achieved using MOSM with the introduction of an air flow rate of 10 l/min. The application of air injection at the UZ in MOSM mixing can clearly reduce the specific energy consumption of the screw rotation speed at the air flow rate specified. Increasing the air flow rate causes an increase in the specific energy consumption. This is a good result, proving a hypothesis that has been previously assumed: that the application of air injection into the mixing process of urea-natural zeolite for the manufacture of SRF urea can reduce power consumption, resulting in lower production costs. It is recommended to implement this mixing system for further development at the scale of production.

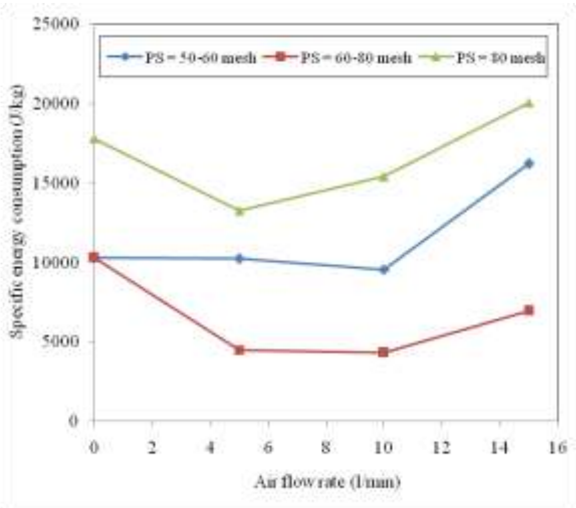

Figure 6 Specific energy consumption with air flow rate variations at the optimum ratio of n_r/n_o.

3.3 Correlations of Power Number

To predict the power consumption required in the mixing process for urea-natural zeolite of varying particle sizes, we developed a power equation for the orbiting screw mixer used in this experiment. The geometry of the mixer is defined in Figure 7. The developed model equations for the mixing performances are summarized in Table 1.

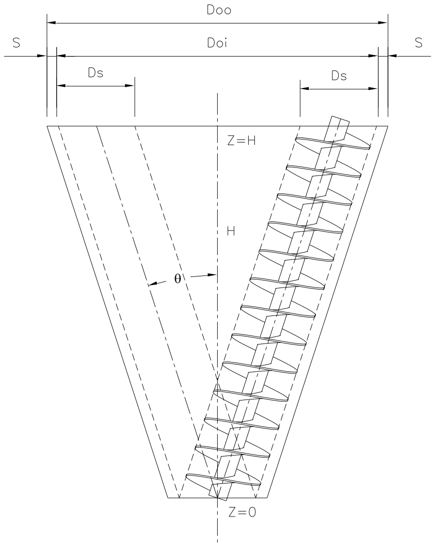

Figure 7 Schematic diagram of a conical mixer with screw.

Table 1 Correlations for Screw mixer performances to Power Number.

Rotation Screw Equation Development

$$\frac{1}{\eta_{ES}} = PowerNumberScrew \tag{5}$$

$$\eta_{ES} = \frac{½\pi^3 \bar{\rho}_m p D_s^4 N_s^3 \eta_m}{(\tau_s \times N_s)/\eta_{el}} = ½ \frac{\bar{\rho}_m \pi^3 p D_s^4 N_s^2 \eta_m \eta_{el}}{\tau_s} \tag{6}$$

$$\dot{W}_{kS} = ½\dot{\rho}_m \pi^3 p D_s^4 N_s^3 \eta_m \tag{7}$$

Orbiting Screw Equation Development

$$\eta_{Eo} = \frac{\dot{W}_{ko}}{(\tau_o N_o)/\eta_{el}} = \frac{\dot{W}_{ko}\eta_{el}}{\tau_o N_o} \tag{8}$$

$$\dot{m}_o = \bar{\rho}_m \pi D_s H^2 N_o \eta_{mo} \left[\frac{D_{oo,z=0}}{H} - \frac{D_s}{H} \sin\theta - \left(\frac{Z_o}{H}\right)^2 \sin\theta\right] \left[\frac{1}{2}(D_{tot} - 2s - D_s)^2 N_o^2 \eta_{ko}\right] \tag{9}$$

$$e_{ko} = ½U_o^2 \tag{10}$$

$$\dot{W}_{ko} = \dot{m}_o \tfrac{1}{2} U_o^2 \dot{\eta}_{ko} \quad (11)$$

Power Number

$$\text{Power Number Screw}, N_{Po,S} = \left(\frac{1}{\eta_{ES}}\right) \quad (12)$$

$$\text{Power Number Orbital}, N_{Po,O} = \left(\frac{1}{\eta_{EO}}\right) \quad (13)$$

$$N_{PO,tot} = N_{PO,S} N_{PO,O} \left[\frac{1}{N_{PO,S} + \beta_{SO} N_{PO,O}} + \frac{1}{N_{PO,S}\frac{1}{\beta_{SO}}}\right]; \quad (14)$$

$$\text{where: } \beta_{SO} = \frac{\tau_s N_s}{\tau_o N_o} \quad (15)$$

$$N_{PO} = f[N_{PO,S}, N_{PO,O}, \beta_{SO}] \quad (16)$$

$$N_{PO} = f[N_{Re}, N_{Fr}] \rightarrow N_{PO} = f[N_{Re}] \text{ and } N_{PO} = f[N_{Fr}] \quad (17)$$

Power numbers are used to estimate the power needed to rotate and revolve a screw mixer. To investigate the effects of varying particle sizes on power consumption, the orbiting screw mixer was used for mixing urea and natural zeolite with three particle sizes, 50-60 mesh, 60-80 mesh and 80 mesh. The optimum specific energy consumption in the mixing process of urea-natural zeolite with air injection shown in Figures 5 and 6 can also be proven with and represented in the form of Total Power Numbers (shown in Figure 8); the lowest power number (1.6 x 10^8) was obtained at an air flow rate of 10 l/min for the 60-80 mesh particle-size group.

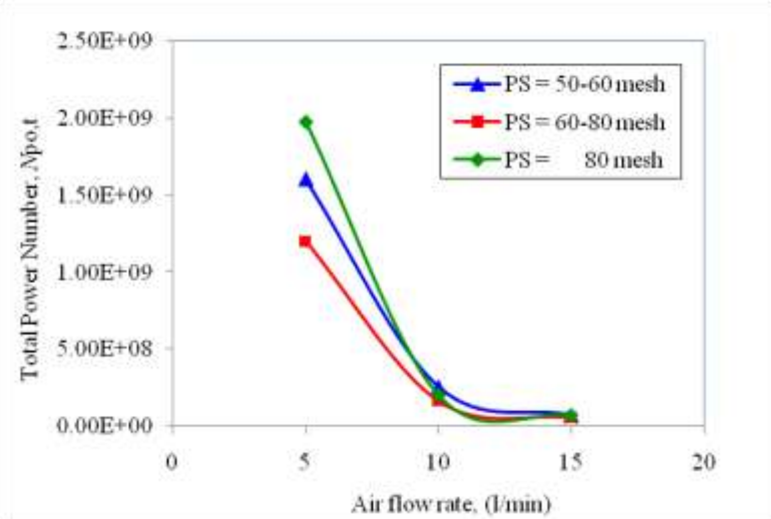

Figure 8 The effect of air injection rate on the Total Power Number.

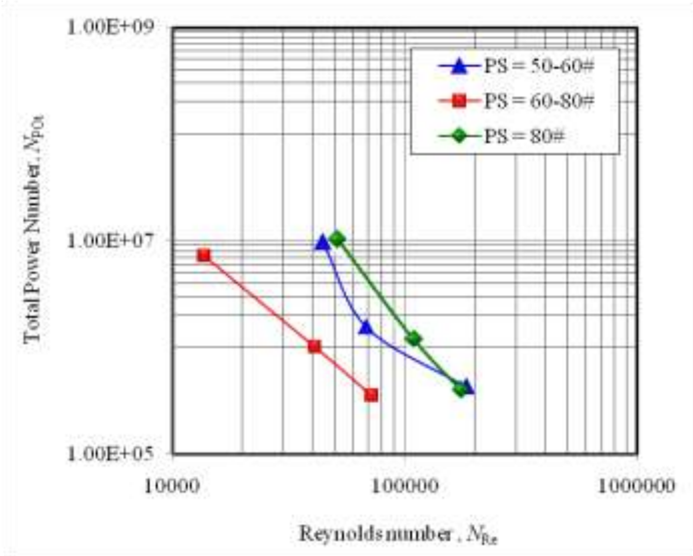

Figure 9 Total Power Number with respect to the Reynolds Number, N_{Re}.

Examining the influence of air injection on the mixing process of UZ, we observed an increase in the Total Power Number with an increased air flow rate, as shown in Figure 8. The effect of the air flow rate is indicated by the high power number for an air flow rate of 5 l/min that decreased sharply when increasing the flow rate to 10 l/min. When flow rates were increased above 10 l/min, the Total Power Number remained a fixed value.

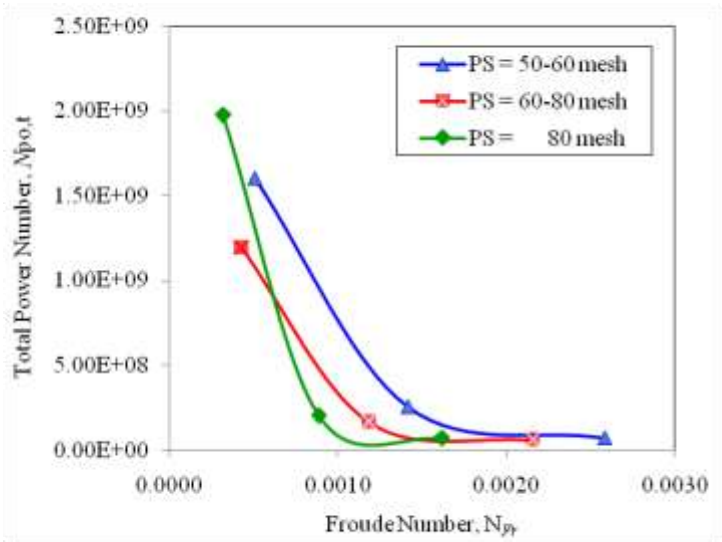

Figure 10 Total Power Number with respect to the Froude Number, N_{Fr}.

Variations in the Total Power Number with N_{Re} are shown in Figure 9 for the three different particle-size groups. The Total Tower Number for mixing urea-natural zeolite with air injection shows that N*po,t* decreased as N_{Re} increased. Figure 10 shows the correlation for the Total Power Number, (N*po,t*) and the Froude Number (N_{Fr}) which indicates that the optimum operating condition for mixing with the lowest specific energy consumption was achieved in mixing of the 60-80 mesh particle-size group with an air flow rate of 10 l/min. The N_{Fr} values obtained ranged between $0.73x10^{-3}$ and $107x10^{-6}$. These results confirmed the results of research conducted by Edward, *et al*. [7], who reported that mixing solids in an orbiting screw mixer generally operates at $N_{Fr}<1$.

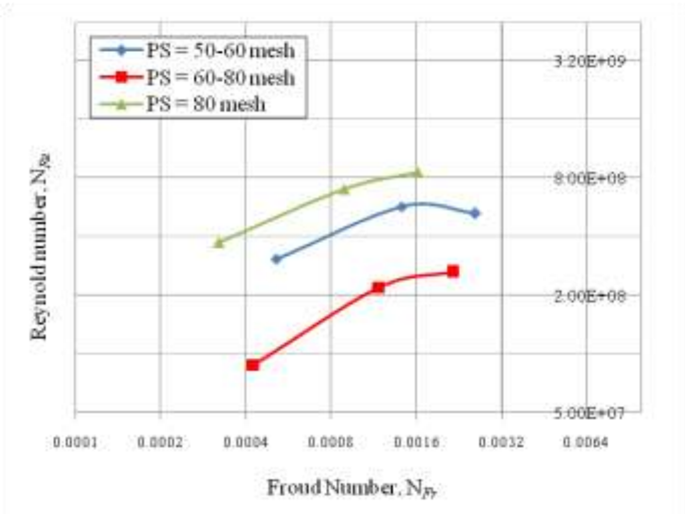

Figure 11 Correlations of N_{Fr} with N_{Re}.

Figure 11 shows that the ideal mixing process takes place when the $N_{Re}<2.19x10^8$ and the $N_{Fr}<1.18x10^{-3}$ for a 60-80 mesh UZ particle size with a combination screw mixer and an air flow rate of 10 l/min.

4 Conclusions

The results of this study indicate that the methodology of combining an orbiting screw mixer and air injection for the analysis of power consumption is suitable for further process development and scale-up. A particularly good result with respect to power consumption is found for mixing the 60-80 mesh particle-size group with a stirrer combination of a screw mixer and air injection with a rotation speed of 67.5 rpm, orbital speed of 5 rpm and air flow rate of 10 l/min. Mixing with the lowest specific energy consumption shows that the best mixing is achieved in the range of N_{Re} values from $8.77x10^7$ to $2.63x10^8$.

The UZ mixing process performed well at $N_{Re}< 2.19x10^8$ and $N_{Fr}<1.18x10^{-3}$ for the 60-80 mesh particle-size group with a combination of a screw mixer and air injection at a flow rate of 10 l/min.

Nomenclature

D_{in}	=	Diameter of the cone [m]
D_s	=	Effective diameter of screw [m]
D	=	Screw diameter
E	=	Specific energy consumption [Joule/kg]
e_{ka}	=	Kinetic power axial [Watt/kg]
e_{ko}	=	Kinetic power orbital [Watt/kg]
F	=	Force [Newton]
g	=	Gravitation force [m/s^2]
H	=	Height of the cones [m]
I	=	Electric current (Ampere)
L	=	Diameter orbit of screw (screw arm) [m]
„m.-s.	=	Mass flow rate displaced by the screw [kg/s]
n	=	Screw rotation speed [rad/s]
N_{Fr}	=	Froud number, $N_{Fr}= \omega_r^2 r_p/g$, [-]
N_s	=	Rotation speed of screw [rpm]
N_o	=	Orbital speed of screw [rpm]
$N_{po,s}$	=	Power number of screw [rpm]
$N_{po,o}$	=	Power number of screw [rpm]
$N_{po,t}$	=	Power Number Total [-]
N_{Re}	=	Reynolds number $(\rho_a.U_{ek}.D_{in})/\mu_{a,}$[-]
m	=	Mass of solid [kg]
p	=	Pitch [m]
PS	=	Particle Size [mesh]
r_p	=	Radius of particle
s	=	Screw distance to the wall [m]
SRF-U	=	Slow Release Fertilizer Urea [-]
t_{mx}	=	Mixing time [second]
U_o	=	Linear velocity of screw orbiting [m/s]
U_{ek}	=	Flow velocity of the air [m/s]
U_s	=	Linear velocity of screw rotation [m/s]
UZ	=	Urea-Natural Zeolite [-]
V	=	Electrical voltage [Volt]
W_{ko}	=	Kinetic Power required for screw rotation [Watt]
„W.-ks.	=	Kinetic Power required for screw orbiting [Watt]
W_l	=	Electrical power [Watt]
W_m	=	Mechanical power [Watt]
Z	=	Height of the cone [m]

Greek letters

βso	=	Power ratio of rotation and orbital screw [-]
ρ_a	=	Density of the air [kg/m^3]
„ρ.-m.	=	Average density of particle [kg/m^3]
θ	=	Screw elevation [degree]
τ_s	=	Rotation torque of screw [Nm]
τ_o	=	Orbital torque of screw [Nm]
η	=	Mechanical efficiency [%]
η_{Es}	=	Kinetic efficiency rotation of screw [%]
η_{Eo}	=	Kinetic efficiency orbital of screw [%]
η_{ms}	=	Efficiency mass transfer solids by screw rotation [%]
η_{mo}	=	Efficiency mass transfer efficiency solids by screw orbit [%]
μ_a	=	Viscosity of the air [kg/m.s]
ω_r	=	Angular velocity [rad/s]

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