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Experimental Study on the Mixing of Binary Polymer Particles in Different Types of Mixer

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Abstract: In this study an experimental study of mixing process of free flowing polymers binary mixtures at different densities and colours in three mixers was investigated. The state of mixing of solids was studied by analysing the variation of the proportions of the marked particles with time and position in the bed or in the mixer. The variation of mixture composition based on the samples was incorporated into Lacey mixing index which describes the degree of mixing of the particles at particular time. This method enables assessment of the overall mixing behaviour in terms of the rate of mixing (through estimation of the time required for the mixing index to increase from zero to a certain value), together with the degree of mixing at the mixing equilibrium. Results showed that gas velocity and bed depth are important parameters influencing solids mixing in a bubbling fluidised bed. Whilst it was observed that the rotation speeds and filled up levels are important parameters influencing solids mixing in V-mixer and Nauta-mixer. From the results, complete mixing was attained at a bed depth of 17 cm and gas velocity of $1.38U_{mf}$ in the fluidised bed; 40% filled up level and 40 rpm in the V-mixer and 50% filled up level and 5 rpm in the Nauta-mixer. From the energy consumption analysis made, it was found that a fluidised bed mixer offers the most efficient and economical process compared to the V-mixer and Nauta-mixer.

Key words: Particle mixing, mixers type, mixing indices, mixture homogeneity

INTRODUCTION

Solids mixing are an important process step in the manufacture of many industrial products (Berntsson *et al*., 2002; Poux *et al*., 1991; Rhodes, 1990). The problem of solids mixture inhomogeneity affects a wide variety of industries including pharmaceutical, chemical, petrochemical, foodstuffs, plastics, metallurgical, fertilizers and grain. For any manufacturing process that involves mixing of solid particles, the level of inhomogeneity must be considered when determining the quality of the final product. This is critical in an area such as the plastics industry where the manufacturer must produce a specific amount of different types of polymer in the final mixtures and the consequences of being wrong can change the properties of products. At present, many (up to 30) mixing indices have been proposed to measure the evolution of the homogeneity of mixture.

In order to characterise, optimise and control the mixing process, the variation of mixture composition must be monitored. Ideally, final powder mixtures should be completely homogeneous, that is unsegregated (Rollins *et al*., 1995).

Achieving good mixing of particulate solids of different size and density is important in many of the process industries and yet it is not a trivial exercise. For free-flowing powders, the preferred state for particles of different size and density is to remain segregated (Rhodes, 1990; Fan *et al*., 1990; Wu and Baeyens, 1998). The mixing process depends on numerous parameters such as time, temperature, sequence of material addition, powder size and shape, shear rate and powder loading (Supati *et al*., 2000).

The objectives of the study include: determine the optimum operating conditions in order to obtain a final mixture of specified compositions of polymer A (white) and B (black), namely, 3:1, respectively, investigate the mixing performance in three types of mixers, namely a V-blender, a Nauta-mixer and fluidised bed and choose the best type of mixer to be used in order to obtain

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the specified mixtures, namely which offers the most efficient but economical process.

QUALITY OF MIXING AND THEORY

The end use of particle mixture determines the quality of mixture required. The quality of mixing can be assessed by examining the degree of mixing of particles in the bed. So far, such studies are only limited to binary and ternary systems in which particle segregation takes place. Wang and Chou (1995), Wu and Baeyens (2001) were studied in this area (Rhodes *et al*., 2001).

Various mixing indices are used in describing the effectiveness of different mixers in the process industry (Poux *et al*., 1991). The most common approach to evaluate mixture homogeneity was first introduced by Lacey (1943) namely the use of mixing indices.

Lacey (1943) showed that the variance of completely segregated mixture, S_0^2, can be expressed as:

$$S_0^2 = P(1-P) \tag{1}$$

where, P and (1-P) are the proportions of the two components estimated from the samples. When any sample is withdrawn from a fully randomized mixture, the variance, S_R^2, may be calculated from:

$$S_R^2 = \frac{P(1-P)}{N} \tag{2}$$

where, N is the number of particles in the sample. This value is normally the minimum attainable variance within a mixture. The well-known Lacey index Lacey (1954) is defined as:

$$M = \frac{S_0^2 - S^2}{S_0^2 - S_R^2} \tag{3}$$

where, S^2 is the variance of the mixture between fully random and completely segregated mixtures. The mixing index obtained from Eq. 3 has a zero value for completely segregated mixture and increases to unity for a fully random mixture. Due to its simplicity, the Lacey index is widely used to characterize mixers used in the process industry (Rhodes *et al*., 2001).

EXPERIMENTAL

Two types of polymer particles referred to as polymer A (white) and B (black) materials were used as the feed material in this study. Table 1 lists the physical properties of polymers used.

Table 1: Some physical properties of polymers used

Parameters	Polymer A (white)	Polymer B (black)
Mean particle size, $\bar{d}_p$ (μm)	3465	3502
Size range, d_p (μm)	4750-2360	4750-2360
Particle density, ρ_p (kg m^{-3})	923	1105
Bulk density, ρ_{ba} (kg m^{-3})	617	745
Geldart classification (1973)	D	D

Type of mixers, experiments set up and methodology in this work. Details are presented elsewhere Almahdi (2003). The quality of mixing is assessed by examining the degree of particles in each sample. In this work, Lacey mixing index defined in Eq. 3, has been used to express the different in compositions throughout the mixture product.

RESULTS AND DISCUSSION

Fluidised bed

Effect of mixing time: There is a certain duration at which maximum mixing index is achieved. The time depends on the fluidisation velocity used, as well as the bed depth. Fig. 1 shows the result of mixing index at different mixing time for different operating velocities. It is interesting to note that the Lacey mixing index for all takes time to reach an equilibrium value. The observation from the Fig. 1 shows that the optimum mixing time depends on the superficial gas velocity. This can be attributed to that, when the velocity increased, the bubble flow rate will increase and hence the mixing process will increase.

Effect of bed depth: The purpose of these experiments was to obtain the best bed depth of fluidised bed to give homogenous mixture at critical time. It was that the mixing index increases when the bed depth decreases. However, it was noticeable that the mixing index increases, as the gas velocity increases. These two remarks illustrate that there is relationship between the bed depth and gas velocity in order to attain good mixing.

V-mixer

Effect of mixing time: There is a certain duration at which equilibrium mixing index value is reached. Figure 2 shows the variation of mixing index value with time at different rotational speeds (20, 40 and 60 rpm) for filled up levels of 40%.

In all cases it was found that the mixing index increased with time until it reach an equilibrium value. This is due to the fact that the exchange rate of particles between the two end of the arms and reaching join of arms is particularly sensitive to mixing time with revolution speeds, also the dispersion the particles inside the V-mixer.

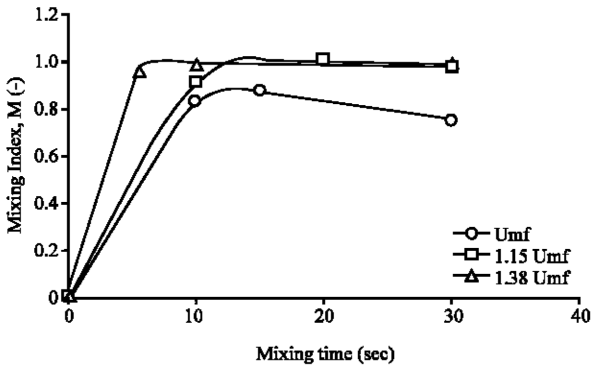

Fig. 1: Effect of mixing time on Lacey mixing index at different gas velocities and bed depth, 10 cm

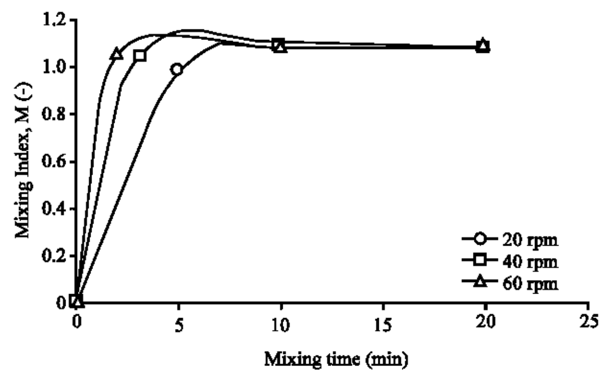

Fig. 2: Effect of mixing time on Lacey mixing index at different rotation speeds and filled up level, 40%

Nauta-mixer

Effect of mixing time in Nauta-mixer: From the results, it was found that the mixing index at 0.5 min is lower than the mixing value at 1 min. Similar trend was found in V-mixer, the mixing index increases as mixing time increases until an optimum maximum value is reached.

Effect of filling up of Nauta-mixer: From the results of 50 and 70% filled up levels and at different speeds, i.e. 5, 7 and 9 rpm, it was found that the mixing index increase slightly with reduction in filled up level, which suggests that particles travel from the bottom of mixer to the top faster than at higher filled up level, as well as the particles travel from the center of mixer to the outer layer of mixer faster than runs which use large quantity of particles mixture.

Power consumption: Process optimisation is important to produce required product at a minimum energy or power consumption. In our case, to get homogenous mixtures at optimal conditions, the relation between the power consumption and the mixing index is established.

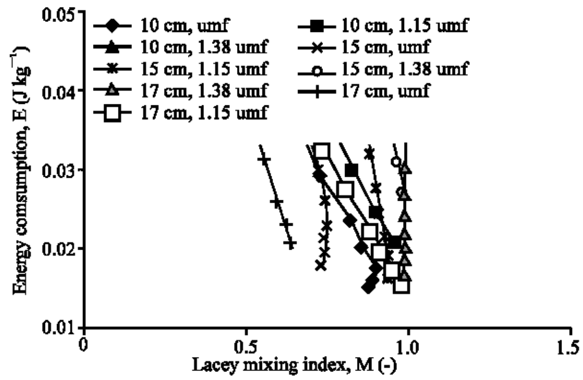

Fig. 3: Specific energy consumption, E (J kg^{-1}). vs. Lacey mixing index, M (-) for mixing by a Fluidised bed

Mixing by fluidised bed: For mixing by fluidised bed, the optimal mixing index depends on the gas flow rate, where the power consumption increases as gas flow rate increases. Fig. 3 shows the results for specific energy consumption in mixing by fluidised bed. The x-axis represent Lacey mixing index, M and the y-axis is specific energy consumption, E based on $Q/[M.t.(A)^{0.5}]$, (J kg^{-1}). It shows for all cases that the energy consumption is not high and within a narrow range i.e. from 0.015 to 0.02 J kg^{-1}.

In order to calculate realistic values of the specific energy consumption (in J kg^{-1}) it is necessary to make assumptions about the pressure drops across the distributor plate, as well as across the fluidised bed. Of course if the pressure drops are assumed to be the same for all the cases an alternative value can be calculated simply based on the gas flow rate and mixing time per mixing index and mass of solids quantity, K namely, $(Q.\rho_g.t)/(M.m)$ against the Lacey mixing index. In this case the optimum operation would be given by the condition at which the K value is a minimum for a specified M value. From Fig. 4 the observation shows that the case of 17 cm bed depth with $1.38U_{mf}$ is the optimum operation, since it offers the minimum value of K, means minimum specific energy consumption, based on mixing index of 0.99.

Mixing by V-mixer and Nauta-mixer: For mixing in V-mixer and Nauta-mixer, the ideal calculation indicated that the mixing index depends on the rotation speeds, as well as filled up levels, which indicate the amount of energy used.

The combination of these two parameters will indicate the optimum operation, namely to give the maximum value of mixing index, M at the lowest power consumed. Justification should be made to produce the largest amount of product but at the least amount of energy yes ia musage. In this case the energy consumed, E, was calculated by $[1.047198*10^{-3}.R_{pm}.t)/M]$ (J kg^{-1}).

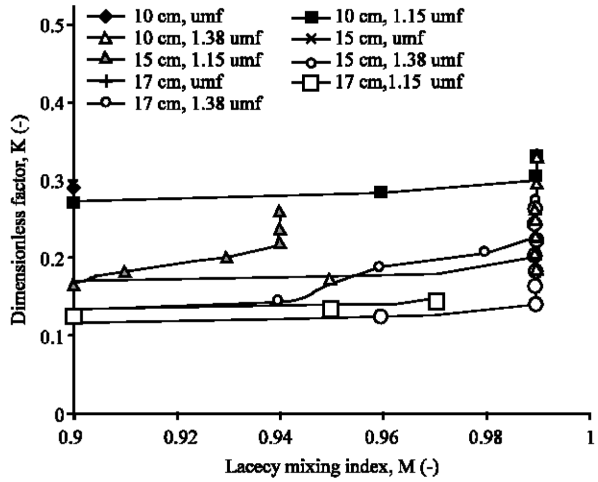

Fig. 4: Dimensionless mixing factor, K. vs. Lacey mixing index, M (-) for mixing by a Fluidised bed

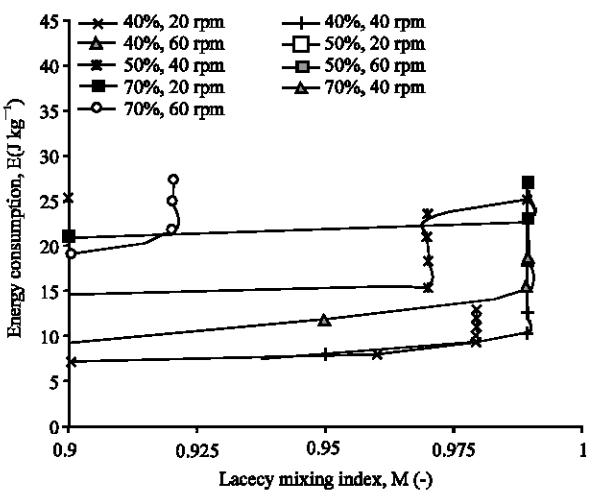

Fig. 5: Specific energy consumption, E (J kg^{-1}). vs. Lacey mixing index, M (-) for mixing by V-mixer

The various mixing index can be compared on the basis of the specific energy consumption (J kg^{-1}). As seen in Fig. 5 for mixing by V-mixer, the lowest overall energy losses (in J kg^{-1}) at a mixing index value of 0.98 are given for conditions at 40% filled up level with 20 rpm and 40% filled up level with 40 rpm. The minimum energy consumption is at 20 rpm rotation speed i.e. E = 8.5 and 9 J kg^{-1} at 20 and 40 rpm, respectively. However, the minimum energy consumption to achieve as low as 0.99 mixing index value, i.e. to produce the best homogenous mixture is given from runs at 40 filled up level with 40 rpm. 40% filled up level with 40 rpm is slightly homogenous than 40% filled up level with 20 rpm but consumed more energy (in J kg^{-1}).

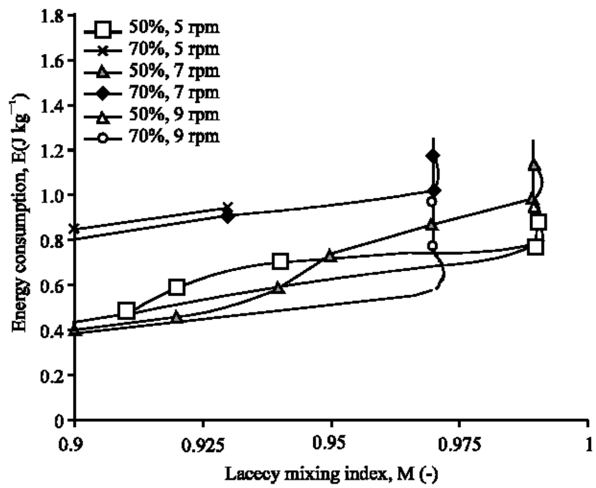

Fig. 6: Specific energy consumption, E (J kg^{-1}). vs. Lacey mixing index, M (-) for mixing by Nauta-mixer

Table 2: Optimum mixing time at best parameters condition and power consumption for each mixer at mixing index of 0.99

Condition	Fluidised bed-mixer	V-mixer	Nauta-mixer
Mass (kg)	1.772	0.467	6.490
Filled up level	17 cm depth	40% filled up	50% filled up
Gas velocity	1.38 unit	-	-
Rotation speed (rpm)	-	40	5
Optimum time (sec)	7	240	120
Power consumption (J kg^{-1})	0.015	9	0.72

As seen in Fig. 6 for mixing by Nauta-mixer, the various mixing index value can also be compared on the basis of the specific energy consumption (J kg^{-1}). The lowest overall specific energy losses (in J kg^{-1}) at minimum mixing index value of 0.97 is given from the condition at 70% filled up level and 9 rpm, (E = 0.56 J kg^{-1}). Whereas at mixing index value of 0.99, the conditions at 50% filled up level and rotation speed of 5 rpm gives the minimum energy consumption E = 0.72 J kg^{-1}. Nevertheless it can be seen that higher mixing index value would consume higher energy per kilogram. Mixture produced at 50% filled up level with 5 rpm is however slightly homogenous than 70% with 9 rpm but consumed more specific energy (in J kg^{-1}).

Optimisation of the mixing by three mixers used: The optimum conditions for the fluidised bed mixer, V-mixer and Nauta-mixer, respectively were compared and are shown in Table 2 The mixing index of 0.99 can be regarded as an ideal mixing condition.

The results indicate that mixing in a fluidised bed is the most efficient and economical way in comparison with the V-mixer and Nauta-mixer. For an ideal mixing of

M equals to 0.99, a fluidised bed may mix particles to an optimum homogeneity within 7 seconds with specific energy consumption of only 0.015 J kg^{-1}, for a bed weight of 1.772 kg. A total weight of 6.490 kg in comparison with the run for the Nauta-mixer, would require an approximate of 0.055 J kg^{-1} to produce an ideal mixture of M = 0.99 within 2 min, which is still the lowest energy consumed compared to the other two types of mixer.

CONCLUSIONS

Three mixing equipments have been used in this work namely, V-mixer, Nauta-mixer and fluidised bed mixer. The conclusions are summarised as follows:

- In the fluidised bed, three gas velocities had been used namely 1.35 m sec^{-1} (U_{mf}), 1.55 m sec^{-1} (1.15U_{mf}) and 1.87 m sec^{-1} (1.38U_{mf}), whilst bed depths used were 10, 15 and 17 cm. The results indicate that the rate of solids mixing increases with increasing gas velocity, whilst the degree of mixing achievable is unaffected by gas velocity. The degree of mixing was found to increases with increasing time until an equilibrium mixing index was achieved. The effect of bed depth was found to decrease with increasing mixing index. Optimising the process by minimising the specific energy consumption and choosing an optimum equilibrium mixing index of 0.99, it has been shown that conditions at 1.38U_{mf} and bed depth of 17 cm gave the most desirable result.
- For the V-mixer, it can be concluded that the rate of mixing increases as the filled up level reduces and the speed of rotation increases. Again, by optimising the mixing process, namely by plotting the ratio of specific energy consumption to mixing index, versus the mixing index and specifying M = 0.99, gave the condition at 40% filled up level and rotation of 40 rpm to be the most optimum mixing operation in the V-mixer.
- Whilst for the Nauta-mixer, similar results were observed on the effect of filled up levels and rotation speed on the rate of mixing. It can also be concluded that run at 50% filled up level and 5 rpm offered the minimum specific energy consumption to give a mixing index of 0.99.
- In conclusion, it is shown that mixing in a fluidised bed is the most efficient and economical way in comparison with the other two methods (mixers). An advantage of this model is that it is easy to use, not as complicated as complete mixing is attained in few seconds and exhibit the lowest power losses.

List of symbols

A : Cross-sectional area of column, m^2
d_p : The arithmetic mean of adjacent sieve size, μm
$\bar{d}_p$: Mean of adjacent sieve size, μm
E : Specific energy consumption, J kg^{-1}
H : Height of gently settled bed, cm
M : Lacey mixing index, defined in Eq. 3, dimensionless
N : No. of particles in a sample
P : Proportion of white particles in the sample
t : Time, sec, min
S : Suare root of the variance of the mixture between fully randomised and completely segregated states, dimensionless.
S_0 : Square root of the variance of the completely segregated states, dimensionless.
S_R : Square root of the variance of the fully randomised states, dimensionless.
U : Superficial gas velocity, m sec^{-1}
U_{mf} : Minimum fluidisation velocity, m sec^{-1}
R_{pm} : Rotational speed, rpm
K : Optimisation value for mixing by fluidised bed, dimensionless.
Q : Gas flow rate, m^3 sec^{-1}
ρ_b : Bulk density, kg m^{-3}.
ρ_p : Particle density, kg m^{-3}.

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