International Journal of Engineering and Management Sciences (IJEMS) Vol. 8. (2023). No. 2
DOI: 10.21791/IJEMS.2023.2.9.

Mixing Power Requirement Determination in Agitated Drum Using Dimensional Analysis

D. HORVÁTH[1], T. POÓS[2]

[1] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Building Services and Process Engineering, horvath.daniel@gpk.bme.hu
[2] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Building Services and Process Engineering, poos.tibor@gpk.bme.hu

Abstract. The mixing of granular materials in an agitated drum can be characterized by the dimensionless power equation. The equation was created by dimensional analysis, for which the parameters affecting the mixing power requirement were collected based on the literature. The most important of these are the rotational speed, the drum loading factor, the geometric and physical properties of the mixing drum and the granular materials. The dimensionless power equation is used to estimate with reasonable accuracy the Power number within the given range of applicability ($0.48\frac{1}{s} \le n \le 1.58\frac{1}{s}$; $10\% \le l \le 25\%$)*, which has been validated by measurements. From the Power number, the mixing power requirement of the mixed granular material can be calculated, which can be used as operational data for selecting the mixing motor.*

Keywords: agitated drum, dimensional analysis, Power number, mixing power requirement

Introduction

In industry, mixing is a common operation. Mixing granular materials can be done for several purposes, e.g. homogenisation or segregation of the granular materials, but also during coating or drying. Different designs, layouts, and operating parameters are available depending on the mixing purpose and materials. The apparatus requires sizing of the electric motor power that performs the mixing. Underestimating the power of the mixing motor will result in the apparatus to be unable to perform the mixing operation. Overestimating the power of the mixing motor by a significant amount may result in unnecessary additional investment and operating costs. The mixing power requirement depends on the quality, physical properties and quantity of the mixed material, as well as the geometry of the mixing apparatus. Various correlations for determining the mixing power requirements of liquids are already available in the literature, but they are still incomplete or specific to solid granular materials. The mixing power requirements of granular materials can be determined by measurement ([1]–[10]) or simulation ([5], [7]–[22]). However, the description of the mixing power requirement by a mathematical method has only been addressed in a few studies ([2], [3], [8], [23], [24]). The relationships they have established differ both in terms of the equation structure and the parameters used. The simplest equations only consider some material properties of the mixed materials (bulk density, particle size, etc.), the main dimensions of the mixing apparatus (e.g. drum diameter, drum length, mixing element diameter, etc.)

DOI: 10.21791/IJEMS.2023.2.9.

and some or a combination of the operating parameters (drum loading factor, rotational speed, etc.). Thus, other designs of mixing apparatus may not be applicable with sufficient accuracy, if at all.

The aim of this research is to collect the parameters affecting the mixing power requirement of granular materials in a horizontal axis agitated drum and to establish a relationship to determine the mixing power requirement.

1. Material

In previous measurements ([4], [16]), the mixing power requirement of hulled millet (*Panicum miliaceum L.*) was determined at different drum loading factors and rotational speeds. The ~8.9% moisture content of air-dry hulled millet was determined by drying it in a drying chamber at 105°C for at least 24 hours [25]. The bulk density for the given moisture content was determined using an air pycnometer [26] and the cohesive force was determined using a $60\ mm \times 60\ mm \times 30\ mm$ direct shear box apparatus [16]. The physical properties of the material are summarised in Table 1.

2. Methods

This research established a relationship using dimensional analysis to estimate the mixing power requirement of hulled millet in an agitated drum. Measurements were performed and results of previous work [4] were used to validate the relationship.

2.1. Experimental method

Figure 1. illustrates the 3D model of the horizontal axis agitated drum. The U-shaped static drum is $765\ mm$ long, $250\ mm$ wide and $270\ mm$ high, so its empty volume is $V_d = 47.4\ dm^3$. The drum loading factor (l) is calculated as the ratio of the volume of the loaded material to the volume of the empty drum. In the laboratory measurements, $l = 10\%; 15\%; 20\%; 25\%$ drum loading factors were used. The size of the mixing paddles is $50\ mm \times 20\ mm \times 2\ mm$ and their inclination angle is 10°. The $22\ pcs$ mixing paddles are welded to flat steel stems of the same cross-section but with their edges turned over. The stems are fixed to the $\emptyset 45\ mm$ shaft by means of a soluble bond. The shaft is driven via a rubber-type coupling by a NORD SK 80 L/4 type three-phase geared motor equipped with a frequency inverter. The laboratory measurements were carried out at rotational speeds of $n = 0.48; 0.79; 0.95; 1.11; 1.27; 1.43; 1.58\ 1/s$. The electric power consumption of the motor was measured with a DATCON PQRM5100 31 type [28] power meter. No-load power consumption measurements were also performed before filling the drum to determine the power requirement due to shaft and mixing element rotations, bearing friction and air resistance [23]. The results were measured with the materials inside the drum (P_{sum}) were subtracted from the no-load power consumption (P_0) to obtain the pure mixing power requirement of the granular material:

$$P_{meas} = P_{sum} - P_0 \tag{1}$$

DOI: 10.21791/IJEMS.2023.2.9.

Power consumptions were recorded at 1 s intervals for a minimum of 30 s long mixing and were averaged.

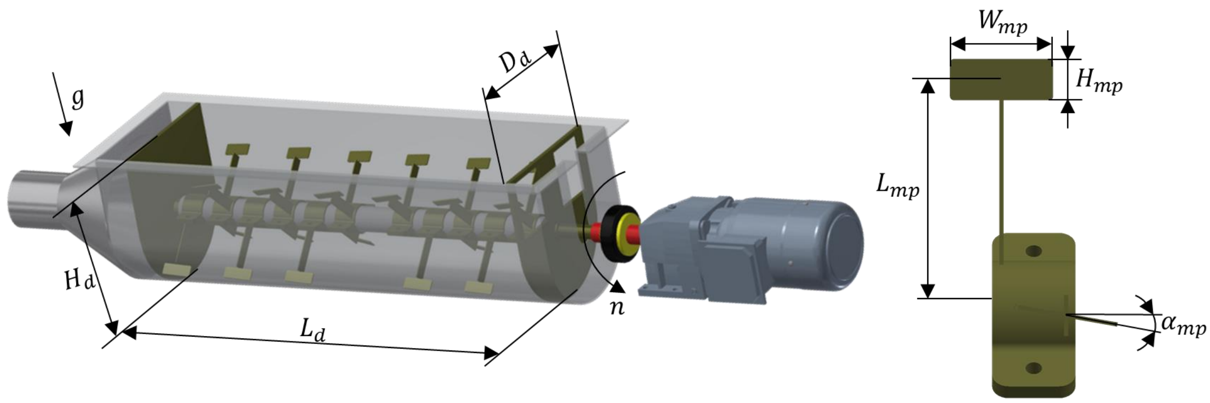

Figure 1. The 3D model of the agitated drum on the left and the mixing paddle on the right side. (L_d: drum length, D_d: drum width, H_d: drum height, W_{mp}: mixing paddle width, H_{mp}: mixing paddle height, α_{mp}: mixing paddle inclination angle, L_{mp}: mixing paddle force lever, n: rotational speed, g: gravity)

2.2. Dimensional analysis

By using dimensional analysis, the similarity criteria of the investigated system can be determined, and a general relationship can be established to describe it. Knowing the quantities that describe and influence the system is necessary to apply the method. Dimensionless groups of quantities can be created, with numerical constants providing the relationship between them. The values of these constants can no longer be determined by dimensional analysis but can be determined numerically and must be validated experimentally. In this work, the Buckingham $\prod$ theorem method ([27], [28]) was used for dimensional analysis. The first step of the method is to collect the parameters affecting the system, which are summarized in Table 1 for the agitated drum.

The mixing power requirement depends, among other things, on the size of the mixing space $(L_d; D_d; H_d)$ and the drum loading factor (l). A larger drum volume allows a larger amount of granular material to be handled simultaneously, which requires higher mixing power requirement. It also depends on the size $(W_{mp}; H_{mp})$, the design $(\alpha_{mp}; L_{mp}; \mu_d)$ and the number (N_{mp}) of the mixing paddles as they perform the mixing. A larger paddle surface area allows more material to be moved simultaneously. The friction coefficient (μ_d) of the paddles and the drum surface also influences the mixing power requirement. In the case of a rough surface, a higher friction force occurs between the particles and the drum wall or between the particles and the paddle surfaces, resulting in a higher mixing power requirement. Other parameters that influence the mixing power requirement are the material properties that describe the granules and the granular bulk, i.e., it matters what material is being mixed. The size of the particles (d_p), the bulk density (ρ_b), the bulk friction coefficient (μ_b), and the static angle of repose (α_{AoR}), as well as the cohesive force (F_c), also influence the amount of material that the mixing paddles can lift from the bulk. In addition, according to the research of Zheng et al. [20], the shape of the particles also influences the mixing power requirement. Since a mixer with a horizontal arrangement is investigated, the mixing paddles must also overcome gravity (g) while moving the particles. Finally, the rotational speed (n) also affects the mixing power requirement.

DOI: 10.21791/IJEMS.2023.2.9.

The diameter of the mixing shaft and the thickness of the mixing paddles were neglected in the dimensional analysis. One of the reasons for this is that at the investigated drum loading factors, the contacts of the grains with the mixing shaft are negligible. The other reason is the small thickness of the mixing paddles ($2\ mm$) concerning the grain size. So the force due to the lateral friction between the bulk and the side of the paddles can be neglected.

The mixing power requirement for a horizontal axis agitated drum depends on the following 17 pcs parameters:

$$P = f\left(L_d; D_d; H_d; W_{mp}; H_{mp}; \alpha_{mp}; L_{mp}; N_{mp}; \mu_d; d_p; \rho_b; \mu_b; \alpha_{AoR}; F_c; l; n; g\right) . \tag{2}$$

Some of the parameters from the 17 pcs have been considered by other authors in their research, but there was none before that applied all of them. The occurrence of each parameter in the relevant literature is indicated in the $Reference$ column of Table 1.

The second step in the dimensional analysis is to create the power product of the parameters:

$$\prod {L_d}^{\alpha} {D_d}^{\beta} {H_d}^{\gamma} {W_{mp}}^{\delta} {H_{mp}}^{\varepsilon} {\alpha_{mp}}^{\eta} {L_{mp}}^{\theta} {N_{mp}}^{\kappa} {\mu_d}^{\lambda} {d_p}^{\upsilon} {\rho_b}^{\xi} {\mu_b}^{o} {\alpha_{AoR}}^{\pi} {F_c}^{\sigma} l^{\tau} n^{\chi} g^{\psi} P^{\omega} . \tag{3}$$

The next step is to insert the dimensions:

$$\prod \begin{matrix} [L]^{\alpha}[L]^{\beta}[L]^{\gamma}[L]^{\delta}[L]^{\varepsilon}[1]^{\eta}[L]^{\theta}[1]^{\kappa}[1]^{\lambda}[L]^{\upsilon}[ML^{-3}]^{\xi}[1]^{o}[1]^{\pi}[MLT^{-2}]^{\sigma}[1]^{\tau}[T^{-1}]^{\chi} \\ [LT^{-2}]^{\psi}[ML^2T^{-3}]^{\omega} \end{matrix} . \tag{4}$$

After rearrangement according to the basic quantities, the following multiplication is obtained:

$$\prod [L]^{\alpha+\beta+\gamma+\delta+\varepsilon+\theta+\upsilon-3\xi+\sigma+\psi+2\omega} [M]^{\xi+\sigma+\omega} [T]^{-2\sigma-\chi-2\psi-3\omega} [1]^{\eta+\kappa+\lambda+o+\pi+\tau} . \tag{5}$$

The sum of the exponents of the basic quantities in the power product is zero, since the product is dimensionless. Thus, the following four equations can be created:

$$\alpha + \beta + \gamma + \delta + \varepsilon + \theta + \upsilon - 3\xi + \sigma + \psi + 2\omega = 0 ; \tag{6}$$

$$\xi + \sigma + \omega = 0 ; \tag{7}$$

$$-2\sigma - \chi - 2\psi - 3\omega = 0 ; \tag{8}$$

$$\eta + \kappa + \lambda + o + \pi + \tau = 0 . \tag{9}$$

The resulting equation system is underspecified because there are 4 pcs equations for 20 pcs variables. In the next step, the exponents of four parameters were expressed. In the expression, care must be taken to choose the appropriate characteristic size, so that the equation obtained at the end of the dimensional analysis includes the parameter describing the chosen characteristic size. In this case, the L_{mp} mixing paddle force lever was chosen, since the force acting on the paddles and the force lever give the torque on the shaft, from which the mixing power requirement can be determined knowing the rotational speed. The exponent for the parameter L_{mp} is θ. Thus, after rearranging and inserting the equations into each other, the following four equations can be created:

$$\theta = -\alpha - \beta - \gamma - \delta - \varepsilon - \upsilon - 4\sigma - \psi - 5\omega \ ; \tag{10}$$

DOI: 10.21791/IJEMS.2023.2.9.

$$\xi = -\sigma - \omega\,; \tag{11}$$

$$\chi = -2\sigma - 2\psi - 3\omega\,; \tag{12}$$

$$\kappa = -\eta - \lambda - o - \pi - \tau\,. \tag{13}$$

Substituting the exponent equations back into Eq. (3) gives the following equation:

$$\prod \begin{matrix} L_d{}^{\alpha} D_d{}^{\beta} H_d{}^{\gamma} W_{mp}{}^{\delta} H_{mp}{}^{\varepsilon} S_{mp}{}^{\zeta} \alpha_{mp}{}^{\eta} L_{mp}{}^{-\alpha-\beta-\gamma-\delta-\zeta-\upsilon-4\sigma-\psi-5\omega} D_s{}^{\iota} N_{mp}{}^{-\eta-\lambda-o-\pi-\tau} \\ \mu_d{}^{\lambda} d_p{}^{\upsilon} \rho_b{}^{-\sigma-\omega} \mu_b{}^{o} \alpha_{AoR}{}^{\pi} F_c{}^{\sigma} l^{\tau} n^{-2\sigma-2\psi-3\omega} g^{\psi} P^{\omega} \end{matrix}\,. \tag{14}$$

After assigning the same exponents to a power base, the following power product is obtained:

$$\prod \begin{matrix} \left(\frac{L_d}{L_{mp}}\right)^{\alpha} \left(\frac{D_d}{L_{mp}}\right)^{\beta} \left(\frac{H_d}{L_{mp}}\right)^{\gamma} \left(\frac{W_{mp}}{L_{mp}}\right)^{\delta} \left(\frac{H_{mp}}{L_{mp}}\right)^{\varepsilon} \left(\frac{\alpha_{mp}}{N_{mp}}\right)^{\eta} \left(\frac{\mu_d}{N_{mp}}\right)^{\lambda} \left(\frac{d_p}{L_{mp}}\right)^{\upsilon} \\ \left(\frac{\mu_b}{N_{mp}}\right)^{o} \left(\frac{\alpha_{AoR}}{N_{mp}}\right)^{\pi} \left(\frac{F_c}{L_{mp} n^2 \rho_b}\right)^{\sigma} \left(\frac{l}{N_{mp}}\right)^{\tau} \left(\frac{g}{L_{mp} n^2}\right)^{\psi} \left(\frac{P}{L_{mp}{}^5 n^3 \rho_b}\right)^{\omega} \end{matrix}\,. \tag{15}$$

The power product can be further simplified in Eq. (15) by dividing the quotients with the same denominator which have the same physical content in their numerator:

$$\prod \begin{matrix} \left(\frac{L_d}{L_{mp}}\right)^{\alpha} \left(\frac{D_d}{d_p}\right)^{\beta'} \left(\frac{H_d}{H_{mp}}\right)^{\gamma'} \left(\frac{W_{mp}}{L_{mp}}\right)^{\delta} \left(\frac{\alpha_{mp}}{\alpha_{AoR}}\right)^{\eta'} \left(\frac{\mu_d}{\mu_p}\right)^{\lambda'} \left(\frac{L_{mp}{}^4 n^2 \rho_b}{F_c}\right)^{\sigma'} \left(\frac{l}{N_{mp}}\right)^{\tau} \\ \left(\frac{L_{mp} n^2}{g}\right)^{\psi'} \left(\frac{P}{L_{mp}{}^5 n^3 \rho_b}\right)^{\omega} \end{matrix}\,. \tag{16}$$

In Eq. (16), ω is the exponent of the power number:

$$N_P = \frac{P}{L_{mp}{}^5 n^3 \rho_b}\,; \tag{17}$$

ψ' is the exponent of the mixing Froude number:

$$Fr_M = \frac{L_{mp} n^2}{g}\,; \tag{18}$$

and σ' is the exponent of the Cohesion number:

$$N_C = \frac{L_{mp}{}^4 n^2 \rho_b}{F_c}\,. \tag{19}$$

The other members of the power product give the geometrical and physical properties of the agitated drum and the granular material, which can be taken to be constant for a particular equipment-material pairing. In this research, the effects of grain size, static angle of repose and bulk friction coefficient were not investigated. The measurements were made with one type of material at one moisture content, so these members are also constant. However, the drum loading factor (l) in the ratio of τ exponent was investigated at different values during the measurements. Thus, the constants can be combined into one parameter:

$$A_1 = f\left(\frac{L_d}{W_{mp}}; \frac{D_d}{d_p}; \frac{H_d}{H_{mp}}; \frac{\alpha_{mp}}{\alpha_{AoR}}; \frac{\mu_d}{\mu_b}; N_{mp}\right). \quad (20)$$

After the dimensional analysis, the mixing Power number can be determined using Eqs. (17)–(20):

$$N_P = A_1 l^{A_2} {N_C}^{A_3} {Fr_M}^{A_4}. \quad (21)$$

No.	**Parameter name**	**Notation**	**Dimension**	**Value**	**SI unit**	**Reference**
1	Drum length	L_d	L	0.765	m	[2], [3], [21], [23]
2	Drum width	D_d	L	0.25	m	[2], [3], [21], [23]
3	Drum height	H_d	L	0.27	m	[2], [3], [21], [23]
4	Mixing paddle width	W_{mp}	L	0.05	m	[24]
5	Mixing paddle height	H_{mp}	L	0.02	m	[24]
6	Mixing paddle inclination angle	α_{mp}	1	0.1745	rad	[22], [24]
7	Mixing paddle force lever	L_{mp}	L	0.114	m	[24]
8	Number of mixing paddles	N_{mp}	1	22	1	[5], [14]
9	Drum wall and mixing paddle surface friction coefficient	μ_d	1	0.7 [16]	rad	[16]
10	Characteristic particle size	d_p	L	0.0018 ± 0.0001 [4]	m	[1], [6], [7], [11]
11	Bulk density	ρ_b	ML^{-3}	867 [4]	kgm^{-3}	[2], [3], [7], [11], [23]
12	Bulk friction coefficient	μ_b	1	0.7348 [4]	rad	[2], [3], [16]
13	Angle of repose	α_{AoR}	1	0.6353 [4]	rad	[23]
14	Cohesive force	F_c	MLT^{-2}	23.7 [4]	N	[2], [3], [15]
15	Drum loading factor	l	1	see Table 2	1	[2]–[4], [7], [13], [14], [16], [17], [29]
16	Rotational speed	n	T^{-1}	see Table 2	s^{-1}	[1]–[10], [13]–[17], [21], [23], [30]
17	Gravitational constant	g	LT^{-2}	9.81	ms^{-2}	[2], [3], [21]
18	Mixing power requirement	P	ML^2T^{-3}	see Table 2	W	main parameter

Table 1. Parameters affecting the mixing power requirement of the agitated drum and their characteristic values.

2.3. Statistical methods

As a first step, the dimensionless quantities N_P, N_c and Fr_M were calculated based on the geometric dimensions and measurement data in Table 1 and Table 2. Then, the unknown coefficients A_1, A_2, A_3 and A_4 were determined numerically by regression analysis using the *'fmincon'* nonlinear solver [31] of MathWorks MATLAB software. The criterion for the solver was the sum of the squared error of the calculated and the predicted Power numbers:

$$N_{P,min} = min\left(\sum_{i=1}^{n}\left(\frac{N_{P,pred,i} - N_{P,calc,i}}{N_{P,calc,i}}\right)^2\right). \tag{22}$$

The use of the *'fmincon'* nonlinear solver requires the initial values of the unknown parameters (A_1, A_2, A_3, A_4) in Eq. (21). Due to the sensitivity of the solver, the range $-2 \leq A_{i,0} \leq 2$ was taken as the initial values. Thus, $5^4 = 625\ pcs$ initial values were tested by combining all possible integers. From the 625 pcs iterated parameter results, the A_1, A_2, A_3, A_4 parameter combination with the minimum least squared deviation defined by Eq. (22) was used to create the new dimensionless Power equation. These parameters can be varied based on literature suggestions and rounded to engineering acceptable values. If the parameters were changed, a statistical analysis was performed to see how much distortion was generated in the fitting accuracy of the equation. The new dimensionless Power equation is characterized using two statistical methods. One is the determination coefficient:

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{n}(N_{P,pred,i} - N_{P,calc,i})^2}{\sum_{i=1}^{n}(\bar{N}_{P,calc} - N_{P,calc,i})^2}, \tag{23}$$

the other is the average relative error:

$$RE = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|N_{P,pred,i} - N_{P,calc,i}|}{N_{P,calc,i}}\right). \tag{24}$$

In addition, relative deviations were determined for each point:

$$\delta N_P = \frac{|N_{P,pred} - N_{P,calc}|}{N_{P,calc}} 100\% . \tag{25}$$

The closer the value of R^2 is to 1, and the closer the values of RE and δN_P are to 0, the power equation is more accurate.

3. Mixing power requirement

In Table 2, the mixing power requirements of hulled millet for different drum loading factors and rotational speeds ([4], [16]) are summarized, which values were used for dimensional analysis. In addition to the measured values, the calculated N_P, N_C and Fr_M are also given.

DOI: 10.21791/IJEMS.2023.2.9.

No.	$l, 1$	$n, 1/s$	P_{meas}, W	$N_{P,calc}, 1$	$N_C, 1$	$Fr_M, 1$	$N_{P,pred}, 1$	$\delta N_P, \%$
1		0.48	15.3	8563	0.001394	0.0026	7646	10.7
2		0.79	22.1	2662	0.003872	0.0073	2322	12.8
3		0.95	23.6	1650	0.005576	0.0105	1517	8.1
4	0.1	1.11	24.4	1074	0.007590	0.0143	1059	1.4
5		1.27	24.9	734	0.009913	0.0186	775	5.7
6		1.43	30.3	627	0.012546	0.0236	589	6.1
7		1.58	32.4	489	0.015489	0.0291	461	5.8
8		0.63	22.4	5275	0.002478	0.0047	5957	12.9
9		0.79	25.6	3086	0.003872	0.0073	3539	14.7
10		0.95	30.3	2118	0.005576	0.0105	2313	9.2
11	0.15	1.11	32.5	1428	0.007590	0.0143	1614	13.0
12		1.27	36.7	1083	0.009913	0.0186	1182	9.2
13		1.43	44.2	915	0.012546	0.0236	898	1.8
14		1.58	44.9	678	0.015489	0.0291	702	3.6
15		0.48	29.8	16634	0.001394	0.0026	15722	5.5
16		0.63	33.2	7831	0.002478	0.0047	8035	2.6
17		0.79	37.3	4499	0.003872	0.0073	4774	6.1
18		0.95	42.9	2995	0.005576	0.0105	3120	4.2
19	0.2	1.11	50.0	2198	0.007590	0.0143	2177	0.9
20		1.27	53.1	1565	0.009913	0.0186	1594	1.9
21		1.43	61.7	1276	0.012546	0.0236	1211	5.1
22		1.58	69.4	1048	0.015489	0.0291	947	9.6
23		0.48	38.6	21587	0.001394	0.0026	19829	8.1
24		0.63	43.9	10357	0.002478	0.0047	10134	2.2
25		0.79	48.8	5887	0.003872	0.0073	6021	2.3
26		0.95	54.9	3832	0.005576	0.0105	3935	2.7
27	0.25	1.11	61.6	2710	0.007590	0.0143	2746	1.3
28		1.27	69.8	2057	0.009913	0.0186	2011	2.3
29		1.43	79.9	1653	0.012546	0.0236	1528	7.6
30		1.58	89.2	1346	0.015489	0.0291	1195	11.2

Table 2. The measured mixing power requirements for air-dry hulled millet at different drum loading factors and rotational speeds, the calculated and estimated dimensionless numbers, and relative deviations of the Power numbers.

It is important to note that the Fr_M number determined in the dimensional analysis characterizes the mixing. This type of modified dimensionless number has already been used previously for mixing liquids [32], and solid granular materials ([2], [3]). However, for comparison with literature data and to characterize the mixing, the following Froude number relationship has to be used:

$$Fr = \frac{L_{mp}(2\pi n)^2}{g}. \tag{26}$$

The resulting Froude number can be used to describe whether the particles are in a rolling ($Fr < 1$), in a fluidisation ($Fr \approx 1$) or in a centrifugal state ($Fr > 1$) during the mixing operation [33].

DOI: 10.21791/IJEMS.2023.2.9.

4. Results

Four unknowns need to be defined to create the Power equation for the mixing of hulled millet in agitated drum. Several combinations of these unknowns can produce acceptable results, but their correctness is questionable. This phenomenon could be avoided if more than one value were available for all the parameters listed in Table 1. However, in this research a specific material for a given mixing drum geometry is investigated. Thus, based on the literature and the nature of the measured data, some parameters were fixed, and then the other parameters were iterated again with the nonlinear solver. Table 3 summarizes the steps performed with the nonlinear solver. The determination coefficient, the maximum deviation and the average relative error were determined for each case.

No.	A_1	A_2	A_3	A_4	Max. δN_P, %	RE, %	R^2, 1
1	42.46	1.0401	-1.0865	-0.0729	14.0	6.2	0.99
2	44.84	1.0401	-1	-0.1594	14.0	6.2	0.99
3	44.83	1.04	-1	-0.1594	14.1	6.2	0.99
4	43.40	1.04	-1	-1/6	14.4	6.3	0.99

Table 3. The steps performed with the nonlinear solver. Grey background indicates the fixed values at each step.

As a first step, we ran the nonlinear solver without fixing any parameters, the results of which are shown in row 1 of Table 3. Based on the research of Gijón-Arreortúa et al. [3], the A_3 exponent of the Cohesion number was fixed to -1 and then the solver was run again. The result of this is shown in row 2 of Table 3. The valuable values of the considered statistical indicators have not been changed compared to the previous step. It can be observed that the A_2 exponent of the filling degree did not change either, so this exponent value was fixed to 1.04, which only changed the maximum deviation by 0.1%. Scargiali et al. [34] applied a $-1/3$ exponent to A_4, but they determined it in an unbaffled stirred tank during liquid mixing under gas dispersion at a supercritical regime. In the present case, the exponent A_4 of the mixing Froude number was fixed at $-1/6$, which is half the value determined during liquid mixing. Finally, after running the nonlinear solver again for A_1, the final dimensionless Power equation was created:

$$N_P = 43.4 l^{1.04} N_C^{-1} Fr_M^{-1/6} , \tag{27}$$

which can be used to determine the Power number of hulled millet in the agitated drum. From the Power number, the mixing power requirement of the hulled millet can be calculated under the following conditions:

- air-dry material of $\sim$8.9% moisture content on a wet basis,
- $10\% \leq l \leq 25\%$,
- $0.48 \frac{1}{s} \leq n \leq 1.58 \frac{1}{s}$.

Fig. 2 illustrates the Power number predicted by Eq. (27) as a function of the Power number calculated from the measured data. The points' fit to the 45° straight line indicates that the estimated values are a good approximation of the calculated values.

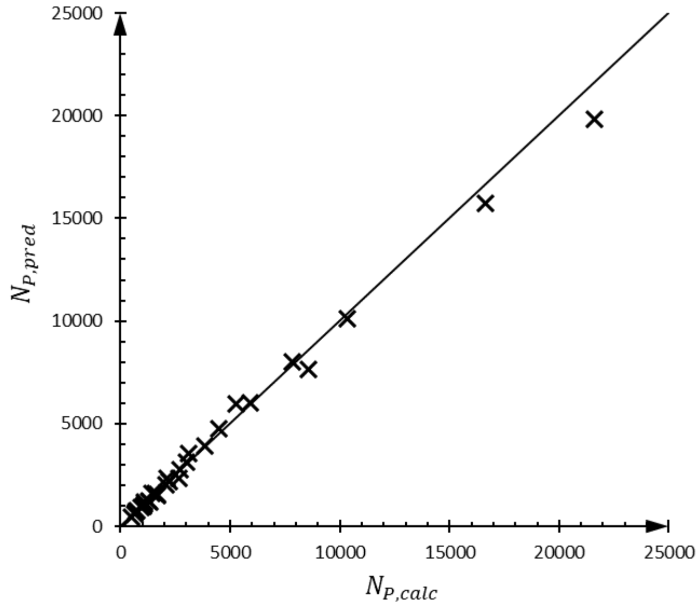

Figure 2. The predicted Power number as a function of the calculated Power number.

Conclusions

The parameters that influence the mixing power requirement of agitated drum have been collected. A dimensionless Power equation for the agitated drum was created with dimensional analysis using the Power number, the drum loading factor, the Cohesion number and the mixing Froude number. Measurements were performed to determine the mixing power requirement of air-dry hulled millet at different drum loading factors and rotational speeds. Based on the measurement results and literature data, and using a numerical nonlinear solver, the unknown parameters of the Power equation were determined. The resulting dimensionless Power equation was characterized by statistical indicators, which allow to compare the Power equation with other research in the future.

The Power number of hulled millet in agitated drum can be calculated using the obtained dimensionless Power equation. Furthermore, it can be used to determine the mixing power requirement for the choice of mixing motor, without the need for time-consuming and costly laboratory measurements.

Acknowledgements

This paper was supported by Gedeon Richter's Talentum Foundation (H-1103 Budapest, Gyömrői str. 19-21, Hungary) and the Hungarian Scientific Research Fund (NKFIH FK-142204).

References

[1] O. Altun, P. Prziwara, S. Breitung-Faes, and A. Kwade, 'Impacts of process and design conditions of dry stirred milling on the shape of product size distribution', Miner. Eng., vol. 163, p. 106806, 0 2021, doi: 10.1016/j.mineng.2021.106806.

[2] I. Gijón-Arreortúa and A. Tecante, 'Mixing Performance of a Curved-Ribbon Impeller during Blending of Food Powders', Chem. Eng. Technol., vol. 38, no. 4, pp. 734–740, 2015, doi: 10.1002/ceat.201400682.

[3] I. Gijón-Arreortúa and A. Tecante, 'Mixing time and power consumption during blending of cohesive food powders with a horizontal helical double-ribbon impeller', J. Food Eng., vol. 149, pp. 144–152, Mar. 2015, doi: 10.1016/j.jfoodeng.2014.10.013.

[4] D. Horváth, T. Poós, and K. Tamás, 'Modeling the movement of hulled millet in agitated drum dryer with discrete element method', Comput. Electron. Agric., vol. 162, pp. 254–268, Jul. 2019, doi: 10.1016/j.compag.2019.03.033.

[5] Z. Zuo, S. Gong, and G. Xie, 'Numerical investigation of granular mixing in an intensive mixer: Effect of process and structural parameters on mixing performance and power consumption', Chin. J. Chem. Eng., vol. 32, pp. 241–252, prilis 2021, doi: 10.1016/j.cjche.2020.10.036.

[6] E. Ford and N. Naude, 'Investigating the effect on power draw and grinding performance when adding a shell liner to a vertical fluidised stirred media mill', Miner. Eng., vol. 160, p. 106698, 0 2021, doi: 10.1016/j.mineng.2020.106698.

[7] C. T. Jayasundara, R. Y. Yang, A. B. Yu, and D. Curry, 'Discrete particle simulation of particle flow in IsaMill—Effect of grinding medium properties', Chem. Eng. J., vol. 135, no. 1, pp. 103–112, 0 2008, doi: 10.1016/j.cej.2007.04.001.

[8] Y. Bao, Y. Lu, Z. Cai, and Z. Gao, 'Effects of rotational speed and fill level on particle mixing in a stirred tank with different impellers', Chin. J. Chem. Eng., vol. 26, no. 6, pp. 1383–1391, 0 2018, doi: 10.1016/j.cjche.2017.11.010.

[9] Y. Bao, T. Li, D. Wang, Z. Cai, and Z. Gao, 'Discrete element method study of effects of the impeller configuration and operating conditions on particle mixing in a cylindrical mixer', Particuology, vol. 49, pp. 146–158, prilis 2020, doi: 10.1016/j.partic.2019.02.002.

[10] J. Long et al., 'Discrete element simulation for mixing performances and power consumption in a twin-blade planetary mixer with non-cohesive particles', Adv. Powder Technol., vol. 33, no. 2, p. 103437, 0 2022, doi: 10.1016/j.apt.2022.103437.

[11] G. R. Chandratilleke, X. Jin, and Y. S. Shen, 'DEM study of effects of particle size and density on mixing behaviour in a ribbon mixer', Powder Technol., vol. 392, pp. 93–107, 0 2021, doi: 10.1016/j.powtec.2021.06.058.

[12] P. W. Cleary, 'Predicting charge motion, power draw, segregation and wear in ball mills using discrete element methods', Miner. Eng., vol. 11, no. 11, pp. 1061–1080, 0 1998, doi: 10.1016/S0892-6875(98)00093-4.

[13] W.-N. Wu, X.-Y. Liu, R. Zhang, and Z. Hu, 'DEM investigation of the power draw for material movement in rotary drums with axis offset', Chem. Eng. Res. Des., vol. 144, pp. 310–317, prilis 2019, doi: 10.1016/j.cherd.2019.02.011.

[14] L. Hu, H. Zhu, and J. Hua, 'DEM simulation of energy transitions in a hammer mill: Effect of impeller configurations, agitation speed, and fill level', Powder Technol., vol. 394, pp. 1077–1093, 0 2021, doi: 10.1016/j.powtec.2021.08.090.

[15] X. Jin, S. Wang, and Y. Shen, 'DEM study of mixing behaviours of cohesive particles in a U-shaped ribbon mixer', Powder Technol., vol. 399, p. 117097, 0 2022, doi: 10.1016/j.powtec.2021.117097.

[16] D. Horváth, K. Tamás, and T. Poós, 'Viscoelastic contact model development for the discrete element simulations of mixing process in agitated drum', Powder Technol., vol. 397, p. 117038, 0 2022, doi: 10.1016/j.powtec.2021.117038.

[17] S. Larsson, B. I. Pålsson, M. Parian, and P. Jonsén, 'A novel approach for modelling of physical interactions between slurry, grinding media and mill structure in wet stirred media mills', Miner. Eng., vol. 148, p. 106180, 0 2020, doi: 10.1016/j.mineng.2019.106180.

[18] W. Rong et al., 'Sensitivity analysis of particle contact parameters for DEM simulation in a rotating drum using response surface methodology', Powder Technol., vol. 362, pp. 604–614, 0 2020, doi: 10.1016/j.powtec.2019.12.004.

[19] H. Sun, H. Ma, and Y. Zhao, 'DEM investigation on conveying of non-spherical particles in a screw conveyor', Particuology, vol. 65, pp. 17–31, 0 2022, doi: 10.1016/j.partic.2021.06.009.

[20] C. Zheng, N. Govender, L. Zhang, and C.-Y. Wu, 'GPU-enhanced DEM analysis of flow behaviour of irregularly shaped particles in a full-scale twin screw granulator', Particuology, vol. 61, pp. 30–40, 0 2022, doi: 10.1016/j.partic.2021.03.007.

[21] A. P. Herman, J. Gan, Z. Zhou, and A. Yu, 'Discrete particle simulation for mixing of granular materials in ribbon mixers: A scale-up study', Powder Technol., vol. 400, p. 117222, 0 2022, doi: 10.1016/j.powtec.2022.117222.

[22] D. Horváth, T. Poós, and K. Tamás, 'Examination of the hulled millet's mixing process in an agitated drum dryer', presented at the EXPRES 2019: 11th International Symposium on Exploitation of Renewable Energy Sources and Efficiency, Subotica, Serbia, Apr. 2019, pp. 27-30.

[23] X. Liu, X. Xu, W. Wu, F. Herz, and E. Specht, 'A simplified model to calculate the power draw for material movement in industrial rotary kilns', Powder Technol., vol. 301, pp. 1294–1298, Nov. 2016, doi: 10.1016/j.powtec.2016.08.005.

[24] Adamčík, 'Design of phosphate fertilizer mixer', Master's thesis, BRNO University of Technology, 2012. [Online]. Available: https://dspace.vutbr.cz/bitstream/handle/11012/12744/Adamcik_2012_DP_hlavni_dokument.pdf?sequence=-1

[25] T. Poós, M. Örvös, and L. Legeza, 'Development and Thermal Modeling of a New Construction Biomass Dryer', Dry. Technol., vol. 31, no. 16, pp. 1919–1929, 0 2013, doi: 10.1080/07373937.2013.799483.

[26] T. Poós, E. Varju, and V. Szabó, 'Determination of medicinal plants' porosity', presented at the International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2017), Debrecen, Hungary, Oct. 2017, pp. 428-432.

[27] G. S. Gupta, S. Sarkar, A. Chychko, L. D. Teng, M. Nzotta, and S. Seetharaman, 'Chapter 3.1 - Process Concept for Scaling-Up and Plant Studies', in Treatise on Process Metallurgy, S. Seetharaman, Ed. Boston: Elsevier, 2014, pp. 1100–1144. doi: 10.1016/B978-0-08-096988-6.00040-7.

[28] Z. Fonyó and G. Fábry, Vegyipari Művelettani Alapismeretek (Basic Knowledge of Chemical Operations). Budapest, Hungary: Nemzeti Tankönyvkiadó Rt, 2004.

[29] A. Li et al., 'The effects of filling level on the milling accuracy of rice in the friction rice mill', Powder Technol., vol. 398, p. 117052, 0 2022, doi: 10.1016/j.powtec.2021.117052.

[30] S. Larsson, J. M. Rodríguez Prieto, H. Heiskari, and P. Jonsén, 'A Novel Particle-Based Approach for Modeling a Wet Vertical Stirred Media Mill', Minerals, vol. 11, no. 1, Art. no. 1, Jan. 2021, doi: 10.3390/min11010055.

[31] 'Find minimum of constrained nonlinear multivariable function - MATLAB fmincon'. https://www.mathworks.com/help/optim/ug/fmincon.html (accessed Oct. 17, 2022).

[32] Z. Berk, 'Chapter 7 - Mixing', in Food Process Engineering and Technology, Z. Berk, Ed. San Diego: Academic Press, 2009, pp. 175–194. doi: 10.1016/B978-0-12-373660-4.00007-7.

[33] 'Froude Number - Mixing Froude Number Calculation - PowderProcess.net'. https://powderprocess.net/Froude_number.html (accessed Oct. 14, 2022).

[34] F. Scargiali, A. Busciglio, F. Grisafi, A. Tamburini, G. Micale, and A. Brucato, 'Power Consumption in Uncovered Unbaffled Stirred Tanks: Influence of the Viscosity and Flow Regime', Ind. Eng. Chem. Res., vol. 52, no. 42, pp. 14998–15005, Oct. 2013, doi: 10.1021/ie402466w.