EXPERIMENTAL STUDY ON TUBE JAMMING THROUGH A WEDGE-SHAPED HOPPER

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ABSTRACT

A wedge-shaped hopper is frequently utilized as a tube feeder in the electric heater process. When falling from a wedge-shaped hopper, the tubes often form an arch near the outlet and stop the feeding process since a pile of tubes pass through a small hopper outlet one by one. This research aims to investigate the effect of process factors on the tube feeding process by applying Taguchi's method and to design a wedge-shaped hopper that never jams. Chosen process factors are the wall angle of the hopper, outlet width of the hopper, number of test tubes, vibration strength of the vibrators and tube materials. Experimental results show that a large wall angle, a wide hopper outlet, a few tubes and a weak vibration are optimal settings. The wall angle and the outlet width of the hopper are more influential to reduce the jamming for all tube materials. A hopper that hardly jams can be designed by using optimum conditions.

Keywords: feeding; jamming; optimization; Taguchi method; wedge-shaped hopper.

ÉTUDE EXPERIMENTALE SUR LE BLOCAGE DES TUBES DANS UNE TREMIE TRIANGULAIRE

RÉSUMÉ

Une trémie triangulaire est fréquemment utilisée comme dispositif d'alimentation de tube dans le processus de chauffage électrique. En tombant d'une trémie triangulaire, les tubes forment souvent une voûte près de la sortie et arrêtent le processus d'alimentation étant donné qu'une pile des tubes passent à travers une petite sortie de la trémie un par un. Cette recherche a pour but d'étudier l'effet des facteurs du processus sur le système d'alimentation de tubes en appliquant la méthode Taguchi, et de concevoir une trémie en forme triangulaire qui ne se bloque jamais. Les facteurs du processus choisis sont l'angle du mur de la trémie, la largeur de la sortie de la trémie, le nombre de tubes de test, la force de vibration des vibrateurs et les matériaux des tubes. Les résultats expérimentaux prouvent qu'un grand angle de mur, une sortie large de distributeur, peu de tubes et une vibration faible sont les paramètres optimaux. L'angle du mur et la largeur de sortie du distributeur sont les plus influents pour réduire le blocage pour tous les matériaux de tubes. Une trémie qui se bloque à peine peut être conçue en utilisant des conditions optimales.

Mots-clés : alimentation; blocage; optimisation; méthode Taguchi; trémie triangulaire.

NOMENCLATURE

d	outer diameter of the tube (m)
DF	degrees of freedom
F	variance ratio
MS	mean square
S/N	signal-to-noise ratio
SS	sum of squares
Greek symbol	
η	signal-to-noise ratio
Subscript	
opt	optimum condition

1. INTRODUCTION

An electric heater is a popular heating appliance in various industries. The global demand of the electric heater is estimated to be over six hundred million pieces every year. For the sake of mass production, a wedge-shaped hopper is frequently utilized as a tube feeder in the process. The structure of the electric heater is shown in Fig. 1.

Two kinds of hopper geometry are widely used for feeding system: conical and wedge-shaped. In the past, many investigations have been made to analyze the material flow in a hopper. Jenike [1] characterized two types of particle motion in a hopper, mass-flow and funnel-flow, regardless of the hopper type. Some investigations discussed the influences of factors on the particle flow such as the hopper wall angle, outlet size, granular shape, gravity, humidity, material friction and friction between the material and the hopper wall [2–6]. Matchett [7] studied the cohesive arch, predicted arch shape and tested the circular arc hypothesis. Steingart and Evans [8] utilized a modified Caram-Hong stochastic model to describe the particle flow in 2D hoppers. Sielamowicz et al. [9] applied the digital particle image velocimetry optical technique to recognize flow patterns and depict evolution of velocity fields. Chou and Yang [10] investigated the flow patterns and stresses on the wall in a 2D bin-hopper with a flow corrective insert. Liu and Sung [11] employed the factorial design method to experimentally determine the effect of key factors on the arching of rigid rods passing through a wedge-shaped hopper.

The discrete element method is a popular technique to analyze the hopper flow [12, 20]. Goda and Ebert [12] studied the distributions of normal wall forces and pressures. Harald et al. [13] modeled moving granular media in which heat and mass transport took place. Anand et al. [14] discussed the effects of particle

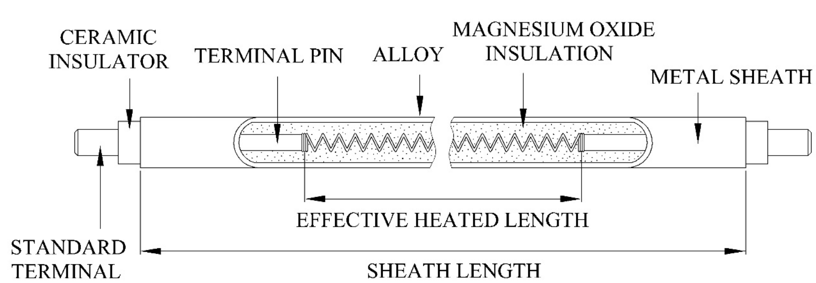

Fig. 1. Structure of the electric heater.

Table 1. The properties of the tubes.

Tube	Inner diameter	Outer diameter	Specific gravity	Weight
Thin Fe tube	6.7 mm	7.9 mm	7.72	0.106 kg/m
Thick Fe tube	8.2 mm	9.5 mm	7.72	0.139 kg/m
Al tube	7.3 mm	9.4 mm	2.68	0.074 kg/m
Al electric heater	–	8.0 mm	2.87	0.144 kg/m

properties and hopper geometry on the discharge rate. Datta et al. [15] studied the flow of noncohesive particles in a hopper where each particle was tracked for its velocity and acceleration. Ketterhagen et al. [16] assessed the powder flow from hoppers and compared the results with widely-used hopper design charts. Tao et al. [17] simulated the corn-shaped particle flow in a hopper and considered the influence of the gravity. Yu and Saxen [18] investigated the effect of the coefficient of static friction of particle-wall on the flow pattern and velocity distribution in a 3D hopper. Langston et al. [19] simulated particle flow under the vibration assistance. Kondic [20] modeled disk-like particle flow in a 2D hopper. Hohner et al. [21] carried out 3D simulations of hopper discharge by using non-cohesive, monodisperse spherical and polyhedral particles.

Most flow materials used in aforementioned researches were granular. However, large and bar-like materials which automatically fell one by one from a wedge-shaped hopper have been rarely discussed. Such situations are often found in the electric heater process. The process of the tube feeding frequently stops because the tubes become stuck at the small hopper outlet. This research experimentally analyzes the effect of process factors on the tube jamming by the Taguchi method [22] and designs a wedge-shaped hopper that never jams.

2. EXPERIMENTAL DESIGN

2.1. Materials and Process

In the electric heater process, metal tubes which are shorter than 400 mm are more suitable for the hopper feeding due to the superior straightness of the tube. Four types of metal tubes were utilized to test the jamming experiments. The properties of the tubes are listed in Table 1.

An experimental apparatus, similar to the one in [11], was designed to conduct the feeding experiment as shown in Fig. 2. The wedge-shaped hopper consisted of a base, two walls, two adjustable bolts and an outlet gate. The wall of the hopper was made of structural steel SS41. The wall angle of the hopper could be adjusted from 30 to 60 degrees and the outlet width could be varied from 8 to 20 mm by adjustable bolts. An outlet gate was inserted to block tubes from falling prior to the test. The tubes fell one by one through the small hopper outlet after the gate was suddenly removed. A senor placed below the outlet was employed to detect the falling tube. Once the tubes stopped falling over ten seconds during feeding, the tube jamming was considered to take place. Two pneumatic vibrators (Netter, Model NCB2) installed in the middle of the hopper wall were utilized to reduce the jamming. The frequency of the vibrator is 28.46 min^{-1} at the pressure of 200 kPa.

2.2. Chosen Factors

In the present study, the tube jamming was similar to the interlocking arch which occurred in large granular materials. Since this research employed circular tubes instead of granular materials, the interesting factors that related to the jamming were the ratio of outlet width of the hopper to the tube diameter, hopper wall angle, specific gravity of the tube material, number of test tubes, frictional coefficient between the hopper wall and the tube and that among the tubes. The jamming was reduced effectively by the vibration [19]. Hence, chosen factors were the wall angle of the hopper, outlet width of the hopper, number of test tubes,

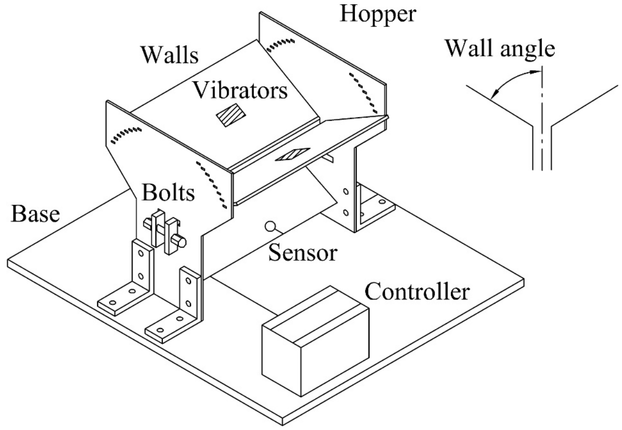

Fig. 2. Experimental apparatus.

Table 2. Factors and factor levels for all types of the tubes.

Factor	Level 1	Level 2	Level 3
A. wall angle (°)	30	45	60
B. outlet width of the hopper (mm)	1.5d	2d-1	2d-1*
C. number of test tubes	30	40	50
D. vibration strength (kPa)	101	151.5	202

vibration strength of the vibrators and tube materials. Note that the hopper outlet must be wider than the outer diameter of the tube but narrower than twice the outer diameter of the tube. However, the feeding of the mixed tube materials does not exist in a real process. That various types of the tubes flow in a hopper involves the specific gravities of the tubes and frictional coefficient between the hopper wall and the tube and that among the tubes. The chosen factors and their levels are listed in Table 2. The levels underlined are selected as initial settings. These factor levels define the experimental region and the region of interest.

2.3. Taguchi's Method

In Taguchi's method, the size of the orthogonal array depends on the number of experimental factors. After calculating the degrees of freedom (DF), the $L_9(3^4)$ standard matrix is applicable as shown in Table 3. The ratio of jamming number to tube number, jamming probability, was utilized to reasonably assess the feeding qualities for matrix experiments using different number of test tubes. The minimization of number of tube jamming is the goal of optimization. A signal-to-noise (S/N) ratio, also denoted by η, depicting the 'smaller the better' characteristic can be calculated using

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right), \qquad (1)$$

where y_i is the measured property and n corresponds to the number of samples in each test trial. The null jamming probability was set to 10^{-6} in order to avoid mathematical faults in Eq. (1).

By performing the analysis of variance (ANOVA), the engineer is able to quantitatively estimate the relative contribution of each control factor to overall measured response. It can typically use the following formula:

$$SS_j = 3\sum_{i=1}^{3}(m_{j_i} - m)^2, \qquad (2)$$

Table 3. $L_9(3^4)$ matrix experiment.

Experiment No.	Jamming probability			
	Thin Fe tube	Thick Fe tube	Al tube	Al electric heater
1. $A_1B_1C_1D_1$	0.33333	0.33333	0.26667	0.13333
2. $A_1B_2C_2D_2$	0.125	0.25	0.175	0.05
3. $A_1B_2C_3D_3$	0.06	0.2	0.1	0.02
4. $A_2B_1C_2D_3$	0.025	0.25	0.2	0
5. $A_2B_2C_3D_1$	0.04	0.04	0.02	0
6. $A_2B_2C_1D_2$	0	0.01667	0.03333	0
7. $A_3B_1C_3D_2$	0.1	0.2	0.1	0.04
8. $A_3B_2C_1D_3$	0	0	0	0
9. $A_3B_2C_2D_1$	0	0	0	0

Table 4. Average η by factor levels.

Factor	Average η by factor level (dB)											
	Thin Fe tube			Thick Fe tube			Al tube			Al electric heater		
	1	2	3	1	2	3	1	2	3	1	2	3
A.	17.3	60.0	86.7*	11.9	53.3	84.7*	15.5	25.8	86.7*	25.8	120*	89.3
B.	20.5	71.7*	–	11.9	69.0*	–	15.2	56.4*	–	55.2	90.0*	–
C.	83.2*	56.7	24.1	83.2*	48.0	18.6	53.7*	49.7	24.7	85.8	88.7*	60.6
D.	52.5	52.7	58.8*	52.5*	48.7	48.7	55.2*	21.6	51.3	85.8	58.0	91.3*

*Identifies optimum level.

where SS_j is sum of squares due to factor. j m indicates the average of the nine η values and m_{j_i} corresponds to the estimation of the effect of factor j at level i. The prediction of η under the optimum conditions, denoted by η_{opt}, is calculated as

$$\eta_{\text{opt}} = m + (m_{A\text{opt}} - m) + (m_{B\text{opt}} - m) + (m_{C\text{opt}} - m) + (m_{D\text{opt}} - m). \tag{3}$$

3. RESULTS AND DISCUSSION

The goal of this study is to find key factors that influence the jamming of metal tube through a wedge-shaped hopper by applying Taguchi's method and to design a hopper that never jams.

Table 4 lists average by factor levels. In order to investigate the relative effect of the different factors on the jamming probability, the ANOVA technique is performed as shown in Table 5.

In Table 5, the variance ratio, denoted by F, is the ratio of the mean square (MS) due to a factor and the error mean square. A large value of F means that the effect of that factor is large as compared with the error mean square. Namely, the larger the value of F is, the more important that factor is in influencing the process response η. The F order of the factor is not identical for different tube materials. The factors in the decreasing order of F are the outlet width of the hopper, wall angle, number of test tubes and vibration strength of the vibrators for Fe tube materials, whereas they are the wall angle, outlet width of the hopper, vibration strength of the vibrators and number of test tubes for Al tube and Al electrical heater. Comparing the cases which have the same F order, the effects of clearance between the tube diameter and the outlet, weight and specific gravity are too insignificant to affect the F order. A previous investigation [11] pointed out that the frictional coefficient among the tubes was more dominant in jamming than that between the tube and the hopper wall. The static frictional coefficient between Al materials is greater than that between Fe materials. Thus, it is reasonable to infer that a high frictional coefficient among tubes enhances the importance of the wall angle in influencing.

Table 5. ANOVA table for η.

Factor		Average η by factor level (dB)											
		Thin Fe tube			Thick Fe tube			Al tube			Al electric heater		
	DF	SS	MS	F	SS	MS	F	SS	MS	F	SS	MS	F
A.	2	7336	3668	6.50	8002	4001	8.00	8866	4433	8.96	13839	6920	14.43
B.	1	5246	5246	9.30	6530	6530	13.05	3410	3410	6.89	2429	2429	5.06
C.	2	5249	2624	4.65	6265	3133	6.26	1485*	742	1.50	1428*	714	1.49
D.	2	78*	39	0.07	29*	15	0.03	2029	1015	2.05	1916	958	2.00
Error	1	1614	1614	1472	1472	0.03	0.03	11	11				
Total	8	19522	2440	22299	2787	15789	1974	19623	2453				
(Error)	(3)	(1692)	(564)	(1501)	(500)	(1485)	(495)	(1439)	(480)				

*Indicates the sum of squares added to estimate the pooled error sum of squares indicated by parentheses.

Table 6. Results of verification experiment.

Tube	Starting condition	Optimal condition (prediction)	Optimal condition (experiment)
Thin Fe tube	4.71×10^{-3}	2.44×10^{-7}	10^{-6}
Thick Fe tube	8.84×10^{-3}	1.42×10^{-7}	10^{-6}
Al tube	3.87×10^{-3}	2.26×10^{-6}	10^{-6}
Al electric heater	5.92×10^{-8}	5.92×10^{-8}	10^{-6}

Factors make the different contributions to the total sum of squares even for the cases with the same *F* order. Taking Al tube as an example, factor A (wall angle) makes the largest contribution to the total sum of squares, namely, $(8866/15789) \times 100 = 56.15\%$. Factors B (outlet width of the hopper) and D (vibration strength of the vibrators) make a 21.6% and 12.85% contribution to the total, respectively. Factor C (number of test tube) makes the least contribution to the total, only 9.4%. Thus, the wall angle and the outlet width of the hopper are more influential to reduce the jamming, while the effects of number of test tubes and vibration strength of the vibrators on the jamming are slight for all cases.

Analyses of the S/N ratio in Table 4 shows that the predicted optimum settings are $A_3B_2C_1D_3$ for thin Fe tube, $A_3B_2C_1D_1$ for thick Fe tube and Al tube, $A_2B_2C_2D_3$ for Al electrical heater, respectively. Generally speaking, a large wall angle, a wide hopper outlet and a few tubes are optimal settings except for Al electrical heater. Actually, the settings $A_3B_2C_1D_3$ and $A_3B_2C_2D_1$ also reduce the jamming effectively for all tube materials as shown in Table 3. Theoretically a small wall angle can reduce the jamming due to a large force in the flow direction in [11]. This work reveals that the jamming mechanism is effectively destroyed by the vibration. Thus, a large wall angle is optimal. The effect of vibration strength on the jamming is slight as stated above. Hence, a weak vibration is preferable due to low noise resulting from tube collisions. Note that the vibration assistance is essential for reducing the tube jamming since the jamming probability is over 70% for all tests without vibration assistance. It indicates that the vibration can enhance tube motion and reduce the jamming at a small outlet width. It agrees with the previous report [19].

After determining the optimum settings and predicting the response under these conditions, the authors conducted a verification experiment with optimum parameter settings and compared the experimental value of with the prediction. The predicted under the optimum settings is 132.25 dB for thin Fe tube, 136.94 dB for thick Fe tube, 112.9 dB for Al tube, 144.56 dB for Al electrical heater, respectively. They are equivalent to null jamming probability except for Al tube according to the aforementioned definition of null jamming probability. The experimental jamming probabilities are close to the predictions as shown in Table 6. It indicates that the additive model is adequate for describing the dependence of on various parameters. A hopper that never jams can be designed by using optimum conditions. On the contrary, if the experimental value is drastically different from the prediction, a strong interaction will exist among the parameters.

The additive model is also useful in predicting the difference in jamming probabilities between two process conditions. Taking Al tube as an example, the anticipated improvement in changing the process from the initial setting $A_2B_2C_3D_3$ to the optimum settings $A_3B_2C_1D_1$ is 64.66 dB, which is equivalent to a reduction in jamming probability by a factor of 1709.9.

4. CONCLUSIONS

An important issue concerning a pile of metal tubes which automatically fell one by one from a wedge-shaped hopper is investigated in the electric heater process. This research is to investigate the effect of process factors on the tube jamming in a wedge-shaped hopper by Taguchi's method. Chosen factors are the wall angle of the hopper, outlet width of the hopper, number of test tubes, vibration strength of the vibrators for four types of tube materials flowing in a hopper. Experimental results show that the more influential factors are the wall angle and the outlet width of the hopper for all tube materials. The influence of wall angle on the jamming raised for the material having a high frictional coefficient among tubes. The effects of clearance between the tube diameter and the outlet, weight and specific gravity are too insignificant to affect the F order. Generally speaking, a large wall angle, a wide hopper outlet, a few tubes and a weak vibration are optimal settings. The vibration assistance can reduce the outlet width and is indispensable for reducing the tube jamming. A substantial improvement is made by changing the process conditions from the initial setting to the optimal settings. A hopper that hardly jams can be designed by using optimal conditions.

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REFERENCES

1. Jenike, A.W., "Gravity flow of bulk solids", *Bulletin of the University of Utah*, Vol. 52, No. 108, pp. 1–309, 1961.
2. Drescher, A., "On the criteria for mass flow in hoppers", *Powder Technology*, Vol. 73, No. 3, pp. 251–260, 1992.
3. Jongejan, M.P., "Theories on channeling. Reviewed and compared with experiments", *Powder Technology*, Vol. 61, No. 2, pp. 143–154, 1990.
4. Marinelli, J. and Carson, J.W., "Solve solids flow problems in bins, hoppers and feeders", *Chemical Engineering Progress*, Vol. 88, No. 5, pp. 22–28, 1992.
5. Reisner, W., "Behavior of granular materials in flow out of hoppers", *Powder Technology*, Vol. 1, No. 5, pp. 257–264, 1968.
6. Marjanovic, P. and Jones, M.G., "Assessment of a new technique for measuring flow properties of powdered materials stored in hoppers", *Journal of Process Mechanical Engineering*, Vol. 210, No. 1, pp. 1–8, 1996.
7. Matchett, A.J., "The shape of the cohesive arch in hoppers and silos – Some theoretical considerations", *Powder Technology*, Vol. 171, No. 3, pp. 133–145, 2007.
8. Steingart, D.A. and Evans, J.W., "Simulation of granular flow in 2-D hoppers using the Caram–Hong model", *Chemical Engineering Science*, Vol. 62, No. 4, pp. 1155–1160, 2007.
9. Sielamowicz, I., Blonski, S. and Kowalewski, T.A., "Digital particle image velocimetry (DPIV) technique in measurements of granular material flows, Part 2 of 3-converging hoppers", *Chemical Engineering Science*, Vol. 61, No. 16, pp. 5307–5317, 2006.
10. . Chou, C.S. and Yang, T.L., "The effect of a flow corrective insert upon flow patterns and wall stresses in a two-dimensional bin-hopper", *Advanced Powder Technology*, Vol. 15, No. 5, pp. 567–582, 2004.
11. Liu, C.L. and Sung, L.Y., "Key factors effecting arching of rigid rods passing through a wedged hopper", *Journal of the Chinese Society of Mechanical Engineers Series C*, Vol. 23, No. 2, pp. 185–193, 2002.
12. Goda, T.J. and Ebert, F., "Three-dimensional discrete element simulations in hoppers and silos", *Powder Technology*, Vol. 158, No. 1–3, pp. 58–68, 2005.

13. Harald, K.E., Siegmar, W., Erdem, S. and Viktor, S., "Modeling of granular flow and combined heat transfer in hoppers by the Discrete Element Method (DEM)", *Journal of Pressure Vessel Technology*, Vol. 128, No. 3, pp. 439–444, 2006.
14. Anand, A., Curtis, J.S., Wassgren, C.R., Hancock, B.C. and Ketterhagen, W.R., "Predicting discharge dynamics from a rectangular hopper using the discrete element method (DEM)", *Chemical Engineering Science*, Vol. 63, No. 24, pp. 5821–5830, 2008.
15. Datta, A., Mishra, B.K., Das, S.P. and Sahu, A., "A DEM analysis of flow characteristics of noncohesive particles in hopper", *Materials and Manufacturing Processes*, Vol. 23, No. 2, pp. 196–2203, 2008.
16. Ketterhagen, W.R., Curtis, J.S., Wassgren, C.R. and Hancock, B.C., "Predicting the flow mode from hoppers using the discrete element method", *Powder Technology*, Vol. 195, No. 1, pp. 1–10, 2009.
17. Tao, H., Jin, B., Zhong, W., Wang, X., Ren, B., Zhang, Y. and Xiao, R., "Discrete element method modeling of non-spherical granular flow in rectangular hopper", *Chemical Engineering and Processing*, Vol. 49, No. 2, pp. 151–158, 2010.
18. Yu, Y. and Saxen, H., "Discrete element method simulation of properties of a 3D conical hopper with mono-sized spheres", *Advanced Powder Technology*, Vol. 22, No. 3, pp. 324–331, 2011.
19. Langston, P.A., Matchett, A.J., Fraige, F.Y. and Dodds, J., "Vibration induced flow in hoppers: Continuum and DEM model approaches", *Granular Matter*, Vol. 11, No. 2, pp. 99–113, 2009.
20. Kondic, L., "Simulations of two dimensional hopper flow", *Granular Matter*, Vol. 16, No. 2, pp. 235–242, 2014.
21. Hohner, D., Wirtz, S. and Scherer, V., "A numerical study on the influence of particle shape on hopper discharge within the polyhedral and multi-sphere discrete element method", *Powder Technology*, Vol. 226, No. 8, pp. 16–28, 2012.
22. Madhav, S.P., *Quality Engineering Using Robust Design*, Prentice Hall, 1989.