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Discrete element simulation for the evaluation of solid mixing in an industrial blender

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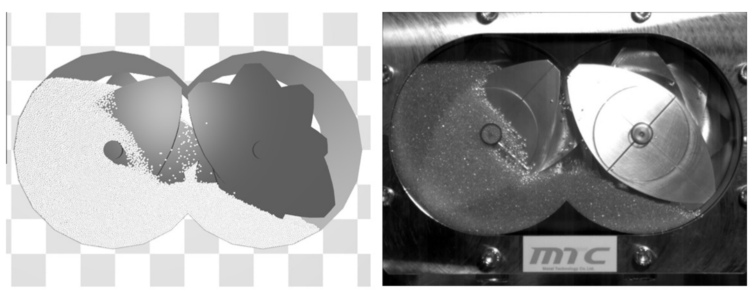
HIGHLIGHTS

- The DEM with signed distance function was validated in a twin-screw kneader.
- Mixing mechanism behind observed phenomena was clarified by numerical simulation.
- Avalanches occurred near the boundary of two rooms enhanced the mixing efficiency.
- Amount of powder greatly influenced mixing efficiency in the twin-screw kneader.

GRAPHICAL ABSTRACT



Simulation result by the DEM/SDF   Experiment

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ABSTRACT

Recent improvements in computer hardware have made it possible to simulate granular flow in an industrial system. There is a desire in industry to apply a numerical technology to design of an actual powder process. In the present study, the discrete element method (DEM) was applied to a twin-screw kneader as an example of an actual industrial blender, and the mixing efficiency was investigated for different operational parameters. The complexly shaped wall boundaries of the paddles and vessel were created using the signed distance function (SDF). Validation tests were first performed to demonstrate the applicability of the DEM employing the SDF-based wall boundary model. In the validation tests, simulations and experiments were shown to be in quantitative agreement in terms of the spatial distribution of solid particles. The mixing efficiency was then investigated for different rotational speeds and amounts of powder, where the degree of mixing was evaluated using Lacey's mixing index. The numerical simulation could clarify the mixing mechanism behind observed phenomena. The study thus illustrated that the total amount of powder affected the mixing efficiency of the twin-screw kneader.

1. Introduction

Industry manufactures many products employing powder-mixing processes. The powder is often agitated in blenders having complex shapes [1,2], such as a twin-screw kneader and a ribbon mixer. In an experimental study, the degree of mixing [3] is often evaluated using marker particles, where it is assessed by sampling the colored particles, e.g., Refs. [4,5]. Evaluation of the mixing degree might not be accurate because the physical properties might differ between types of marker particles owing to different material or surface properties and because sampling might

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Nomenclature

m	particle mass (kg)
$\boldsymbol{v}$	particle velocity (m/s)
$\boldsymbol{F}_C$	contact force (N)
$\boldsymbol{F}_g$	gravitational force (N)
$\boldsymbol{T}$	torque (N m)
I	moment of inertia (kg m^2)
k	spring constant (N/m)
e	coefficient of restitution (–)
$\boldsymbol{n}$	normal vector (–)
$\boldsymbol{t}$	tangential vector (–)
d	minimal distance (m)
s	sign (–)
$\boldsymbol{x}$	position vector (m)
$\boldsymbol{F}$	elastic force (N)
P	potential energy (J)
p	total number of sampling cells from this system (–)
c_i	local concentration in sampling cells (–)
c_m	overall proportion of one type of particle in the system (–)
q	average particle number over all sampling cells (–)
N	number of particles (–)
N_w	number of white particles (–)
N_b	number of black particles (–)

Greek letters

$\boldsymbol{\omega}$	angular velocity (rad/s)
$\boldsymbol{\delta}$	displacement (m)
η	damping coefficient (–)
μ	coefficient of friction (–)
ϕ	signed distance function (m)
$\sigma_t{}^2$	variance based on the current particle location (–)
σ_0^2	variance in a completely segregated system (–)
$\sigma_r{}^2$	variance in a perfectly mixed system (–)
Ω	rotational speed of a paddle (rad/s)

Subscripts

n	normal component
t	tangential component

Superscript

SDF	signed distance function

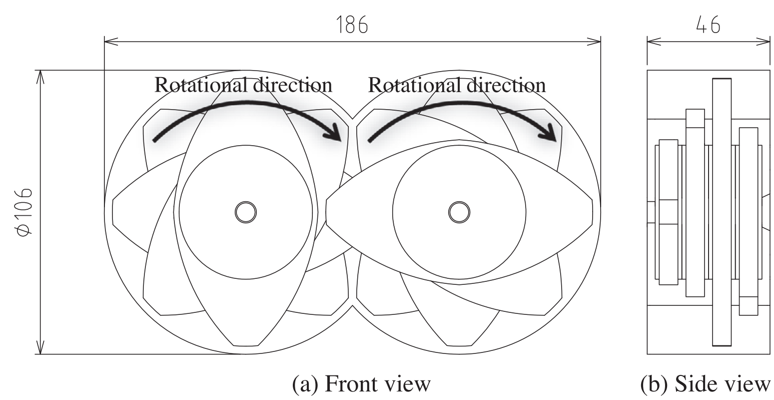

Fig. 1. Schematic diagram of a twin-screw kneader.

change the particle location when the powder is scooped up. Besides, scale of scrutiny might influence the evaluation of the degree of mixing. Hence, experimental studies on the degree of mixing might face some problems from the viewpoint of accuracy. To solve the problem, numerical simulation is desired to be applied to the evolution of the degree of solid mixing. The numerical simulation can set ideally the physical properties of all particles, although the particles are colored differently. Effect of scale of scrutiny on the degree of mixing can also be investigated by the computer simulation. Additionally, the particle location is unaffected when numerical simulation is employed to evaluate the mixture state.

The discrete element method (DEM) [6] is often employed as a numerical method for granular flow. The DEM is a Lagrangian approach, where individual particle motion is computed according to the Newton's second law of motion. In the usual DEM simulations, the contact force acting on a particle is simply modeled using springs, dashpots and a friction slider. When more accurate contact modeling is required, sophisticated models such as a non-linear spring model [4,7]can be employed. The DEM has been applied to various industrial powder processes, such as those of a screw conveyer [8] and a mill [9]. The DEM can also be applied to simulate complex phenomena related to agglomeration due to cohesive forces [10], segregation in a poly-dispersed system [11] and the behavior of non-spherical particles [12,13]. Recently, the

Table 1
Physical properties in the validation tests.

Item	Unit	Value
Diameter	mm	1.0
Density	kg/m^3	2500
Spring constant	N/m	1000
Coefficient of restitution	–	0.9
Coefficient of friction	–	0.3

Table 2
Conditions in the validation tests.

		Case 1–1	Case 1–2
Powder weight	kg	0.262	0.524
Number of particles	–	200,000	400,000
Time step	s	1.0×10^{-5}	
Rotational speed	rpm	20	60