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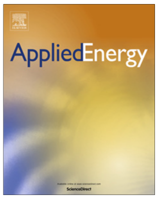

Effect of process parameters on energy performance of spray drying with exhaust air heat recovery for production of high value particles

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HIGHLIGHTS

- We study heat recovery from spray dryer using air-to-air heat exchanger.
- We examine dryer energy performance using advanced mathematical model.
- We use the response surface methodology to study the effect of process parameters.
- Energy efficiency up to 43.3% is obtained at high flow rate of dilute slurry.
- Energy saving up to 52.4% is obtained at high drying air temperature.

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ABSTRACT

Spray drying process has been widely used in various industries for many decades for production of numerous materials. This paper explores the energy performance of an industrial scale spray dryer equipped with an exhaust air heat recovery system for production of high value particles. Energy efficiency and energy saving were calculated using a comprehensive mathematical model of spray drying. The response surface methodology (RSM) was utilized to study the effect of process parameters on energy performance using a space-filling design. The meta model equations were formulated employing the well-fitted response surface equations with adjusted R^2 larger than 0.995. The energy efficiency as high as 43.3% was obtained at high flow rate of dilute slurry, while the highest energy saving of 52.4% was found by combination of positive effect of drying air temperature and negative effect of slurry mass flow rate. The utilization of efficient air-to-air heat exchanger leads to an increase in energy efficiency and energy savings. The detailed temperature and vapor concentration profiles obtained with the model are also valuable in determining final product quality when spray dryer is operated at energy efficient conditions.

1. Introduction

The engineered nanoparticles have found broad applications in various fields including advanced ceramic materials, optoelectronics, food and cosmetics. For example, alumina-based ceramic materials have been widely used as biomaterials for orthopedic applications due to their excellent biocompatibility and high strength [1]. The spray drying process is frequently utilized to form nanoparticle agglomerates of several tens of micrometers [2]. This is a favored industrial production method as it improves the handling of sub-micrometer particles. Agglomerates produced with spray drying have good flow properties owing to their spherical shape and relatively large size [3]. The spray drying was also successfully utilized for preparation of nanoparticle agglomerates with specific internal structures such as porous, hollow, doughnut, core–shell, or multicomponent composite particles [4]. This ability to manipulate structural features is important for production of nanoparticle agglomerates for advanced applications.

Spray drying is also known to be an energy intensive operation and attributed to a significant portion of final industrial energy use worldwide [5,6]. According to Mercer [7], around 500,000 tons of coal equivalent are consumed yearly in spray dryers in the United Kingdom. Baker and McKenzie [6] reported that spray dryers with a capacity of less than one tone per hour typically consumes 4–5 times more energy in evaporating unit mass of moisture than dryers of large capacity. They also estimated that around 29% of the energy supplied to spray dryers was wasted. With rising cost of energy, it is important to increase the energy utilization efficiency for industrial scale spray dryer. With the

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Nomenclature

Symbols

A	surface area of spray drying chamber (m^2)
b	coefficient of regression equation
C	concentration ($kmol\ m^{-3}$)
C_D	drag force coefficient
Cp	specific heat ($J\ kg^{-1}\ K^{-1}$)
D_{cr}	effective diffusivity of water vapor in crust layer ($m^2\ s^{-1}$)
d_p	droplet diameter (m)
df	degree of freedom
ES	energy saving (%)
F	Fisher probability distribution
h	axial position along the chamber height (m)
H	height of drying chamber (m)
i	specific enthalpy ($J\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k_m	convective mass transfer coefficient ($m\ s^{-1}$)
m	mass flow rate ($kg\ s^{-1}$)
M_l	molecular weight of water ($kg\ kmol^{-1}$)
$m_{\min}$	smaller of $m_{fa,d}$ and $m_{ea,d}$
MS	mean square
n	number of runs
Q_{in}	amount of energy supplied to dryer in unit time ($J\ s^{-1}$)
$Q_{in,S1}$	amount of energy supplied to dryer without heat recovery in unit time ($J\ s^{-1}$)
Q_{loss}	amount of energy lost in unit time ($J\ s^{-1}$)
Q_{req}	amount of energy required for evaporation in unit time ($J\ s^{-1}$)
r	radial position in droplet (m)
R	droplet radius (m)
r_c	radial position of droplet in drying chamber (m)
r_o	nozzle orifice radius (m)
Rc	drying chamber radius (m)
s	position of evaporation interface (m)
SS	sum of squares
t	time (s)
T	temperature (K)
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
$U_{ta,i}$	air velocity in i direction ($m\ s^{-1}$)
U_p	relative droplet velocity ($m\ s^{-1}$)
$U_{p,i}$	droplet velocity in i direction ($m\ s^{-1}$)
W	weight percentage of water (%)
x	coded variable
X	mass fraction of water ($kg\ kg^{-1}$)
y	response variable
Y	humidity ($kg\ kg^{-1}$)

Greek symbols

ε	porosity
ε_h	total effectiveness factor of heat exchanger
η_R	energy efficiency (%)
θ	half spray angle (degree)
λ	latent heat of water ($J\ kg^{-1}$)
ρ	density ($kg\ m^{-3}$)

Subscripts

0	drying chamber inlet
a	air
aa	atomizing air
av	average
co	core
cr	crust
d	dry base
da	drying air
ea	exhaust air
fa	feed air
h	wet base
H	humid air
in	inner
l	liquid
oa	ambient air
out	outer
p	solid product
r	radial
ra	preheated air
ref	reference
s	solid
sl	slurry
t	tangential
ta	total air
v	vapor
va	vent air
x	axial

increasing attention to the production of high value particles by spray drying, the precise design of particle morphology is important for production of particles with desired properties [8]. Therefore, the advanced model analysis on drying behavior of particles in spray dryer combined with energy performance optimization will be useful for practical applications. To the best of our knowledge there are no publications in open literature that analyze the heat recovery in spray dryer using heat exchanger and also provide detailed information on the drying behavior of particles.

Several mathematical models with different degrees of complexity are currently available to simulate the spray drying process [9]. The coarse-scale models account for the overall mass and energy balances while the finest-scale models use the computational fluid dynamics (CFD) approach. The Particle Source-in-Cell method [10] was developed to solve the conservation equations by treating the gas as a continuous phase and the spray as a discrete tracked phase. The recent advances in application of CFD models for spray drying are reviewed by Mezhericher et al. [11]. One of the shortcomings of a CFD model is that it is commonly combined with the simple model of drying kinetics of the slurry droplet. In addition, incorporation of detailed droplet drying kinetic models into the CFD model is still a challenging computational task [12]. Thus, the repetitive simulations for various drying parameters required for energy performance evaluation will take a prohibitively long calculation time when the finest-scale model is combined with the detailed drying kinetic model. In the present study, we have chosen to use the fine-scale model that combines the detailed droplet drying kinetic model with the mass, energy and momentum balances of droplets and drying gas in the drying chamber. Using this model, we are able to calculate the temperature and moisture profiles in the partially dried agglomerate at various heights of the dryer. Therefore, not only is it possible to evaluate the energy performance of spray drying system at particular drying conditions, but also to confirm the product quality.

Recently, several methods have been proposed for minimization of energy consumption in spray drying, such as combination of spray dryer with a fluid bed dryer [13] and recovery of exhaust air energy [14]. Various configurations of the system of exhaust air heat recovery have been suggested for the spray drying process, including deployment of run-around loop, cross-flow air-to-air heat exchangers, or exhaust air recycle [15]. The run-around-loop heat exchanger utilizes the intermediate liquid to absorb heat from