Applied Thermal Engineering 73 (2014) 899–913

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Simulation of exhaust gas heat recovery from a spray dryer

Boris Golman*, Wittaya Julklang

School of Chemical Engineering, Institute of Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon-Ratchasima 3000, Thailand

HIGHLIGHTS

- We model industrial-scale spray drying process with the exhaust gas heat recovery.
- We develop an Excel VBA computer program to simulate spray dryer with heat recovery.
- We examine effects of process parameters on energy efficiency and energy saving.
- High energy efficiency is obtained during drying of large amount of dilute slurry.
- Energy saving is increased using the large amount of hot drying air.

ARTICLE INFO

Article history:
Received 10 May 2014
Accepted 20 August 2014
Available online 30 August 2014

Keywords:
Spray drying
Energy recovery
Exhaust gas
Simulation
Visual Basic for Applications
Excel

ABSTRACT

This study explored various alternatives in improving the energy utilization of spray drying process through the exhaust gas heat recovery. Extensible and user-friendly simulation code was written in Visual Basic for Applications within Microsoft Excel for this purpose. The effects of process parameters were analyzed on the energy efficiency and energy saving in the industrial-scale spray drying system with exhaust gas heat recovery in an air-to-air heat exchanger and in the system with partial recirculation of exhaust air. The spray dryer is equipped with an indirect heater for heating the drying air. The maximum gains of 16% in energy efficiency and 50% in energy saving were obtained for spray drying system equipped with heat exchanger for exhaust air heat recovery. In addition, 34% in energy efficiency and 61% in energy saving for system with recirculation of exhaust air in the present range of process parameters. The high energy efficiency was obtained during drying of large amount of dilute slurry. The energy saving was increased using the large amount of hot drying air.

1. Introduction

Spray drying process has been widely used for production of particulate products on large scale in ceramic, food and other industries [1]. Recently, spray drying has been utilized for manufacturing various high value particles in the form of agglomerates of nanoparticles [2,3]. These agglomerates are in high demand as they can be processed in dry phase due to their enhanced flowability. In addition, the materials produced using these agglomerates possess the superior functional properties due to their nano-sized constituents.

The spray drying process consists of the spraying of a feed in the form of liquid or a slurry of nanoparticles into a drying chamber, drying of small droplets in contact with hot stream of the drying medium and recovering powder product from exhaust stream. In order to enable the slurry to be sprayed, the solid content of the slurry is typically limited by its viscosity requirement. Thus, since large amount of water in the slurry needs to be evaporated, spray drying is an energy demanding process. The rising energy cost and growing concerns over greenhouse gas emissions urge companies to utilize the energy improving measures. Various approaches to energy conservation in spray drying have been reported in the literature including optimization of process parameters [4], utilization of exhaust air energy in a heat recovery system [5] and use of an exhaust air recirculation system [6].

The spray drying is a complex process that involves the heat, mass and momentum transfer between the droplet and the drying medium as well as the heat and mass transfer in the partially dried agglomerates. The models of various complexities have been reported in the literature for modeling of spray drying. Empirical correlations have been developed for droplet diameter change during drying of certain products, such as milk powder [7]. The

* Corresponding author.
E-mail addresses: golmanboris@gmail.com, golman@sut.ac.th (B. Golman).

http://dx.doi.org/10.1016/j.applthermaleng.2014.08.045
1359-4311/

Nomenclature

A	total surface area of drying chamber (m^2)
C_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
ES	energy saving (%)
h	specific enthalpy ($J\ kg^{-1}$)
m	mass flow rate ($kg\ s^{-1}$)
Q	amount of heat in unit time ($J\ s^{-1}$)
RR	recirculation ratio (%)
T	temperature (K)
tol	tolerance
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
w	weight percentage of water on wet basis (%)
X	mass fraction of water on dry basis ($kg\ kg^{-1}$)
Y	humidity on dry basis ($kg\ kg^{-1}$)
Z	fractional water balance discrepancy (−)

Greek symbols

ε	heat exchanger overall effectiveness (%)
η_R	energy efficiency (%)
λ	latent heat of vaporization of water ($J\ kg^{-1}$)

Subscripts

a	dry air
aa	atomizing air
d	dry base
da	drying air
dew	dew point
ea	exhaust air
fa	feed air
h	wet base
ha	hot air
i	ith stream
in	inlet, input
l	liquid
loss	loss
ma	mixed air
oa	ambient air
out	outlet
p	solid product
ra	recirculating air
rec	recovered
ref	reference
req	required
s	solid
sl	slurry
v	vapor
va	vent air

models based on a characteristic drying rate curve have been used for simulation of industrial spray drying [8]. For example, Patel and Chen [9] presumed that the drying rate is a linear function of the particle moisture content. The reaction engineering approach was developed to describe the droplet drying with an assumption that evaporation is an activation process similar to the chemical reaction [10,11]. The equations of models described above are simple, but these approaches require experimental determination of the material-specific parameters or relationships such as the activation energy as a function of the average free moisture content or the characteristic drying curve. However, such data are not readily available in the literature. The comprehensive mathematical models were also developed to describe the heat and mass transfer in the droplet during the constant and falling drying rate periods [12–14]. These models involve a numerical solution of the coupled system of partial and ordinary differential equations with moving boundaries. The complete mathematical analysis of spray drying process presents a challenging task and the numerical simulations in three dimensions tend to take a prohibitively long time. Therefore, Langrish [15] proposed a multi-scale approach to the modeling of spray dryers. The coarsest scale models are derived on the basis of overall heat and mass balances in a well-mixed dryer. These models are useful for preliminary analysis of the effect of process parameters on the drying system performance and quick evaluation of various methods for minimization of energy consumption [16]. The finer scale models include momentum, heat and mass transfer equations for droplets and drying gas assuming that they are flowing in parallel to each other [17,18]. Furthermore, the detail analysis of flow pattern in the chamber is implemented in the finest scale models using a computational fluid dynamic approach [19,20]. For the present analysis on effect of process parameters on efficiency of energy utilization in spray drying the coarsest scale model was chosen as such analysis will require iterative solutions of mass and energy balances for every set of parameters and the computation will take long time if we use fine approach.

Computer simulation has proven to be an invaluable tool for the feasibility analysis of energy saving process alternatives [21]. Currently, a few commercial software packages are available for design and analysis of drying system [22]. However, these packages are quite complex as they cover a wide range of drying processes, which require steep learning curve to operate. In addition to not be able to be modified due to their closed source code, these packages are costly. The general commercial simulation packages, such as Matlab, were also used for spray drying simulation [17]. However, such software packages are expensive especially for the university research groups with limiting budget or for small companies in developing countries. There are also free open-source alternatives to Matlab, such as GNU Octave [23]. Yet, they are not as user-friendly as the commercial packages and, generally, demand deep knowledge of programming language to modify the program.

The evaluation of the possibilities of energy improvement and optimization of spray drying process require development of user-friendly and relatively simple software to be used not only by university researchers but also by industrial engineers. Microsoft Excel is the most widely utilized spreadsheet in industry and in academia. Bilic and Glavac [24] published one of the early articles on spray drying simulations utilizing spreadsheets. Velic et al. [25] extended the spreadsheet software to the analysis of possible fuel saving by recirculation of exhaust air. However, their model required a-priory knowledge of exhaust air temperature. In addition, only a few parameters, such as the temperature of drying air and the recirculation rate, were investigated on energy efficiency of spray dryer. Lately, Grasmeijer et al. [26] developed an Excel program for the simulation of spray drying of pharmaceutical products. Their model is mainly intended for simulating laboratory scale spray dryers, as it is based on the estimation of heat losses from experimental data. However, the heat losses in industrial scale dryers are usually assumed to be negligible in comparison with the total energy input into the dryer [1]. Therefore, their model and, accordingly, their simulation program require substantial development in order to be utilized for simulating spray dryers with exhaust gas heat recovery. Furthermore, their simulations were performed using the spreadsheet commands, which would hamper understanding of complicated expressions and limit further development and extension of the computer program.