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Experimental and numerical study of the effects of pre-drying of S-PVC using a pneumatic dryer

Salem Banooni, Ebrahim Hajidavalloo, Masoud Dorfeshan *

Department of Mechanical Engineering, Engineering Faculty, Shahid Chamran University of Ahvaz, Ahvaz, Iran

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ABSTRACT

Pneumatic conveying drying (PCD) has been widely used in industrial processes because it is regarded as a highly efficient technique in heating, and mass transfer of product operation. Despite the fact that the use of multi-stage drying techniques is now justifiable, many industrial complexes still use older single-stage systems. The purpose of this article is to investigate the effects of using a pneumatic dryer as a pre-dryer in PVC suspension production line at Bandar Imam Petrochemical Complex (BIPC). The current operating system in PVC suspension production line is fluidized bed drying. In the present work, computational fluid dynamics (CFD) is utilized to predict the hydrodynamics and drying mechanisms of a three-dimensional, dilute-phase, gas-solid turbulent flow in the laboratory-scale. The experimental study is carried out in two pilot-scale spiral pneumatic conveying dryers of diameter 5 cm and 13.45 m length and diameter 10 cm and 7.2 m length. As the main goals of this research, the influence of diameter and length of the dryer are investigated in two pilot-scale vertical pneumatic conveying dryers. In addition, the effects of gas velocity and temperature, particle temperature, mass flow rate and initial moisture content on the dryer performance are examined. The variations in the air velocity, air temperature, air pressure and particle moisture content are investigated along the length of the dryer. The results of energy analysis show that by using the pneumatic dryer as a pre-dryer, the specific energy consumption is reduced about 23.1%.

1. Introduction

Drying is an important unit operation used in many industries that converts a wet solid, semisolid, or liquid feedstock into a solid product by evaporation of the liquid into a vapor via a heating process [1]. Essential features of the drying process are phase change and solid phase production as an end product [2]. This process generally consumes large amounts of energy. Any development in the design of existing dryer and reducing the cost will be extremely favorable for the industries that use drying systems [3].

At the starting point of drying, moist particle surface is covered with a very thin layer of water. The process of liquid evaporation starts due to the contact between the surfaces of the moist particles and the hot drying agent. Within this process, the liquid evaporates faster at the start (the first period of drying), since it is physically unbound moisture. In the second period, the speed of drying falls down rapidly since it is bound moisture at this moment [4]. In the PCD technique, the material is dried in a turbulent stream of hot gas (usually air), which also acts as a conveyor system [5]. Pneumatic dryers are widely used in industrial processes because it is regarded as highly efficient at heating and mass transfer of product operation [6]. In such dryers, the external conditions for the particles vary in the direction of flow. The friction between the gas and the walls and the momentum losses caused by the acceleration of the particles will reduce the drying medium pressure.

Pneumatic conveying refers to the co-current transport of solid particles using gas at the velocities greater than the terminal velocity of particles [7]. The handling of a gas-solid mixture is along with the flash evaporation of the particle surface moisture and separation by a cyclone system respectively [8]. The wet materials are simply allowed to be conveyed vertically or horizontally in a pipe by hot gas and hence dried simultaneously [9]. Pneumatic dryers have technically and economically advantages. In these types of dryers the contact time between the drying medium and particulate material is comparatively short (usually few seconds only). Therefore, these dryers are suitable for heat-sensitive materials and also for eliminating external moisture. Because of the parallel flow of drying medium and wet solid, high inlet gas temperatures can be applied even to heat sensitive materials, whose temperature never exceeds the gas outlet temperature [10]. Pneumatic dryers are simple in construction and have a low cost of capital and have a large effective surface area of the material to be dried since solids are well dispersed within the dryer and high drying capacity due to a continuous process [6]. Among different kind of dryers, pneumatic dryers show the highest removal rate of the liquid from the

* Corresponding author.
E-mail address: M.dorfeshan@gmail.com (M. Dorfeshan).

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Nomenclature

Symbols

g	Acceleration due to gravity ms^{-2}
D	Diffusion coefficient m^2s
C_D	Drag coefficient –
F	Friction force N
h	Heat transfer coefficient $Wm^{-2}K^{-1}$
X	Moisture content $g\ g^{-1}$
Nu	Nusselt number –
d	Particle diameter m
Pr	Prandtl number –
P	Pressure Pa
Re	Reynolds number –
Sc	Schmidt number –
C_p	Specific heat $m^2s^{-2}C^{-1}$
T	Temperature K
t	Time s
k	Turbulence kinetic energy m^2s^{-2}
u	Velocity ms^{-1}
β_v	Volume fraction of solid –
y	Mole fraction –

Greek symbols

ρ	Density $kg\ m^{-3}$
μ	Dynamic viscosity $kg\ m^{-1}\ s^{-1}$
μ_t	Turbulent viscosity $kg\ m^{-1}\ s^{-1}$
ε	Volume fraction –

Subscripts

ave	Average
g	Gas
$\mathfrak{R}$	Gas constant
in	Inlet
p	Particle
sat	Saturation
s	Solid
σ_h	Turbulent Prandtl number
v	Vapor

solid particle [11]. Pneumatic conveying finds many applications of conveying of solids because of the advantages of dust-free movement, flexibility in routing, ease of maintenance, and, etc. [12]. The short residence time can be a disadvantage attendant upon this system because the small variation in feed rate can suddenly change the heat and mass balance on the tube and give variable exit conditions. Moreover, management and turn down are difficult because the gas velocity must be held constant in order to convey the particles.

In modeling process of pneumatic dryers, a stable feed system and correct modeling of the entry region into the tube are required to obtain reliable predictions of overall dryer performance [13]. The prediction of distributions over the flow field of the variety of characteristic properties, such as solid concentration, pressure drop, gas and solid velocities, and temperatures is very important for understanding the flow phenomena and better design of the flow system. Thus, various mathematical models have been developed for the investigation of flow in pneumatic dryers. From a hydrodynamic standpoint, pneumatic drying is similar to pneumatic conveying. Hence, several pneumatic conveying models [12, 14] have inspired the pneumatic drying models presented in the literature. One-dimensional models were among the first models were provided for analysis of pneumatic dryers. A prevalent approach to predict the drying process is according to a steady state one-dimensional mathematical formulation of the conservation equations. Using this approach, it is possible to predict the average values of various properties of the phases in cross sections of the dryer [15, 16].

Pelegrina and Crapiste [17] developed a one-dimensional model for pneumatic drying of food particles and applied the simulation for drying potato particles of different shapes and dimensions. This model investigated the interactions (mass, heat, and momentum) between a gas and a dispersed phase coupled with internal mechanisms. The model took into account the changes in gas and solid properties with temperature and humidity as well as solid shrinkage during drying and assumed that internal resistance does not control mass and energy transfer between solid particles and gas.

Narimatsu et al. [18] presented a one-dimensional model for the pneumatic drying of porous alumina and solid glass particles in a small-scale vertical module. They also presented the experimental testing for validation purposes. This model is adequate to predict and control the mean moisture content of a batch, however, it provides limited information for quality evaluation studies during PCD.

To analyze the effects of radial distribution on the flow and solids characteristics and other cross-sectional distribution of flow properties in pneumatic drying, Skuratovsky et al. [19, 20] applied a steady-state two-dimensional model, based on the two-fluid theory, to simulate the drying of particulate solids. The predictions of the model were compared to the same experimental data used to verify the one-dimensional model proposed by Levy and Borde [21].

The aforementioned researches pointed out that the two-dimensional simulations provide more information about the behavior of the flow properties in every point of computational domain. As demonstrated by two-dimensional numerical simulations, the radial distribution of the flow characteristics leads to uneven product quality. Thus a reliable two-dimensional model is required to improve the drying process.

Several models ([22–24]) considered the interactions (mass, heat, and momentum transfer) between a gas and a dispersed phase coupled with internal mechanisms. Rocha and Paixao [25] developed pseudo two-dimensional models for a vertical pneumatic dryer that predicted the axial and radial profile for the gas-solid velocity and solid moisture content. They also used the mathematical model developed earlier to perform a parametric study of the diameter of the tube and particle in the pneumatic drying process [16]. The results showed that increasing gas and particle flow rate and initial moisture content of the panicle led to a higher value for the final moisture content of the panicle.

Radford [26] proposed an easily understood, practical, ready-to-use method that did not assumed advanced mathematical abilities and need only readily determined the properties of solid and the gas and solid flow rates to be inserted to determine a reliable prediction of drying performance. The method was tested in both an industrial and laboratory situation and it could closely predict the drying rate in an alumina pneumatic conveyor.

Bhattarai et al. [27] studied a one-dimensional incremental model to describe the changes in moisture content, temperature, and velocity of the air and particles that took place within the dryer. In addition, the modeling was performed using buffers in the pilot-scale dryers. Their results showed that the use of a buffer noticeably increased the drying efficiency.

Matsumoto and David [9, 28] studied experimentally the flash drying and proposed a model for drying particulate materials in the constant drying period. This model considered steady state one-dimensional flow and uniform non-shrinking spherical particles. The results showed that the choice of the initial value of the gas velocity is very important to ensure the stability of pneumatic transport.

Kemp [29] presented a model to scale-up pneumatic conveying dryers to real size. The results of the model showed that the duct length decreased with decreasing gas velocity. The drying kinetics of small