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Review

Contact drying: A review of experimental and mechanistic modeling approaches

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ABSTRACT

Drying is one of the most complex unit operations with simultaneous heat and mass transfer. The contact drying process is also not well understood as several physical phenomena occur concurrently. This paper reviews current experimental and modeling approaches employed towards a better understanding of the contact drying operation. Additionally, an overview of some fundamental aspects relating to contact drying is provided. A brief discussion of some model extensions such as incorporation of noncontact forces, interstitial fluids and attrition rate is also presented.

Contents

1. Introduction

Drying is a complicated process with simultaneous heat and mass transfer accompanied by physicochemical transformations. Drying occurs as a result of vaporization of liquid by supplying heat to wet feedstock (Mujumdar, 2007). Although the importance of drying and its control has been recognized for many years, it is still more of an art than a science due to the intricacies involved in the process. To preserve the quality of the product, a balance must be achieved between the time of drying and product quality.

Based on the mechanisms of heat transfer, drying is categorized into direct (convection), indirect or contact (conduction), radiant (radiation) and dielectric or microwave (radio frequency) drying. Direct or the adiabatic units use the sensible heat of the fluid that contacts the solid to provide the heat of vaporization of the liquid. In contrast, contact dryer is an indirect method of removal of a liquid phase from the solid by application of heat such that the heat transfer medium is separated from the product to be dried by a metal

Abbreviations: APIs, active pharmaceutical ingredients; DEM, discrete element method; DPM, distributed parameter models; GC, gas chromatography; HPLC, high performance liquid chromatography; KF, Karl Fischer; LOD, loss on drying; LPM, lumped dynamic models; NIR, near-infrared; NIRS, near-infrared spectroscopy; NMR, nuclear magnetic resonance; ODE, ordinary differential equations; PAT, process analytical technology; PDE, partial differential equations; PM, penetration model; TGA, thermo-gravimetric analysis; TPD, thermal particle dynamics.

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Nomenclature

$\dot{m}$	drying rate, kg m^{-2} s^{-1}
p	pressure in dryer, bar
p_b	bulk pressure, bar
p_s	saturation pressure at drying front, bar
q_o	heat flux into bed, W m^{-2}
q_{zT}	heat flux into drying front, W m^{-2}
T_b	bulk temperature, K
T_o	interfacial temperature, K
T_s	saturation temperature, K
T_w	hot surface temperature, K
α_p	particle heat transfer coefficient, W m^{-2} K^{-1}
α_{sb}	bulk heat transfer coefficient, W m^{-2} K^{-1}
α_{ws}	contact heat transfer coefficient, W m^{-2} K^{-1}
β_b	bulk permeation coefficient, m s^{-1}
β_p	particle permeation coefficient, m s^{-1}

wall (Root, 1983). Heat transfer to the product is predominantly by conduction through the metal wall and/or the impeller. Therefore, these units are also called as conductive and/or non-adiabatic dryers. Different types of heat transfer fluid may involve condensing (such as steam, hot gas, and diphenyl fluid) or liquid types (e.g. hot water and glycol solutions such as propylene glycol). Radiant dryers utilize radiation from a hot gas or a surface as the primary source of heat transfer, whereas in dielectric dryers, microwaves or high frequency electromagnetic fields are employed to transfer energy and achieve drying (Root, 1983; Malhotra and Okazaki, 1992).

Although more than 85% of the industrial dryers are of the convective type (Mujumdar, 2007), contact dryers offer higher thermal efficiency and have economic and environmental advantages over the convective dryers. Table 1 lists and compares the advantages of direct vs. indirect dryers (Root, 1983; McCormick, 1988; Uhl and Root, 1962; Malhotra, 1989). An important advantage of indirect dryers is lower energy consumption. Moreover, several energy resources can be utilized (condensing or liquid type), unlike the direct dryers that typically use light fuel-oil or natural gas. Tables 2 and 3 illustrate the selection criteria and solids exposure time respectively for various contact dryers. The main challenge associated with contact dryers is that they are difficult to design and engineer (Malhotra and Okazaki, 1992). An article by McCormick (1988) explains in detail the handling capacities of dryers (both direct and indirect) and how to choose the right unit for specific needs.

The authors do not intend to discuss the fundamentals of drying in the current review. The reader is referred to the textbooks, principles and practices in drying by Keey (1972) and the handbook of industrial drying by Mujumdar (2007) which provide a comprehensive description of the basic principles of drying processes with different types of dryers. This current review is limited, to the contact drying process, mainly concentrating on the approaches; both experimental and modeling, used in the literature to understand the physics behind the process and briefly discusses the parameters affecting the drying process. To this end, some of the fundamental aspects are reviewed briefly, including a short overview of the commonly used experimental and modeling approaches. Next, a review of relevant process analytical technology and recent modeling techniques are discussed at length, including some extensions of the modeling approaches, such as modification of the existing model to study drying in agitated, packed and intermittent stirred beds, as well as incorporation of noncontact forces and interstitial fluid effects. As the scope of the study is confined to the granular beds where contact drying is the primary mode of drying, direct dryers viz., spray, fluid bed, flash, tray and tunnel are excluded from the article. The review focuses primarily on simple indirect dryers, viz., paddle, disc type, filter dryer, and vibrated fluidized bed dryer. The information gathered from the literature is illustrated in tables to aid and equip the reader with a knowledge of practices that have been used in the past.

2. Background

Drying, being an integral part of pharmaceutical manufacturing is a bottleneck of the manufacturing process because of long drying times (Murru et al., 2011). Moreover, the product quality often depends on drying conditions and efficiency. In order to increase the driving force required for heat transfer, drying rates can be increased by increasing the jacket temperature and reducing the head-space pressure, in addition to mechanical agitation of the granular bed (Michaud et al., 2007; Michaud et al., 2008a,b). However, many pharmaceuticals are thermo-labile. Additionally, phenomena such as attrition and agglomeration can take place during extreme drying conditions, which may have a major impact on the functionality as well as the quality of the material being dried (Lekhal et al., 2003, 2004). Hence, in order to preserve the quality of the product, it is important to understand the parameters influencing the drying operation so one may achieve the most favorable conditions and avoid excessive drying. There are few reports in literature that deal with different types of contact dryers to evaluate the effect of process parameters (Malhotra and Mujumdar, 1987; Malczewski and Kaczmarek, 1989; Sztabert, 1989; Suzuki et al., 1985). Despite the perceived high industrial importance of vacuum contact drying, reliable correlations for the prediction of drying behavior in a dryer of a particular geometry are not available (Malhotra and Okazaki, 1992).

Contact dryers are generally preferred for heat sensitive materials such as foods, pharmaceuticals, and other biomaterials. Drying is also an essential part of the manufacturing process for active pharmaceutical ingredients (APIs). Contact drying is one of the least understood drying processes (Slangen, 2000) because several physical phenomena occur simultaneously (Whitaker, 1977, 1980). The drying kinetics depends on two different groups of parameters: operational conditions and material properties. In contact drying, the wet material is held as a layer in contact with heated surfaces, and the heat required for the evaporation of moisture is transported into the material by conduction (Mujumdar, 2007; Lachman et al., 1990). The residual solvent content of a material, usually expressed as percentage of the weight of the dry material, may be present as either free or unbound moisture. Unbound moisture which is in excess of the equilibrium moisture content is relatively easy to evaporate. Bound moisture is moisture that exerts a vapor pressure less than that of the free solvent at the same temperature (Malhotra, 1989). Such solvent may be physically or chemically adsorbed to the material and is more difficult to remove. Typically drying consists of three stages, i.e., the preheating, constant rate period and falling rate period (Lachman et al., 1990) as shown in Fig. 1 for moisture content vs. drying time and for drying rate vs. moisture content. In the preheating period, the unbound moisture in contact with the heated surface is evaporated. After this initial heating up period, the maximum drying rate is attained. This period is further followed by a constant rate period during which the drying rate remains constant and the unbound moisture is being evaporated; the decrease in the drying rate is caused by a reduction of heat transfer into the bed as the solids dry out. In the falling rate period, the drying rate continues to decrease until the bound moisture is removed. The temperature of the bed continuously increases to approach the temperature of the heat exchange surface. The first drying period is determined by temperature and velocity of the drying air; the second drying period depends mostly on the internal structure of