Chemical Engineering Science 134 (2015) 399–413

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Influence of wall friction on flow regimes and scale-up of counter-current swirl spray dryers

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HIGHLIGHTS

- We study the vortex flow in swirl dryers across full scale designs and conditions.
- Three air flow regimes are related to the effects of friction and design features.
- The characteristics of deposits are vital to explain the evolution of the vortex.
- Friction reduces the swirl drastically and it has a major impact on the turbulence.
- Flow regime prediction facilitates the use of new control and scale-up criteria.

ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form
25 March 2015
Accepted 23 April 2015
Available online 2 May 2015

Keywords:
Spray drying
Vortex flow
Scale up
Roughness
Recirculation
Swirl decay

ABSTRACT

The structure of the vortex flow in swirl spray dryers is investigated after having fouled the walls with deposits typical of detergent manufacture. The range of *Re* and swirl intensity Ω characteristic of industry are studied using three counter-current units of varying scale and design. The friction with the deposits increases the flow turbulence kinetic energy and causes a drastic attenuation of the swirl and as a result, the vortex breaks down in the chamber forming recirculation regions (i.e. areas of reverse flow). Three flow regimes (1) no recirculation, (2) central and (3) annular recirculation have been identified depending on the swirl intensity. New control and scale up strategies are proposed for swirl dryers based in predicting the decay and the flow regime using the unit geometry (i.e. initial swirl intensity Ω_i) and experimental decay rates function of the coverage and thickness of deposits. The impact in design and numerical modelling must be stressed. Adequate prediction of the swirl is vital to study fouling and recirculation, which surely play an important part in the dispersion and aggregation of the solid phase. Current models have no means to replicate these phenomena, and yet, in this case neglecting the deposits and assuming smooth walls would result in (a) over-prediction of swirl velocity up to $40-186\%$ (b) under-prediction of turbulent kinetic energy up to $67-85\%$ and (c) failure to recognise recirculation areas.

1. Introduction

Spray drying serves many industries for the generation of particulate products. Co-current dryers are used for production of temperature degradable powders such as food, pharmaceuticals or enzymes, and are the main focus of research into fluid dynamics, wall deposition and inter-particle interactions in spray drying systems (e.g. Verdurmen et al., 2004). Research into counter-current towers is much more limited; being larger in volume, there are very few data at full scale. They are used in the manufacture of thermally stable products such as detergents, and in some cases make use of a strong swirling flow, which entails a more complex fluid dynamics but improves the heat and mass transfer efficiency. Swirl is introduced in many other devices with the same objective but at much smaller scale. It is in this context, for instance in open tubes with tangential inlets (e.g. Chang and Dhir, 1994, 1995), or pipes where most of the studies of decaying swirling flows have focused (e.g. Kitoh, 1991; Steenbergen and Voskamp, 1998). In larger devices such as centrifugal separators, frictional losses (Kaya et al., 2011) and the solids loading are also known to attenuate the swirl (e.g. Hreiz et al., 2011) and affect the collection efficiency in a

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http://dx.doi.org/10.1016/j.ces.2015.04.039

range of designs (e.g. Hoffmann et al., 1992; Kim and Lee, 2001; Cortes and Gil, 2007; Chen and Shi, 2007).

On the other hand, the stability of turbulent swirling flows is a very wide subject, characteristic of confined units such as combustors where the intensity of the swirl is higher. The confinement and the centrifugal effects give rise to instabilities and result in drastic changes in the structure referred to as a vortex breakdown (*VBD*), documented as function of the Reynolds, *Re*, number and the circulation (Luca-Negro and O'Doherty, 2001). The breakdown can manifest in the form of periodical structures as the precession of the vortex core (*PVC*) (Syred, 2006) and produce recirculation regions depending on the effect of the downstream boundaries (Luca-Negro and O'Doherty, 2001) particularly when the flow faces a restrictive exit contraction (Escudier et al., 1980; Derksen, 2005). Similar instabilities occur in cyclones where many authors have examined the flow structure and turbulence fields (e.g. Hoekstra et al., 1999; Liu et al., 2006). In particular, reverse-flow designs provide clear evidence of the consequences of swirl attenuation. The vortex can break down within the outlet exit (Derksen and Van den Akker, 2000), and in occasions the decay of the swirl gives rise to the "end of vortex" phenomenon (Peng et al., 2005; Pisarev et al., 2011) whereby the core deviates from the centreline of the chamber and attaches to the wall, with a serious detriment in performance. The end of vortex then leads to the concept of "natural length" of cyclones used in design to prevent the destabilization (Hoffmann et al., 1995; Cortes and Gil, 2007; Avci et al., 2013). Swirl dryers present a similar set up, but in a once-through flow whereby the vortex reaches a contraction at high swirl velocities. The work in dryers however is much more limited because gathering measurements in full scale (i.e. volume $>100-1000\ \mathrm{m}^3$) is a serious practical challenge. Visualisation studies were common to describe counter-current units (e.g. Paris et al., 1971; Sharma, 1990) but detailed air velocity data have only been obtained in laboratory (Bayly et al., 2004) or pilot scale facilities where laser based methods are more easily applied (Zbicinski and Piatkowski, 2009). The quantity and level of detail is much more restricted in full scale, and limited to small sections (Hassall, 2011; Wawrzyniak et al., 2012). Yet, it is vital to study the flow in production units because only they can replicate characteristics such as: (a) the presence of deposits at the walls (b) the range of designs of the cone, the air distributor to the inlets or the exhaust lines and b) the range of *Re* and swirl intensity, Ω.

In our previous paper (Francia et al., 2015a) we investigated the structure, turbulence and stability of the vortex in a swirl spray dryer after having cleaned the walls. In these conditions the swirl intensity, Ω, decays further than anticipated in the past, which is linked to the large wall roughness characteristic of production dryers even after having cleaned the walls mechanically. The data in a cleaned full scale tower explained the origin of historical discrepancies between velocities in dryers with smooth walls (Bayly et al., 2004) or numerical simulations, and the few reports in large dryers (Hassall, 2011).

In this paper, we explore the influence of the presence of actual wall deposits in production units and how they must be considered in control and scale up. The scenario in Hassall (2011) or Francia et al. (2015a) provides a useful base to understand the flow behaviour and advance in numerical modelling (Ali, 2014), but it is still far from the real system as accounts not for (a) actual wall conditions, since deposits are known to grow very thick as bands and patches of wet powder, or (b) the range of designs and scales of swirl tall-form dryers, which changes substantially across for instance the detergent industry (Huntington, 2004). Clearly, the question of how friction responds to the relevant production conditions is open. This paper addresses some of these questions gathering air velocity and turbulence measurements in three industrial dryers having fouled the walls with deposits characteristic of detergent manufacture. The units are selected to cover the actual range of geometries typical of industry and the operational ranges of swirl intensity Ω and *Re*, including the tower studied in Francia et al. (2015a) for a direct comparison with data under cleaned walls. This study permits one to correlate the swirl decay to the coverage, distribution and thickness of the deposits, and identify three flow regimes dependent on Ω. General standardisation and scale up criteria are then proposed based in the control of the inlet swirl intensity and the use of the equations and rates provided to predict the attenuation of the swirl, and subsequently the recirculation in the dryer.

2. Experimental methodology

2.1. Design, generation of the swirling flow and scale up of counter-current swirl dryers

Three full scale counter current swirl spray drying towers, denoted Scales I, II and III, property of Procter & Gamble Co. have been investigated. Fig. 1 illustrates the design, nomenclature, position of measurements and the design of the inlet ports, and Table 1 summarises the operational conditions and the main aspect ratios. Air velocity measurements have been taken in isothermal conditions and in the absence of particles, by adjusting the relative head of the inlet and exhaust air fans manually in order to obtain a stable target mass rate and exit pressure.

The generation of the vortex is consequent upon the orientation of the inlets and the design of the hip and the cone sections at the bottom of the dryer. An open bustle ring is used as the air distributor, denoted plenum in Fig. 1. It feeds the air into a series of ports that are arranged symmetrically at the bottom of the cylinder. The inlet ports inject the air flow towards the conical section with a certain angular momentum given by the alignment angles, φ and ξ, to the radial axis and the horizontal plane respectively (see Fig. 1b). The swirling motion generated causes the formation of a vortex that rises into the cylinder until converging inwards and exiting through a central duct at the top, denoted vortex finder. The exit presents a series of internal channels named straighteners, which break the swirl before the air is directed into cyclone separators. The strength of the swirling motion is quantified by the use of a circulation parameter, or swirl intensity, Ω. Section 3 defines Ω in the chamber as the non-dimensional flux of angular momentum, G_θ, normalised by an average axial momentum, $G_{z,av}$, based upon the superficial air velocity, $\overline{U}_{av}$. On the same basis, an initial geometrical value denoted Ω_i can be defined Eq. (1) as a characteristic design parameter (Francia et al., 2015a)

$$\Omega_i = \frac{G_{\theta,i}}{R \cdot G_{z,av}} = \frac{\overline{M}_i \overline{U}_{i,\theta} R_i / \pi R^2}{\overline{M}_C \overline{U}_{av} R / \pi R^2} = \frac{\overline{M}_i^2}{\overline{M}_C^2} \frac{A_C}{A_i} \frac{R_i}{R} \cdot \ \sin\ \varphi \cos \xi \quad (1)$$

function of the inlet alignment(s), the ratio between the mass rate through the inlets $\overline{M}_i$ and the cylinder $\overline{M}_C$ (i.e. owed to air entrainment from the bottom end, $<5\%$ of $\overline{M}_C$) and ratios specific to the tower design, between the cylinder radius R_C and the radius at the inlet R_i ring, and between the combined area of the inlets, A_i and the cylinder, A_C.

Scaling spray dryers is a very complex task. The work of Oakley (1994, 2004) describes salient dimensionless numbers and the difficulty in scaling the flow of the solids. A co-current dryer achieves dynamic similarity in low or high *Re* numbers (associated to entrained particles or high velocity drops) through scaling the ratio of the droplet sizes with the square or the ratio of the chamber diameters, somewhere in between the design values for chambers with centrifugal atomizers ~ 1.5. Oakley (1994) recognises these criteria are valid for particles unaffected by gravity. Otherwise patterns are difficult to scale, (e.g. big chambers or large