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An experimental investigation of the swirling flow in a tall-form counter current spray dryer

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ABSTRACT

This work studies the air flow in a large swirl counter-current dryer using sonic anemometry. Air velocity and turbulence fields are reported at isothermal conditions and in the absence of particles. In a tall-form unit the structure of the flow is largely influenced by the design of the exit. A contraction originates a central jet and suppresses the formation of recirculation zones despite the vortex acquires a high swirl intensity Ω (i.e. $1 < \Omega < 2$). Access to a full scale tower has permitted to: (a) identify asymmetries owed to the design of inlet and exhaust ducts, (b) present the first detailed turbulence data in production units, characterized by a highly anisotropic field and the axial decay of the turbulence kinetic energy, (c) study the flow stability, identifying the precession of the vortex core and oscillations at a constant Strouhal number and (d) study the impact that a rough wall has in the strength of the swirl. This work presents the first clear evidence of significant friction in spray dryers. The swirl intensity Ω decays exponentially in the dryer at a rate between 0.08 and 0.09, much higher than expected in pipe flow and independent of Re in the range 10^5–$2.2 \cdot 10^5$. Production dryers have a large characteristic wall roughness due the presence of deposits, which explains the stronger friction and the discrepancies found in the past between data at full scale or clean laboratory or pilot scale units. It is essential to address this phenomenon in current numerical models, which are validated on laboratory or pilot scale facilities and ignore the role of deposits, thus causing an overprediction of the tangential velocity above 30–40%.

1. Introduction

Among the main advantages of spray drying processes is the generation of low density granules with an open structure [1]. Product properties, particularly the morphology of the final granules, depend on the temperature history and the agglomeration undergone in the dryer, for which understanding the air fluid dynamics is a fundamental. Counter-current swirl dryers are used for the manufacture of thermally stable powders, such as detergents, and in occasions they apply strong swirling flows to enhance the heat and mass transfer and optimize the contact between the phases [2]. The structure of a strong turbulent swirling flow under confinement has been studied in detail for free developing or non-recirculating systems (i.e. also referred to as once through swirling flows, such as open pipes, tubes or concentric cylinders) and in systems where the confinement restricts the vortex development (i.e. combustors or cyclones). The study of large scale units such as a swirl drying tower is far more limited. In a long confinement the swirling motion decays due the development of the boundary layer and the action of the wall shear stress (frictional losses). This phenomenon is described in the research over open pipes (e.g. Kitoh [3]; Steenbergen and Voskamp [4]) and extended by Chang and Dhir [5,6] to a higher swirl intensity with the use of tangentially injected flows. By contrast, in a spray drying tower the swirl causes most of the solids to concentrate near the wall, and generates thick multi-layered deposits [7,8], which increase roughness and are expected to disrupt significantly the boundary layer and the structure of the turbulence [9,10].

Recirculation patterns and the stability in vortices are often studied in terms of the Reynolds number Re and the ratio between the angular and axial momentum, characterized by a swirl number or intensity, Ω. When the swirl develops in an open cylinder, at a sufficiently high intensity the adverse pressure gradient generated by the centrifugal force causes the reversion of the flow. This originates a central recirculation zone, denoted *CRZ*, in the region upstream. As the swirl decays along the cylinder, the centrifugal

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Nomenclature

A	swirl decay rate in Eq. (12)
A_c	cross sectional area in the cylinder, m^2
A_i	combined area of all inlet nozzles, m^2
B	swirl decay constant in Eq. (12)
D	diameter of the cylinder, m
G_θ	axial angular momentum flux, kg m^{-1} s^{-2}
G_z	axial momentum flux, kg s^{-2}
$\overline{M}_c$	mass rate through the cylinder, kg s^{-1}
$\overline{M}_i$	combined mass rate through the inlets, kg s^{-1}
H	distance from air inlets to vortex finder, m
P	static pressure, kg m^{-1} s^{-2}
R	radius of the cylinder, m
R_i	radius of the cross-section at the inlets, m
Re	Reynolds number $Re = DU_{av}/v$
S	swirl number in Eq. (6)
$\overline{U}$	time averaged air velocity, m s^{-1}
$\overline{U}_{av}$	bulk or superficial velocity, $\overline{U}_{av} = \overline{M}_c/\overline{\rho}A_C$, m s^{-1}
$\overline{U}_i$	velocity at the inlets, $\overline{U}_i = \overline{M}_i/\rho A_i$, m s^{-1}
St	Strouhal number, $St = f \cdot D/\overline{U}_{av}$
d	diameter of the vortex finder, m
f	oscillation frequency, Hz
r	coordinate in the radial direction, m
u	velocity fluctuation, m s^{-1}
x	distance from the centreline, m
z	axial position, m

Greek letters

Ω	swirl intensity
α	anemometer misalignment over a_2 in Fig. 2, rad
β	anemometer misalignment over a_3 in Fig. 2, rad
ε	roughness height, m
ξ	axial alignment of the air inlet nozzles, rad
γ	anemometer misalignment over a_1 in Fig. 2, rad
λ	swirl decay rate in Eq. (10).
κ	specific turbulent kinetic energy, m^2 s^2
ρ	density, kg m^{-3}
τ	shear stress, kg m^{-1} s^{-2}
υ	kinematic viscosity/Eddy viscosity, m^2 s^{-1}
φ	radial alignment of the air inlet nozzles, rad

Subscripts, superscripts

r, z, θ	along radial, vertical and tangential direction
$^\circ, -, +$	best estimate, under and over estimation
ref	a reference height, or length, in Eqs. (10) and (12).
w	at the wall

Abbreviations

CRZ	central recirculation region
PVC	precession of the vortex core
VBD	vortex breakdown

force decreases and a stagnation point forms, after which the flow reverses back in what is referred to as a vortex breakdown, *VBD*, that often carries some associated oscillations. The instabilities are complicated by the interaction with the design in cases where the confinement is more restrictive, such as in a combustor or a drying tower. In these units, an increase in Ω or *Re* interacts in a more complex manner with the exit boundaries, which is referred to as downstream effects. Escudier et al. [11], Escudier and Keller [12] or Derksen [13] provide a detailed study of the effect that an exit contraction can have in stabilizing the flow upstream. The origin of periodic oscillations associated to the *VBD*, such as the precession of the vortex core, *PVC*, has been discussed extensively in the case of combustors [14] and cyclonic flows [15,16]. While these are beneficial in combustion, for they increase mixing and stabilize the flame, they are considered detrimental to the collection efficiency in cyclones. In co-current dryers, the studies of turbulence of among others, Usui et al. [17], Langrish et al. [18] and Kieviet et al. [19] report similar aerodynamic instabilities, followed by the work of Southwell and Langrish [20] and Langrish et al. [21], but no data in this regard is available for counter-current swirl units.

It is also very important to provide turbulence data in swirl dryers because large numerical simulations often lack any means to evaluate how the closure models actually perform. In counter-current swirl units an accurate turbulence prediction is particularly important to (a) determine the elutriation of fines, which concerns with the description of a high angular velocity core [22] and requires the application of a Reynolds-Stress Transport Model, *RSTM* [23,24], (b) describe the flow near the wall, in particular, assess how semi-empirical functions for rough walls could apply to strong swirling flows [24], (c) obtain an adequate replication of anisotropy and particle dispersion, and (d) the description of the aerodynamic instabilities observed experimentally, which increase the level of mixing and affect the inner jet.

In spite of the complexities above, experimental data on the air flow patterns in counter-current tall form dryers are rare and very restricted in nature. The studies in pilot scale facilities included flow visualization and *RTD* analysis reported by Place et al. [25], Paris et al. [26] and Sharma [22] or Keey and Pham [27] in co-current units. Only in the last decade a higher level of detail has been obtained by taking advantage of laser-based flow diagnostic techniques in laboratory [28] or pilot plant units [29]. Data at production scales is much more restricted, from vane [30] to thermal anemometers [31], and a similar level of detail is not yet available. Detailed studies are of small scope and limited to particle image velocimetry, *PIV*, analysis near the wall [7].

This paper addresses the lack of data at a full scale providing the flow characterization on an industrial spray drying tower at isothermal conditions and in the absence of particles. Time average velocity and the turbulence field are reported at the cylindrical chamber of the unit. The common features to similar swirling flows in pipes, combustors or cyclones are discussed, including (a) the effects linked to the design of an exit contraction, Section 4.1.1, and *Re*, Section 4.1.2, (b) the asymmetry, Section 4.1.3, (c) the effect of wall roughness and the decay of the swirl intensity, Section 4.1.4, (d) the description of turbulence, Sections 4.2.1–4.2.3 and (e) periodic structures, Section 4.2.4.

2. Unit and instrumentation

An industrial scale counter-current swirl spray drying tower has been used for the conduction of the measurements, property of Procter & Gamble Co. The main design features are depicted in Fig. 1a, including the nomenclature and location of measurements. The air delivery system consists of inlet and exhaust fans, set manually to deliver a constant flow rate to the tower and a target exit pressure. Table 1 summarizes the design and the operating conditions. The air enters the unit near the bottom of the cylindrical body through a series of symmetrical nozzles, and exits through a top conduit, known as tubular guard or vortex finder. The alignment of the inlet ports, shown in Fig. 1b, imparts the flow with