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Use of sonic anemometry for the study of confined swirling flows in large industrial units

Víctor Francia [a,b,*], Luis Martín [b], Andrew E. Bayly [b,1], Mark J.H. Simmons [a]

[a] School of Chemical Engineering, University of Birmingham, Birmingham, UK
[b] Procter & Gamble R & D, Newcastle Innovation Centre, Newcastle upon Tyne, UK

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ABSTRACT

This work explores the methodology and errors involved in using a commercial sonic anemometer to study confined industrial swirling air flows, such as those in large cyclones or dryers in the order of hundreds of m^3. Common sources of uncertainty in time-of-flight techniques and multiple-path anemometry are evaluated and corrections and methodology guidelines are proposed to deal with issues typical of full scale measurement. In particular, this paper focuses on quantifying the error associated with the disruption of the local flow caused by a $HS-50$ horizontal sonic anemometer under a range of turbulence characteristic of industrial swirl towers. Under the guidelines proposed and the conditions studied here, the presence of the instrument originates a measurement error $<1-4\%$ in velocity, $<1-3°$ in direction and $<7-31\%$ in turbulent kinetic energy for an isothermal flow in the absence of solids. These ranges are above traditional uses of sonic anemometry in meteorology due to the limitations inherent to industrial units, but remain within reasonable margins for engineering applications. Laser diagnostic methods are widely used in laboratory and pilot scale cyclones or dryers but are rarely applicable to large production scales. In this context, the data collected with sonic anemometers render much lower resolution but appear in agreement with historical Particle Image Velocimetry. Methods such as the one proposed here can be a useful alternative to improve the level of detail of fluid dynamic studies in industrial units, which are often qualitative or with a limited validation.

1. Introduction

Laser diagnostics methods such as Particle Image Velocimetry, *PIV* [1], or Laser Doppler Anemometry, *LDA* [2–4], and the use of hot-wires [5,6] are widely applied to study swirling flows in small devices (e.g. pipes, swirlers, concentric cylinders or combustors) and larger process units such as cyclones [7–9] and dryers [10,11] in laboratory or pilot devices. On a large scale, access to these units is more complicated. The space and time available are restricted and the cost to collect data increases significantly, which makes experimentation less frequent. Lasers can provide a high spatial and time resolution but are difficult to apply in an industrial environment. Most studies are limited to scaled down devices designed *adhoc*. The application to pilot [12] or even large geometries [13] is possible but it is typically uneconomical because it carries important drawbacks: (a) disruption due to optics, (b) time and lack of flexibility due to set up and safety protocols, (c) reliability in industrial environments, (d) limited measurement range and importantly, costs associated to (e) engineering modifications, (f) time production units need to be shut down and (e) seeding. In full scale cyclones or dryers, vane anemometers [14] and flow visualization [15,16] are commonly used, but they provide a poor level of detail and cannot address many of the questions arising from models, optimization or scale up. In addition to new acoustic sensors, thermal anemometers represent a good compromise between quality and robustness [17]. Typical arrays of hot-wires are an excellent alternative for studies in a pilot scale [10,18] thanks to a high response frequency, but the set up is time consuming and too delicate for a quick and reliable use in industrial cases.

As a result of the lack of alternatives, to this date the data in large scale swirl towers or cyclones are mostly qualitative, comprised of unidirectional velocities, with no turbulence information or restricted to small sections. Consequently, scaling up the particle dynamics into the largest devices remains a challenge [19–21]. Scale-up rules arise from the experience of manufacturers, dimensional analysis of response times and the tendency of the

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[*] Corresponding author at: School of Chemical Engineering, University of Birmingham, Birmingham, UK
E-mail address: v.francia.chemeng@gmail.com (V. Francia).
[1] Present address: School Chemical and Process Engineering, University of Leeds, Leeds, UK

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Nomenclature

D	Cylinder diameter, m
G_i	The *i-th* gyration matrix
H	Distance from air inlets to vortex finder, m
R	Cylinder radius, m
Re	Reynolds number $Re = \bar{\rho}\,.D.\,\bar{U}_{av}/\mu$, -
$\bar{M}_A$	Inlet mass rate of air, kg s^{-1}
P_s	Combined path shadow $P_s = \sum_{i=1}^{i=3} s_i$
$\bar{U}_i$	Air velocity / or component in *i-th*-axis , m s^{-1}
$\bar{U}_{av}$	Bulk or superficial air velocity $\bar{U}_{av} = \bar{M}_A/\pi\rho R^2$, m s^{-1}
d	Diameter of the vortex finder, m
g	Gyration angle, °
r	Radial position, m
ra	Rotation angle, °
s_i	Shadow of the *i-th* path x 1/3
u_i	Air velocity fluctuation in the *i*-axis, m s^{-1}
x	Distance from the inner wall along D, m
y	Cartesian axis in Fig. 12, $y = 0$ for $r = 0$, m
z	Coordinate in the axial direction, m

Greek letters

Δ	Absolute error, $\Delta = \bar{X}_C - \bar{X}_E$ for variable X.
α	Misalignment, gyration over a_2, °
β	Misalignment, gyration over a_3, °
δ	Angle of attack to the horizontal plane, °
ε	Relative error, $\varepsilon = 100.(X_C/X_E - 1)$ for variable X.
γ	Misalignment, gyration over a_1, °
λ	Angle of attack to the frame axis a_2, °
κ	Specific turbulent kinetic energy, m^2 s^{-2}
ρ	Density, kg m^{-3}
σ_{ij}	Variance/Covariance $u_i u_j$, m^2 s^{-2}

Subscripts , superscripts and caps

1,2,3	Auxiliary axis in Fig. 5 or sonic path numbers.
a_1, a_2, a_3	Frame of reference of the anemometer in Fig. 3.
r, z, θ	Polar coordinates, along radial, vertical and tangential direction.
W', U', V'	Spar measurement axis of the HS50 Solent Anemometer in Fig. 3.
C, O	With and without the use of the internal calibration.
E	Reference estimated value.
t, b	Associated with top or bottom transducers.
*	For the door-anemometer ensemble.
−	Indicates time average.

powder to migrate to the walls [22]. Fluid dynamics models develop new designs and study stability [23,24], collection efficiency [25] or heat and mass transfer [26–28], but are hardly ever validated in full scale, which implies that some characteristics inherent to production are neglected, namely: (a) specific designs in industry, in particular inlet nozzles and exhaust lines (b) range of Reynolds, *Re*, and hence swirl stability and (c) comparable friction, materials or deposits. Counter-current swirl drying towers are good examples of the issues that may arise. Extensive efforts have been made to numerically describe the swirling flow [15,29,30] and compare models to data collected in laboratory [31] and pilot scale towers [12]. The attenuation of the swirl was found negligible in simplified scenarios, but *PIV* data [13] collected in production units, and later measurements with the method described here indicate that friction [32] is key to explaining how the flow and turbulence structure are generated in units with rough walls and deposits [33]. The effects of friction are beginning to be brought into modelling [34] but could only be identified after the experiments moved into full scale.

In the interest of exploring measurements in an industrial environment, this work discusses the application of a sonic anemometer to characterise the flow in large cyclones or dryers. The paper develops an alternative to characterise swirl flows in an array of industrial devices where lasers cannot be generally applied [17]; it provides engineers with insight to use sonic anemometers in this context and with a reasonable evaluation of some of the errors that must be expected. Guidelines to collect and correct velocity and turbulence data with a *HS-50* solent sonic anemometer are given, along with a range for the measurement error under turbulence levels characteristic of industrial swirl towers.

2. Application to a large confined swirling flow

2.1. Operation of swirl tall-form dryers

This work discusses data collected in two industrial counter-current swirl dryers property of Procter & Gamble. An outline of the typical unit is given in Fig. 1a; Table 1 summarizes the design. The air enters the bottom of the unit with angular momentum due to the alignment of the inlet ports. It forms a vortex entering the cylindrical chamber and exiting through the top duct. The method proposed here allows the study of the flow in the cylindrical section where the drying droplets spend most of their residence time. The experiments were conducted under a target air mass flow rate and exit pressure, under ambient conditions and without particle production. Control loops are disabled to reduce noise.

Fig. 1b describes the velocity and turbulence profiles observed in the chamber [32]. Within the cylinder the vortex exhibits a *“concentrated”* shape [35] whereby the tangential velocity $\bar{U}_\theta$ shows a forced inner core and an outer free vortex that changes in extension as the flow approaches the top exit. At the central region, an axial jet (Fig. 1b2) coveys the flow towards the top exit duct. In this area, the core of the vortex core precesses around the cylinder axis. The displacement of the core results in an area of higher variability (Fig. 1b3), which indicates a periodical change in the core position rather than any real turbulent kinetic energy [32]. A more thorough description of the structure of the flow is out of the scope of this paper ; the reader is referred to other works to find more a detailed analysis of stability, structure and turbulence in a cleaned dryer [32], and how the scale and the deposits affect the structure [33]. The following sections report data sets in two spray drying towers, denoted Scale I and II in Table 1. Section 4 reports data at three radial positions in the tower Scale I. Section 5 discusses particularities of the method using data from both towers and Section 6 provides a comparison of sonic anemometry and laser based measurements.

2.2. Selection of the technique

Common techniques to study swirling flows cannot deal with the largest scales in the process industry, where some units lack fluid dynamic information to validate models and draw design and scale up criteria. As discussed before, some of the limitations arise from the use of lasers and the cost of a delicate and time