chemical engineering research and design 87 (2009) 1371–1378

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Scale-adaptive simulation (SAS) modelling of a pilot-scale spray dryer

*D.F. Fletcher**, *T.A.G. Langrish*

School of Chemical and Biomolecular Engineering, University of Sydney, NSW 2006, Australia

ABSTRACT

It is now well-established that flows occurring when a jet enters a large vessel are highly transient. Such is the case in spray dryers, where the inlet gas flow can generate transient flow patterns that affect the droplet trajectories and wall deposition behaviour in the dryer significantly. This paper applies the relatively recent scale-adaptive simulation (SAS) approach to the simulation of flow in a pilot-scale dryer. It is shown that this approach produces a much more realistic flowfield than use of URANS equations that have not been adapted to resolve problems associated with their inability to predict turbulence length-scale distributions correctly. A study of the effect of the inlet swirl angle is used to illustrate some features of the transient results. This work makes it clear that transient, 3D simulations of spray dryers can now be made that capture the large-scale turbulence behaviour and that the questionable practice of using unconverged steady-state simulations to provide information is no longer justified.

Keywords: Scale-adaptive simulation; Turbulence model; Length-scale; Spray dryer; Wall deposition; Swirling jet

1. Introduction

Flow patterns of gas and particles in spray dryers have fundamental effects on the rate and pattern of particle deposition on the walls of such equipment, limiting the use of spray dryers due to the need to shut them down for cleaning (Masters, 1991). Hence understanding the flow patterns using computational fluid dynamics (CFD) is fundamental to improving spray-dryer operation and design. Axi-symmetric and computationally two-dimensional CFD simulations of the flow patterns inside spray dryers have been made since Crowe (1980) and were the earliest approaches to these CFD simulations (Oakley et al., 1988; Oakley and Bahu, 1991). Effectively two-dimensional, axi-symmetric, steady-state simulations of spray dryers continue to be performed (Huang et al., 2003; Li and Zbicinski, 2005; Mezhericher et al., 2008), while even three-dimensional simulations have still been largely steady-state in nature (Huang et al., 2005). However, the need for three-dimensional and transient spray dryer CFD simulations was evident in the axi-symmetric studies of Oakley and Bahu (1991). Such steady-state simulations of transient phenomena are fundamentally debatable, particularly since good convergence of steady-state simulations for transient phenomena cannot be achieved, and the errors between the actual and the predicted flow fields in the resulting un-converged steady-state simulations are difficult, if not impossible, to quantify in any sense. The present work shows very clearly that a physically based simulation approach is now available.

Experimental work measuring the flow patterns in spray dryers (Southwell and Langrish, 2000) indicates that the flow fields inside this equipment are inherently three-dimensional and transient. The most significant transient feature is that a central jet of hot air precesses (wobbles) around the central axis of the dryer. CFD simulations have predicted the time-scales of this precession very closely. The self-sustained precession of the global flow field around the expansion centre-line is caused (Guo et al., 2001, 2002) by a dynamic balance between the pressure difference across the inlet jet and the transverse momentum of the jet. Previous researchers (Guo et al., 2003) have found that the extent to which water droplets spread out in the drying chamber is affected by the amount of swirl in the inlet air. This phenomenon affects wall deposition fluxes because the particles will approach closer to the walls if the particles spread out widely.

The need to do transient simulations for three-dimensional sudden expansions has been realized and implemented

* Corresponding author.
E-mail address: d.fletcher@usyd.edu.au (D.F. Fletcher).
Received 2 September 2008; Received in revised form 2 March 2009; Accepted 4 March 2009
0263-8762/$ – see front matter
doi:10.1016/j.cherd.2009.03.006

for combustors (Frohlich et al., 2008; Wegner et al., 2007; Malalasekera et al., 2007), pharmaceutical inhalers (Ilie et al., 2008) and cyclones (Cortés and Gil, 2007). Outside the work of Guo et al. (2001, 2002, 2003), Langrish et al. (2004) and Fletcher et al. (2006), one of the few CFD simulations of spray drying that has used transient simulations is that of Gabites et al. (2006), who found substantial transient effects in the flow patterns for a large industrial spray dryer used for milk powder production. Unfortunately, the authors did not present any information about the dimensions of the dryer that they studied, due to their cited reason of confidentiality.

Transient simulations of the flow patterns in spray dryers using the Reynolds-averaged Navier Stokes (RANS) approaches (transient RANS, URANS, TRANS) can be used to determine the large-scale unsteady flow features (Fletcher et al., 2006). Whilst the mesh-scale determines the length-scale of the features that can be resolved, these are not the same as large Eddy simulations (LES), as without modification these models add the turbulent viscosity everywhere and have the tendency to be overly diffusive, damping out important flow features. The Shear-stress transport (SST) model (Menter, 1994, 1996), which combines features of the k–ε and k–ω turbulence models, has been used in such a manner (Langrish et al., 2004) and gave reasonable predictions of the frequencies of the flow oscillations inside a pilot-scale spray dryer (1.8 m high). However, the SST model has the tendency to predict a turbulence field that has a length-scale which is too large and does not allow a spectrum of length-scales to be resolved (Menter and Egorov, 2005). This paper extends the previous SST modeling work, by using the recently developed scale-adaptive simulation (SAS) approach of Menter et al. (2003) and Menter and Egorov (2005) which overcomes this limitation to investigate the consequences of using this more sophisticated approach.

2. The computational model

2.1. Conservation equations

In this section we present the equations used in the modelling and explain the turbulence modelling approaches adopted. The flow is treated as incompressible and Newtonian. Reynolds-averaging is used to obtain the following equations for conservation of mass and momentum

$$\nabla.(\rho \mathbf{U}) = 0 \tag{1}$$

and

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla.(\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla p + \nabla.(\mu_{\text{eff}}(\nabla \mathbf{U} + (\nabla \mathbf{U})^T)) \tag{2}$$

where

$$\mu_{\text{eff}} = \mu + \mu_t \tag{3}$$

is the sum of the laminar and turbulent contributions to the effective viscosity. The turbulence model provides an expression for μ_t.

The SST model was developed by Menter (1994) to combine the best features of the k–ω and k–ε models and to also, as the name suggests, control the level of the turbulence viscosity in the near wall region. It is widely used for flow and heat transfer simulations and is the "recommended" model in ANSYS CFX. The values of k and ω come directly from the transport equations for the turbulence kinetic energy (k) and the turbulence eddy frequency (ω), which are given in Eqs. (4) and (5), respectively.

$$\frac{\partial \rho k}{\partial t} + \nabla.(\rho \mathbf{U} k) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_{k3}}\right)\nabla k\right] + P_k - \beta' \rho k \omega \tag{4}$$

$$\frac{\partial \rho \omega}{\partial t} + \nabla.(\rho \mathbf{U} \omega) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_{\omega 3}}\right)\nabla \omega\right] + (1 - F_1) 2\rho \frac{1}{\sigma_{\omega 2} \omega} \nabla k.\nabla \omega + \alpha_3 \frac{\omega}{k} P_k - \beta_3 \rho \omega^2 \tag{5}$$

In the above equations P_k is the turbulence production rate and is given by

$$P_k = \mu_t \nabla \mathbf{U}.(\nabla \mathbf{U} + \nabla \mathbf{U}^T) \tag{6}$$

The turbulence viscosity is calculated via

$$\mu_t = \frac{\alpha_1 \rho k}{\max(\alpha_1 \omega, S F_2)} \tag{7}$$

where S is the magnitude of the shear strain rate and α_1 is a constant. F_1 and F_2 are blending functions that switch smoothly between the two limiting models based on local solution values and the distance from the wall. Constants with a subscript containing a 3 are blends between the constants in the k–ω and k–ε. The form taken by these functions and the values of the model constants are given in CFX (2008) and Menter et al. (2003). In this model, the wall treatment changes smoothly from integration of the equations to the wall to use of a log-law wall function at the near wall node as the distance of the first node from the wall is increased.

Whilst the SST model has many advantages in the near wall region, where it can be integrated right to the wall, it behaves very much like the k–ε model away from the wall. When used in transient simulations, there is the problem that the SST model produces length-scales that are too large and consequently turbulence viscosities that are too high (Menter and Egorov, 2005). A key feature of the SAS approach is that it avoids this problem and allows much more realistic flow fields to develop. In the SAS modelling approach, this inability to resolve the turbulence length-scale correctly is overcome by introducing the von Karman length-scale, which in Cartesian tensor notation is given by

$$L_{vK} = \kappa \sqrt{\left| \frac{(\partial U_i/\partial x_j)(\partial U_i/\partial x_j)}{(\partial^2 U_l/\partial x_m^2)(\partial^2 U_l/\partial x_n^2)} \right|} \tag{8}$$

where κ is the von Karman constant. This modification stems from the original work of Rotta, who sought to introduce a transport equation for the turbulence length-scale itself and is discussed in detail in Menter and Egorov (2004).

The turbulence length-scale derived from the SST model is given by

$$L = \frac{\sqrt{k}}{c_\mu^{0.25} \omega} \tag{9}$$

The ratio of this length-scale to the von Karman length-scale plays a key role in switching between the SST and SAS