Chemical Engineering Science 66 (2011) 5024–5044

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Experimental and computational study of T- and L-outlet effects in dilute riser flow

G. Van engelandt, G.J. Heynderickx*, Juray De Wilde [1], G.B. Marin

Laboratory for Chemical Technology, Ghent University, Krijgslaan 281 (blok S5), B-9000 Ghent, Belgium

ARTICLE INFO

Article history:
Received 23 November 2010
Received in revised form
22 April 2011
Accepted 28 June 2011
Available online 8 July 2011

Keywords:
Circulating fluidized bed
Riser
Gas–solid flow
Laser Doppler Anemometry
Outlet effects
CFD

ABSTRACT

Riser outlet effects induced by an L-outlet and by abrupt T-outlets with different extension heights and outlet surface areas are studied experimentally and computationally.

Experiments are carried out in a cold flow riser. The cold flow riser has a diameter of 0.1 m and a height of 8.765 m and is operated in the dilute flow regime with a superficial gas velocity of 2.48–7.43 m/s and a solids flux of 3.0 kg/m^2/s. Particle velocities are measured using Laser Doppler Anemometry (LDA).

Vortex formation in the extension part of the riser is observed. The vortex circulates the solids along the wall opposite to the outlet, thus inducing a solids reflux. The flow pattern upstream the outlet is, however, hardly affected in the small diameter riser. The vortex position and length are affected by the extension height, but hardly by the outlet surface area and the superficial gas velocity. The use of an L-outlet significantly reduces the vortex formation.

The experimental measurements are used to validate a 3D Eulerian–Eulerian and Kinetic Theory of Granular Flow (KTGF) based gas–solid flow model. In general, the calculated trends are qualitatively in agreement with the experimentally observed phenomena. The exact shape of the vortex is not always accurately predicted.

1. Introduction

The performance of risers can be strongly influenced by hydrodynamic effects, in particular inlet and outlet effects. The effects of outlet configurations on the gas–solid flow pattern in risers have been investigated by some research groups and limited experimental data are available for rectangular and cylindrical shaped risers. Reviews by Horio (1997), Werther and Hirschberg (1997) and Lim et al. (1995) concluded that the riser exit configuration can significantly affect the flow density in the upper region of a riser. The majority of the studies focus on local flux, pressure drop and concentration measurements. The flow behavior in abrupt (blinded T) and smooth (bended) outlet geometries is found to be different. Reflux phenomena induced by abrupt outlets have been reported (Zheng et al., 1995; van der Meer et al., 2000).

Zheng et al. (1995) compared three types of outlet configurations (L-type, abrupt T and smooth outlet with 45° plate) in a 0.12 m diameter riser, 5.25 m high, measuring local mass fluxes with an extraction probe. An increase of the bulk density in the vicinity of the outlet opening, especially in abrupt T-outlets with a non-zero extension height, and internal recirculation phenomena were reported.

Van der Meer et al. (2000) quantified the internal circulation of solids induced by 7 different outlet configurations (short, medium and long radius bend exit, zero extension, short and long extension blind T, bend/right angle exit) by introducing a reflux ratio k_m. In smooth bends, the internal recirculation grows with increasing radius and can become even more intense than in abrupt T-outlets. Van der Meer et al. (2000) confirms the observations by Zheng et al. (1995) that internal recirculation increases with increasing extension height of an abrupt T-outlet.

Harris et al. (2003) investigated three outlet configurations (short radius bend, zero extension height and bend/right angle exit). Concentration measurements (based on pressure drop measurements) showed a C-shaped profile for a bend/right angle exit. They suggested a mathematical equation to quantify the distance from the riser top to the position where the pressure profiles for smooth and abrupt exits coincide.

Lackermeier and Werther (2002) performed measurements in a rectangular riser with L- or T-outlet (0.5 m extension) using sand. The L-outlet gave higher external recirculation rates for a given gas velocity and fixed inventory. For a fixed solids flux and gas velocity, the T-outlet resulted in lower pressure drops and lower hold-ups, contradictory to the conclusions of Zheng et al. (1995). However,

* Corresponding author. Tel.: +32 9 264 9656; fax: +32 9 264 49 99.
E-mail address: geraldine.heynderickx@ugent.be (G.J. Heynderickx).
[1] Currently at: Department of Materials and Process Engineering (IMAP), Université catholique de Louvain (UCL), Belgium.

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doi:10.1016/j.ces.2011.06.060

according to the former authors, the accuracy of the flux measurement was only 10%.

Johnsson et al. (1999) verified the influence of the outlet geometry on the flow pattern in a 1/9 scaled model of a 12 MW CFB-boiler. Except for an outlet with a zero extension height, no significant changes were detected when outlets with different extension heights were used. Reducing the outlet surface was observed to avoid sedimentation (saltation) in the riser-cyclone connector. Sedimentation in the connector can induce reflux into the riser (Harris et al., 2003; Glicksman et al., 1993). Glicksman et al. (1993) found that local aeration in the connector could significantly reduce the reflux into the riser.

Yan et al. (2003) verified the flow field disturbances introduced by a smooth outlet under dense flow conditions (550 $kg/m^2/s$) and compared the results with experiments at dilute flow conditions (100 $kg/m^2/s$) and additionally compared with data obtained by Senior (1992a,b). Remarkably, it was shown that a "smooth" outlet behaves like an "abrupt" outlet under dense flow conditions.

Bai et al. (1992) performed measurements using a smooth outlet with 45° plate and an abrupt T-outlet with short extension. A C-shaped concentration profile was determined for the short extension T-outlet. Moreover, they found that the distance over which the effect of a given type of outlet configuration was felt did not depend on the total riser height. Dilute industrial scale riser simulations (De Wilde et al., 2004) show that inlet and outlet effects are not independent, but interact. Inlet and outlet effects can oppose or cooperate, resulting in a complex riser flow behavior.

Zheng and Zhang (1993) performed measurements in a 0.12 m diameter riser (with L-type, abrupt T (0.45 m extension) and smooth 45° plate outlet). For both abrupt types a C-shaped concentration profile was determined, while for the smooth exit no particular increase in solids concentration was seen in the vicinity of the outlet. Moreover, it was concluded that the size of the outlet opening influences the hydrodynamics to a large extent. Brereton and Grace (1993) also reported C-shaped concentration profiles for high restrictive abrupt outlets and L-shaped concentration profiles for smooth non-restrictive outlets. Lim et al. (1995), Jin et al. (1988, 1997), Cheng et al. (1998) and Gupta and Berruti (2000) confirmed the C-shaped concentration profiles for restrictive outlets and related the size of the zone of influence to the overall restrictiveness of the outlet.

Pugsley et al. (1997) performed pressure drop measurements in risers of different diameters and heights, with two kinds of particles (sand and FCC) using two types of outlet configurations (90° bend and a 0.1 m extension T-outlet configuration) under various operating conditions. With increasing solids flux and/or lower gas velocity the outlet effects stretched towards the bottom of the riser for the large diameter riser.

These findings of Pugsley et al. (1997) are in agreement with observations by De Wilde et al. (2004) showing that in a dilute large diameter (industrial scale) riser (1.56 m diameter, 14.4 m high) inlet and outlet effects are interacting and influence the flow pattern in the entire riser. In a smaller scale unit (as used in this work), however, the effects of the inlet and outlet configuration were found to be independent and quickly dissipating. The latter is due to the increased impact of the viscous forces in small diameter risers.

It can be questioned whether outlet effects can be considered as a scaling-effect (Johnsson et al., 1999; Pugsley et al., 1997). Many research teams state that outlet effects are only detected in small scale set-ups but are not observed in large scale units or industrial scale units (Johnsson et al., 1999 (1/9 scale model of 12 MW Chalmers boiler), Leretaille et al., 1999 (600 MW boiler in Gardanne)). An opposite example is the work of Martin et al. (1992) where in a circular industrial FCC size riser (0.95 m diameter, 26 m high) with a T-outlet operated at 325 $kg/m^2/s$ flux, outlet effects (i.e. C-shaped concentration profiles) were detected by means of radioactive tracer experiments. Using CFD, De Wilde et al. (2003b) demonstrated in a simulation of a dilute industrial scale large diameter riser with extended T-outlet how restrictive outlet configurations can influence the flow pattern in the entire riser, inducing vortex formation in the extension part of the abrupt T-outlet. For non-restrictive outlets the outlet effects are limited to the vicinity of the outlet, but the vortex formation in the extension persists. However, the simulation results cannot be validated based on the industrial data. In the present work simulation results are validated based on experimental data obtained in a cold-flow set-up.

The impact of outlet configurations on the velocity profiles (mean and fluctuating) is not well documented in the literature (Yan et al., 2003). Lackermeier and Werther (2002) performed detailed velocity measurements using a high-speed video camera and a fiber optical probe in a rectangular riser using sand. Reflux in the plane perpendicular to the outlet opening and asymmetrical velocity profiles were measured with an L-outlet and a T-outlet with a 0.5 m extension.

Only few studies on outlet effects compare experimental and numerical results. The present work aims to investigate outlet effects, in particular vortex formation, induced by abrupt T- and L-outlet configurations. The effect of riser exit design on flow patterns was also investigated by Van der Meer et al. (2000), in a riser with a square section, and by Kim et al. (2008). In the present work, experiments are carried out in a cold flow circulating fluidized bed riser (0.1 m diameter, 8.765 m high). The particle velocities are measured using Laser Doppler Anemometry (LDA). The gas–solid flow model presented by De Wilde et al. (2000, 2002, 2003a, b, c, 2004) and in particular its capability of describing the complex outlet behavior of T- and L- abrupt outlets is validated using experimental data obtained in the cold flow riser.

The one probe or two-component LDA measurement technique used in the presented work is limited to dilute gas–solid flow, as at solids volume fractions above 0.005 the data rate decreases considerably. Furthermore, measurements and calculations are limited to dilute gas–solid flow (3 $kg/m^2/s$), as for example encountered in the SO_2–NO_x Adsorption Process (SNAP) (Das et al., 2004). The currently available Eulerian–Eulerian gas–solid flow models need to be adapted for denser gas–solid flow conditions to account for the presence of meso-scale structures, like clusters, which are not explicitly calculated in coarse mesh simulations (Agrawal et al., 2001; Zhang and VanderHeyden, 2002; Heynderickx et al., 2004). In the current study, formation of meso-scale structures, like clusters, is unlikely due to the dilute nature of the flow. Cluster formation has not been visually observed during the experiments. A grid dependency and grid aspect ratio study has been performed in detail by De Wilde et al. (2005b).

2. Mathematical model and solution method: FLOW-MER

An in-house CFD code, FLOW-MER, has been developed in order to reduce the calculation time and to overcome limitations of commercial CFD codes on the number of reactive components and reactions that can be accounted for. The long-term objective of the research is to combine the flow model with the Single Event MicroKinetic (SEMK) (Quitana-Solórzano et al., 2005) model for Fluidized bed Catalytic Cracking (FCC). An in-house code, FLOW-MER, has been developed, replacing commercially available codes. In the in-house developed CFD code FLOW-MER the Eulerian–Eulerian