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Flow visualization and modelling of scrubbing liquid flow patterns inside a centrifugal wet scrubber for improved design

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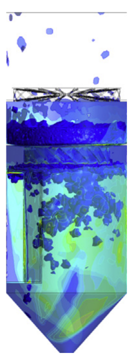
HIGHLIGHTS

- Experimental and CFD study of a centrifugal wet scrubber.
- Test rig scale model for measurements and flow visualization.
- Eulerian-Eulerian modelling of air and water flow patterns.
- Improved understanding of the flow processes in centrifugal wet scrubbers.
- Design enhancements proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an experimental and computational study of flow aspects in a commonly used centrifugal wet scrubber design. While manufacturers advertise up to 99.9% collection efficiency for dust particles >10 μm in diameter, operators complain of compromised efficiency at low loads and droplet carryover at high loads. Similar problems are also faced by flue gas desulphurization towers. The industry requires satisfactory scrubber performance at varying factory conditions. Different scrubber flow parameters and dimensions were studied to discover the cause of the reported problems. Together with the CFD findings, the project delivered an improved understanding of the scrubbing liquid flow pattern which is crucial for high performance and was used as a basis to carry out design improvements.

1. Introduction

Dust collectors are widely used to reduce the environmental footprint of industrial plants. Common types of dust collectors include electrostatic precipitators, venturi scrubbers, dust cyclones, baghouse collectors and wet centrifugal scrubbers. The collector type used for a particular application depends on a number of factors including the required collection efficiency, the composition and temperature of the gas being cleaned and the density and size distribution of the dust to be collected. If high collection efficiency is not essential then dust cyclones are normally the least expensive option. Baghouse collectors and electrostatic precipitators have very high collection efficiencies but are also a high capital cost (Vasarevicius, 2012). Wet scrubbers are used in applications where high collection efficiency is required but the cost of baghouse collectors or electrostatic precipitators cannot be justified. They range from those used for dust collection in process industries to a combination of dust collection and harmful gas absorption produced by fossil fuel run boilers (Mussatti and Hemmer, 2002).

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Nomenclature

Symbols

p	pressure [Pa]
α_q	volume fraction of phase q
α_p	volume fraction of phase p
ρ_q	density of phase [kg/m^3]
$\bar{\bar{\tau}}_q$	stress tensor [kg/m^1 s^2]
$\vec{v}_q$	phase q velocity [m/s]
$\vec{v}_p$	phase p velocity [m/s]
C_d	drag coefficient
Re	Reynolds number
We	Weber number
We_c	critical Weber number
Oh	Ohnesorge number
y^+	non dimensional distance

Abbreviations

CFD	computational fluid dynamics
SSM	scale scrubber model
RSM	Reynolds stress model
fps	frames per second

Venturi scrubbers and centrifugal wet scrubbers are two of the most common types of wet scrubbers used for dust collection. In a venturi scrubber the gas to be cleaned is accelerated by a reduction in flow area and the scrubbing liquid is injected into this high velocity gas flow and broken up into fine droplets. This maximises the collecting surface area of the scrubbing liquid. The large collecting surface area and the high velocities make venturi scrubbers very effective for removing very small (<1 μm diameter) particles although this comes at the expense of high pressure drop, often exceeding 15 kPa. Centrifugal wet scrubbers are not as effective as venturi scrubbers for removing these extremely small particles but they usually have a lower pressure drop and are better able to handle high inlet dust loadings (Mussatti and Hemmer, 2002).

The principal mechanisms of dust removal in a wet scrubber are inertial impaction, interception and diffusion (Azzopardi et al., 1991; Goniva et al., 2009). In most wet scrubbers, inertial impaction, where the kinetic energy of the particle is used to penetrate the surface tension of the scrubbing liquid (water in most cases), is the dominant means of particle removal. Interception occurs when a dust particle makes contact with a liquid droplet at a lower relative velocity than that required for impaction and adheres to the droplet surface. Diffusion, where particles migrate and come into contact with droplets due to gas density and turbulence fluctuations, is only important for extremely small particles (<1 μm diameter) (David and Alley, 2011). All these dust collection mechanisms depend on contact between dust particles and droplets/water films which makes the distribution of scrubbing liquid critical for high collection efficiency.

In contrast to the large number of studies on venturi scrubbers (Ali et al., 2012) and dust cyclones (Narasimha et al., 2007) and a few modelling studies on flue gas desulphurization towers (Marocco and Inzolu, 2009) which face similar problems, there are no experimental or modelling studies on centrifugal wet scrubbers. Furthermore, a major shift was observed in literature, wherein research focus for emission control devices moved from fluid flow experimentation for velocity and pressure measurements in the last century to the use of Computational Fluid Dynamics in the past decade (Ali et al., 2012). This shift however, did not benefit from the use of flow visualization techniques such as high speed photography which experienced a twofold performance increase at the turn of the century.

CFD has become a more widely used tool for the design and troubleshooting of industrial equipment such as dust collectors. The Eulerian-Eulerian approach has been most widely used to simulate the distribution of the scrubbing liquid in venturi scrubbers (Guerra et al., 2012; Sharifi and Mohebbi, 2014) whereas the Eulerian-Lagrangian particle tracking method has been used to simulate the flow inside dust cyclones (Shin et al., 2005; Akiyama and Marul, 1986; Mohebbi et al., 2003) and dust particle capture by venturi scrubbers (Pak and Chang, 2006; Majid et al., 2013). Individual droplet collection and interaction with dust particles for a range of Reynolds numbers have also been modelled (Wang et al., 2016). Others, (Marocco and Inzolu, 2009; Brogren and Karlsson, 1997) applied simulation techniques based on empirical modelling to simulate SO_2 absorption in flue gas desulphurization towers. However, all these publications lack a direct comparison with experiments for model validation and where a comparison was presented; data from literature for collection devices with different dimensions and/or flow parameters was used.

This paper highlights that although fluid flow modelling techniques are being increasingly used by researchers for simulation of industrial processes, the importance of experimentation for understanding the flow dynamics remains crucial and cannot be disregarded (Slater, 2008). When CFD simulations are performed, experiments must be used in conjunction; to not only gain a better understanding of the flow processes but also to help make correct modelling assumptions and validate the CFD results. Although no international standards exist for the verification and validation of CFD predictions, for confidence in design making based on CFD results, some experimental validation should continue (Slater, 2008).

Fig. 1 shows the centrifugal wet scrubber design studied in this project. Dust laden gas enters the cylindrical vessel tangentially below the scrubbing vanes (zone B) while water enters through a pipe onto a distribution cone located between the scrubbing vanes and demister vanes (zone C). Water from the edges of the water distribution cone then mixes with the gas in an agitated water bath that forms between the scrubbing and demister vanes (zone C). Dirty water drains through the scrubbing vanes into zone B. The swirling dust laden gas is partially wetted by this water before it passes into scrubbing vanes and then into the agitated water bath above the scrubbing vanes where further gas scrubbing takes place. The gas and any entrained droplets then pass through the demister vanes that spin the flow against the wall of the vessel to remove the droplets (zone D). Dirty water exits the scrubber through the conical section at the bottom of the vessel (zone A).

2. Experimental procedure and flow visualization

Measurements and observations of fluid flow in an operating wet scrubber are extremely difficult so in this work a scale scrubber model (SSM) was constructed. Acrylic was chosen for the SSM fabrication as it would allow unobstructed visualization of the flow pattern. This approach was also recently adopted by Hreiz et al. (2014) to perform flow visualization and experimental study of a gas-liquid cylindrical cyclone. The outlet of this SSM (approximately one ninth the size of a full scale scrubber) was connected to an extraction fan (1.5 kW) with flexible and rigid ducting.