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Geometry optimisation of a gravity dust-catcher using computational fluid dynamics simulation

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ABSTRACT

A gravity dust-catcher is a high tonnage device that is widely used to separate a mixture of dusts from blast furnace (BF) top gas flow. Dusts include limestone, iron ore and coke/coal. The flow pattern within the dust-catcher is complex due to the turbulent vortices formed within, consequently making it hard to accurately predict dust-catcher performance. Using data from an on-site dust-catcher, CFD simulations are conducted on a range of geometry modifications to produce an optimised dust-catcher design specification.

The effect on particle separation efficiency during a typical blast furnace (BF) operational cycle is analysed. An attempt is made to develop and optimise a more efficient gravity dust-catcher using CFD simulation results at distinct stages of the design process. It is concluded that the newly patented dust-catcher design, can control the air flow profile much more effectively than the existing on-site design, being approximately 48% more efficient on average, from a particle separation efficiency perspective. The design may provide an effective low cost alternative to a gas separation cyclone.

1. Introduction

Tata Steel Strip Products UK (TSSP UK) at Port Talbot has two blast furnaces (No. 4 and 5) with a combined production output of approximately 86 kT of iron per week. Blast furnace operation requires high efficiency top gas cleaning equipment to cope with changes to the top gas composition, dust loading, pressure and temperature fluctuations to match the campaign life of the furnace.

The dust-catcher is the first of the major dust separation and cleaning devices, and functions to remove the majority of the incoming dust (on a mass in-flow/out-flow basis) with efficiencies of up to 55–60%. Removing as much dust during this primary separation stage enables the processes downstream of the dust-catcher, i.e. the wet scrubber and demister, to work more efficiently.

Duty of care to the surrounding environment requires that top gas is cleaned to a reasonable level reducing the environmental impact of the iron making process. The recycling of blast furnace top gas provides a major source of energy for heating the blast furnace stoves. The amount of dust in this recycled gas affects the efficiency of the burn in the hot blast stoves, leading to 'sooting up' of the burners. With studies being carried out by TSSP UK into the incorporation of a top gas recovery turbine on blast furnace 4 (BF4), the importance of clean, dust free top gas has never been higher.

This paper addresses the problem of optimising the design of a gravity dust-catcher to suit a particular set of flow characteristics. There appears to be no evidence of CFD simulation work undertaken to calculate the particle separation performance of a gravity dust-catcher over an operational cycle; where CFD simulation has been carried out its focus has mainly been on cyclone technology [1–3]. This paper explains how fluid flow performance is assessed using CFD simulation and presents results on an optimised dust-catcher design for blast furnace 4 (BF4) gas cleaning plant at Tata Steel Strip Products UK at Port Talbot. An outline of the dust-catcher and its role in iron-making is followed by an outline of the CFD model and its application to the design and efficiency assessment.

2. Gas cleaning plant layout

A typical blast furnace gas cleaning plant (*see* Fig. 1) contains three main pieces of equipment for the extraction and separation of dust and particulates from blast furnace top gas flows. Gas, which is injected and produced through numerous chemical reactions in the blast furnace passes out of the uptakes and into a down comer before entering a primary separation phase [4]. In the case of BF4

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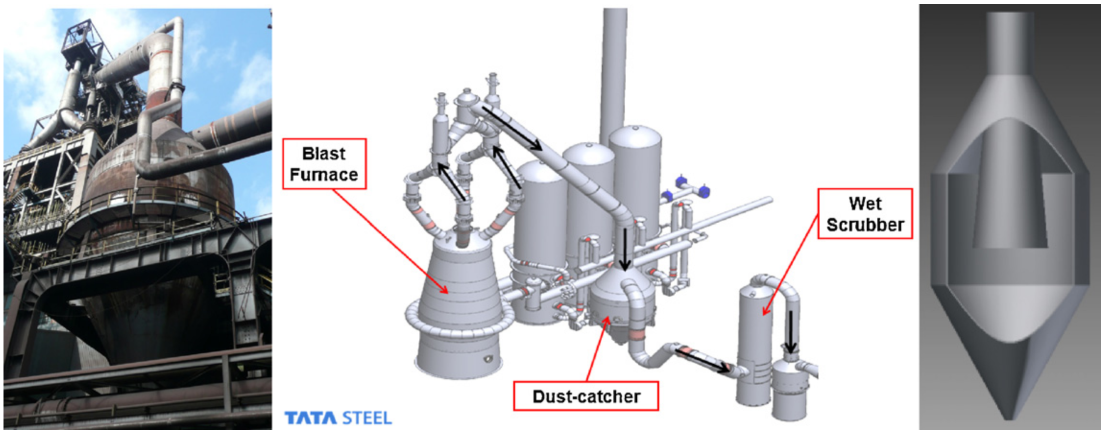

Fig. 1. Left to right; blast furnace (BF) 4 dust-catcher at Port Talbot, gas cleaning plant layout on BF4 at TSSP UK (black arrows signify direction of gas flow from the blast furnace), internal geometry profile of the gravity dust-catcher showing trumpet.

at Tata Steel Strip Products UK (TSSP UK) this phase comprises a gravity dust-catcher.

At other plants throughout the world a gas separation cyclone is also specified for this phase of the operation. Gas passes out of this primary phase and into a wet scrubber where gas is mixed with injected water and passed through two cones under very high pressure enabling the majority of the dust laden gas to be recovered as slurry. Finally, the remaining gas is dried in a demister before being recycled back through the system and used to heat up incoming clean gas in the hot blast stoves which are injected into the blast furnace, so the whole cycle is repeated again.

2.1. Dust-catcher principles of operation

A gravity dust-catcher consists of four main parts; the inlet section, an internal trumpet, the main body and hopper, and the gas outlet pipe. The dust-catcher trumpet is the main feature which affects flow performance and the consequent particle separation efficiency. A dust-catcher relies solely on gravity to separate out dust particles from the blast furnace top gas flow. These particles, carried by the free flowing gas pass out the top of the furnace and through a down-comer section where they enter another section which reduces the incoming velocity of the top gas through its diverging expansion profile (known as a trumpet). The flow then passes into the main body of the dust-catcher. The flow is then forced to turn 180° in the bottom third of the dust-catcher causing the heavier particles to deposit themselves in the dust-catcher hopper.

The dust-catcher has an inlet diameter of 3.15 m, trumpet outlet diameter of 5 m, outer shell diameter of 10.7 m, and nominal height of 27 m (see schematic in Fig. 2). The average top gas flow is 385×10^3 N m^3/h (13.17 m s^{-1}) with a dust-catcher inlet temperature and pressure of 403 K and 1.5 barg respectively. Air density used for the model is specified from blast furnace data to be 1.420 kg m^{-3}. The dust-catcher outer wall temperature is 293 K.

3. Outline of the CFD model

The CFD model has a number of key components. The core component involves a solution of the Navier–Stokes equations to capture the detailed flow behaviour of the blast furnace gas. The volume fraction of the particulate material is <1.5% by mass, so the modelling approach assumes the dust laden fluid can be solved as a single phase fluid with a density adjusted for the presence of the particulates. Of course, the behaviour of the particulates has to be distinctively incorporated, and this is done by tracking individual particulates of differing sizes and densities from a range of inlet entry locations. The efficiency of the dust-catcher can then be assessed from a statistical analysis of the fate of each of the particle tracks.

One issue that has been addressed in modelling the dust-catcher behaviour is the potential for particle lift-off from the surface of the dust pile in the hopper as it is filled. The CFD model together with the lift-off model has been described and verified in a sister paper [5] and the model is summarised here for convenience of the reader.

3.1. The core CFD governing equations

The conservation equations for momentum and mass for 3D fluid flow in an inhomogeneous mixture expressed in vector notation are:

$$\frac{\partial}{\partial t}(\rho \underset{\sim}{u}) + \nabla \cdot (\rho \underset{\sim}{u}\underset{\sim}{u}) = \nabla \cdot (\mu \nabla \underset{\sim}{u}) - \nabla p + \underset{\sim}{S}, \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underset{\sim}{u}) = S_m \tag{2}$$

where $\underset{\sim}{u}$ is the mixture velocity vector, p is the pressure, ρ is the mixture density and μ is the mixture effective viscosity. The source vector in the momentum equation, $\underset{\sim}{S}$, includes the body forces such as buoyancy, boundary effects and for solidification problems the Darcy source and S_m represents any source of mass. A number of options are available for calculating the mixture property. Most are based on an arithmetic mean [6], or harmonic mean [7], of the property concerned of the components present weighed by the mass fraction or its concentration. So, for example, mixture density could be calculated from either:

$$\rho = \sum_p \sum_c m_{pc} \rho_{pc} \tag{3}$$

or

$$\frac{1}{\rho} = \sum_p \sum_c \frac{m_{pc}}{\rho_{pc}} \tag{4}$$

where the summations are over all phases, p, and all components, c, of the phase; m_{pc} is the mass fraction of the cth component of the phase p and ρ_{pc} is the value of density for the same phase-component. For turbulence, the k–ε model of Launder and Spalding [8] involves the solution of the turbulent kinetic energy (k) equation given by:

$$\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho \underset{\sim}{u} k) = \nabla \cdot \left(\left[\mu_{lam} + \frac{\rho \upsilon_t}{\sigma_k} \right] \nabla k \right) + \rho \upsilon_t G - \rho \varepsilon \tag{5}$$