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A numerical parametric and optimization study of an industrial air-slide conveyor system

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ABSTRACT

A numerical investigation has been conducted to model the cement flow behaviour associated with a full-scale industrial air-slide conveyor (ASC) system. Steady-state simulations on the ASC were performed to predict its operational and the cement flow characteristics, and comparisons with actual operational data of the ASC demonstrate satisfactory agreement. Subsequently, hopper input loading, velocity as well as the suction fan pressure were varied and simulated to identify how cement conveying capacity by the ASC may be increased. Simulation results indicate that an increase in air chamber pressure leads to a corresponding increase in conveying capacity because of the enhanced capability of air chamber to sustain the cement flow, whereas increasing hopper input velocity and suction fan pressure both lead to lower demands in the air chamber pressure required to sustain existing conveying capacity. Detailed results associated with the cement and air flow mixture behaviour within the ASC reveal that, while the cement and air mixture flow is highly complex and three-dimensional, gross trends between the various operational parameters can be isolated successfully and may offer insights into how the existing ASC may be modified to increase conveying capacity.

1. Introduction

1.1. Research background

Due to increased demand for cement powder in the construction industry, greater attention is now being paid towards optimizing its delivery throughout the entire logistical chain. For regions where shortages in local cement production are being faced, the cement is typically transported from the place of origin via bulk marine vessels from port to port. Upon the arrival of these bulk vessels at their ports-of-call, the cement is commonly offloaded through shore side screw unloaders to the hopper systems via pneumatic conveying pipes, before the cement is transported to the storage silos via the pneumatic air-slide conveying systems. It should be noted that a pneumatic based delivery process is one of the most efficient ways to transport powdery materials and hence, it should not come as a surprise that it is a well-accepted and common practice to transport cement and other different powdery or granular materials [1,2].

1.2. Literature review

To better understand and improve the operations associated with various components associated with pneumatic conveying systems, experiments and numerical studies have been conducted previously to isolate the key conveying characteristics [3,4]. Take for instance, Li et al. [3] numerically studied the effects of material properties on horizontal pneumatic conveying based on discrete element method, and observed that friction and restitution coefficients of particles affect particle velocity, solid concentration and pressure drop, amongst others. Yan et al. [5] measured particle velocity and concentration distributions using high-speed particle image velocimetry (PIV) technique to look into the conveying velocity and pressure drops in a soft-fin based self-excited horizontal pneumatic conveying. Additionally, Gupta et al. [6] made use of a 3.7 m long fluidized conveying system to investigate dry particulate material transportation behaviour at different conveyor inclinations. The resulting increases in air velocity were found to lead to increases in the material mass flow rate, and the material mass flow rate tends to decrease when the conveying orientation varies from downwards to upwards direction.

Mittal et al. [7] studied the flow mechanisms associated with the pneumatic conveying of fine powders conveyed from fluidized dense phase to dilute phase. Different signal analysis techniques were also applied to pressure fluctuation results, from which the nature of the flows within the pipelines was revealed. Pu et al. [8] incorporated a kinetic-

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friction model into the two-fluid model in their numerical study of dense phase pneumatic conveying of pulverized coal, where the simulations predicted pressure gradients and solid concentration distributions that agreed well with experimental results. Other parameters such as particle fluctuation velocity [9], particle agglomeration [10], solid friction factor [11], wall roughness induced secondary flow [12], and more research into pneumatic conveying systems can be found in other experimental/numerical studies [13–17]. In particular, it is worthwhile to highlight that numerical simulations are able to capture the most important characteristics associated with powdery flows successfully, despite some of the limitations faced in modelling particle dynamics.

1.3. Research significance

The large-scale nature of industrial pneumatic conveying systems naturally implies that full-scale experiments and numerical simulations of the entire cement transport behaviour from the port side all the way to the silo are daunting, cost-ineffective and impractical. In particular, it should be noted that numerical simulations require adequately small mesh cell size to resolve the cement flow behaviour properly, which clearly is an issue when it comes down to modelling full-scale industrial pneumatic conveying systems. On the other hand however, it may be possible to do so for select components of the pneumatic conveying system, provided that a satisfactory compromise is struck between accuracy and computational resources. Hence, this leads to one of the primary motivations driving the present study. The second primary motivation stems from the desire to understand the relationships between the various operating parameters of a real-world industrial air-slide conveyor (i.e. ASC) for cement flows through a numerical study, so as to optimize its operations. In particular, the ASC in question here is one of two presently in operation at Jurong Port Pte Ltd. (i.e. abbreviated as the operator hereafter), Singapore. It has to be highlighted that the operator is currently the only port-of-call in Singapore that handles cement powder via bulk vessels and its handling capacity directly affects the building and construction sector in Singapore.

An ASC system relies on pressurized air being injected into a lower chamber, from which the air will flow across a fabric and produce an air film for the cement powder to flow down the entire upper conveying chamber. To illustrate, Fig. 1 shows a schematic diagram of the industrial ASC system working process. It is generally used to transport the cement from the hopper system to the silos for storage purposes and its conveying capacity is influenced by the pressurized air pressure, upstream initial conditions, downstream exit conditions, downstream suction air pressure, inclination, physical geometry and behaviour of cement powder flows, just to name a few. While earlier studies might have look at selected sections or scaled-down of an ASC and provided useful insights, studying an actual industrial ASC system numerically with engineering data from the operator used for validation provides a rare opportunity to assess if state-of-the-art numerical simulations are able to predict industrial flow applications satisfactory. It is also worthwhile to mention that such operation data remains very limited in the open literature, due to potential concerns over proprietary commercial information. Nevertheless, it will be seen later that bulk flow data provided by the operator are sufficient for validation and hence prediction purposes.

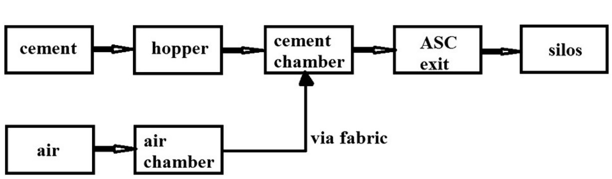

Fig. 1. Schematic diagram of the industrial ASC system working process.

In the next few sections, the physical design and actual operational details associated with the industrial ASC system will be introduced. This will be followed by a description of the numerical procedures, input parameters and boundary conditions used in the simulations. Thereafter, numerical results from steady state simulations will be presented and discussed. In particular, relationships between the various operational parameters mentioned earlier and the cement transport rates when the former was varied will be discussed in detail, providing insights into how the operation of the ASC system may be potentially altered to increase overall cement transport rates.

2. Physical design and operational details of air-slide conveyor

The ASC currently used by the operator was designed to deliver cement from the hopper system to the storage silos. Due to the present operational conditions faced by the operator, the ability to transport cement to the silos by the ASC currently limits the maximum overall cement conveying speed from the bulk vessels. Key physical design details of the ASC are provided in Table 1. Firstly, the ASC comprises two separate upper and lower chambers, the former for cement conveying while the latter is where pressurized air is being injected. The two chambers are separated by a porous fabric. The ASC was installed with an inclination of $\beta = 7°$ and there are a total of four separated lower air chambers with a 0.63 m (W) × 0.07 m (H) cross-section. Each air chamber is supplied with air from a central pump separately and no air crosses between the four air chambers. The first air chamber has a length of approximately 3 m, with subsequent three air chambers having lengths of 30 m each. In contrast, the upper cement chamber is a continuous rectangular channel with a 0.63 m (W) × 0.52 m (H) cross-section.

Porous fabric was used to separate the cement chamber from the air chamber, allowing pressurized air to pass through and form a fluidized bed for cement transportation. The current operating air pressures in the first and subsequent three air chambers are 7500 Pa and 6000 Pa respectively. In addition, a suction fan with a 2500 Pa pressure drop was installed at the cement chamber exit to aid cement transportation. The air velocity through fabric is estimated to be 0.033 m/s, where it was determined based on the air supplied under typical working conditions and fabric porous area. Lastly, the design operation capacity of the ASC is rated at about $C_o = 800$ tons/h under ideal conditions, assuming no significant cement input suspension occurs during operation. Fig. 2 shows a photo of the actual ASC and its dimensions.

3. Numerical simulation procedures

3.1. Geometry and mesh generation

Based on the physical geometries of the ASC, structured mesh based computational domains and meshes were generated for both the air and cement chambers and shown in Fig. 3. To simplify matters, x-axis refers to the streamwise direction, though it should be reminded that the ASC

Table 1
Design and operation details of the ASC.

Total length	94 m
Width	0.63 m
Height of cement chamber	0.52 m
Height of air chamber	0.07 m
Conveyor inclination	7°
Number of air-injection points	4
First air chamber length	3.012 m
Second, third and fourth air chamber length	30 m (per chamber)
First air chamber pressure	7500 Pa
Second, third and fourth air chamber pressure	6000 Pa
Suction fan pressure drop, $p_{suction}$	2500 Pa
Operation capacity, C_o	800 tons/h
Air velocity through fabric, v_{fabric}	0.033 m/s