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Article

Recent Advancement in Pneumatic Conveying for Application in Feed Industry: A Review

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Abstract: The transportation of feed pellets via pneumatic conveying plays an improtant role in feed industry. In recent years, many efforts are made both exprimentally and numerically to gain a better understanding of the underlying mechanism for pneumatic conveying. Though few of those research is directly related to feed pellets, it can be beneficial to draw a full picture of rencent development in pneumatic conveying, with emphasis on aspects extendable to feed transportation. This paper reviews first the major factors concerning feed pellets pneumatic conveying, such as particle breakage, pipe wear and electrostatic. Building on that, new advancement including emerging new technologies in experiments and simulations are discussed, with a focus on the experimental measurements and mathematical models, repectively. The needs for future research and the analogy to feed pellets tranportation is given lastly.

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1. Introduction

The production of animal feed is growing rapidly worldwide given the increasing demand for meat consumption. It is estimated that 2/3 of global fish consumption is supplied by aquaculture, which further leads to thriving needs for feed production [1]. As a pervasive technology that touches almost all branches of solids processing, pneumatic conveying finds its application in many industries, from mining to chemistry to food, which of-course covers the area of feed production [2]. Both the advantages and disadvantages of pneumatic conveying are quite obvious. On one hand, pneumatic conveying is associated with relatively low initial and operational cost, ease for automation and maintenance; on the other hand, it requires higher horsepower, more complex operational technology and suffers from problems like pipe erosion [3]. Therefore, in this research area, how to address problems mentioned ahead has received great attention, in pursuit to provide better understanding of fundamental physics as well as support for design, control and optimizations of pneumatic conveying. The same also apply to pneumatic conveying systems built for feed pellets, but they receive much less attenion despite the gigantic scale of feed processing, especially considering the unique characteristics of feed pellets.

Generally speaking, the major components of a typical pneumatic conveying system consist of blower(s), pipelines and some other auxillary devices. Depending on the layout, properties of transported material and operational conditions, the flow falls into different regimes, spanning from slug flow, unstable transition flow to suspension flow. The pneumatic conveying is thus classified into two catogories based on flow regimes involved: dilute phase and dense phase. One can roughly conclude that dense phase pneumatic conveying experiences less energy consumption, pipe wear and material damage such as attrition or breakage, whereas dilute phase pneumatic conveying is suited for broader range of applications [2,3]. Most of pneumatic conveying systems for feed pellets are operating in dillute phase to the best of the author's knowledge, leading to serious problems like pipe erosion, pellet breakage and dust generation, or even dust explosion. These limitations along with the

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complicated flow dynamics impose difficulties on not only the design and operation of robust feed pellet pneumatic conveying systems, but also a comprehensive understanding of fundamental theory.

However, only a few studies are published specifically about feed pellet pneumatic conveying in the past decade and they are summarized as following. Aas *et al* carried out a research to study the degradation of salmonid feeds taking airspeed and feeding rates into consideration [4]. Oehme *et al* studied the feed pellet distribution in a sea cage employing a pneumatic conveying system [5]. Halstensen *et al* reported their design of an on-line monitoring device to acquire the velocity of feed pellet [6]. Rajabnia *et al* investigated into the relationship between the time constant ratio and plug-flow behavior on differet biomass materials including cottonseed and wood pellet [7]. Apart from the aforementioned experimental works, some other researchers focus on theoretical simulation. Ghafori carried out an computational fluid dynamic (CFD) analysis of pipeline in the food pellets cooling system, in which particle sedimentation and erosion are covered [8]. Kong and his colleagues' simulation focuses on the breakage of feed pellet in pneumatic conveying [9,10]. Song *et al* explore the conveying characteristics of shrimp feed pellets and constructe a correlation between system energy consumption and solid-gas ratio based on CFD simulation [11]. By now, there is not enough research on the pneumatic conveying of feed pellet and thus makes it a research area with great potential.

The research on pneumatic conveying in other industries, such as chemistry, mineral, plastics, is quite abundant and thorough, which could be treated as good reference knowledge for the study in feed pellet pneumatic conveying. Not only the focuses of these research, such as flow patterns, parameter measurement, particulate attrition, pipe erosion, overlap with that for feed pellet, but the methodology is necessary for carrying out similar analysis. It is fairly important to promote the growing technology in acquring experimental data and more advanced simulation method to feed industry. On one hand, there is currently a lack of review on the useful information aforementioned; on the other hand, the physical properties of feed pellets differ significantly from particles in other industries, so it is a good practice to review relevant research in combination with universal characteristics of feed pellets.

In light of above, this paper focuses mainly on reviewing findings related to pneumatic conveying in other areas that could be applied to the study on feed pellet, rather than summarizing only the research done for feed pellet. The paper is organized as follows. In Section 2, key factors affecting the pneumatic conveying of feed pellet are listed. In Section 3, experimental studies are discussed. In Section 4, works related to theoretical simulation are detailed discussed, with emphasis given to pipe wear, particle attrition and breakage, electrostatic and moisture effects within the frame of CFD-DEM method. In Section 5, some emerging new methods applied to pneumatic conveying analysis are reviewed. Section 6 provides a summary and discussed some needs and directions for future research.

2. Factors concerning feed pellet pneumatic conveyance

2.1. Particle breakage

It is a common phenomenon to observe the breakage of feed pellets during transportation, especially in pneumatic conveying [9]. Breakage can be harmful in ways such as increasing the difficulty in sensory measurement, higher energy consumption and causing respiratory diseases in livesytock [1,2,9]. Particle breakage are normally classified into three categories in terms of physical properties: continuum solids, agglomerates and crystaline particle, of which feed pellets mainly fall into the agglomerate regime [12]. Agglomerates consist of several primary particles, which adhere together by binding forces. By nature of the agglomeration process, material bridges between liquid and solids form the dominating factor influencing adhesive forces [13,14]. According to some experimental research in the past, the breakage patterns of agglomerates are further categorized into three modes, surface abrasion, chipping and fragmentation [15–18].

In capturing the mode of breakage, the most direct parameter has been employed is the particle size distribution (PSD) [19–21]. For instance, surface abrasion and chipping are mainly observed during surface breakage, where particles are subject to low-level of external stress due to compression

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and impact, hence generate finer particles. The decrease in particle uniformity leads to a little bit shift of the PSD to the end of smaller particles, with the orignal particle distribution remains evident. It means the original particles are still dominant by volume but become minor in numbers. The occurrence of a bi-modal PSD is thus can be expected [22–25]. To tell apart between surface abrasion and chipping, the small peak in the bimodal PSD is observed at larger particle size for chipping. As a contrast, fragmentation corresponds to even larger scale breakage of particles under higher stress, which may take place through the entire volume of particle. It leads to a PSD of multi-modal, where the original curve moves to the left with a broader spectrum of particle sizes [26,27].

2.2. Pipe wear and abrasive erosion

The surface erosion of pipe components has long been a serious concerns across almost all industrial processes [28,29] and it holds true for pneumatic conveying of feed pellets as a result of intensive impact of solid particles. The erosion of pipes may lead to problems like a reduction in system service life, more frequent and costly maintainance operations [30,31]. A concensus from literature concludes that it is extremely hard or even not possible to eliminate pipe erosion completely and thus the majority of research carried out in the past focus on the mitigation of its negative effects.

Out of all research, the primary parameters to consider in evaluating pipe erosion consist of surface roughness, particle number, particle-surface collisions in terms of velocity and angle, particle-particle interations involving particle shape and shear energy [32–35]. Most of these research are conducted numerically via either the Lagrangian particle tracking (LPT) approach or the combination of computational fluid dynamics (CFD) and discrete element method (DEM), leaving an urgent need for experimental validation on their conclusions [3,36]. Rather than being restricted to regular-shape elbows which are more vulnerable to erosive wear, some other researchers concentrate on developing special elbows in hope of control the flow patterns of particle. Examples of these specially designed elbows include the Vortice-Ell elbow, the Gamma and Hemmerteck elbow *et al* [37]. The performance of special elbows are reported to be better in erosive wear resistance compared to standard ones as a result of reduction in particle-wall interaction, but they cause other issues like more significant pressure drop. Moreover, the particle-particle interactions are enhanced in the elbow zone for the special designs, which can potentially cause more severe particle breakage [38].

2.3. Energy dissipation

Energy efficiency is a major industrial concern in pneumantic conveying systems. In order to minimize power consumption, the energy efficiency of a pneumatic conveying process is usually assessed according to pressure drop, gas flowrate, and other process parameters. So far, there remains uncertainty regarding how energy dissipation occurs in a gas-solid flow within a pipeline, even though this knowledge is closely tied to power consumption.

The most commonly used method to examine energy dissipation in literature remains the Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) model mentioned earlier. Within the framework of a CFD-DEM model, a range of valuable data can be readily extracted through simulations, which includes not only the trajectories of individual particles but also the dynamic forces that come into play. These forces encompass interactions between particles themselves, between particles and the pipeline walls, and between particles and the surrounding fluid. Researchers have successfully harnessed this capability to conduct in-depth analyses of energy dissipation within the system under consideration. Numerous investigations have showcased the potential of utilizing CFD-DEM simulations to gain a comprehensive understanding of energy dissipation phenomena. Moreover, it is worth noticing that the majority of these research concentrate primarily on systems involving pure particles, with only minimal emphasis on the complex dynamics of particle-fluid flows that occur within pneumatic conveying systems. Kuang and his colleagues extended the subject to inclined pneumatic conveying system by constructing a 3D CFD-DEM model facilitated by periodic

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boundary conditions for gas and solid phases in the conveying direction [39]. They quantified the enery dissipation as a result of different interations among particles, fluid and wall.

To date, there still is a notable gap in the existing body of knowledge, as there is a dearth of comprehensive research and data regarding the intricate energy dissipation processes that involve solids like feed pellets. This deficiency underscores the need for further exploration and analysis in this specific area of study to better understand the underlying mechanisms governing energy dissipation in pneumactic conveying systems meant for feeds.

2.4. Electrification

Electrostatic phenomena have wielded a significant and, at times, detrimental influence on various industries throughout the years, with notable implications for sectors like flour and grain handling [2]. Among all the processes involved in handling solids, pneumatic conveying stands out as the one generating the most significant electrostatic buildup within the system. The multitude of interactions among particles themselves and between particles and the pipeline system can potentially result in the transfer of electrostatic charges. This transfer's occurrence depends on several factors, including the material's characteristics, shape, the humidity levels within the operation, and the properties of the pipeline. Two pivotal considerations when dealing with electrostatic issues in pneumatic conveying are the relative humidity of the conveying gas and the necessity to ensure that the entire system and its components are either grounded or constructed from conductive materials, such as conductive polymers. When an electrostatic charge is present within the system, it tends to induce erratic behavior, particularly when discharging events occur [3].

As such, understanding electrostatics has attracted increasing both therectical and experimental research interests. Klinzing and his students conducted some fundamental studies on the effect of electrostatics on the overall energy loss in pneumatic conveying. They explored electrostatics charging and discharging of particles in pneumatic transport with different relative humidities and glass beads of different size, where the pressure drop loss due to electrostatic was also meansured [40]. Zhang *et al* from the Masuda Team used a Faraday cage to measure the charge-to-mass ratio in a wide variety of materials and further extended their research by employing this in pneumatic conveying collecting the particles on a filter [41]. Zaltash *et al* studied the stability of pneumatic conveying with electrostatics to establish the regime of flow stability by linearizing the dynamic equations of flow [42]. Dhodapkar also observed the differences in the flow patterns in pneumatic conveying with and without electrostatics [43]. Larouere, Joseph and Klinzing also studied the concepts of stability with electrostatics in pneumatic conveying using the Liapunov criteria and the asymptotic stability and perturbations analysis of Jackson [44].

Meanwhile, some other researchers have concentrated on the simulation of electrostatic and their effects on solid transportation employing CFD-DEM method [45–47]. Lim *et al* studies the effects of an electrostatic field in pneumatic conveying of granular materials through inclined and vertical pipes and the ratio of the electrostatic force arising from the charged pipe wall to the gravitational force exerted on each particle has a huge impact on the flow pattern [48]. Watano explored the mechanism of electrification in pneumatic conveying of powders as well as ways to control it [49]. Korevaar *et al* carried out research on the contact charging of pnuematically conveyed powders [50]. Despite the fact that simulations are able to successfully predict the experimental observations, further efforts are still needed to develop models considering the effect of particle shape and study flow regimes related to electrostatics.

When it comes to the pneumatic conveying of feed pellets, electrostatic can be especially harmful considering the breakage of pellets leads to the generation of a great amount of powder. Furthermore, moisture is inevitable in the bulk tranportation of feeds, which has a big impact on the conveying performance. This modelling effort is lacking for pneumatic conveying, though it can be found for other particulate systems.

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3. Evaluation of pneumatic conveying performance

The appearance of pneumatic conveying systems in real applications emerged much earlier than the supporting theories. Even nowadays, the scaling theroy remains the most important method in designing pnuematic conveying systems, where massive preliminary tests are necessary to determine the empirical values throughout the process [2]. From the academic perspective, researchers have carried out extensive experimental studies, in pursuit to acquire better understanding of the mechanism underlying pneumatic conveying processes.

3.1. Perspective of experiment

Depending on material properties, pipe geometries, and operational conditions, different flow regimes and their transition take place along conveying pipelines. The determination of flow transition mode and further a suitable flow regime represents two major tasks in the design of a pneumatic conveying system [3]. To determine the flow transition mode, emphasis are put on materials properties, in particular, those properties which involve particle-gas interaction (e.g., permeability, air retention and de-aeration). Song *et al* carried out experiments alongside with simulation to study the conveying characteristics of shrimp feed pellets, where they constructed a correlation between system energy consumption and solid-gas ratio [11]. Rajabnia *et al* investigated the aeration and deaeration behaviours of four different biomass materials and further proposed a new algorithm to reduce trial test, providing a novel approach for predicting flow modes [7]. Alizadeh *et al* specifically carried out study on perennial ryegras to examine the effects of particle mass, size and moisture content on the performance of pneumatic conveying, with an emphasis on terminal velocity and drag coefficient [51]. In the work of Huang *et al*, the properties of sawdust are evaluated in dense-phase pneumatic conveying [52]. Also within the frame of dense-phase pneumatic conveying, Liang *et al* compared the flow characteristic of biomass powder and pulverized coal at high pressure [53]. Guo and colleagues investigated the shear properties, flow energy and aeration with a FT4 Powder Rheometer to demonstrated the flow characteristic [54].

The orientation of pipelines themselves as well as the connecting bends located at the position where change of orientation takes place receive great attention from researchers. Considering the orientation of a specific pipe segment could be horizontal, vertical or inclined, there are up to 9 combinations of bends. For short systems with several bends, the energy loss due to bends existence may be the dominant energy requirement for transport, whereas for long distance systems, the bend contribution to the energy requirements is not very significant and often can be neglected. The whole field of bends has been widely studied and may come with conflicting results. It is worth noting that the measurements of pressure drop should be taken over the entire bend influences, which sometimes require a long distance of pipe after the bend for the particles to return to a steady state. Bends introduce secondary flow in the flow regime, which produces complicated interactions between the fluid, particles and the walls of the pipe [2]. Many unique designs of unusual bends have been incorporated into the conveying systems, all aimed at reducing the erosion of the pipe and attrition of the particles and striving to reduce the pressure drop and thus the energy requirements [55].

Recently, auxillary devices are receiving more attentions from researchers. Gomes *et al* specifically designed a feeding system to control the biomass flow rate and then evaluate feeding efficiency at varying air velocity, valve rotational speed [56]. Lourenco's team also investigated into the air velocity in the pipeline and the filling rate with 3(k) factorial design for powders and grains [57]. Wang and colleague developed a novel dual pneumatic feeder to achieve constant and steady biomass conveying for pyrolysis [58]. As a typical form of dust collector, cyclones contribute to the overall pressure drop and further affect the system performance [59,60]. Cyclones may be optional in some applications, but is essential in the bulk handling of feed pellets via pneumatic conveying considering the significant generation of dust during transportation [61].

3.2. Flow measurements

It is usually unavoidable to measure the flow rates of gas and solid when conducting experiments on a pneumatic system. While the gas flow rate or in other words, the air velocity, is relatively straightforward to acquire making use standard orifice meter or venture meter, the solid flow rate measurement can be difficult to handle. The simplest but perhaps less accurate way is to implement load cells in the converying system. The difference in weights of the container or containers over a period of time can give the solids flowrate of capacity [2]. More often, one is concerned with the solid flow rate at certain point along the pipeline, where sound measurement or electrostatic effects may come into play.

The use of sound measurement in solids flows has been explored by Davies and Tallon [62–64]. The sound wave intensity is propagated by the presence of solids, giving a direct relationship to the amount of solids flowing. Tallon and Davies explored the attenuation of acoustic pulsed pressure waves for concentration measurement of gas-solid flow [65]. Sun *et al* presents a novel instrumentation system for on-line nonintrusive detection of wood pellets in pneumatic conveying pipelines using vibration and acoustic sensors. Time-frequency analysis technique is used to identify the presence of wood pellets [66]. Ihunegbo *et al* performed a feasibility study on application of acoustic chemometrics for at-line prediction of size fractions of biomass material [67].

In Section 2.4, electrostatic has been argued to be harmful in pnuematic conveying systems. However, using the charge generate to obtain a signal that could be measured and analyzed and indicate the amount of solids flowing is a positive way to address the charging issue. In real applications, one must be careful not to construct a capacitor of the pipe in a non-conducting section. In their paper, Coombes reported the application of a novel electrostatic sensor array that is capable of measuring the particle velocity and concentration profiles over the whole diameter of the pipe [68]. Zhang's team presented an integrated instrumentation system, which combines electrostatic sensors with capacitive sensors and incorporates data fusion techniques, for the volumetric-concentration measurement of biomass/coal/air three-phase flow in a pneumatic conveying pipeline [69]. Qian *et al* combined electrostatic sensor arrays and data fusion algorithms to provide a non-intrusive solution to the measurement of fuel particle velocity, relative solid concentration and flow stability under pneumatic conveying conditions in their series work [70–72]. Shao *et al* reported their findings of electrostatic sensors for the continuous velocity measurement of particles in pneumatic conveying pipelines [73].

4. Modelling and simulation of key pneumatic conveying characteristics

In recent years, with the rapid development in computational technology, numerical models have been widely accepted as a tool to study fundamental principles governing pneumatic conveying and to assess process performance. The models are categorized as either continuum-based or discrete-based, depending on their treatment of particles or the solid phase.

The continuum model is typically represented by the Two-Fluid Model(TFM). Computationally convenient and efficient as it may be [74–83], the effective use of a continuum model depend heavily on constitutive relations employed to close the governing equations of the model. As a result of its limitation, TFM studies have predominantly been applied to the pneumatic transport of powders or fine particles [74–80], even though real-world scenarios often involve mixtures of fine and coarse particles. Furthermore, it remains a significant challenge to develop a TFM model to reproduce all the typical flow regimes and transition. The discrete-based model, on the other hand, is typically represented by the the combination of CFD and DEM(CFD-DEM) or LPT(CFD-LPT), where the CFD-LPT is normally treated as a simplified model of CFD-DEM ignoring particle-particle interactions [84,85]. Different from TFM, the CFD-DEM is applicable to a wider range of flow conditions because there is no need to consider the complex constitutive relations. In addition, the CFD-DEM approach is capable of generating microscopic information such as the trajectories of particles and forces acting on them [86,87]. Since its proposal and rationalization [88–91], pneumatic conveying has been one of the

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major area of application for CFD-DEM approach. This paper hence will review the modelling and simulation of key pneumatic conveying characteristics within the frame of CFD-DEM approach.

4.1. Framework for mathematical modelling

In CFD-DEM method, there exist three sets of equations, which resepctively describe the solid phase, the gas flow and the coupling scheme.

For the solid phase, the particle is treated as individual with two types of motions obeying Newton's second law: translational and rotational. The governing eauqtions at any time t are given as follows,

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_{p-f,i} + \sum_{j=1}^{k_i+k_w} \left(\mathbf{f}_{c,ij} + \mathbf{f}_{d,ij}\right) + m_i\mathbf{g} \tag{1}$$

$$\mathbf{I}_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_i+k_w} \left(\mathbf{T}_{t,ij} + \mathbf{T}_{r,ij}\right) + \mathbf{T}_{ls,i} \tag{2}$$

where m_i, $\mathbf{I}_i$, $\mathbf{v}_i$ and $\mathbf{!}_i$ are the mass, moment of inertia, translational and angular velocities of partilce i, respectively; $\mathbf{f}_{p-f,i}$ is the particle-fluid force; $\mathbf{f}_{c,ij}$ and $\mathbf{f}_{d,ij}$ are the elastic and viscous contact damping forces between particle i and particle/wall j, repectively; $m_i\mathbf{g}$ is the gravitational force; $\mathbf{T}_{ij}$ is the torque acting on particle i due to particle/wall j. For a particle undergoing multiple interactions, the forces and torques are summed over the k_i particles and the k_w walls in contact with particle j. The particle-fluid force $\mathbf{f}_{p-f,i}$ is the sum of all types of particle-fluid interaction forces acting on individual particles by fluid, which consists of the fluid drag force, the pressure gradient force and in some occasion, viscous force, virtual mass force and lift forces such as the Saffman force and the Magnus force. It is also necessary to take into account the turbulent dispersion effect when a particle experiences an instantaneous fluid velocity in turbulent gas flow. Similarly, the torque acting on a particle consists of different components: one arises from the tangential forces $\mathbf{T}_{t,ij}$ and another is the rolling friction torque $\mathbf{T}_{r,ij}$. A third torque $\mathbf{T}_{ls,i}$ may come into play if one considers the interaction between partcle and viscous fluid. Different models have been developed for the forces and torques described in Equations (1) and (2) is summarized elsewhere [86,92].

The governing equations for the gas flow are nothing more than the conservation of mass and momentum in terms of local mean variables given that it is treated as a continous phase. In its original form [93,94], the mass conservation and momentum equations are given as follows,

$$\frac{\partial\left(\rho_f \epsilon_f\right)}{\partial t} + \nabla \cdot \left(\rho_f \epsilon_f \mathbf{u}\right) = 0 \tag{3}$$

$$\frac{\partial\left(\rho_f \epsilon_f \mathbf{u}\right)}{\partial t} + \nabla \cdot \left(\rho_f \epsilon_f \mathbf{u}\mathbf{u}\right) = -\nabla P - \mathbf{F}_{p-f} + \nabla \cdot \boldsymbol{\tau} + \rho_f \epsilon_f \mathbf{g} \tag{4}$$

where $\mathbf{F}_{p-f} = \frac{1}{\Delta V}\sum_{i=1}^{k_c}\left(\mathbf{f}_{drag,i} + \mathbf{f}_{\nabla p,i,i} + \mathbf{f}_{\nabla\cdot\tau,i,i} + \mathbf{f}_i''\right)$ and $\mathbf{f}_{p-f,i} = \mathbf{f}_{drag,i} + \mathbf{f}_{\nabla p,i} + \mathbf{f}_{\nabla\cdot\tau,i} + \mathbf{f}_i''$. The above momentum equation takes another form if the fluid stress tensor in treated differently, as described below,

$$\frac{\partial\left(\rho_f \epsilon_f \mathbf{u}\right)}{\partial t} + \nabla \cdot \left(\rho_f \epsilon_f \mathbf{u}\mathbf{u}\right) = -\epsilon_f \nabla P - \mathbf{F}_{p-f} + \epsilon_f \nabla \cdot \boldsymbol{\tau} + \rho_f \epsilon_f \mathbf{g} \tag{5}$$

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where $\mathbf{F}_{p-f} = \frac{1}{\Delta V}\sum_{i=1}^{k_c}\left(\mathbf{f}_{drag,i} + \mathbf{f}_i''\right)$ and $\mathbf{f}_{p-f,i} = \mathbf{f}_{drag,i} + \mathbf{f}_{\nabla p,i} + \mathbf{f}_{\nabla \cdot \tau,i} + \mathbf{f}_i''$. The momentum equation of the original form can be further simplified by adopting the steady and uniform flow assumption in calculating the pressure gradient and viscous forces, see below,

$$\frac{\partial\left(\rho_f \epsilon_f \mathbf{u}\right)}{\partial t} + \nabla\cdot\left(\rho_f \epsilon_f \mathbf{uu}\right) = -\nabla P - \mathbf{F}_{p-f} + \nabla\cdot\boldsymbol{\tau} + \rho_f \epsilon_f \mathbf{g} \tag{6}$$

where $\mathbf{F}_{p-f} = \frac{1}{\epsilon_f \Delta V}\sum_{i=1}^{k_c}\left(\mathbf{f}_{drag,i} + \mathbf{f}_i''\right) - \frac{1}{\Delta V}\sum_{i=1}^{k_c}\left(\rho_f V_{p,i}\mathbf{g}\right)$ and $\mathbf{f}_{p-f,i} = \left(\mathbf{f}_{drag,i} + \mathbf{f}_i''\right)/\epsilon_f - \rho_f V_{p,i}\mathbf{g}$. In Eqs.3-6, ρ_f, $\mathbf{u}$, P, **ø** are the fluid density, fluid velocity and pressure, and fluid viscous stress tensor, respectively. The stress tensor **ø** takes the following form in analogy to Newtonian fluid,

$$\boldsymbol{\tau} = \left(\eta_{laminar} + \eta_{turbulent}\right)\left[(\nabla\mathbf{u}) + (\nabla\mathbf{u})^{-1}\right] \tag{7}$$

where $\eta_{laminar}$ is fluid molecular viscosity and $\eta_{turbulent}$ is the turbulent viscosity. Different models can be used to acquire the value for turbulent viscosity depending on the specific application [95]. In real application, the model represented by Eqs.6 has limitations, e.g., performs not well in calculation of complex flow, due to the adoption of certain assumption. Therefore the original model is recommended to solve the ill-posed problems linked to the other two models [3].

As depicted by the governing equations, it is crystal clear that the particle flow is modelled on individual particle scale, whereas the CFD method describes the gas flow on the aspect of computational cell scale. The descrepency is resolved by the numerical coupling of the two methods, as proposed by Xu and Yu [90]. During each time step, the Discrete Element Method (DEM) supplies essential data, including the positions and velocities of individual particles, which are crucial for assessing parameters like porosity and the volumetric particle-fluid force within each computational cell. Subsequently, the Computational Fluid Dynamics (CFD) model utilizes this data to calculate the gas flow field, which, in turn, is instrumental in determining the particle-fluid forces acting on individual particles. These computed forces are then incorporated into the DEM, allowing for the prediction of the movement of individual particles in the subsequent time step. It's important to note that the particle-fluid forces acting on individual particles also exert an equal and opposite reaction on the fluid phase, thereby ensuring compliance with Newton's third law of motion.

During the process, mapping technique, e.g., the least-square interpolation [96], is used to convert properties from cell-based scale to particle-based level. To efficiently compute porosity, a particle is considered to belong to a cell if its center lies within the cell's boundaries, even if it partially overlaps. Errors due to partial overlap are typically ignored, but neighboring cells can be considered to reduce these errors [97,98]. Various methods have been proposed to calculate the partial volumes of particles that overlap cell boundaries, including analytical methods [99], particle meshing methods [100,101], local averaging theory [102], two grids [103], and diffusion-based averaging theory [104,105]. The diffusion-based averaging method is primarily designed for spherical particles and may not extend well to non-spherical particles. The two-grid method involves a mapping procedure between extra Cartesian grids and the original grid, which can lead to accuracy loss. In contrast, the local averaging theory-based method is consistent in handling source terms imposed by particles on fluid, using a spherical cell approach similar to granular materials' local averaging.

4.2. Particle attrition and breakage

Particle attrition and breakage are inevitable in pneumatic conveying, particularly in dilute-phase mode, affecting conveying characteristics and material quality. Various particle attrition test apparatus exist, but there are research gaps, especially in connecting characterization methods to the specific processes involved. Successful particle attrition modeling must account for both material and process aspects to yield meaningful results. One early effort by Frye and Peukert used the CFD-LPT model to determine impact conditions and employed experiments to assess particle attrition [106]. Currently, a

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promising approach combines the CFD-DEM model and particle attrition modeling, as demonstrated by different researchers [1,106–109].

Three types of breakage models have been integrated into the CFD-DEM approach, i.e., the empirical models, the bonded particle model and the comminution model. In terms of empirical model, Han *et al* successfully implemented Ghadiri's attrition model to simulate particle breakage, in which chipping and fragmentation are analyzed separately [107]. The respective equations for calculating particle sizes produced by the two mechanisms are as follows:

$$\begin{array}{llll} Chipping & d_s = \left(\alpha_f \frac{\rho_p H v_{impact}^2 d_{s0}^4}{K_c^2} \right)^{1/3} & 4m/s < v_{impact} < 13m/s \\ Fragmentation & (3-\zeta')ln\left(\frac{d_s}{d_{s0}}\right) = ln\lambda' + \zeta' ln\left(\frac{\rho_p H v_{impact}^2 d_{s0}}{K_c^2}\right) & v_{impact} > 13m/s \end{array} \tag{8}$$

where α_f is a proportionality factor, d_s is the diameter of the smaller part of a particle after impact, d_{s0} is the diameter of the mother particle before impact, H is the material hardness, v_{impact} is the particle impact velocity, λ' and ζ' are the parameters that are determined experimentally, and K_c is the critical stress intensity factor.

The bonded particle model operates by interconnecting particles using elastic beams and subsequently analyzing stress levels to identify instances of breakage [110]. In this model, the particles that are bonded together can either possess uniform sizes or exhibit size distributions. Breakage events are determined by computing both normal and shear stresses and then comparing these values against predetermined critical thresholds. This modeling approach is particularly well-suited for materials characterized by brittleness, such as coal, granite, sandstone, and concrete, among others [1,106]. Notably, Kong and colleagues applied this model to investigate the breakage of feed pellets in the context of pneumatic conveying. Their study focused on evaluating the effects of inlet velocity and bend radius on the breakage process, with the model representing clusters of particles, often up to ten in number [9].

The comminution model, initially introduced by Kalman and colleagues, involves assigning each particle a strength distribution function [111]. As the simulation unfolds, these particles undergo a series of impact events. During each impact event or collision, a selection function is invoked to determine whether the particle will break. If a breakage occurs, the breakage function is activated to create new fragments with strengths in accordance with the assigned strength distribution. However, if the particle manages to withstand the impact, it will experience fatigue, which subsequently influences its strength following the collision. It is worth noting that this attrition model is specifically tailored to describe the compression strength of particles. The selection function is derived from impact experiments, necessitating the establishment of an equivalence function between impact and compression strength [112]. Brosh *et al* have extended the model to study particle attrition in dilute-phase pneumatic conveying, focusing primarily on the effect of the impact velocity [109]. No such research has been found on the application of this model to feed pellets however to the best of the author's knowledge, especially considering that feed pellets are generally modelled as non-spherical particles. Actually, the modeling of non-spherical particles within attrition models remains a complex challenge in this research area.

4.3. Pipe wear

Wear is a significant concern in bulk solids handling, leading to increased maintenance costs, environmental impact, productivity loss, and component replacement needs. Pipeline wear primarily occurs due to surface abrasion caused by moving particles in the pipeline. This abrasion encompasses deformation wear due to normal particle impact and cutting wear resulting from oblique particle

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impact. To estimate surface abrasion quantitatively, researchers use the concept of time-averaged collision intensity (TACI) in CFD-DEM studies for pneumatic bends [113,114], as described below,

$$TACI = \frac{1}{\Delta t_{sp}} \sum_{\Delta t_{sp}} \left(\frac{\sum_{i=1}^{k_w} |\mathbf{f_{cn,ij}} + \mathbf{f_{dn,ij}} + \mathbf{f_{ct,ij}} + \mathbf{f_{dt,ij}}|}{A_{sp}} \right) \tag{9}$$

where A_{sp} is the surface area of sample wall, Δt_{sp} is the simulation time or sampling time period. TACI helps identify the pipe wall position experiencing the highest particle-wall interaction and likely to wear out first, aligning with experimental observations [115].
To provide quantitative predictions of pipeline wear, numerical gas-solid flow models are combined with wear equations, among which the Finnie's equation is commonly used [116,117]:

$$Q_{erosion} = \begin{cases} \frac{mv_{impact}^2}{8p} \left[sin2\alpha - \frac{6}{\kappa} sin^2\alpha \right] & \alpha \leq 18.5 \\ \frac{mv_{impact}^2}{24p} & \alpha \geq 18.5 \end{cases} \tag{10}$$

where $Q_{erosion}$ is the volume of material removed by the impact of a single particle; p is the plastic flow pressure of erosion surface, m is the particle mass, v_{impact} is the particle impact velocity, κ is the ratio of vertical to horizontal force components on the particle and α is the particle impact angle. Previous studies have primarily focused on pneumatic conveying, particularly in bends susceptible to erosion, using the CFD-LPT-Wear model [118]. However, this model cannot explicitly consider particle-particle collisions in pipe erosion. Some recent efforts have applied a CFD-DEM-wear model to study pneumatic pipe wear, combining CFD-DEM with a wear equation tailored for DEM modeling [1,119–121].

It is crucial to choose the right wear equation for numerical models to predict wear rates. There are more than 150 wear equations, of which none is universally practical [122]. Developing a more general wear equation supported by theoretical and experimental analysis, possibly using finite element methods, is essential [123,124]. Additionally, to facilitate industrial applications, a predictive wear model should be established based on systematic numerical studies.

4.4. Electrostatic and moisture effects

The CFD-DEM method is capable of capture the effect of electrostatics on solid transportation [45–50]. The electrostatic force acting on particle i is described as follows [46,48],

$$\mathbf{f_{e,i}} = \mathbf{f_{ep,i}} + \mathbf{f_{ew,i}} \tag{11}$$

where the first term on the right side of Equation (11) refers to the electrostatic forces owing to surrounding charged particles and the second term represents that from pipe walls. In evaluating the electrostatic force arising from other particles, each particle is normally treated as a constant point charge obeying Coulomb's law. To assess the forces exerted by the pipe walls, an estimation of the average electric field strength near the wall of the pneumatic conveying pipe is conducted, which is based on the assumption that the pipe can be treated as an infinitely long flat plate along its axial direction, see Lim *et al* [46,48]. In following studies, Grosshans and co-authors have extended the electrostatic force model to encompass situations where charge exchange occurs during particle collisions, either between particles or with the pipe wall [47]. In a similar context, Korevaar and colleagues [50] have employed a modeling approach where the wall is assumed to be both grounded and conducting. This technique involves placing an image charge at the same distance but on the opposite side of the conducting planar wall, with a charge of equal magnitude but opposite sign. Most research so far focus on spherical particles with no consideration over over shapes at all, again confines the probability to apply those models on the analysis of feed pellets and thus requires more efforts.

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In addition, it is inevitable to encounter moisture in the bulk transportation of feed pellets via pneumatic conveying [125]. The modelling of moisture is in principle similar to that of electrostatics within the framework of CFD-DEM. [liupy2013] has carried out research for other particulate systems. The work by Ghafori, where the CFD modelling based on the Euler-Euler method is used to study the sedimentation of particles and the erosion problem of pipes in a feed pellets transportation system, offered a good startpoint for the simulation of moisture. Further efforts are needed in this area.

5. Emerging new techniques

5.1. Large-scale simulation

The simulation of pneumatic conveying systems can be computationally expensive, especially when the pipeline is long and thus limits its application in industry. To overcome the deficiency, the periodic boundary conditions (PBC) is introduced in a simulation to consider a short pipe that represents the established-flow section and can be scaled up straightforwardly according to the length. To use a CFD-DEM model with PBC to solve practical pneumatic conveying, it is necessary to establish methods to exclude the start-up section from the pipeline simulated, determine length of PBC pipe, and control the solid flow rate simulated as constant as done in a common operation in practice. Moreover, to be accurate in this PBC application, a numerical iterative method has also been proposed to control the solid flow rate simulated to achieve a given value. This CFD-DEM model with PBC has been applied to different studies to pneumatic conveying [39,126,127]. Further studies are needed to test whether the CFD-DEM with PBC can be used to simulate a realistic pneumatic conveying system by dividing pipelines into start-up sections and developed sections and conducting the simulations sequentially.

The CFD-DEM simulations can also possibly be accelerated for large-scale industrial applications with the involvement of a "scaled" method. Coarse-grain models fall under this category, wherein a particle assembly is represented by a reduced number of original particles, and a scaling law is established based on the force balance between a coarse-grain or parcel-particle and its corresponding original particles [128,129]. The application of such a model has shown promising results, notably in reproducing slug flow patterns [128]. However, there are certain limitations to consider. It’s still unclear whether a coarse-grain model can accurately predict various flow regimes, their transitions, and the phenomenon of pipe wear. Furthermore, these models may not be suitable for simulating particle attrition and electrification, as these processes heavily rely on precise descriptions of particle-particle interactions to generate realistic results.

The rapid advancement in computer hardware performance has brought Graphics Processing Units (GPUs) to the forefront, no longer limited to rendering 3D scenes but also capable of supporting increasingly complex computations. In the context of DEM simulations for granular flow, the speed-up achieved by GPU parallel codes over their serial CPU counterparts is remarkable, ranging from several times faster to even tens of times faster. What’s particularly noteworthy is that the utilization of multiple GPUs is making it feasible to simulate systems containing millions of particles, which holds great promise for various engineering applications [130,131]. However, it’s essential to point out that this technology has not yet been applied to the study of pneumatic conveying processes, not to mention the specific application in transfering feed pellets. This area represents a promising frontier for future research and development, where dedicated efforts can harness the power of GPUs to enhance our understanding and capabilities in pneumatic conveying studies.

5.2. Application of machine learning theory

Ever since its proposal, machine learning has long been an active research area. Until recently, a few attempts have been made to integrated machine learning theories into the characterization of pneumatic conveying systems. Wang and colleagues designed a cross-rod electrostatic sensor array structure to measure the flow pattern signals. The data is then fed to a probabilistic

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neural network to identify the gas-solid two-phase flow patterns [132]. Li *et al* developed a deep learning-based tomographic imaging of electrical capacitance tomography (ECT) to characterize the particle concentration distribution in a circulating fluidized bed [133]. In Sethi's work, Artificial Neural Networks (ANNs) models are used to study the effect of wall friction coefficient and coefficient of wall cohesion on the pressure drop in a dense phase pneumatic conveying system [134]. Shijo investigated the capability of machine learning (ML) techniques to estimate the drop in pressure in fluidized dense phase conveying of powders [135].

It is noted that the performance of machine learning algorithms rely heavily on the quality and quantity of datasets. Careful tuning of algorithm parameters is necessary to get the best prediction. Though there are limited research available as of today, it shows great potential to incorporate machine learning into pneumatic conveying system, given that a well trained model will not only improve the operational efficiency, but also help future system design.

6. Conclusions and remarks

As noted in the article, the research of pneumatic conveying systems have experienced lots of improvements, both experimentally and theoretically. A huge gap exists between simulation and experimentation, however, in that simulations require less cost to perform. It means that additional experiments are needed in order to validate the simulated results. Moreover, deeper understanding of the experiments will provide a more fundamental appreciation for the assumptions that are made in simulations. This is especially true for the applications in feed industry, where neither experimentation nor simulation receives enough attention depite the huge market. While one may draw lessons from existing works, the unique characteristics of feed pellets should be taken into consideration in future research, such as irregular shapes, wide range of size distribution, particle breakage, moisture and so on.

Better instrumentation are needed for measurement of solid flows. It has been proved that technologies such as sonic and electrostatic are plausible in capturing the values of interest with an acceptable range of error. But these intruments fall short in the ease of deployment or being too expensive.

We have seen also the rapid development of new technologies in this research field, such as the large scale simulation and the incorporation of machine learning. In terms of large scale simulation, it is necessary in the future to not only employ advanced GPU computing technology but also develop general scaling theories to reduce the computational effort. As for machine learning techniques, the primary challenge is how to acquire training data of both good quality and quantity. Both techniques have shown great potential in possible online adaptive control of pneumatic conveying systems, which of-course require further and deeper research. The extension of those emerging new technologies to the pneumatic conveying system for feed pellets should be straightforward.

Abbreviations

The following abbreviations are used in this manuscript:

PSD	Particle Size Distribution
TFM	Two-Fluid Method
CFD	Computational Fluid Dynamics
DEM	Discrete Element Method
TACI	Time-Averaged Collision Intensity
GPU	Graphic Processing Unit
ECT	Electrical Capacitance Tomography
ANN	Artificial Neural Network
ML	Machine Learning

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