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CFD approach for simulation of bitumen froth settling process – Part I: Hindered settling of aggregates

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Abstract

Bitumen or heavy oil aggregates are formed when bitumen emulsions, consisting of emulsified water droplets dispersed solids and precipitated asphaltenes, are treated with aliphatic solvents. While settling, the aggregates exhibit zone settling mode with the development of a sharp oil and settling zone interface. Previous research [Long Y, Dabros T, Hamza H. Structure of water/solids/asphaltenes aggregates and effect of mixing temperature on settling rate in solvent-diluted bitumen. *Fuel* 2004;83:823–32] provides settling experimental data for bitumen aggregate settling and a Richardson–Zaki approximation was proposed by the authors with modified exponents for simulating the settling behavior of aggregates. However, the need for modified exponents and their dependence on aggregates and solvents used was not explained. Since the aggregates exhibit hindered settling, where the settling rate is different from that of individual particles or aggregates, numerous settling models have been proposed to correlate particle swarms to single particle via drag correlations [Richardson JF, Zaki WN. Sedimentation and fluidization: Part I. *Trans Inst Chem Eng* 1954;32:35–53; John G, Maan RA. Velocity–voidage relationships for fluidization and sedimentation in solid–liquid systems. *Ind Eng Chem Proc Des Dev* 1977;16:206–14]. The compaction zone, due to high concentrations of solids and the effect of their resultant weight during settling is also often ignored. In this work, the hindered settling behavior of bitumen aggregates is first studied in a CFD framework using two models: (a) modified Richardson–Zaki approximation by Long et al. [Richardson JF, Zaki WN. Sedimentation and fluidization: Part I. *Trans Inst Chem Eng* 1954;32:35–53] and (b) the Syamlal–O’Brien model [John G, Maan RA. Velocity–voidage relationships for fluidization and sedimentation in solid–liquid systems. *Ind Eng Chem Proc Des Dev* 1977;16:206–14]. To address the limitations of the two models, a new model is proposed that incorporates the irregular (fractal) structure of aggregates by considering the aggregates as porous liquid-filled solids that are fractal in nature. Results, from the new fractal model, are found to be in good agreement with empirical data.

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Keywords: Aggregates; Drag model; Fractal dimension; Settling

1. Introduction

Bitumen from shallow oil sands deposits, are recovered and processed primarily via surface mining, hot water extraction and froth treatment. Typically, bitumen froth consists of 60 wt% bitumen, 30 wt% water, and 10 wt% coarse sand and fine solids. The water and solids in froth need to be removed for further solvent-based processing

(settling) of the bitumen. Bitumen aggregates, consisting of emulsified water droplets (WD), dispersed solids (DS), and precipitated asphaltenes (PA) are treated with aliphatic (e.g., *n*-heptane) and aromatic solvents (e.g., naphtha). In this study, numerical analysis of the settling of aliphatic solvent treated bitumen aggregates was performed. To perform efficient separation via froth treatment, there is a need to develop a detailed understanding of the local fluid–solid interactions and its effect on the overall solid fluid behavior of the settling or froth treatment systems. Advantages of further developing and controlling the settling process lead to lower downstream processing costs

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Nomenclature

A	coefficient in the Syamlal–O’Brien drag model	v_S	solids velocity (m/s)
B	coefficient in the Syamlal–O’Brien drag model	v'_S	fluctuating particle velocity (m/s)
C_D	drag coefficient	v_T	terminal velocity of a single particle (m/s)
d_A	diameter of aggregates (m)	$v_{T,F}$	terminal velocity of a single fractal particle (m/s)
d_P	diameter of primary particles (m)	V	volume (m ³)
d_S	diameter of particles (m)	V_A	volume of an aggregate (m ³)
D	fractal dimension	V_P	volume of a primary particle (m ³)
e_{SS}	coefficient of restitution of particles	<i>Greek symbols</i>	
f_{drag}	drag force (N)	α_L	volume fraction of liquid phase (–)
g	gravitational constant (m/s ²)	α_q	volume fraction of phase q (–)
$g_{0,SS}$	radial distribution function	α_S	volume fraction of solids phase (–)
I	unit tensor	$\alpha_{S,\text{max}}$	maximum packing limit of solids phase (–)
K_{LS}	momentum transfer coefficient (kg/m ³ s)	ε	porosity of aggregates (–)
m	coefficient in the Syamlal–O’Brien drag model	ϕ_{LS}	energy exchange between fluid and solids phase (kg/m s ³)
n	exponent of Richardson–Zaki drag model	Φ_S	granular temperature of solids phase (m ² /s ²)
N	number of primary particles forming an aggregate	γ_{Φ_S}	collisional dissipation of energy (kg/m s ³)
p_S	solids pressure (N/m ²)	κ_{Φ_S}	diffusion coefficient (kg/m s)
P	fluid pressure (N/m ²)	λ_S	bulk viscosity (Pa s)
R_{pq}	interaction force between phases (N)	μ_L	viscosity of liquid phase (Pa s)
Re_S	Reynolds number (–)	$\mu_{S,\text{kin}}$	solids shear viscosity (Pa s)
Re_T	Reynolds number based on terminal velocity of a single particle	ρ_A	density of aggregates (kg/m ³)
t	time (s)	ρ_L	density of liquid phase (kg/m ³)
v_L	liquid velocity (m/s)	ρ_P	density of primary particles (kg/m ³)
v_q	velocity of phase q (m/s)	ρ_q	density of phase q (kg/m ³)
$v_{R,S}$	ratio of the settling rate of particles to the terminal velocity of a single particle (–)	ρ_S	density of solids phase (kg/m ³)
		τ_S	stress tensor of solids phase (N/m ²)

and lower hydrocarbon losses in the tailings, thereby enhancing resource utilization and has the potential to reduce GHG emissions from tailings ponds significantly. Thus, detailed knowledge of local fluid–solid interactions during settling and the solid–fluid dynamic interactions is critical for improving the settling process.

In recent years, computational fluid dynamics (CFD) has emerged as a powerful tool for understanding the multiphase interactions prevailing in process systems. The success of CFD in single phase processes is significant while the presence of multiple phases makes the description of the flow difficult to quantify. This requires the combination of fundamental process models that explain the local fluid–solid behavior and the incorporation of the local models into CFD to determine the settling rates computationally. CFD provides a framework for solving the fluid flow and accounting for solid properties such as shear and solids pressure that cannot be done efficiently in a 1-D model. In this work, the Richardson–Zaki model [3], discussed by Long et al. [1,2], has been implemented in a CFD framework and the settling rates have been determined for the model system proposed by Long et al. [2]. Also, the modified Richardson–Zaki exponent, outlined in the work by Long et al. [2] has been validated to provide the basis for

further modeling in scaled froth treatment systems. Further, an alternate modeling approach, the Syamlal–O’Brien model [4], was also applied due to the low settling rates encountered during the settling.

Long et al. [1,2] reported that bitumen froth treatment can be enhanced (high settling fluxes can be achieved) by operating the settling system (mixing of bitumen froth with solvent and subsequent settling of the solvent diluted froth) at elevated temperatures and described the irregular structure of bitumen aggregates. In this work, a framework for studying bitumen settling process numerically at different process temperatures has also been examined. CFD results were validated by the settling tests conducted by Long et al. [2].

Aggregate structure has been well-recognized to be of great importance to solid–liquid settling processes. The aggregate structure and density influence the strength of the aggregates and undergo growth, breakup and possible re-arrangement in settling systems. It has been widely accepted that flocculated aggregates can be represented by fractal structures [5,6]. Fractal dimensions relate physical size to a geometric property in the equivalent dimension. Masliyah et al. [5] measured the fractal dimension of asphaltene aggregates formed in toluene–heptane

solvent mixture by settling experiments and imaging techniques. In this work, volume-based fractal dimension, D_3 or D , based on Euclidean geometry, was applied to describe the irregular structure of aggregates. In this work, we propose a new model that relies on the initial fractal dimension and other physical properties of aggregates only and was implemented via the original Richardson–Zaki drag equation to account for the aggregate structure in the overall settling model. This approach minimizes the dependence on experiments for simulating settling rates and depends on initial WD/DS/PA properties only.

2. Theoretical

2.1. The Eulerian granular multiphase model

In this work, the Eulerian multiphase granular model was applied to model the aggregates settling in solvent. In the model, the two phases are treated as interpenetrating continua by incorporating the concept of phase volume fractions. The model solves a set of momentum and continuity equations for each phase. For granular flow, the solids or aggregates dynamics and physical properties such as solids pressure, bulk and shear viscosity, radial distribution function and granular temperature are obtained by applying kinetic theory. The equations of continuity and momentum conservation of liquid and solids phase are given in the following sections. Also, the equations of kinetic theory for granular flow are shown in Eqs. (1)–(3).

2.2. Continuity and momentum conservation equations

The volume fraction balance equation is ($q = L, S$)

$$V_q = \int_V \alpha_q dV. \quad (1)$$

The mass conservation equation is

$$\frac{\partial(\alpha_q \rho_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0. \quad (2)$$

The momentum conservation equation is

$$\begin{aligned} \frac{\partial(\alpha_q \rho_q \vec{v}_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \vec{v}_q \vec{v}_q) \\ = -\alpha_q \nabla P + \nabla \cdot \bar{\tau}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^n (\vec{R}_{pq}). \end{aligned} \quad (3)$$

$\vec{R}_{pq}$ is the interaction force between the two phases. In this work, only drag force was considered.

2.3. Phenomenological description of settling process

Bitumen aggregate concentrations of ~40% and higher tend to settle in “hindered settling” mode in which all solids, irrespective of their size, tend to settle at the same rate due to the close proximity of the particles. The solids or aggregates, thus settle to a smaller volume leaving a layer

of supernatant above separated by a sharp interface. Kynch [7] reported that the hindered settling behavior is only a function of the concentration of solids and that the aggregates swarms move downward and a compacted zone moves upwards from the base of the settling column until it reaches the upper surface of the consolidating solids. As the solids settle and their concentration in the settled zone increases, the inflection point for hindered settling is eventually reached and the settling rate slows down as the aggregates settle on top of each other and compact under their own weight. At this point, the column consists of two layers: (1) aggregates settled over each other with the voids or interstitial spaces filled with liquid (oil) and (2) a supernatant or clear liquid (oil) above the aggregates. Each layer is separated by a sharp interface. Compaction or compression settling begins at this point and the aggregates can be expected to release liquid from the interstitial spaces between the aggregates due to their resultant weight. The compaction of aggregates can be modeled by the effective solids pressure and physical properties of the solids.

The settling process is thus modeled as a two-step process: (1) hindered settling and (2) compression settling. In Part I, the hindered settling behavior has been studied in detail for bitumen aggregates.

2.4. Simulation of hindered settling of aggregates

The hindered settling process for the WD/DS/PA aggregates in solvent diluted bitumen can be modeled well by the Kynch theory of kinematic sedimentation as discussed by Long et al. [1,2]. The settling flux can be determined by the generalized settling rate model or the Richardson–Zaki approximation [3]. The Richardson–Zaki approximation with the exponent terms proposed by Long et al. [2] and the Syamlal–O’Brien model [4] were implemented in fluent computational fluid dynamics (CFD) Software via the interphase exchange or drag terms.

2.5. Interphase exchange terms

In general, drag force acting on a particle in fluid–solids system can be represented by the product of momentum transfer coefficient, K_{LS} , and the slip velocity, $(\vec{v}_L - \vec{v}_S)$, between the two phases

$$f_{\text{drag}} = K_{LS}(\vec{v}_L - \vec{v}_S). \quad (4)$$

Richardson and Zaki proposed the following correlation for the momentum transfer coefficient [3]:

$$K_{LS} = \frac{(\rho_S - \rho_L)\alpha_S g}{v_T(1 - \alpha_S)^{n-2}}, \quad (5)$$

where ρ_S and ρ_L are the density of solids and liquid, respectively. α_S and g are the volume fraction of solids and gravity, respectively. The exponent n is depends on the Reynolds number based on terminal velocity, v_T , of a single particle. For low Reynolds number ($Re_T < 0.2$), n is 4.65.

Syamlal and O'Brien suggested an alternate model of the two phase drag coefficient based on the terminal velocities of particles in fluidized and settling beds in the form [4]

$$K_{LS} = \frac{3\alpha_S \alpha_L \rho_L}{4v_{R,S}^2 d_S} C_D |\vec{v}_S - \vec{v}_L|, \quad (6)$$

where d_S is the diameter of particles. And the drag coefficient, C_D , is expressed by

$$C_D = \left(0.63 + \frac{4.8}{\sqrt{Re_S/v_{R,S}}} \right)^2, \quad (7)$$

$$Re_S = \frac{\rho_L d_S |\vec{v}_S - \vec{v}_L|}{\mu_L}, \quad (8)$$

where $v_{R,S}$ is the ratio of the settling rate of particles to the terminal velocity of a single particle. The expression of $v_{R,S}$ is

$$v_{R,S} = 0.5 \left(A - 0.06 Re_S^m + \sqrt{(0.06 Re_S^m)^2 + 0.12 Re_S^m (2B - A) + A^2} \right),$$

$$A = \alpha_L^{1.28},$$

$$B = \alpha_L^{2.65} (\alpha_L > 0.85), \quad B = 0.8 \alpha_L^{1.28} (\alpha_L \leq 0.85),$$

$$m = \alpha_L + 0.2. \quad (9)$$

These models, however, require a modified experimental exponent or other a priori knowledge of settling experiments for predicting the settling behavior. Hence a model based on initial structure of aggregates was proposed in this work.

2.6. Proposed fractal approach for modeling the aggregate settling process

It has been widely accepted that flocculated aggregates can be represented by fractal structures [5,6]. To represent the fractal structure of aggregates, we introduce the fractal dimension into the model. Masliyah et al. [5] measured the fractal dimension of asphaltene aggregates formed in toluene–heptane solvent mixture by settling experiments and imaging techniques. In this work, the fractal dimension of aggregates was defined and implemented in the Richardson–Zaki drag model.

From Stoke's law, terminal velocity of a single particle is

$$v_T = \frac{g \Delta \rho d_A^2}{18 \mu_L}, \quad (10)$$

$$\Delta \rho = (\rho_E - \rho_L) = (1 - \varepsilon)(\rho_P - \rho_L),$$

where subscripts A and P represent aggregates and primary particles forming aggregates, respectively. ε is the initial porosity of aggregates and expressed by

$$1 - \varepsilon = \frac{NV_P}{V_A} = N \left(\frac{d_P}{d_A} \right)^3, \quad (11)$$

where N is the number of primary particles forming aggregates. N is expressed with the fractal dimension, D , as follows:

$$N = \left(\frac{d_A}{d_P} \right)^D. \quad (12)$$

Combing the above equations, we have

$$\Delta \rho = \left(\frac{d_A}{d_P} \right)^D \left(\frac{d_P}{d_A} \right)^3 (\rho_P - \rho_L), \quad (13)$$

$$v_{T,F} = \frac{g(\rho_P - \rho_L) d_A^2}{18 \mu_L} \left(\frac{d_P}{d_A} \right)^{3-D}. \quad (14)$$

The expression for $v_{T,F}$ can be introduced in Eq. (5) for determining the settling rate and also accounts for the fractal structure of aggregates. As a result of this, the need to vary the Richardson–Zaki exponent, n , is eliminated and only aggregate structure needs to be accounted for by determining the fractal dimension D .

2.7. Kinetic theory of granular flow equations

Due to the high concentrations of aggregates in the settling system, a network or matrix of solids is eventually formed in the suspension that leads to a compression zone and shows a significant compressive yield value. In the compression zone, the suspension can be considered as a network of channels through which the liquid flows upwards resulting in a slow subsidence rate of the interface between the concentrated suspension and the clear liquid. The subsidence rates of the layers of aggregates are controlled by the internal mechanism of consolidation or compaction in the matrix of solids. The characterization of porous beds (formed in compression range suspensions) is accomplished by accounting for the porosity and permeability of fluid through the porous matrix. These two parameters depend on the nature of the initial suspension and the subsequent loading, as determined by the effective pressure of solids. This solids pressure can be established as the pressure from which the structure of particles responds to changes in stress, and consequently is the pressure caused by the un-buoyed weight of solids above the layer considered.

Closure of the solids phase momentum equation requires a description of the solids phase stress. The granular kinetic theory derived by Lun et al. [8] is adopted in this study. Analogous to the granular temperature Θ_s can be introduced as a measure of the particle velocity fluctuations

$$\Theta_s = \frac{1}{3} \langle v_s^2 \rangle. \quad (15)$$

The solids phase stress depends on the magnitude of the particle velocity fluctuation. The granular temperature conservative equation is

$$\begin{aligned} & \frac{3}{2} \left[\frac{\partial(\rho_s \alpha_s \Theta_s)}{\partial t} + \nabla \cdot (\rho_s \alpha_s \vec{v}_s \Theta_s) \right] \\ & = \left(-p_s \bar{I} + \bar{\tau}_s \right) : \nabla \vec{v}_s + \nabla \cdot (k_{\Theta_s} \nabla \Theta_s) - \gamma_{\Theta_s} + \phi_{LS}, \end{aligned} \quad (16)$$

where $\left(-p_s \bar{I} + \bar{\tau}_s \right) : \nabla \vec{v}_s$ is the generation of the energy by solids stress tensor, $k_{\Theta_s} \nabla \Theta_s$ is the diffusion of energy, γ_{Θ_s} is the collisional dissipation of energy,

$$\gamma_{\Theta_s} = \frac{12(1 - e_{ss}^2)g_{0,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \Theta_s^{3/2}, \quad (17)$$

and $\phi_{LS} = -3K_{LS}\Theta_s$ is the energy exchange between fluid and solids phase.

The solids pressure is given by

$$p_s = \alpha_s \rho_s \Theta_s + 2\rho_s(1 + e_{ss})\alpha_s^2 g_{0,ss} \Theta_s, \quad (18)$$

where $g_{0,ss}$ is the radial distribution function expressed by

$$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,max}} \right)^{\frac{1}{3}} \right]^{-1}. \quad (19)$$

The solids bulk viscosity is given as

$$\lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\Theta_s}{\pi} \right)^{\frac{1}{2}}. \quad (20)$$

The solids shear viscosity developed by Gidaspow [9] is as follows:

$$\begin{aligned} \mu_{s,kin} &= \frac{4}{5} \alpha_s^2 \rho_s d_s g_{0,ss} (1 + e_{ss}) \\ &+ \frac{10d_s \rho_s \sqrt{\Theta_s \pi}}{96\alpha_s(1 + e_{ss})g_{0,ss}} \left[1 + \frac{4}{5} g_{0,ss} \alpha_s (1 + e_{ss}) \right]^2. \end{aligned} \quad (21)$$

3. Computational details

Long et al. [2] conducted settling experiments in laboratory columns using bitumen froth and two different aliphatic solvents, a 50/50 by wt light *n*-pentane/*n*-hexane solvent mixture (C5–C6) and a heavier *n*-heptane (C7) solvent at different temperatures, and obtained experimental settling curves. They also analyzed the aggregates structure and properties. The solvent and aggregates properties corresponding to the experimental conditions are shown in Table 1. The CFD model was developed and validated

using experimental results on laboratory scale batch settling columns by Long et al. [2].

The commercial CFD package FLUENT was used to simulate the settling of bitumen aggregates in liquid. The set of governing equations are solved by a finite control volume technique. To model settling columns used by Long et al. [2], two different 2-D symmetric numerical grids have been used. Grids were generated with GAMBIT software and imported into FLUENT CFD software. The grids were structured grids consisting of uniform hexahedral cells. The columns diameter are 44 mm and the height are 0.370 m and 1.15 m, respectively. In the case of the 0.37 m column, 1295 (185 × 7) hexahedral cells were used and in the case of the 1.15 m column 4025 (7 × 575) hexahedral cells were used. The top of the column was set to 101.3 KPa. and modeled as an open column. Liquid and solids phase properties were set according to the experiments described in their work and summarized as liquid and solids phase properties in Table 1. Interphase exchange term was implemented using user defined function (UDF) code in Fluent. The initial volume fraction of solids was patched to the numerical domain and the solution was initialized.

4. Results and discussion

4.1. CFD results of batch froth settling

Figs. 1–4 show the simulation results of two drag models and experimental data reported by Long et al. [2] for four cases that describe the use of C5–C6 and C7 solvents for bitumen froth treatment at 30 °C and 70 °C. In these simulations, the exponent, n , in the Richardson and Zaki approximation are set to the values determined experimentally by Long et al. [2] as shown in Table 2 and hence the simulation results using the Richardson–Zaki approximation are in good agreement with the experimental curves. Syamlal–O’Brien model [4] was also found to be in good agreement for hinder settling with experimental data from the C5–C6 solvent system. However, in the C7 solvent diluted separation, the hinder settling velocities predicted by both models are higher than those of experimental data. This limitation arises since the drag model proposed by Syamlal and O’Brien [4] is based on the settling experiments for rigid spheres. That is, Syamlal–O’Brien drag model does not consider the irregular shape of aggregates

Table 1
Test properties of aggregates and solvent

Solvent	C5–C6	C5–C6	C7	C7
Mixing temperature (°C)	30	75	30	70
Volume fraction of aggregates (–)	0.121	0.121	0.123	0.127
Average effective density of aggregates (kg/m ³)	1015	996	884	868
Average diameter of aggregates (μm)	62	114	56	90
Density of solvent (kg/m ³)	723.8	723.8	740.3	740.3
Viscosity of solvent (Pa s)	0.000812	0.000812	0.000817	0.000817
Average density of primary particles (kg/m ³)	1213	1206	1247	1248
Diameter of primary particles (μm)	10	10	5	5

Fig. 1. Hindered settling curve for C5–C6 solvent diluted bitumen froth treatment at 30 °C – empirical settling data Long et al. and CFD simulation using Long et al. and Syamlal–O'Brien models.

Fig. 2. Hindered settling curve for C5–C6 solvent diluted bitumen froth treatment at 75 °C – empirical settling data Long et al. and CFD simulation using Long et al. and Syamlal–O'Brien models.

and their porosity and permeability that may explain the discrepancy between the experimental settling curves and the simulation results. The Richardson–Zaki approximation shows good agreement for hinder settling rates with experimental data for all four experimental conditions. This is because that the exponent n in the drag correlation used in the simulations was derived experimentally by Long et al. [2] and the exponent indirectly accounts for the aggregate structure. This approach also eliminates the need for a model since the settling process needs to be performed for each experimental and the exponent is valid only for that specific experiment.

Fig. 3. Hindered settling curve for C7 solvent diluted bitumen froth treatment at 30 °C – empirical settling data Long et al. and CFD simulation using Long et al. and Syamlal–O'Brien models.

Fig. 4. Hindered settling data for C7 solvent diluted bitumen froth treatment at 70 °C – empirical settling data Long et al. and CFD simulation using Long et al. and Syamlal–O'Brien models.

Table 2
Table of Richardson–Zaki exponent, n

Solvent	Mixing temperature (°C)	n
C5–C6	30	4.27
C5–C6	75	4.00
C7	30	7.02
C7	70	11.43

The generalized Richardson–Zaki model [3] was originally derived from the experimental data of the fluidization and sedimentation tests of rigid spheres and the exponent was dependent on the particle Reynolds number only. The exponent n is generally 4.65 for low Reynolds number. Therefore, independent of empirical results and solely dependent on the initial simulation conditions, the fractal approach described earlier, was applied in the CFD model. Figs. 5–8 show simulation results of hindered settling with

Fig. 5. Hindered settling data for C5–C6 solvent diluted bitumen froth treatment at 30 °C – empirical settling data Long et al. and CFD simulation using R – Z approximation with fractal dimension for aggregates structure.

Fig. 6. Hindered settling data for C5–C6 solvent diluted bitumen froth treatment at 75 °C – empirical settling data Long et al. and CFD simulation using R – Z approximation with fractal dimension for aggregates structure.

Fig. 7. Hindered settling data for C7 solvent diluted bitumen froth treatment at 30 °C – empirical settling data Long et al. and CFD simulation using R – Z approximation with fractal dimension for aggregates structure.

Fig. 8. Hindered settling data for C7 solvent diluted bitumen froth treatment at 70 °C – empirical settling data Long et al. and CFD simulation using R – Z approximation with fractal dimension for aggregates structure.

the original Richardson–Zaki drag model ($n = 4.65$) and also accounts for the fractal structure. This approach makes the model physically significant as well. The settling curves are validated with experimental data reported by Long et al. [2]. The fractal dimension for each test condition was obtained by calculating the settling velocity from

Table 3
Proposed fractal dimensions of aggregates

Solvent	Mixing temperature (°C)	Fractal dimension D (–)
C5–C6	30	2.7
C5–C6	75	2.7
C7	30	2.1
C7	70	2.4

Eq. (15). The fractal dimensions obtained are based on the solvent used and are shown in Table 3. The fractal dimensions for the C7 solvent system are lower than those of C5–C6 solvent system, suggesting that the porosity of aggregates for C7 solvent system is higher than that of C5–C6 solvent system. The settling curves of these simulations show good agreement with experimental data in hinder settling zone and their inclusion in the model reduces the dependency of experimental variables.

5. Conclusion

By introducing two drag models, Richardson–Zaki model and Syamlal–O’Brien model, into the two-fluid model, the experimental settling rates of solvent diluted bitumen aggregates was simulated by computational fluid dynamics. The drag model by Richardson and Zaki with the exponent n defined by Long et al. from their experimental data showed good agreement with the hindered settling curves, while the drag model by Syamlal and O’Brien showed some deviation from the experimental settling data. The exponents n defined by Long et al. are determined empirically and hence the aggregate structure is accounted for indirectly in the exponent. The limitation in the original Richardson–Zaki approximation, due to its development on sphericity of solids, for this work has been overcome by accounting for the porous and fractal nature of the aggregates. The general exponent n in drag model, suggested by Richardson and Zaki, has been used

with the structure and properties of solids to develop a new settling model that simulates the settling behavior of bitumen froth quite well. The fractal dimensions of C7 solvent system were also found to be lower than those of C5–C6 solvent system. This numerical approach outlines an alternate physically significant approach for predicting settling rates and improving froth settling or intermediate oil sands processing.

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