ATTRITION PREDICTION FOR NEW MATERIALS IN CIRCULATING FLUIDIZED SYSTEMS

Ronald Breault[1], Samuel Bayham[1], Nathan Galinsky[2], Esmail Monazam[1,3]

[1]*National Energy Technology Laboratory, 3610 Collins Ferry Rd, Morgantown, WV, USA 26507-0880*

[2]*Oak Ridge Institute for Science and Education, Morgantown, WV, USA*

[3]*REM Engineering Services, Collins Ferry Rd, Morgantown, WV, USA 26507-0880*

*Email: *Ronald.Breault@netl.doe.gov*

Abstract- Novel technologies for carbon capture and chemical productions utilizing circulating fluidized bed (CFB) reactor configurations have garnered much attention in recent years. An example of these technologies is the chemical looping combustion (CLC) scheme for CO_2 capture. Uncertainty lies in these technologies economic feasibility, which is partially due to the required solids makeup rate. Among other factors, attrition, due to impact and wear, affect the solids makeup rate. Attrition can take place in various locations inside the CFB configuration including: cyclones, risers, fluidized beds, standpipes, and at corners such as L-valves. While models estimating attrition at these locations are available, they require extensive testing in the corresponding unit operation. This work introduces a zero-dimensional order model for estimating the attrition rates in a hematite chemical looping combustion scheme. The initial simple spreadsheet model is used to confirm the capability of predicting the attrition rates. For obtaining the rate of attrition in a configuration, material properties are required including the density (ρ), particle diameter (d_p), hardness (H), and fracture toughness (K_c) as well as attrition coefficients for wear (k) and impact (α). Additionally, flow velocities and solid's mass flow rates within a configuration are known. This allows for a sub-model based on the given configuration, material properties, attrition mechanism, and flows to be called. From this information, the sub-model will calculate and give an estimate on the attrition rate in the unit operation. Sensitivity analysis is also conducted to determine the effect of certain variables on the overall attrition rate.

INTRODUCTION

A circulating fluidized bed (CFB) system contains a fluidized bed that operates at a high entrainment flux of the solids in the bed. Separation of the solids from the carrying gas occurs before reintroduction of the solids to the fluidized bed. CFB systems are a staple in several process industries including catalytic cracking of petroleum, fluidized bed combustion, ore roasting, gasification, etc. Besides these, CFB systems are also used in newer advanced technologies such as chemical looping combustion (CLC) which is designed for CO_2 capture. Separate from traditional combustion techniques, CLC uses oxygen supplied to the fuel via oxygen inside the lattice of a metal oxide also termed an "oxygen carrier." Once the oxygen is depleted in the oxygen carrier through reaction with the carbonaceous fuel, it is circulated to a separate reactor where it can regenerate its oxygen in air.

A challenge facing chemical looping and other technologies implementing a CFB reactor scheme is from attrition of the solids due to high gas and particle velocities that CFB systems exhibit. Attrition is defined as the breakdown of solids in a system whose main design intent is not comminution as defined in the book by British Materials Handling Board (1987). For novel energy technologies, such as chemical looping, attrition is not desired due to a cost associated with replacing the attrited materials that might offset the economic benefits that chemical looping and other novel energy technologies try to obtain. In addition to the mechanical stresses of the movement of oxygen carriers in chemical looping, oxygen carriers also experience stresses caused by high operating temperatures, and chemical stresses undergone by the oxygen carrier during the reduction and oxidation reactions. The thermal and chemical reaction stresses add more propensity for the oxygen carrier to attrit during operation.

Attrition has two primary types: abrasion and fragmentation as discussed by Werther and Reppenhagen (1999). The abrasion mechanism of attrition typically occurs when particles are subjugated to low velocities. Abrasion occurs through the rubbing of a particle along another particle's surface or wall inside a reactor unit. Abrasion results in very fine particles being worn from surface asperities. Assuming mother particles of a given particle size distribution, abrasion gives rise to a bimodal distribution due to the fine particles. At higher velocities, attrition shifts to a fragmentation mechanism. In fragmentation, a mother particle is split into two or more fragments. These fragments are usually not elutriated, unlike the fines produced in abrasion, resulting in change of mean bed particle size which can upset the overall system control and decrease performance of the particles (Lupiàñez et al. 2011). Attrition can occur in several locations in CFB reactors including the fluidized bed reactors, which include both grid jet and bubble attrition, cyclones, risers, standpipes, and flow through L-valves. In addition, attrition of materials is typically determined through experimental testing which is time intensive and costly. Common experimental testing uses three-orifice fluidized beds, jet cup, ASTM, and others. While modelling have been done in several locations of the CFB reactors, they often need experimental results to determine the attrition of materials such as oxygen carriers used in chemical looping applications.

In this work, we take a simple, zero-order spreadsheet model to predict the total attrition in a CFB unit. We use models from the individual locations of the CFB reactor as well as our newly developed models utilizing only the material properties (hardness and fracture toughness) as well as temperature, pressure, and hydrodynamics observed in the locations to estimate attrition in a CFB reactor. Individual models give good correlation to data found in literature leading to an overall approximation of the total particle attrition predicted in different CFB reactor configurations such as chemical looping combustion.

SPREADSHEET MODEL

The developed initial spreadsheet model is used to determine whether predictive modelling can be used to determine the attrition observed in circulating fluidized bed reactors. The model is developed in Microsoft Excel©. The modelling approach (also shown in Fig. 1) first starts with choosing a model configuration will be implemented among the following: fluidized bed (grid jet and bubble attrition), cyclone, riser, standpipe, and L-valves.

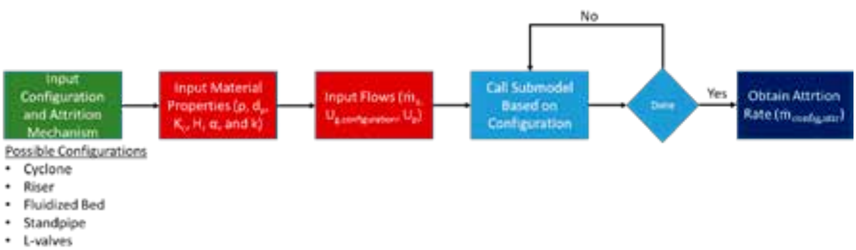

Fig. 1- Model approach to estimating attrition rate in various unit operations based on material properties.

Following the configuration choice, input of material properties which include hardness, fracture toughness, density, particle size, and attrition coefficients will need to be entered. Input flows for the configurations are then added. The spreadsheet is laid out into several sheets: (1) the main flowsheet where data is entered, (2) individual spreadsheets for analysis of each configuration, and (3) a sensitivity analysis. The main flowsheet (as shown in Fig. 2) is where the user will input data needed for the model calculations that include material and gas properties, configuration specifications, and flowrates.

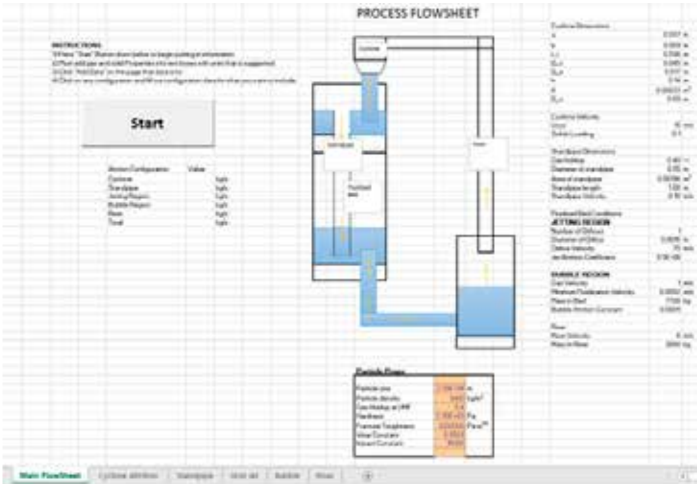

Fig. 2- Screenshot of the spreadsheet main flowsheet. Contains all input information, instructions for running the model, and results. Additional sheets containing individual calculations for each configuration are also shown.

The user inputs this data through a user form after the “Start” button is clicked. The user form is shown in Fig. 3. The form will guide the user through data needed for calculations to be performed. This initial model will only support specific metric units as shown in the user form.

Fig. 3- User form for inputting data for the material properties, gas properties, and information for the various configurations. The values must be in the units specified in parentheses.

Developed predictive models that are programmed (to be discussed below) for each configuration are called, and with the inputs of material properties, temperature, pressure and flows, attrition for the configuration is calculated through the individual configuration sheets and displayed on the main flowsheet. Total attrition will be determined through the summation of the individual configurations as shown in equation (1).

$$\dot{m}_{attr,total} = \dot{m}_{attr,jet} + \dot{m}_{attr,bubble} + \dot{m}_{attr,cyc} + \dot{m}_{attr,riser} + \dot{m}_{attr,sp} + \dot{m}_{attr,valve}$$

(1)

Individual configuration models are developed from previous literature that have shown good correlation with experimental work. The model for standpipe attrition is derived in previous literature by Bayham et al. (2016b) and shown in equation (2):

$$\dot{m}_{attr,sp} = \frac{k}{H}\frac{\rho_s^2(1-\epsilon_g)g}{4f_w}\pi D_s^2 L u_p \tag{2}$$

In the same publication, Bayham et al. (2016b) derived an attrition model for cyclones that fitted with experimental data found in literature and is shown in equation (3):

$$\dot{m}_{attr,cyc} = \frac{2k\dot{m}_s}{HD_c}\left[\left(\frac{\bar{r}_i}{D_c}\right)^2 \frac{\pi\left(D_c^2-D_e^2\right)S}{A}\sqrt{4\left(\frac{\bar{r}_i}{D_c}\right)^2 + \left(\frac{4A}{\pi\left(D_c^2-D_e^2\right)}\right)^2}\right]u_{c,in}^2 \tag{3}$$

To calculate the mass of particles going into the cyclone, the solids loading (μ) is needed. Equation (4) shows the equation for solids loading that relates the loading to the mass flow rate into the cyclone.

$$\mu = \frac{\dot{m}_s}{\rho_g u_{c,in} A} \tag{4}$$

However, this equation is only valid for low velocities, since this equation only describes attrition through wearing of particles. For cyclones with high gas velocities where fragmentation is the primary source of attrition, a previous model developed by Ghadiri and Zhang (2002) will be used (see equation (5)).

$$\dot{m}_{attr,cyc} = \dot{m}_s \alpha \frac{\rho_s d_p u_p^2 H}{K_c^2} \tag{5}$$

Attrition occurring in a fluidized bed falls under two regimes grid jet attrition and bubble attrition. Due to the extremely high velocities encountered in the jetting region of a fluidized bed, grid jet attrition is primarily controlled by impact attrition, while bubble attrition is the rubbing of particles together through wear. Thon and Werther (2009) implemented equations (6) and (7) for the attrition observed in the bubbling and jetting regions, respectively.

$$\dot{m}_{attr,bubble} = m_{bed} C_b (u_g - u_{mf}) \tag{6}$$

$$\dot{m}_{attr,jet} = n_{or} C_j d_p \rho_g d_{or}^2 u_{or}^3 \tag{7}$$

Due to lack of detailed model development for risers, previous literature, as cited by Thon et al. (2011) and Werther and Hartge (2004), estimated attrition in risers can be extrapolated through treatment as a bubbling fluidized bed despite the much higher velocities encountered in the riser. L-valves in the current model are ignored due to lack of model development and previous literature data.

EXAMPLE CASE

The purpose of the spreadsheet model is to be easily predict attrition observed in circulating fluidized bed systems through input of known material properties, flows, temperature and pressure. An example case is discussed in this section based on a hematite/alumina oxygen carrier that is commonly used in chemical looping applications as cited in Galinsky et al. in 2013. Hematite and alumina material properties are readily available in literature and are presented in table 1. Certain properties such as density are estimated from the average values of pure hematite and alumina.

Table 1- Material properties used in spreadsheet model example using a hematite supported with alumina oxygen carrier.

MATERIAL PROPERTIES		
PROPERTY	***VALUE***	***UNITS***
Particle Density (ρ_p)	4600	kg/m^3
Average Particle Size (d_p)	$2.0x10^{-4}$	m
Hardness (H)	$2.89x10^9$	Pa
Wear Coefficient (k)	0.0824	-------
Total Inventory	100	kg

Experimental values for hardness and wear coefficients for pure hematite have been reported in the previous work by Bayham et al. in 2016a and 2016b. Gas properties are assumed based on the gas being pure nitrogen at an average temperature of 900°C in the fluidized bed. A total inventory of 100 kg is chosen for a small scale circulating fluidized bed system, since most experimental data provided rely on small scale experimental data.

Table 2 discusses the flows, dimensions, and specific constants needed for the attrition calculations for the various configurations.

Table 2- Configurational dimensions, flow rates, and specific constants for attrition calculations

Configurational Parameters	
Standpipe	$\epsilon_g = 0.4$ $f_w = 0.2$ $D_s = 0.05m$ $L = 1m$ $k = 0.01$ $u_p = 0.1 - 0.5m/s$
Cyclone	$D_c = 0.045m$ $D_e = 0.017m$ $\bar{r_i} = 0.036m$ $S = 0.14m$ $A = 3.33x10^{-4}m^2$ $k = 0.01$ $\mu = 0.1 - 1$ $u_{c,in} = 5 - 15m/s$
Jetting Region of Fluidized Bed	$d_{or} = 0.0015m$ $C_j = 0.2s^2/m^3$ $u_{or} = 35 - 100m/s$
Bubbling Region of Fluidized Bed	$m_{bed} = 35\ kg$ $C_b = 0.00004m^{-1}$ $u_g = 0.1 - 1m/s$
Riser	$u_{g,riser} = 1.5 - 5m/s$

With the values from Tables 1 and 2, equations (1) – (7) are used to calculate the attrition in each individual configuration. The estimated attrition rates and the total attrition expected under these conditions are shown in Table 3.

Table 3- Attrition rates (kg/s) in the various locations in circulating fluidized beds using the material properties, flows, and specifications of each location as shown in Tables 1 and 2.

CONFIGURATION	VALUE (kg/s)
Standpipe	$3.8x10^{-5}$
Cyclone	$4x10^{-3}$
Jetting Region of Fluidized Bed	$3.6x10^{-3}$
Bubbling Region of Fluidized Bed	$7.4x10^{-4}$
Riser	$1.5x10^{-3}$
TOTAL	$9x10^{-3}$

As can be seen that the main sources of attrition come from the cyclone, jetting region of the fluidized bed, and riser. As discussed in the model discussion, the attrition model for the riser uses highly extrapolated data for the bubbling bed and can be a source of some error in the overall attrition observed. The spreadsheet model can be updated as new attrition models are developed that give more overall accuracy to experimental data.

In addition to calculating the attrition rates for individual locations of CFB systems, sensitivity analysis can be conducted to analyze the effects of various variables on the individual attrition of each configuration. An example of this can be seen from Table 4, where a sensitivity analysis is conducted on the cyclone attrition varying of solids loading (μ) and cyclone velocity ($u_{c,in}$). At higher velocities, the cyclone attrition rate changes from a wear primary mechanism to an impact attrition, so more error may be seen at the higher velocities.

Table 4- Sensitivity analysis on the cyclone attrition rate (kg/s) using varying solid loading and cyclone velocities.

			Cyclone Velocity (m/s)									
	3.98E-03	5	6	7	8	9	10	11	12	13	14	15
Solids Loading	0.1	4.98E-04	8.60E-04	1.37E-03	2.04E-03	2.90E-03	3.98E-03	5.30E-03	6.88E-03	8.75E-03	1.09E-02	1.34E-02
	0.2	9.95E-04	1.72E-03	2.73E-03	4.08E-03	5.80E-03	7.96E-03	1.06E-02	1.38E-02	1.75E-02	2.19E-02	2.69E-02
	0.3	1.49E-03	2.58E-03	4.10E-03	6.12E-03	8.71E-03	1.19E-02	1.59E-02	2.06E-02	2.62E-02	3.28E-02	4.03E-02
	0.4	1.99E-03	3.44E-03	5.46E-03	8.15E-03	1.16E-02	1.59E-02	2.12E-02	2.75E-02	3.50E-02	4.37E-02	5.37E-02
	0.5	2.49E-03	4.30E-03	6.83E-03	1.02E-02	1.45E-02	1.99E-02	2.65E-02	3.44E-02	4.37E-02	5.46E-02	6.72E-02
	0.6	2.99E-03	5.16E-03	8.19E-03	1.22E-02	1.74E-02	2.39E-02	3.18E-02	4.13E-02	5.25E-02	6.56E-02	8.06E-02
	0.7	3.48E-03	6.02E-03	9.56E-03	1.43E-02	2.03E-02	2.79E-02	3.71E-02	4.82E-02	6.12E-02	7.65E-02	9.41E-02
	0.8	3.98E-03	6.88E-03	1.09E-02	1.63E-02	2.32E-02	3.19E-02	4.24E-02	5.50E-02	7.00E-02	8.74E-02	1.07E-01
	0.9	4.48E-03	7.74E-03	1.23E-02	1.83E-02	2.61E-02	3.58E-02	4.77E-02	6.19E-02	7.87E-02	9.83E-02	1.21E-01
	1	4.98E-03	8.60E-03	1.37E-02	2.04E-02	2.90E-02	3.98E-02	5.30E-02	6.88E-02	8.75E-02	1.09E-01	1.34E-01

CONCLUSION

A major challenge facing novel energy technologies utilizing circulating fluidized bed systems is attrition of the solid materials. Attrition affects the overall economics of the process and can be detrimental for implementation. Attrition of materials are usually determined through extensive experimental testing. Predictive modelling of attrition is highly desired to help determine whether certain materials in a system will be commercially viable. Attrition can occur in various locations of circulating fluidized bed systems including risers, standpipes, cyclones, jetting regions in fluidized beds, bubbling regions in fluidized beds, and valves (such as rotary and L-valves). This work presents a spreadsheet model for predicting attrition in these different locations by using already developed predictive models for these locations. The model contains 3 main sections: (1) the main process flowsheet for data input and results, (2) individual attrition calculations for each configuration, and (3) sensitivity analysis for certain parameters. An example case is presented using literature data based on hematite and alumina properties a commonly used oxygen carrier utilized in chemical looping.

ACKNOWLEDGEMENTS

This research was supported in part by an appointment to the National Energy Technology Laboratory Research Participation Program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education.

DISCLAIMER

This project was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government, through a support contract with URS Energy & Construction, Inc. Neither the United States Government nor any agency thereof, nor any of their employees, nor URS Energy & Construction, Inc., nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the

United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTATION

A	Area of tangential cyclone inlet (m^2)
C_b	Attrition rate constant for bubble-induced attrition (m^{-1})
C_j	Attrition rate constant for jet region (s^2/m^3)
D_c	Cyclone barrel diameter (m)
D_e	Vortex finder diameter (m)
d_p	Average particle diameter (m)
d_{or}	Orifice diameter (m)
D_s	Standpipe diameter (m)
f_w	Particle-wall friction coefficient (--)
g	Acceleration due to gravity (9.8 m/s^2)
H	Hardness (Pa)
k	Wear coefficient constant from Archard's Law(--)
K_c	Fracture Toughness ($Pa \cdot m^{0.5}$)
L	Length of standpipe (m)
m_{bed}	Mass in the bed of the reactor (kg)
$\dot{m}_{attr,i}$	Rate of attrition in a configuration (kg/s)
$\dot{m}_s$	Solids mass flow rate in the cyclone (kg/s)
n_{or}	Number of orifices in multi-hole gas distributor (--)
$\bar{r}_i$	Cyclone dimension for velocity calculation (m)
S	Barrel height (m)
$u_{c,in}$	Gas velocity into the cyclone (m/s)
u_g	Superficial gas velocity (m/s)
u_{mf}	Minimum fluidization velocity (m/s)
u_{or}	Orifice velocity (m/s)
u_p	Particle velocity (m/s)
α	Impact attrition constant (--)
ε_g	Gas hold-up (--)
ρ_g	Gas density (kg/m^3)
ρ_p	Particle density (kg/m^3)
μ	Solids loading in cyclone (--)

REFERENCES

Bayham, S., Breault, R., Monazam, E. 2016a. Particulate Solid Attrition in CFB Systems – An Assessment for Emerging Technologies. Powder Technology 302, 42-62.

Bayham, S., Breault, R., Monazam, E. 2016b. Applications of Tribology to Determine Attrition by Wear of Particulate Solids in CFB Systems. Powder Technology.

British Materials Handling Board. 1987. Particle Attrition: State-of-the-Art Review. Trans Tech Publications.

Galinsky, N., Huang, Y., Shafiefarhood, A., and Li, F. 2013. Iron Oxide with Facilitated O^{2-} Transport for Facile Fuel Oxidation and CO_2 Capture in a Chemical Looping Scheme. ACS Sustainable Chemistry and Engineering 1, 364-373.

Ghadiri, M. and Zhang, Z. 2002. Impact Attrition of Particulate Solids. Part 1: A Theoretical Model of Chipping. Chemical Engineering Science 57, 3659-3669.

Lupiàñez, C., Scala, F., Salatino, P., Romeo, L.M., and Dìez, L.I. Primary fragmentation of Limestone Under Oxy-firing Conditions in a Bubbling Fluidized Bed. Fuel Processing Technology 92, 1449-1456.

Thon, A. and Werther, J. 2010. Attrition Resistance of a VPO catalyst. Applied Catalysis A: General 376, 56-65.

Thon, A., Püttmann, A., Hartge, E.U., Heinrich, S., Werther, J., Patience, G. S., and Bockrath, R. E. 2011. Simulation of Catalyst Loss from an Industrial Fluidized Bed Reactor on the Basis of Labscale Attrition Tests. Powder Technology 214, 21-30.

Werther, J. and Reppenhagen, J. 1999. Attrition in Fluidized Beds and Pneumatic Conveying Lines. Fluidization, Solids Handling, and Processing. William Andrew Publishing.

Werther, J. and Hartge, E.U. 2004. A Population Balance Model of the Particle Inventory in a Fluidized-Bed Reactor/Regenerator System. Powder Technology 148, 113-122.