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Improved gas-solid mixing and mass transfer in a pulsed fluidized bed of biomass with tapered bottom

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Improved Gas-solid Mixing and Mass Transfer in a Pulsed Fluidized Bed with a Tapered Bottom Section

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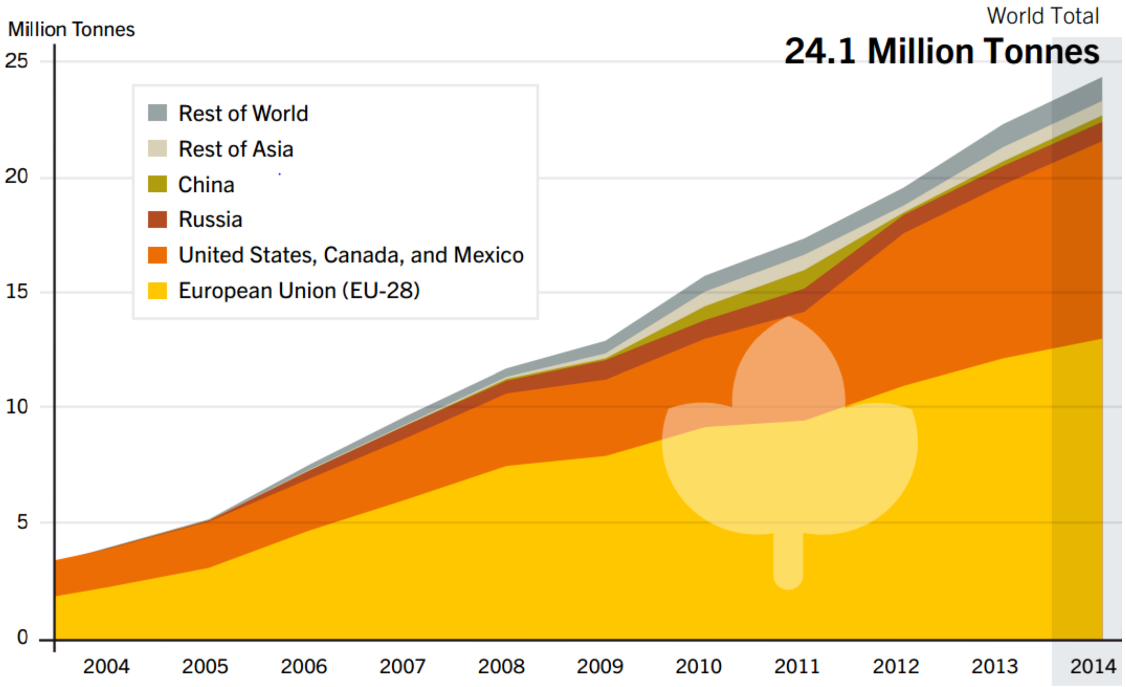
a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

Faculty of Applied Science
Department of Chemical and Biological Engineering

1.1 Biomass in BC

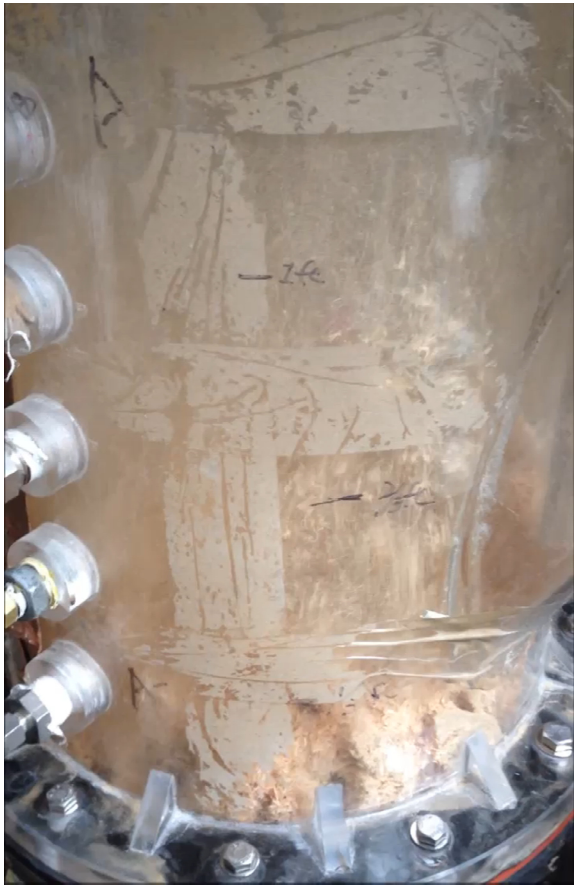
- Biomass is a sustainable energy source, 24.1 million tonnes of wood pellets produced and transported in 2014 [1]
- In BC only 2 Mt/year of biomass are made into pellets, while a shockingly 32 Mt/year biomass residue available
- Biomass resource in BC has the potential of replacing more than half of fossil fuel



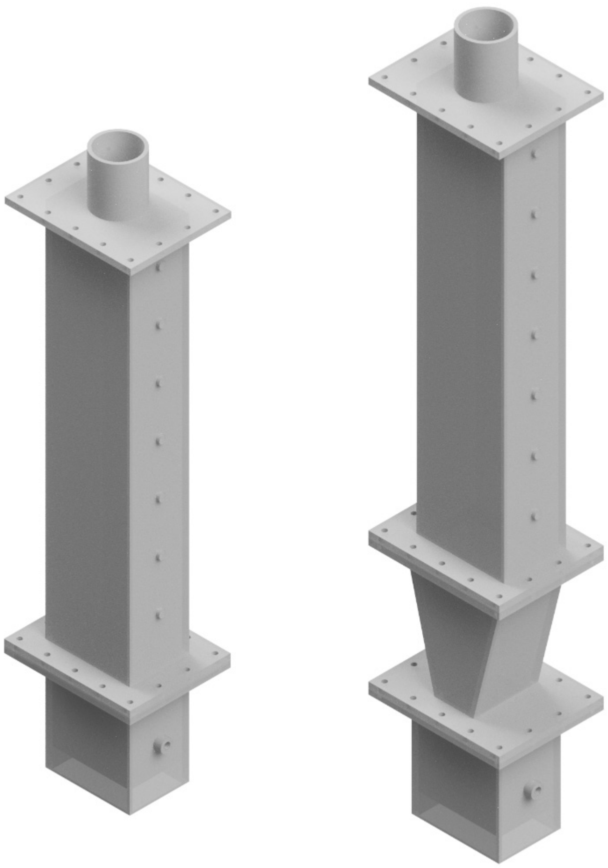
[1] Secretariat R. Renewables Global Status Report. Paris: REN21; 2015.

1.2 Unconventional Properties of Biomass

- Drying, torrefaction and pyrolysis are essential biomass conversion operations
- Fluidized bed is suitable due to high heat/mass transfer rate and ease of scale-up
- Issues associated with biomass:
  - high moisture content
  - irregular shape
  - low bulk density
  - wide particle distribution
- Difficult to fluidize: strong interparticle forces cause channeling, bypassing, partial and full defluidization
- Bed material (e.g. sand) increases ash content and contaminates solid biofuel
- Pulsation, vibration, sonication, magnetic/eclectic field, new distributors are all possible solutions



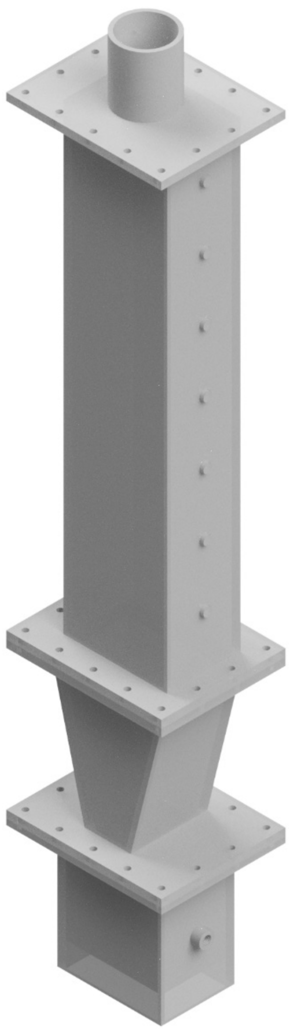
1.3 Research Objective

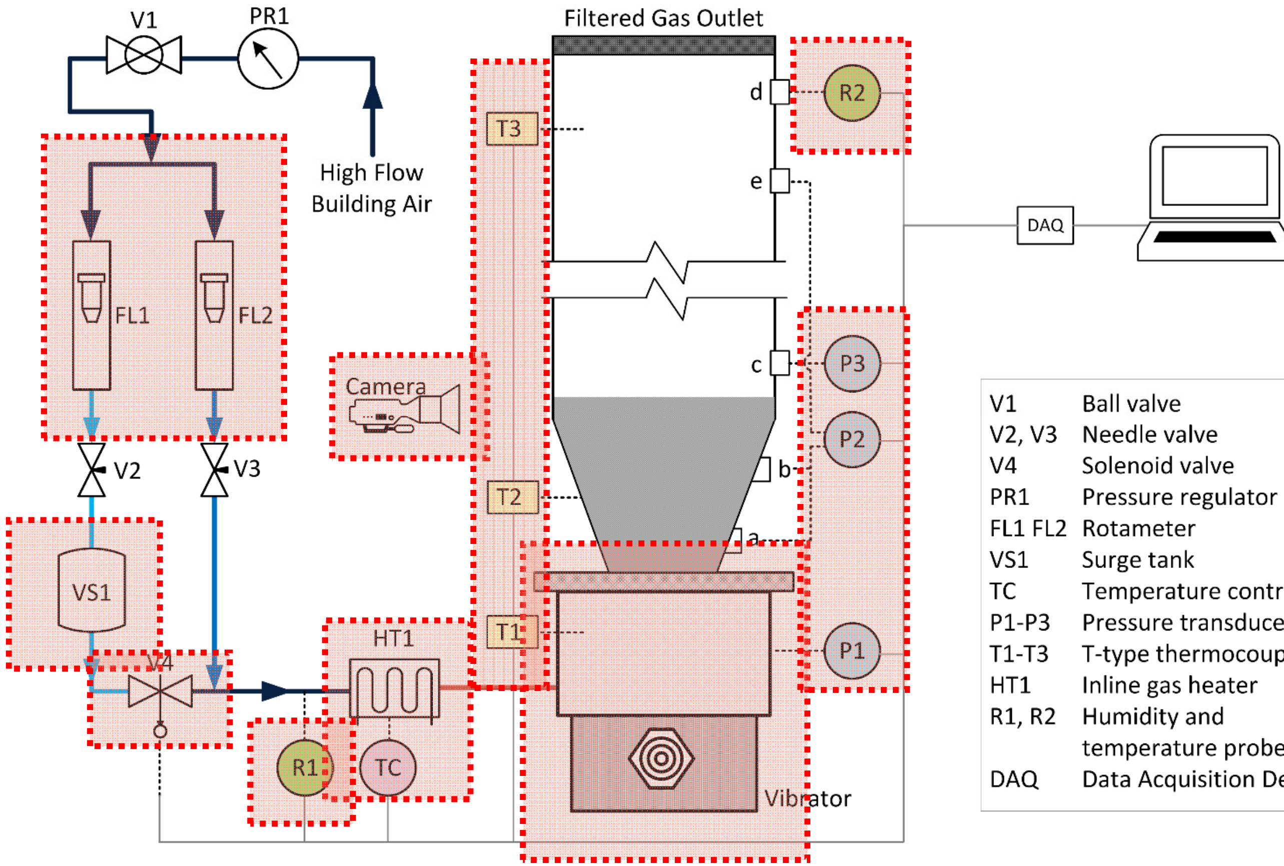


- 15cm x 10cm pulsed gas fluidized bed
- Significantly improved mixing and heat/mass transfer [1]
- Dead zones discovered at the bottom
- A tapered section inserted, to further improve reactor performance
- Drying tests as benchmarks to evaluate performance against original design
- Key parameters investigated including,
  - gas flow rate
  - pulsation frequency
  - Initial bed height
- A simple mathematical model

[1] D. Jia, O. Cathary, J. Peng, X. Bi, C.J. Lim, S. Sokhansanj, Y. Liu, R. Wang, A. Tsutsumi, Fluidization and drying of biomass particles in a vibrating fluidized bed with pulsed gas flow, Fuel Processing Technology, 138 (2015) 471-482.

1.4 Experimental Setup



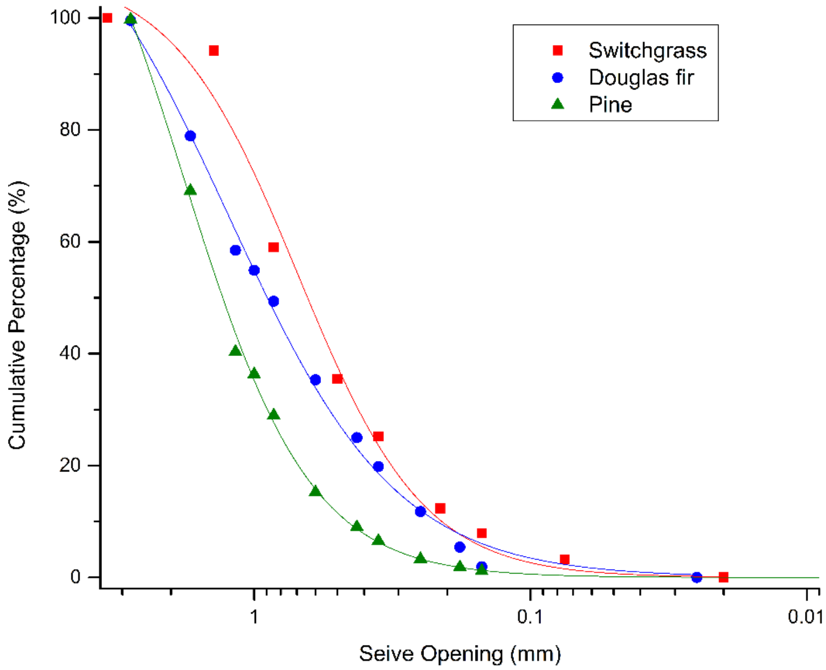


V1	Ball valve
V2, V3	Needle valve
V4	Solenoid valve
PR1	Pressure regulator
FL1 FL2	Rotameter
VS1	Surge tank
TC	Temperature controller
P1-P3	Pressure transducer
T1-T3	T-type thermocouple
HT1	Inline gas heater
R1, R2	Humidity and temperature probe
DAQ	Data Acquisition Device

1.5 Biomass Properties

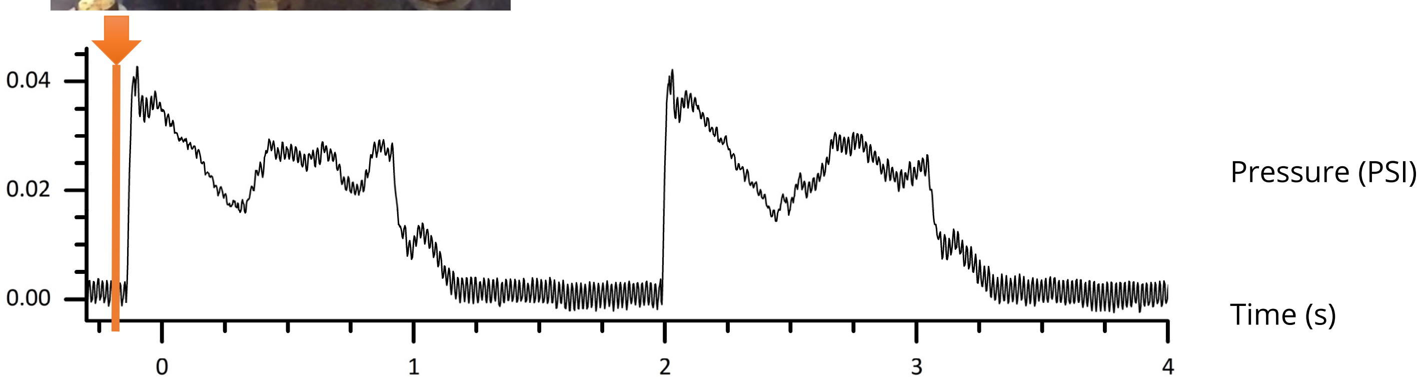
- Three types of biomass particles, including **Douglas-fir**, pine and switchgrass
- Batch drying with 200 g of sample, duration of 30 min
- Sample moisture content determined by oven drying at 103 ℃ for 24 h

Biomass species	Bulk density (7% moisture, d.b), kg/m³	True density, kg/m³	Sauter mean diameter, mm	Sphericity
Douglas-fir	164	1375	1.449	0.42
Pine	139	1242	1.469	0.43
Switchgrass	184	1446	0.755	0.35



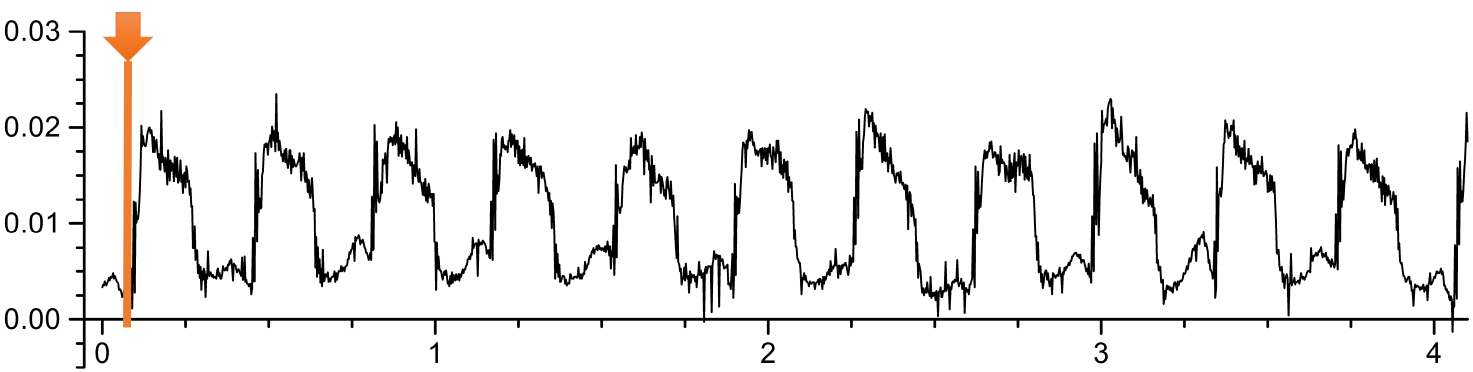
2.1 Pulsed Gas Flow at 0.5 Hz

- Typical pulsed gas-solid flow (1/8x playback)
- Partially fluidized, distinct “ON” and “OFF” period
- Strong pulsation from long pressure build up
- Horizontal layer of slugs above distributor
- Slugs → gas channels
- Acceptable gas-solid flow during “ON” period, long dormant “OFF” period
- Largest amplitude of bed expansion
- Dampened pressure oscillations, 5+ peaks observed, $f < f_N$



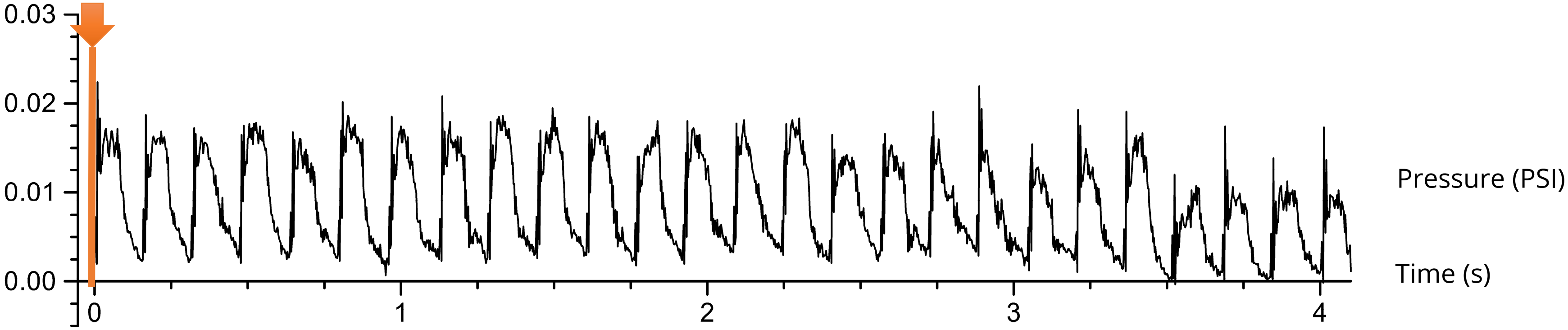
2.2 Pulsed Gas Flow at 3.0 Hz

- OFF period starts to disappear
- Less bed expansion and particle entrainment
- Horizontal slugs quickly splits into large bubbles as opposed to gas channels
- Barely visible pressure oscillation peaks on the pressure profile
- System becomes more ordered as a result of pulsation.

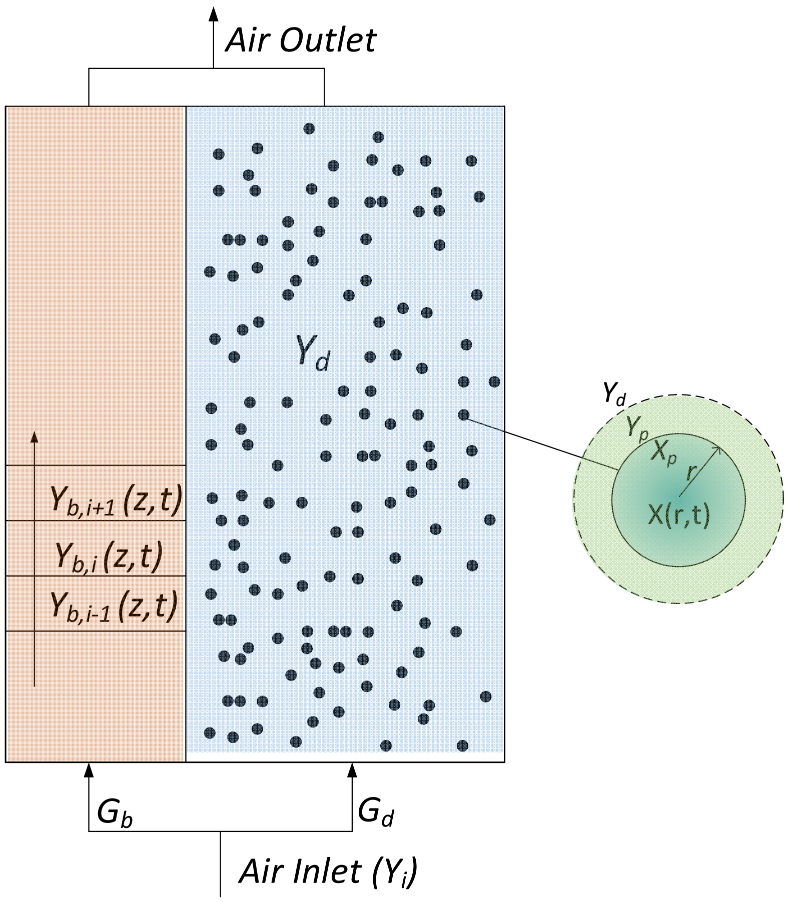


2.3 Pulsed Gas Flow at 6.67 Hz

- Pulsed fluidized bed starts to mimic a conventional system
- Horizontal slugs quickly splits and give rise to bubbles
- Faster gas renewal and less excessive gas leads to the reduction in bubble size, bed expansion and entrainment
- Offer better gas solid contact compared to lower *f*, but requires higher flow rates to avoid channelling and lateral segregation.

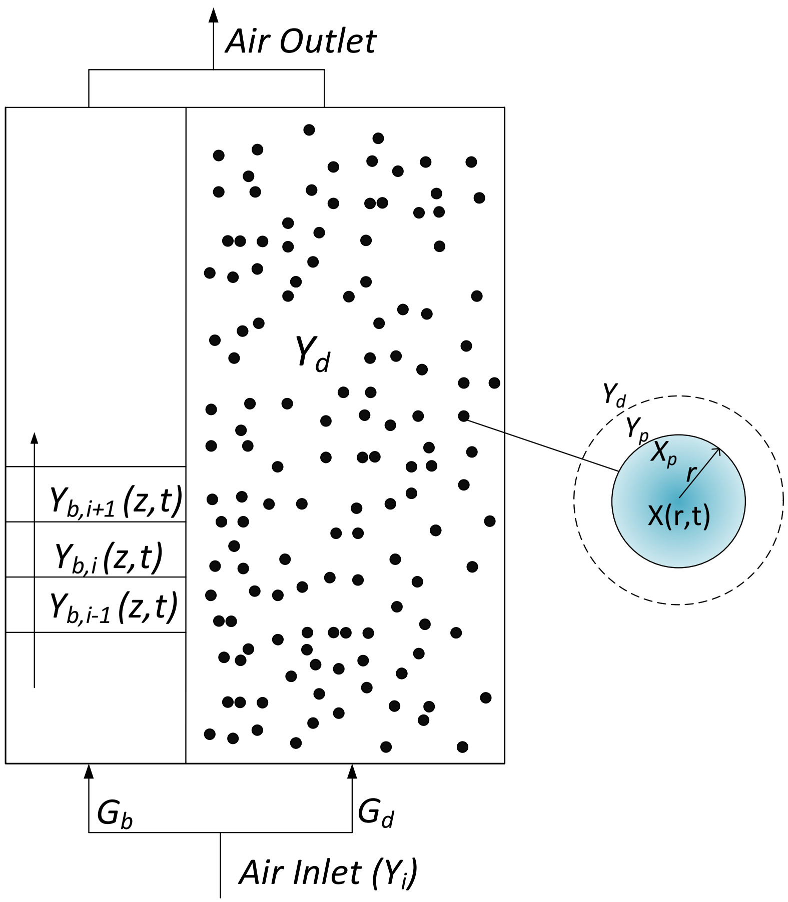


3.1 Two-phase Drying Model: Basics



- Coupled fluidized bed hydrodynamics with drying kinetics
- 3 mass transfer steps:
  - Internal moisture transport in biomass particles
  - Particle-to-gas convective mass transfer in interstitial gas
  - Interstitial gas and bubbles
- Basic assumptions to name a few,
  - Bubbling regime in the bed
  - Particles are spherical, isotropic and identical in size
  - Particles are well mixed (CSTR)
  - Interstitial gas is stagnant (uniform composition)
  - Bubbles are in plug-flow
  - No solids associated with bubbles

3.2 Two-phase Drying Model: Equations



- Liquid moisture travelling through solid particle due to concentration gradient, described by Fick's law,

$$\frac{\partial X(r,t)}{\partial t} = D_{eff}\left(\frac{\partial^2 X}{\partial r^2} + \frac{2}{r}\frac{\partial X}{\partial r}\right)$$

  - Initial condition: $t = 0,\ 0 \le r \le R_p,\ X = \bar{X} = X_0$
  - Boundary condition 1: $t > 0,\ r = 0,\ \frac{\partial X}{\partial r} = 0$
  - B.C.2: $t > 0,\ r = R_p,\ -D_{eff}\frac{\partial M}{\partial r} = K_i(Y_p - Y_d)$

- Macroscopic mass balance on interstitial gas,

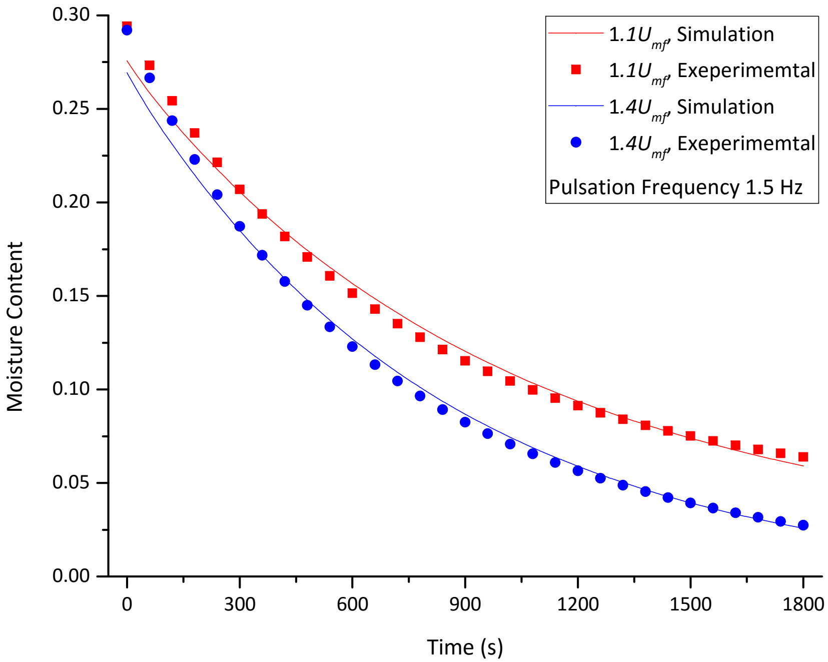
$$\frac{6K_c\rho_g\varepsilon_b}{d_b}(Y_b - Y_d) - \rho_g G_d(Y_d - Y_i) + \omega = \rho_g\varepsilon_{mf}(1-\varepsilon_b)\frac{dY_d}{dt}$$

- Bubble phase,

$$\rho_g\varepsilon_b\frac{\partial Y_b}{\partial t} + \rho_g\varepsilon_b\frac{\partial}{\partial z}(Y_b U_b) + \rho_g G_b(Y_b - Y_i) = \frac{6K_c\varepsilon_b}{d_p}(Y_d - Y_b)$$

- Experimental data fitted to model to obtain $D_{eff.}$
- Finite element method utilized to solve PDEs.

3.3 Two-phase Drying Model: Effect of Flow Rate

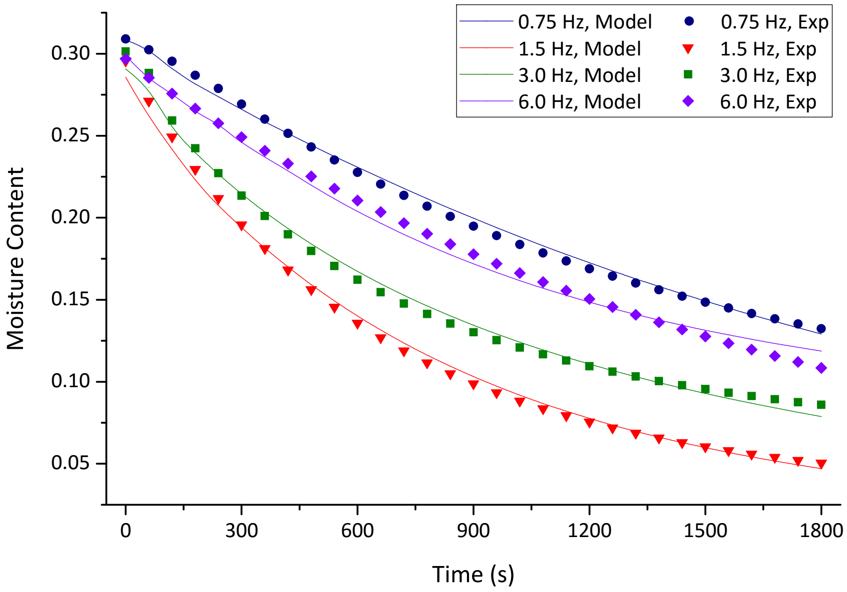


- Drying curve at different flow rate with satisfying agreement
- Higher flow rate leads to faster drying
- D_{eff} independent of flow rate, average 7.4×10^{-9} m^2/s
- 25% higher mass transfer performance compared to original design (5×10^{-9} m^2/s)
- Calculated D_{eff} are of the same order of magnitude as literature reported values [1-3]
- Model is capable of capturing drying/mass transfer

Average Gas Flow rate (U/U_{mf})	Effective Diffusivity in tapered design (m^2/s)	Coefficient of Determination (R^2)	Moisture Removed	D_{eff} in original design
1.1	7.320×10^{-9}	0.9888	78.3%	5.1833×10^{-9}
1.2	7.591×10^{-9}	0.9970	81.7%	5.0002×10^{-9}
1.4	7.305×10^{-9}	0.9854	90.6%	5.1753×10^{-9}

[1] D.Y. Chen, X. Liu, X.F. Zhu, A one-step non-isothermal method for the determination of effective moisture diffusivity in powdered biomass, Biomass Bioenerg., 50 (2013) 81-86.
[2] D. Chen, Y. Zheng, X. Zhu, Determination of effective moisture diffusivity and drying kinetics for poplar sawdust by thermogravimetric analysis under isothermal condition, Bioresource Technology, 107 (2012) 451-455.
[3] H. Resch, H. Kang, M.L. Hoag, DRYING DOUGLAS-FIR LUMBER - A COMPUTER-SIMULATION, Wood and Fiber Science, 21 (1989) 207-218.

3.4 Two-phase Drying Model: Effect of Pulsation



Pulsation Frequency (Hz)	Effective Diffusivity (m^2/s)	Coefficient of Determination (R^2)
0.75	6.735×10^{-9}	0.9978
1.5	**7.467×10^{-9}**	0.9926
3.0	7.232×10^{-9}	0.9943
6.0	4.993×10^{-9}	0.9953

- Fastest drying and mass transfer observed at f=1.5Hz
- Corresponding D_{eff} =7.47×10^{-9} m^2/s, quickly decreases as f moves away from 1.5 Hz
- Variations in D_{eff} : Influence of pulsation on hydrodynamics (e.g. bubble size/rise velocity, bed expansion) not properly addressed in above model
- Indicator of mass transfer rate, highest heat/mass transfer rate at 1-3 Hz,
  - Resonance effect close to natural frequency
  - Stronger pulsation to break up cohesive forces
  - Relatively short intermittence
  - Regular bubbles instead of slug chains and channels

CONCLUSION AND FUTURE WORKS

- Inserted tapered bottom section improved gas-solid mixing and heat/mass transfer
- 1 Hz ~ 3 Hz pulsation with 1.1-1.3 U_{mf} gas flow offer satisfying gas-solid mixing for most biomass particles investigated
- D_{eff} at different flow rate verified drying model, D_{eff} at different pulsation frequency reflected effect of pulsation on mass transfer
- Bed-to-wall heat transfer in fluidized beds of biomass is greatly needed for design and scale-up of biomass reactors, which also allows better understanding of the complex gas-solid flow in such systems.

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and

THANK YOU

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