Modeling and Experimental Study of Rotary Kilns equipped with Lifters

Alex BONGO NJENG

Dimensional Analysis

08-03-16

Introduction

Research Work

JLD

MINES Albi-Carmaux

RAPSODEE Centre

&

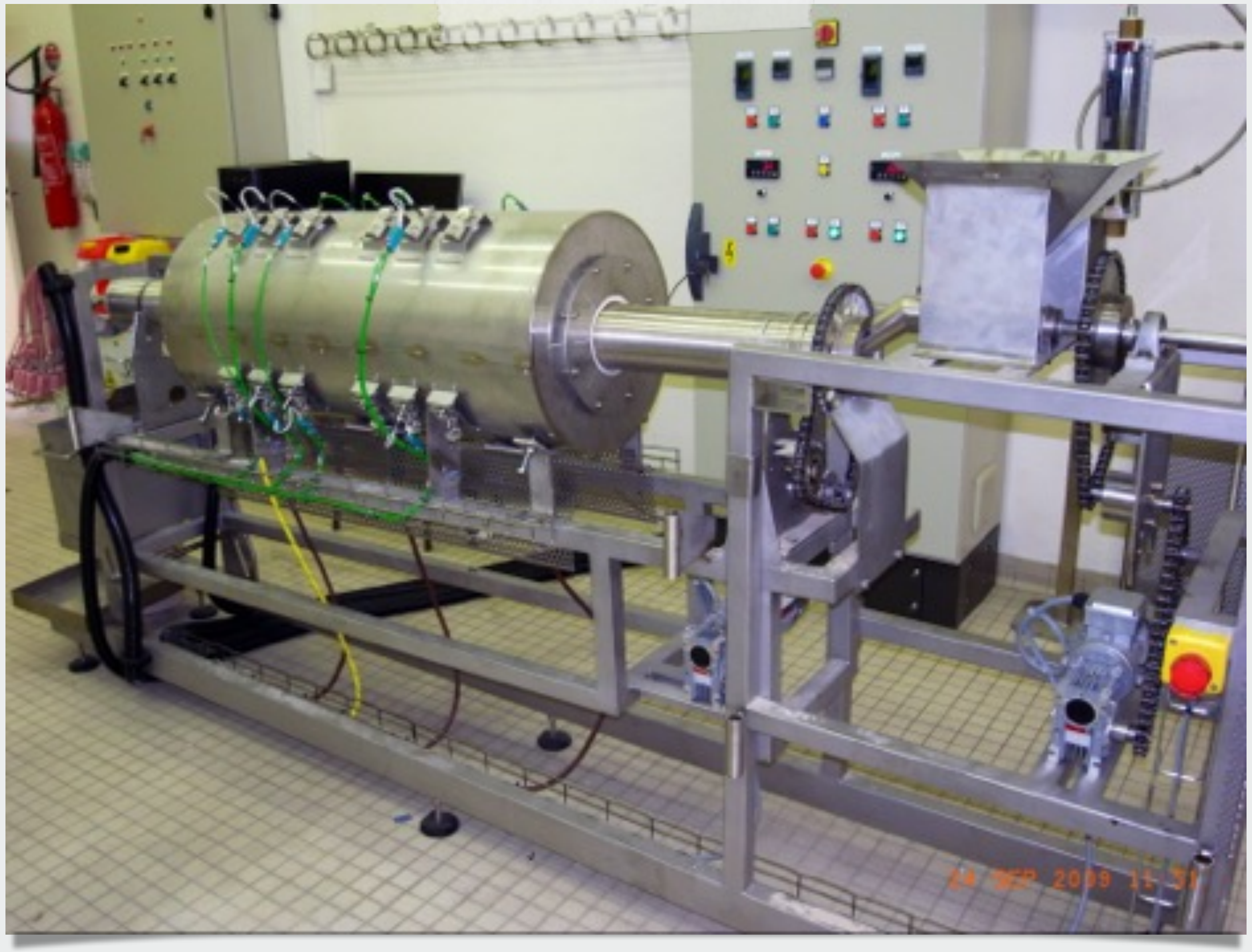
MD

SV

MC

le cnam

CMGPCE Laboratory

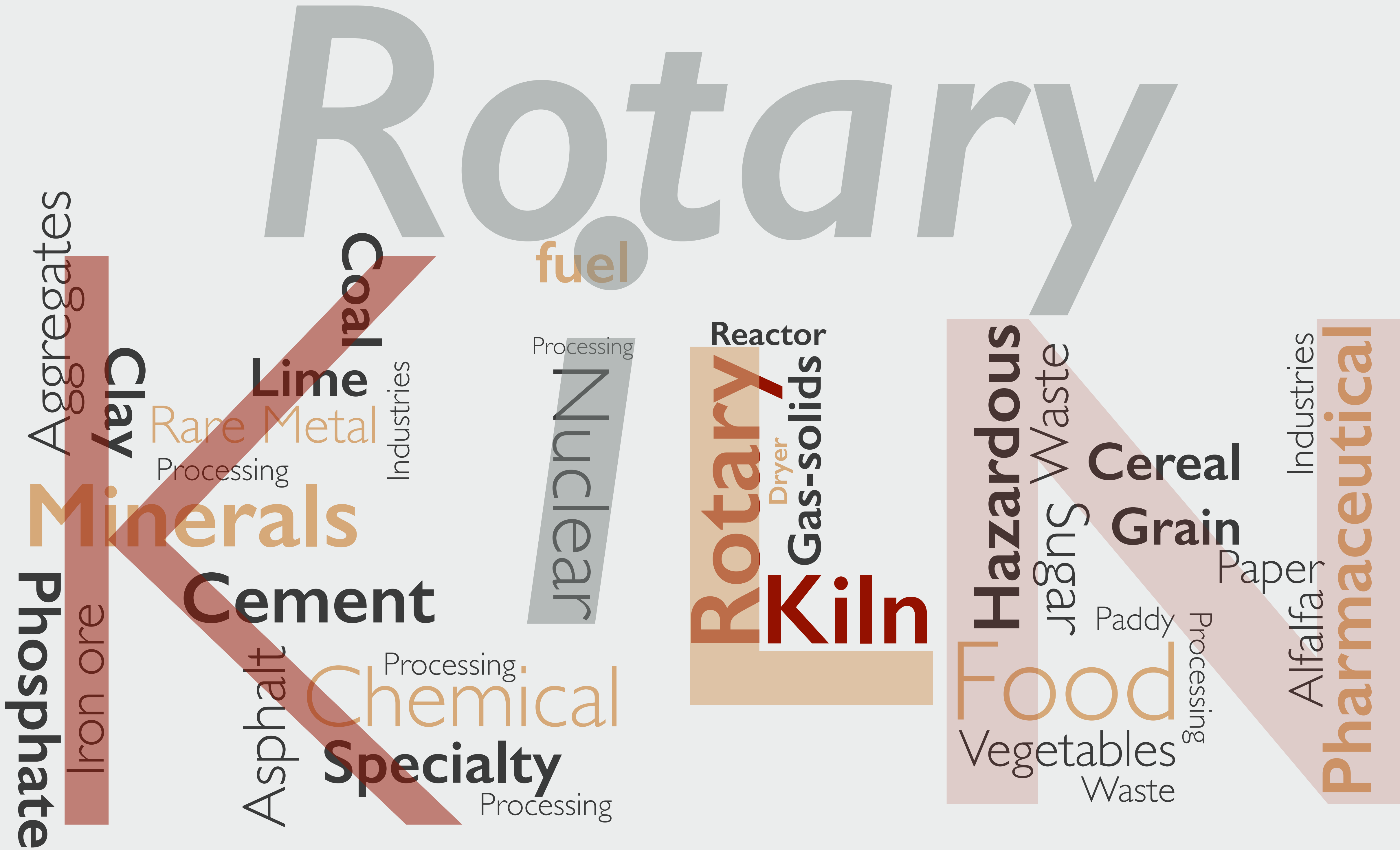


Mines Albi - Centre RAPSODEE
4 m in length

CNAM - LGP2ES
2 m in length

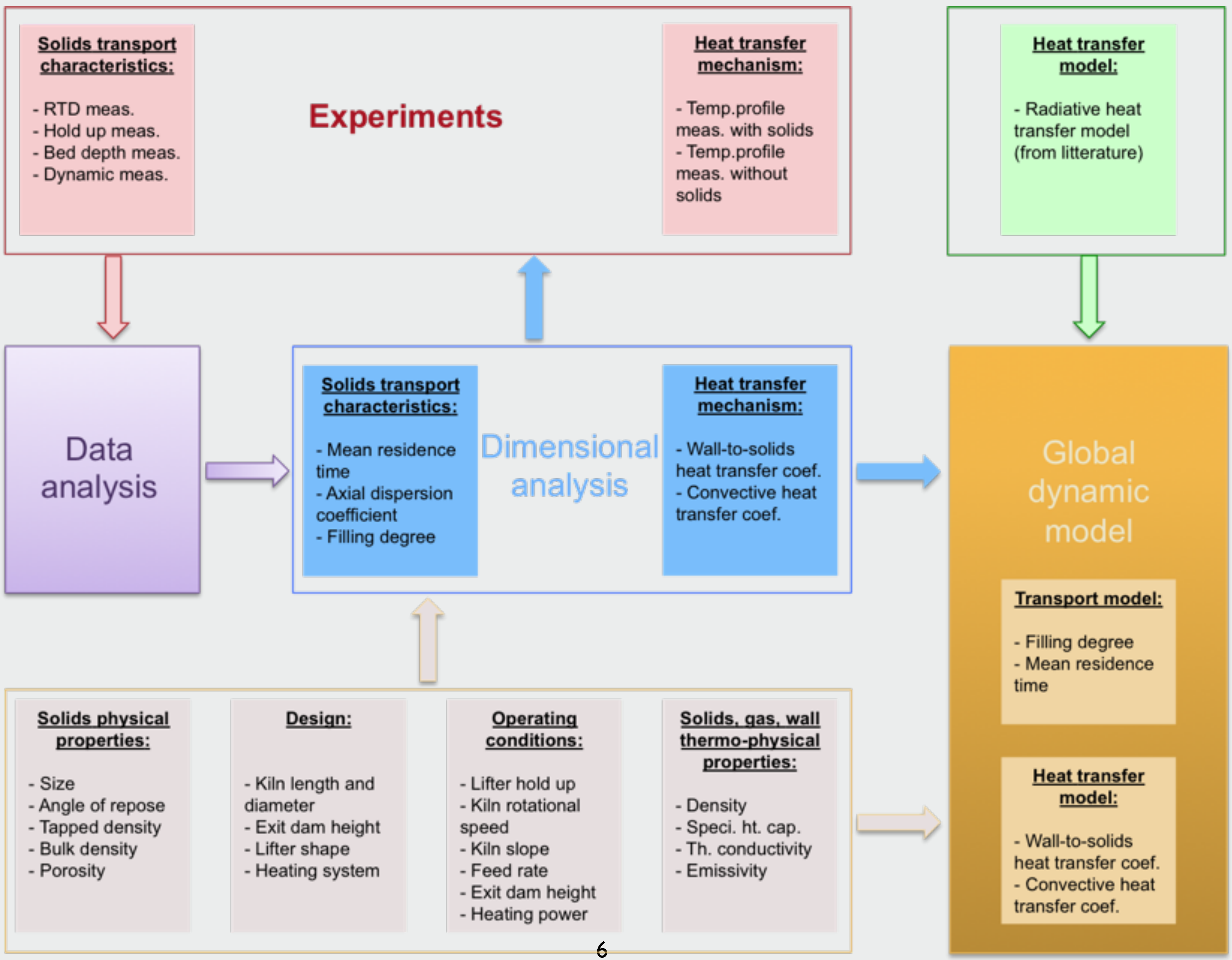
Experimental Setups

Background



Rotary
fuel
Aggregates
Clay
Coal
Lime
Rare Metal
Industries
Processing
Minerals
Cement
Phosphate
Iron ore
Asphalt
Processing
Chemical
Specialty
Processing
Processing
Nuclear
Reactor
Rotary
Dryer
Gas-solids
Kiln
Hazardous
Waste
Cereal
Sugar
Grain
Paper
Paddy
Processing
Food
Vegetables
Waste
Industries
Alfalfa
Pharmaceutical

Research Methodology



Dimensional Analysis: summary

- Modeling of the flow characteristics of solids materials within continuously fed rotary kilns equipped with lifters:
    - Mean Residence Time,
    - Hold-Up,
    - Axial Dispersion Coefficient,
- Modeling of the heat transfer mechanisms in continuously fed rotary kilns equipped with lifters:
    - Convective heat transfer Coefficient (wall-to-gas),
    - Wall-to-solid Heat Transfer Coefficient.

Hydrodynamic Characteristics

KEY FACTORS

Main factors to be taken in consideration:

12 variables

- Kiln design: L, Di
- Kiln operating conditions: N, M, S, D_{ex}, S_{lift}
- Solid characteristics: ρ_{bulk}, ρ_{tapped}, θ
- Physical property: g

$$D_{ex} = D_i - 2h_{exit}$$

$$S_{lift} = \frac{\pi D_i^2}{4} - \frac{n_{lift} - 1}{2} S_{horlift}$$

Buckingham's Π Theorem

If there is a physically meaningful equation:

$$F(N,\, \dot{M},\, S,\, D_{ex},\, S_{lift},\, L,\, D_i,\, \rho_{bulk},\, \rho_{tapped},\, \theta,\, g) \cdot \bar{t} = 1$$

involving a certain number r=**12 physical variables**,

then the original equation can be rewritten in terms of

a set of p=r-n=12-4=**8 dimensionless parameters.**

p: number of dimensionless grouping to define
r: number of variables
n: number of fundamental units among the variable

Dimensionless Grouping (ρ_{bulk}, g, L, S)

- Dynamic ratio between inertial and gravitational forces: $\frac{N^2 D_i}{g}$ $\frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}}$
- Solids characteristics: $\frac{\rho_{bulk}}{\rho_{tapped}}$ $\frac{\theta}{S}$
- Geometric ratio: $\frac{L}{D_i}$ $\frac{4S_{lift}}{\pi D_i^2}$ $\frac{D_{ex}}{D_i}$
- Solids transport coefficients: $\frac{\bar{t}}{\sqrt{gL}}$ $\frac{HU[\%]}{\frac{\rho_{bulk} L \pi D_i^2}{4}}$ $\frac{D}{\sqrt{D_i^2 g L}}$

MRT: $$\frac{\bar{t}}{\sqrt{gL}} = F\left[\left(\frac{N^2 D_i}{g}\right), \left(\frac{D_{ex}}{D_i}\right), \left(\frac{\theta}{S}\right), \left(\frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}}\right), \left(\frac{4S_{lift}}{\pi D_i^2}\right), \left(\frac{\rho_{bulk}}{\rho_{tapped}}\right), \left(\frac{L}{D_i}\right)\right]$$

Correlations

$$\bar{t} = \quad k\sqrt{gL}\left(\frac{N^2 D_i}{g}\right)^{\alpha}\left(\frac{D_{ex}}{D_i}\right)^{\beta}\left(\frac{\theta}{S}\right)^{\gamma}\left(\frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}}\right)^{\delta}\left(\frac{4S_{lift}}{\pi D_i^2}\right)^{\epsilon}\left(\frac{\rho_{bulk}}{\rho_{tapped}}\right)^{\zeta}\left(\frac{L}{D_i}\right)^{\eta}$$

$$HU[\%] = k\frac{\rho_{bulk} L \pi D_i^2}{4}\left(\frac{N^2 D_i}{g}\right)^{\alpha}\left(\frac{D_{ex}}{D_i}\right)^{\beta}\left(\frac{\theta}{S}\right)^{\gamma}\left(\frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}}\right)^{\delta}\left(\frac{4S_{lift}}{\pi D_i^2}\right)^{\epsilon}\left(\frac{\rho_{bulk}}{\rho_{tapped}}\right)^{\zeta}\left(\frac{L}{D_i}\right)^{\eta}$$

$$D = \quad k\sqrt{D_i^2 gL}\left(\frac{N^2 D_i}{g}\right)^{\alpha}\left(\frac{d_p}{D_i}\right)^{\beta}(S)^{\gamma}\left(\frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}}\right)^{\delta}\left(\frac{4S_{lift}}{\pi D_i^2}\right)^{\epsilon}\left(\frac{\rho_{bulk}}{\rho_{tapped}}\right)^{\zeta}\left(\frac{L}{D_i}\right)^{\eta}$$

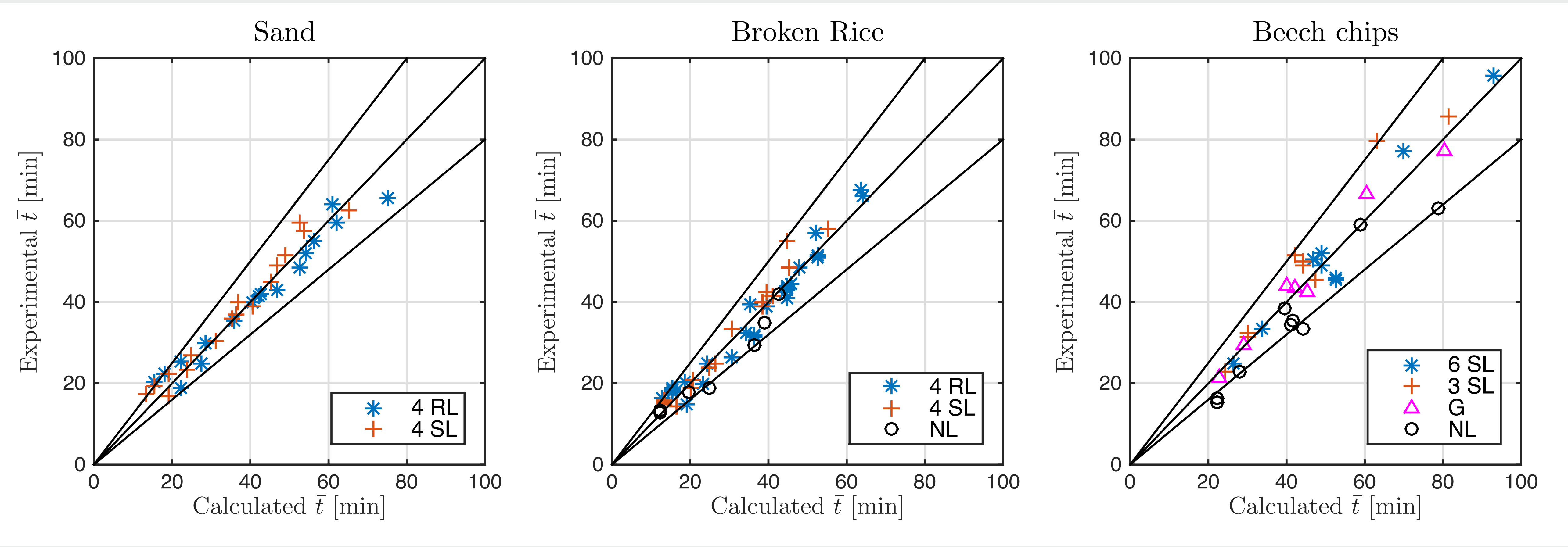
	k	α	β	γ	δ	ϵ	ζ	η[1]
MRT	0,0026	-0.4422	-0.3597	0.9276	-0.1130	-8.8835	2.4641	1.1
HU	45.65	-0.4439	-0.3987	0.7780	0.9584	-3.8197	16763	0
D	-8.92 10-4	0.3033	-0.1362	0.6477	-1.2280	-13809	-4.7868	0

Experimental variables & materials

Parameters	Notation	Order of magnitude	Unit
Kiln length	L	1,95-4	m
Kiln diameter	D	0.1-0.2	m
Rotation speed	N	1-12	rpm
Kiln slope	S	1-5	degree
Mass flow rate	M	0.6-7.5	kg/h
Exit dam height	h	0-33.5	mm
Lifters	SL, RL, NL - 3SL, 6SL		-

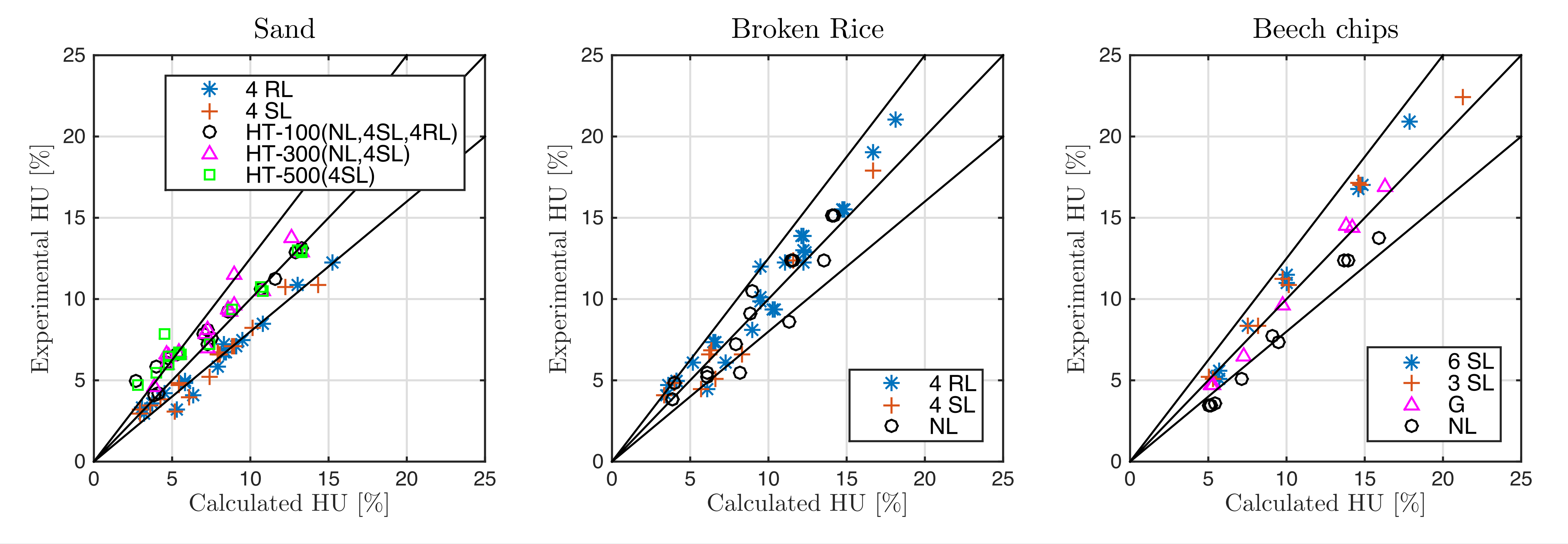
Materials	Bulk density [$kg.m^{-3}$]	Tapped density [$kg.m^{-3}$]	Size [mm]	Repose Angle [°]
Sand	1422	1543	0,55	39
Rice	889	934	3.8*1.9	36
NaCl	1087	1184	0,6	35,4
Dyed rice	889	934	3.8*1.9	36
Beech chips	260	284	10*4.5 *2	42

Mean Residence Time



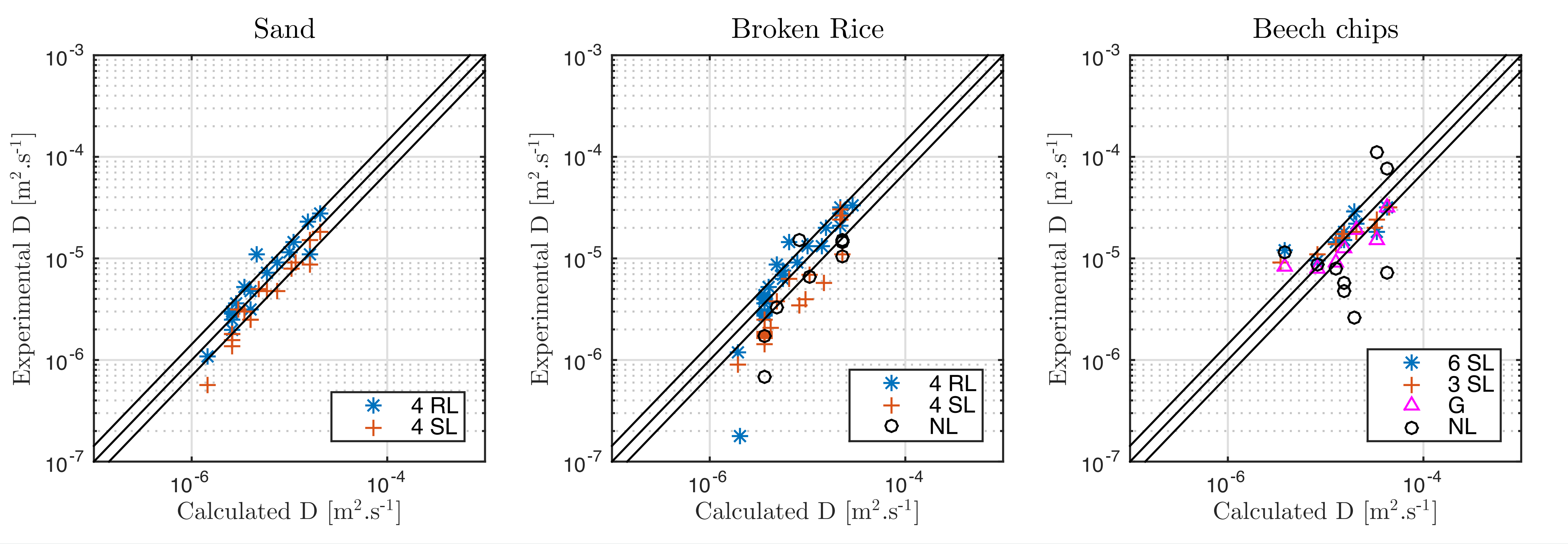
Good agreement within the ±20% margins

FILLING DEGREE



Good agreement within the ±20% margins

AXIAL DISPERSION COEFFICIENT



Good agreement except in cases of slipping motion

Heat Transfer Mechanisms

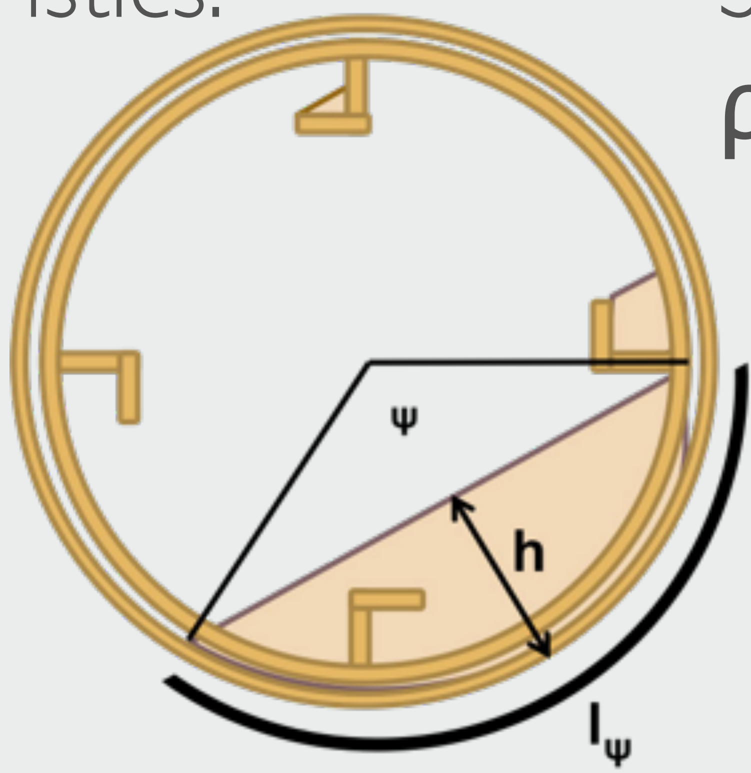
KEY FACTORS

Convective heat transfer:

- Kiln design: D
- Kiln operating conditions: ω, lg, T
- Solid characteristics: ρ_g, μ_g, c_{pg}, k_g

Wall-to-solid heat transfer:

- Kiln design: D
- Kiln operating conditions: ω, l_ψ, T, HU
- Solid characteristics: ρ_b, c_{pg}, k_b



BUCKINGHAM'S Π THEOREM

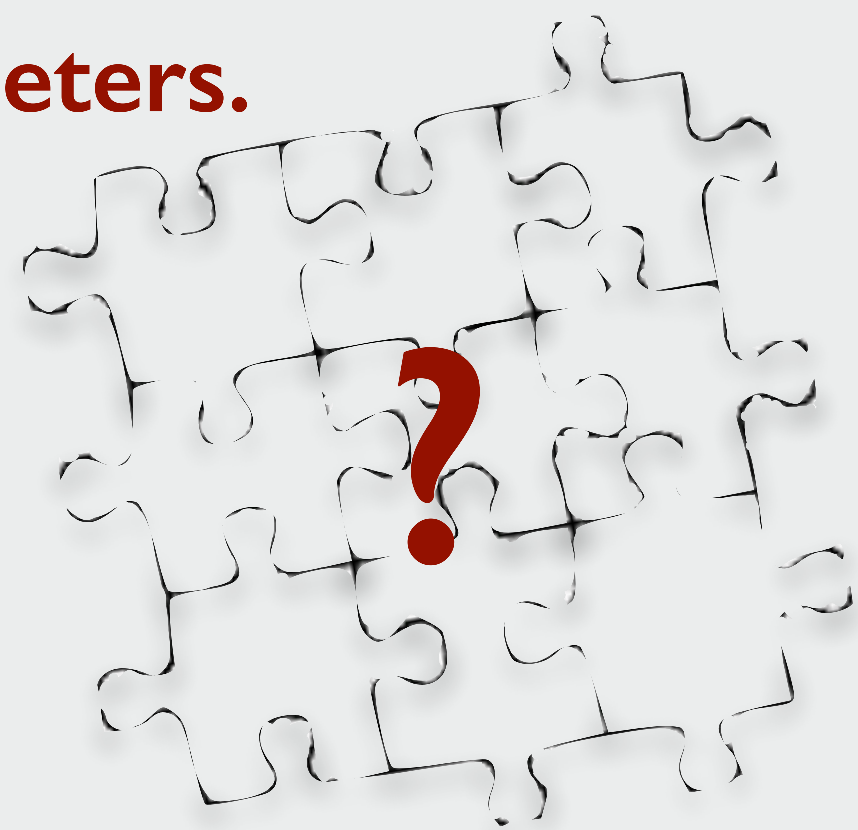
If there is a physically meaningful equation:

$$F(c_{pg},\ \rho_g,\ \mu_g,\ k_g,\ \omega,\ D,\ l_g,\ T_g) \cdot h_{ew-g} = 1$$

$$F(c_{pb},\ \rho_b,\ [HU]\%,\ k_b,\ \omega,\ D,\ l_\psi,\ T_w) \cdot h_{cw-cb} = 1$$

involving a certain number r=9 **variables**, then the original equation can be rewritten in terms of a set of p=r-n=9-4=**5 dimensionless parameters.**

p: number of dimensionless grouping to define
r: number of variables
n: number of fundamental units among the variable



Correlations

$$Nu_{ew-g} = \frac{h_{ew-g}D}{k_g} = K Re_\omega^\alpha Pr^\beta \left(\frac{l_g}{D}\right)^\gamma \left(10^{-10}\frac{c_{pg}\rho_g T_g^\infty}{\omega \mu_g}\right)^\delta$$

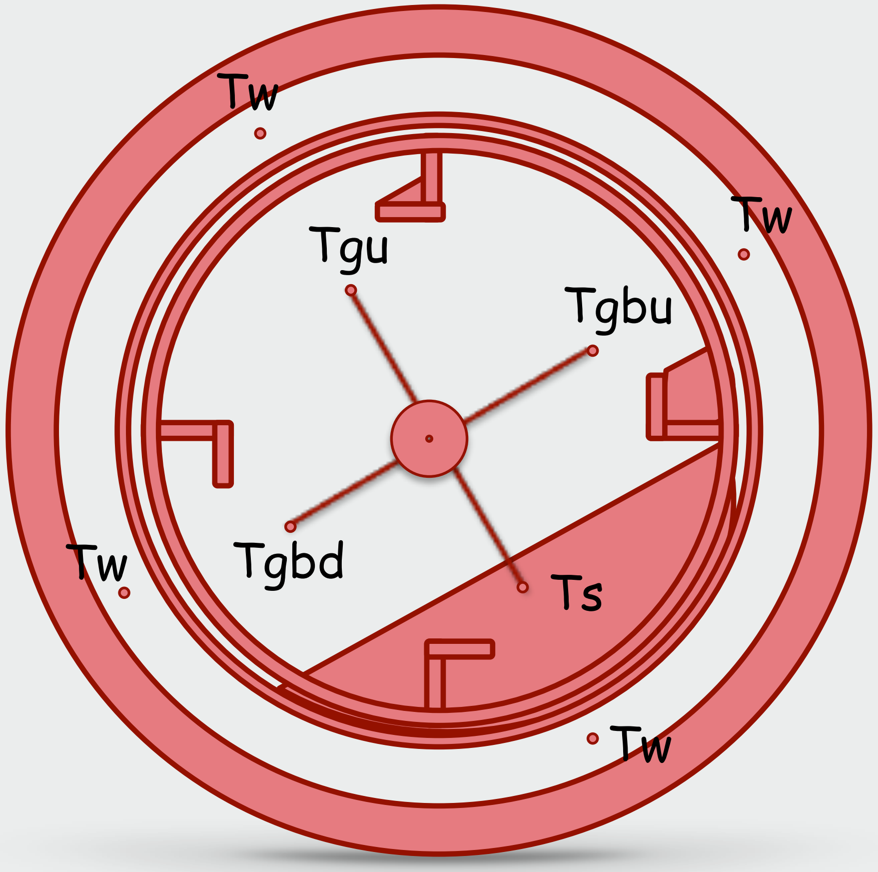
$$Re_\omega = \frac{\omega \rho D^2}{\mu_g} \quad Pr = \frac{c_{pg}\mu_g}{k_g}$$

$$Nu_{cw-cb} = \frac{h_{cw-cb} l_\psi}{k_b} = K \left(10^{-3}\frac{\omega D^2}{a_b}\right)^\alpha \left(10\frac{l_\psi}{D}\right)^\beta \left(10^{-2}[HU]\%\right)^\gamma \left(10^{-4}\frac{T_w k_b^{0.4} c_{pb}^{0.6}}{\rho_b^{0.4} D^{2.8}}\right)^\delta$$

	K	α	β	γ	δ
Nu_{ew-g}	0.1085	0.0275	-0.4839	-1.9284	-0.2208
Nu_{cw-cb}	2.1371	0.4531	-0.3507	0.9693	1.4177

Materials and Methods

1. Set the variable parameters to desired value, and achieve steady state (of the bulk flow)
2. Start the logging of temperatures (wall, gas and solids) ~30 min before starting heating the bulk bed)
3. Collect the power supply, the ambient temperature and freeboard gas temperatures at the inlet end, every 30 min.
4. Set the desired temperature at wall and turn on the heating in zone 2 or in the two zones (1 and 2)
5. Achieve steady state of wall, gas and solids temperature
6. Collect and weigh the solids hold up



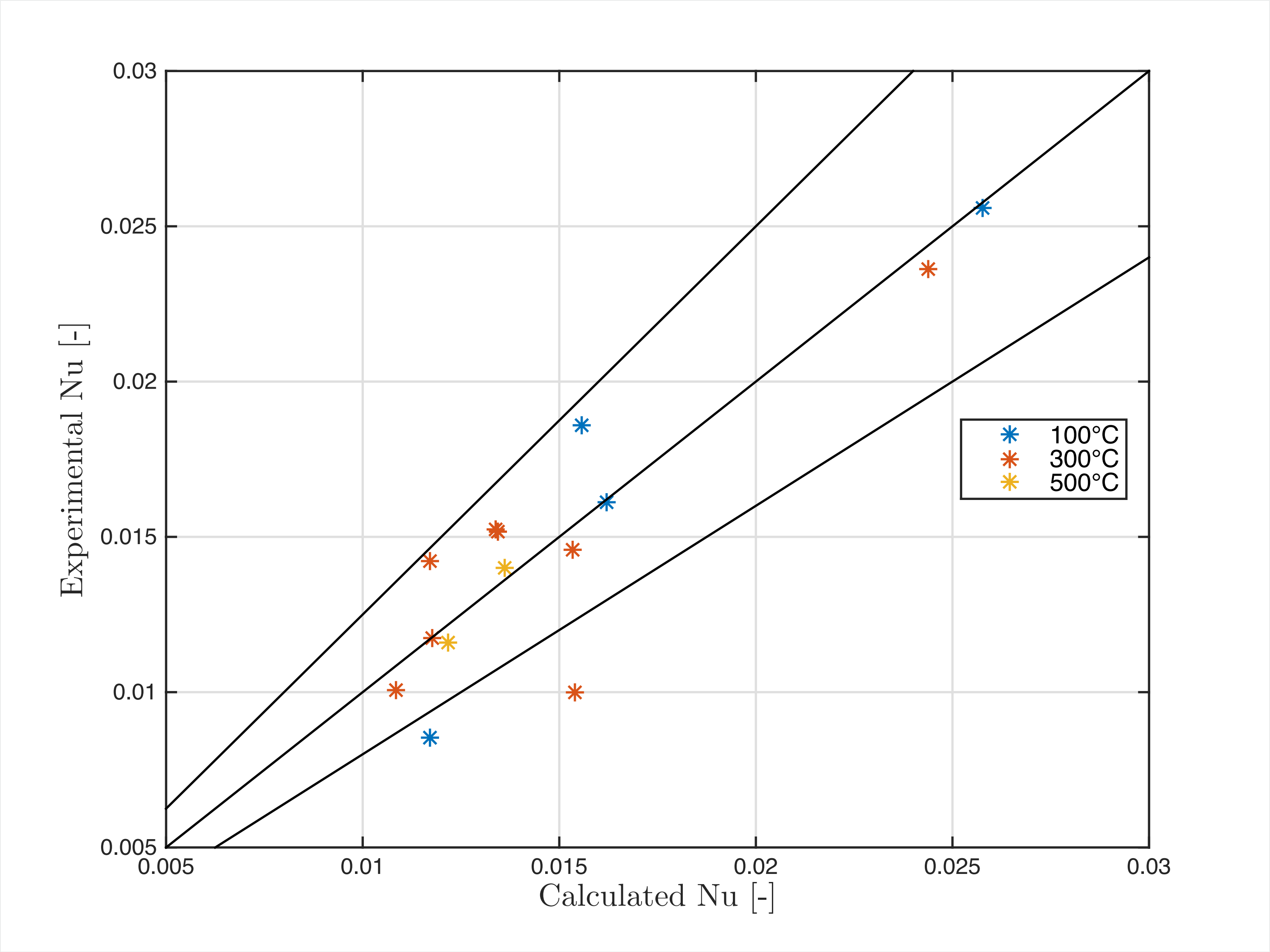
300 °C	Materials	Bulk density [kg.m^{-3}]	Sp. heat cap. [J.kg^{-1}.K^{-1}]	Therm. conduc. [W.m^{-1}.K^{-1}]	Therm. diffus. [m^2.s-^{1}]	Emissivity[1] [-]
Bulk	Sand	1422	835	0,1786	0.01 10^{-5}	0,76
Gas	Air	1,177	1005	0,0262	2.21 10^{-5}	0.01 (esttimated)
Wall	Inconel 800	7950	427	14,660	0.43 10^{-5}	0.85 (esttimated)

[1] Thammavong, P., Debacq, M., Vitu, S., Dupoizat, M., 2011. Experimental Apparatus for Studying Heat Transfer in Externally Heated Rotary Kilns. Chemical Engineering & Technology 34, 707–717.

Experimental Variables

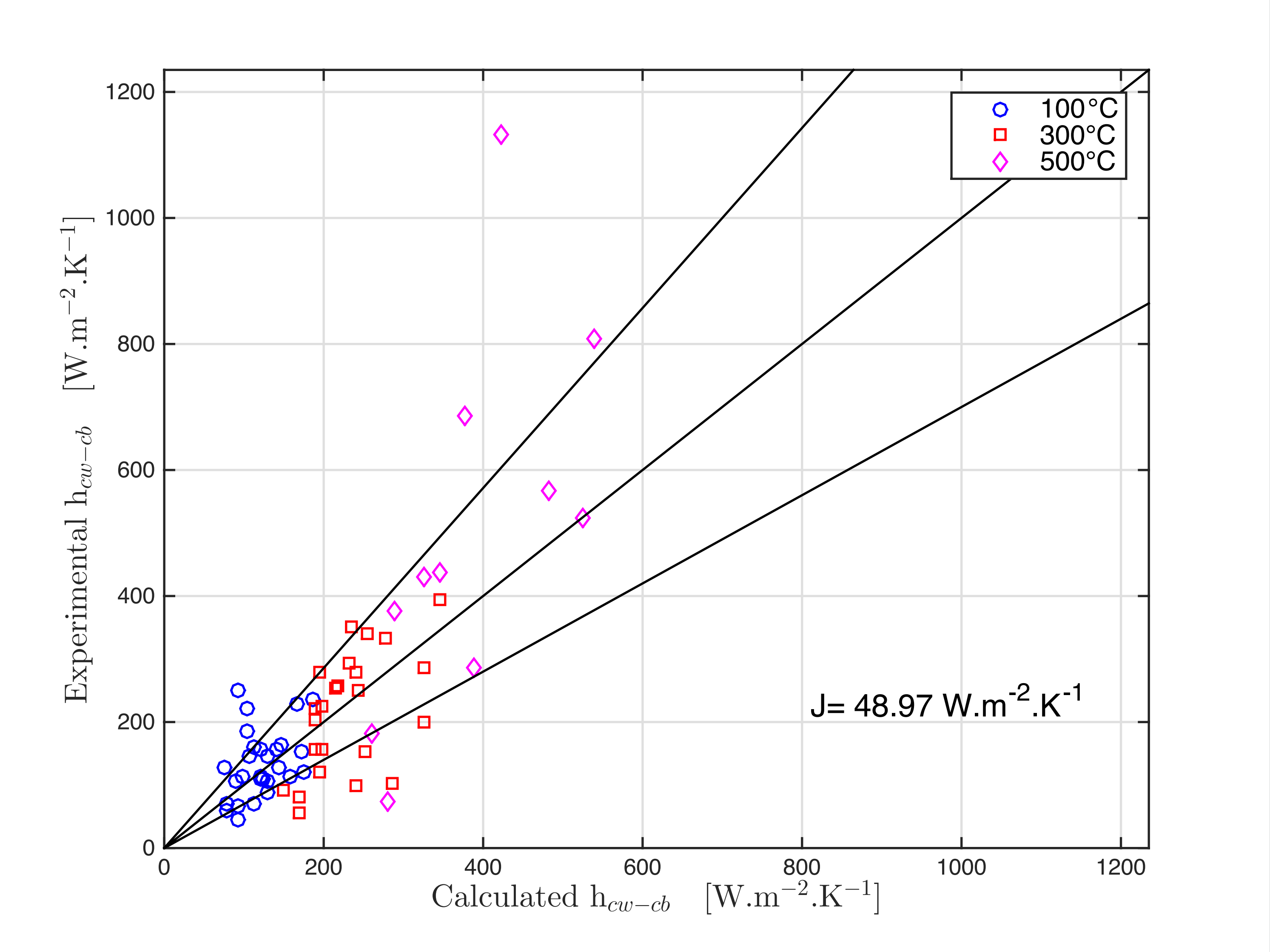
Parameters	Notation	Order of magnitude	Unit
Kiln length	L	1,95	m
Kiln diameter	D	0,101	m
Rotation	N	2-12	rpm
Kiln slope	S	3	degree
Mass flow	M	0.7-2.6	kg/h
Exit dam	h	23.5-33.5	mm
Lifters	SL, RL, NL	-	-
Temperature	Tw	100-500	°C

Convective Heat Transfert



Good agreement within the ±20% margins

Axial Dispersion Coefficient



Good agreement within the ±20% margins

Conclusions

Conclusion - Hydrodynamic

- Residence Time Distribution (RTD): 🔆 about 170 experiments used for the model validation
- Mean Residence Time Modeling ✅ successfully represents the Exp. MRT of this study and other works
- Hold-up / Filling degree correlation show good agreement with experimental data
- Axial Dispersion Model ✅ successfully represents the Exp. RTD within rolling motion

Conclusion - Heat Transfer

- Analysis of the temperature profiles following a heating operation: 90 experiments
- Experimental determination of the heat transfer coefficient between wall and solid particles:
  - Lumped system formulation Methods
  - Global heat balance using supply power measurements
- Convective heat transfer model in good agreement with experimental data but need a few other data for consolidation
- Wall-to-solid heat transfer model ✅ successfully represents the experimental data
- Some difficulties encountered to take into account effect of the temperature and proceed the calculations in the mean time

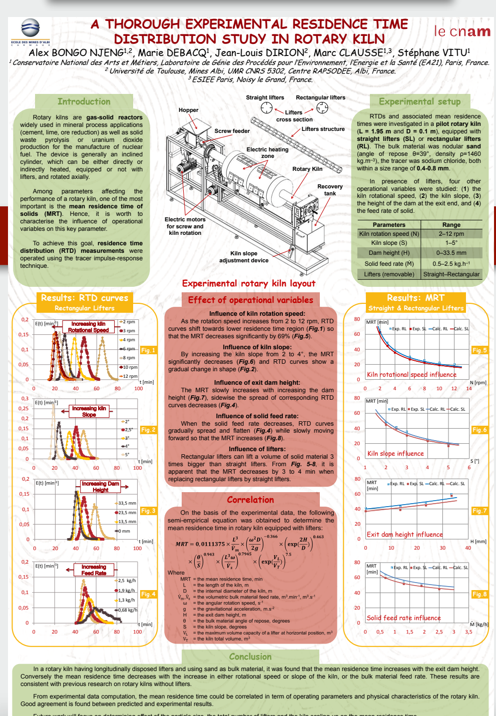
Valuation of the Results

VALUATION OF THE RESULTS

6 months

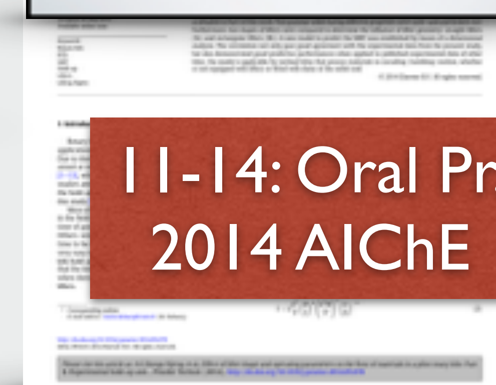
18 months

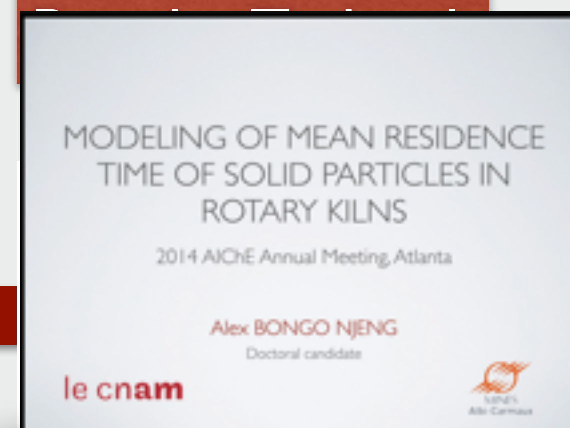
04-13: Poster ECCE9



03-14: Powder Technol.

04-14:





11-14: Oral Pr. 2014 AIChE

10, 11-15: Oral Pr. ECCE, AICHE

Effect of lifter shape and operating parameters on the flow of materials in a pilot rotary kiln: Part I. Experimental RTD and axial dispersion study

A THOROUGH EXPERIMENTAL RESIDENCE TIME DISTRIBUTION STUDY IN ROTARY KILN

Modeling of Mean Residence Time of Solid Particles in Rotary Kilns

Evaluation of the Wall-to-solids Heat Transfer coefficient in Rotary Kilns

modeling

Thank You for Your Attention