FUTURE
INVENTER LES VILLES DE DEMAIN

Energy and waste valorization from construction and building materials

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4th Meeting of the French-Singaporean Research Network on Renewable Energy (SINERGIE) held at NTU Singapore - 6th nov. 2019

École d'architecture de la ville & des territoires à Marne-la-Vallée
EIVP
École des Ponts ParisTech
ENSG Géomatique
ESIEE PARIS
IFSTTAR
UPEM UNIVERSITÉ PARIS-EST MARNE-LA-VALLÉE

Energy issues

(1) **Embodied energy** (EE) : « *sequestred in building materials during all processes of production, on site construction, and final demolition and disposal* »

(2) **Operating energy** (OE) : « *expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating* »

→ EE and OE difficult to assessed

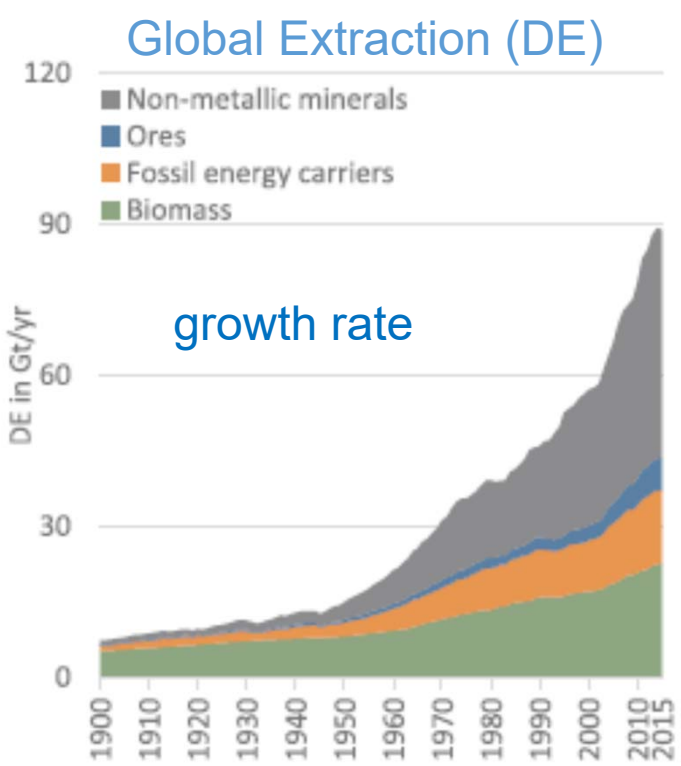
→ Datas inconsistency linked to the temporal variability from micro- to the system-scale

Needing of experimental characterization and relevant physical modelling

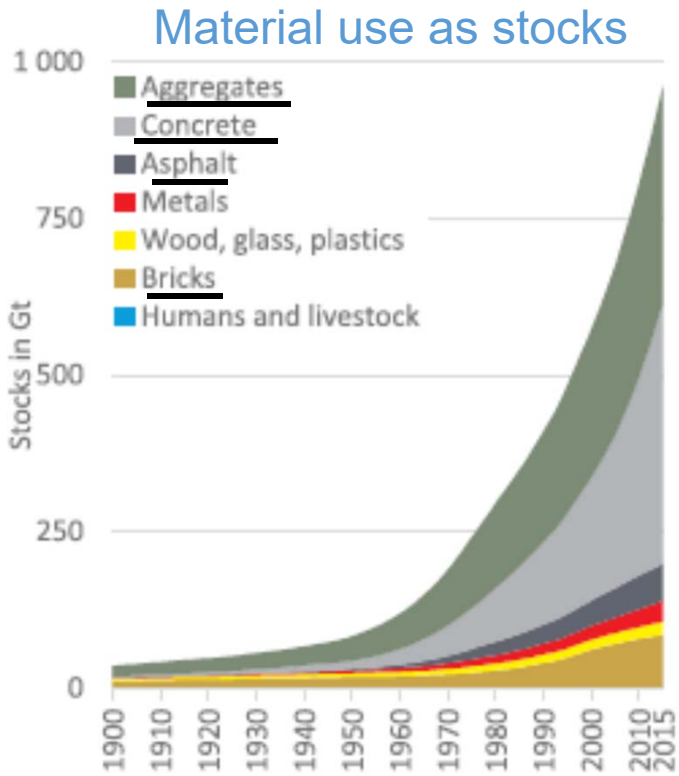
Dixit M.K. et al. (2010), Energy and Building 42 1238-1247

Asphalt materials

- Few numbers



Process transformation



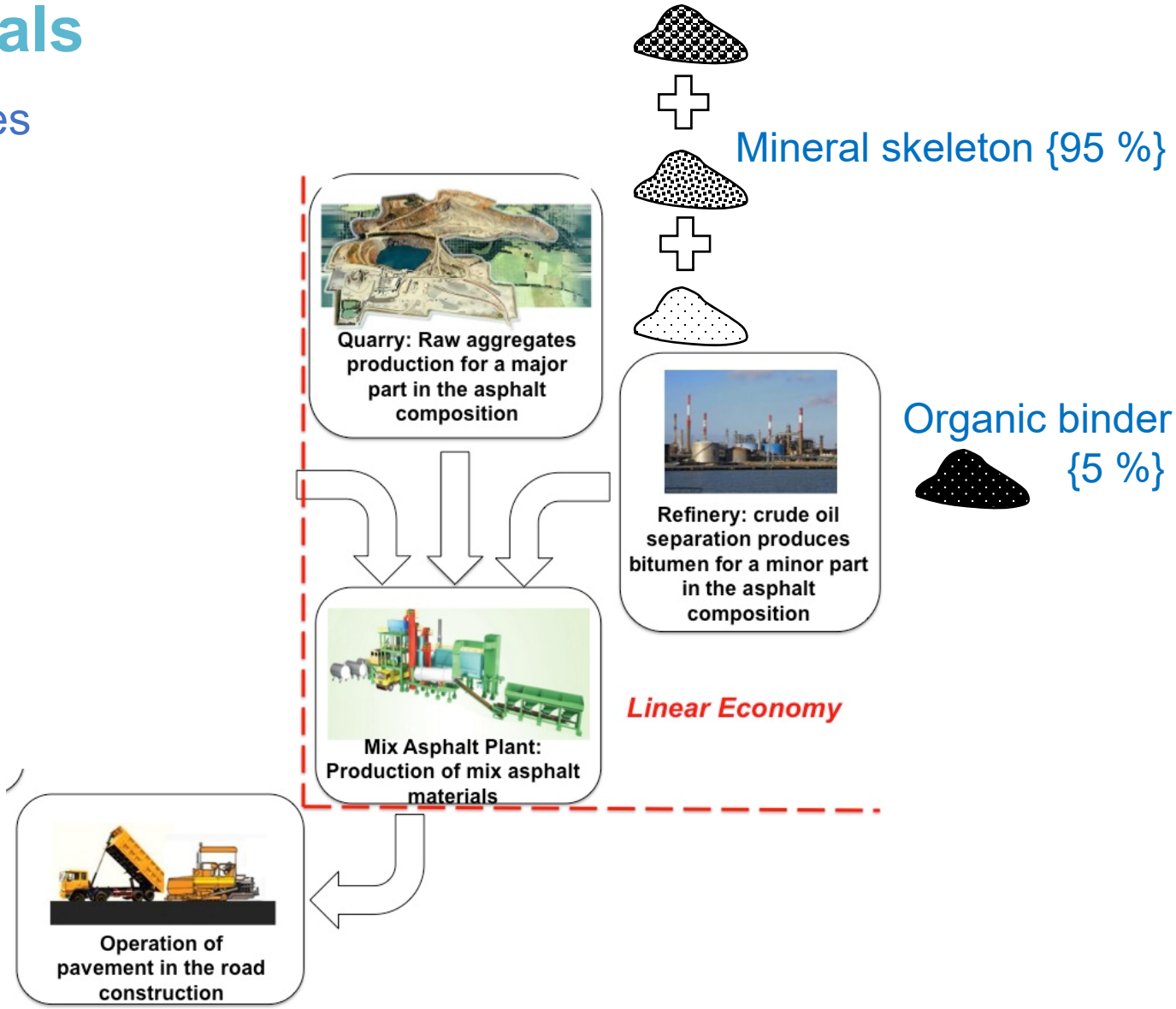
- High increase of DE since 20 years
- Increasing of the non-metallic minerals

- Dissipative at low time-constant of life
  → Food, energy conversion (not stored)
- In-use stocks at elevated time-constant of life
  → **Construction & Building materials**

Krausmann et al. (2018), Global Environmental Change 52 131-140

Asphalt materials

- Industrial issues



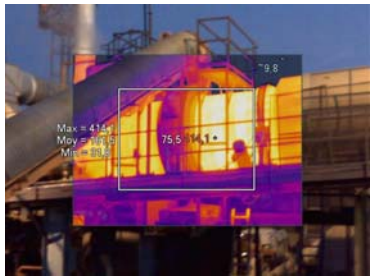
Huchet F., Le Guen L., Richard P. et al., Road Materials and Pavement Design 19:1 104-119 (2018)

Asphalt materials

- Industrial issues

Energy : 100 up to 360 MJ/$T_{asphalt}$

Waste Heat excess



$5< \%_{wall} <15$

$25< \%_{gases} <40$

By-products from demolition

Recycled Asphalt Pavement

Europe : 38.5 Million tons/year

USA : 76.9 Million tons/year

1 Million of tons ~15 Milions € saving of bituminous binder

Exchange loops between energy and matter

Zhang K. et al. Construction and Building Materials (2019)

Asphalt materials

- Industrial issues

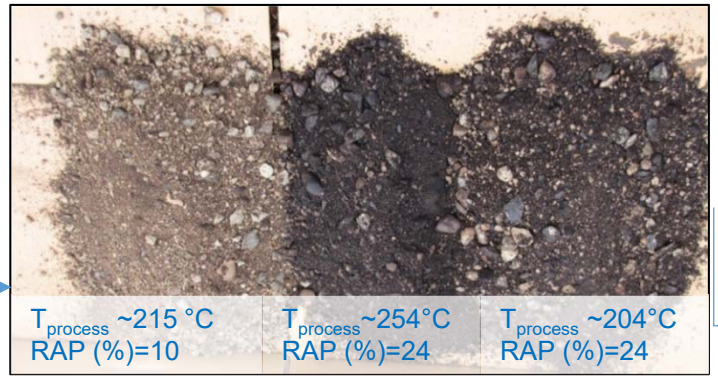
- Batch plant (Intermittent production)

  Waste Heat Excess to manage

- Heterogeneous materials

Process parameters of production to control
Temperature and **Rate of recycling**

Composite materials
[Mineral stones+Aged binder to activate]



Albedo

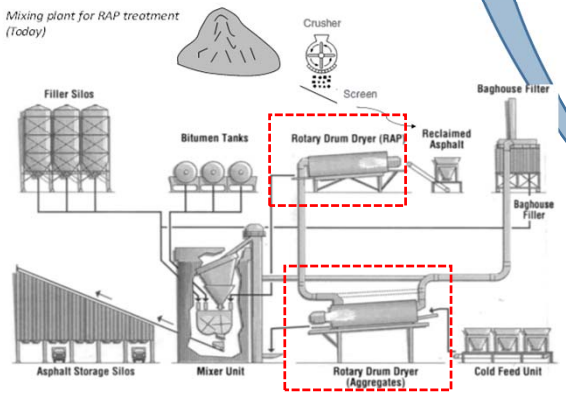
Zhang K. et al. Construction and Building Materials (2019)

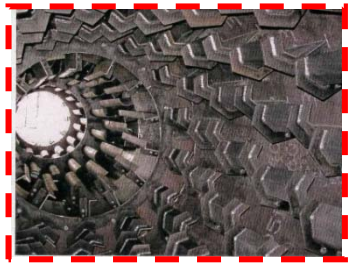
Asphalt materials

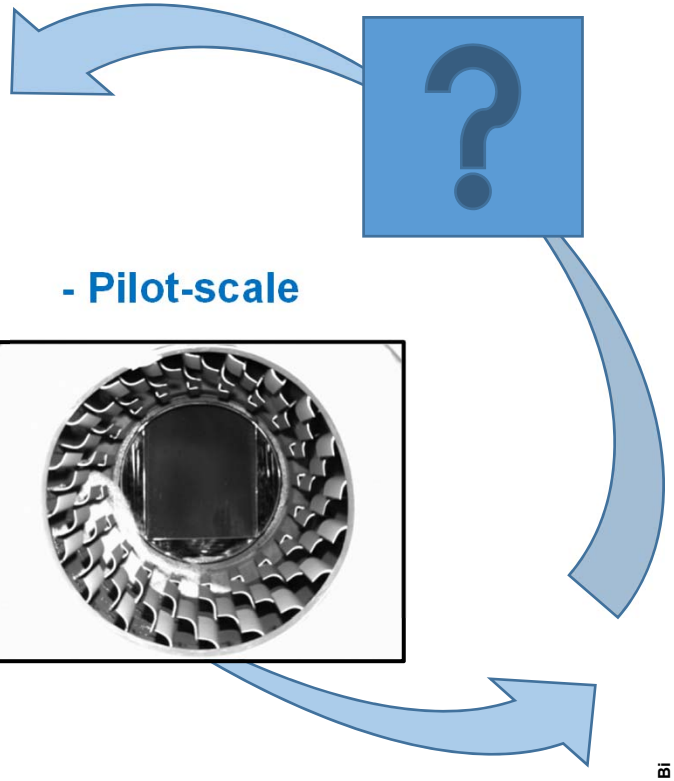
- Process modelling : a multi-scale approach

  - Industrial-scale

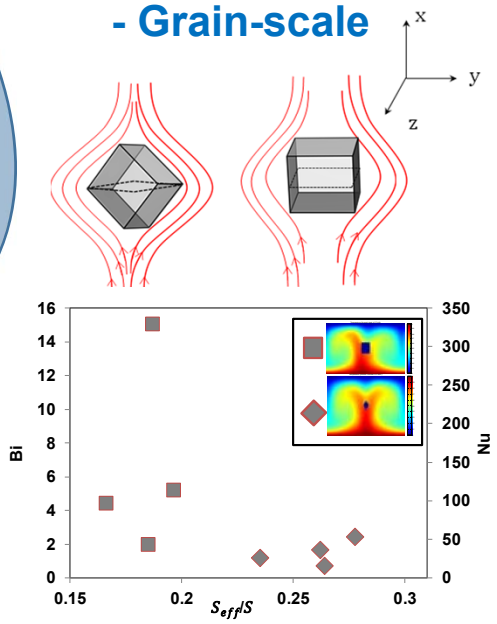
Complexity
→ Grains size, shape
→Blending
→ Design







- Grain-scale



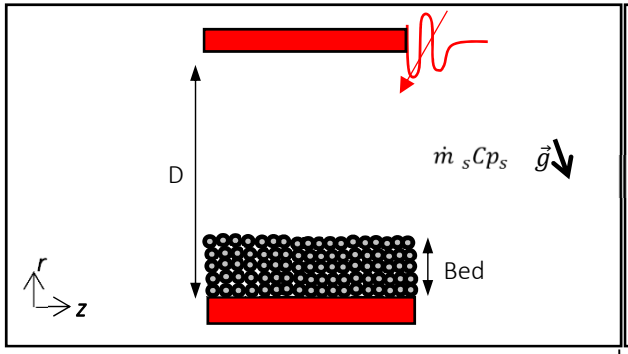
Le Guen L., Huchet F., Tamagny P. Journal of Applied Fluid Mechanics, 4 2 Special Issue 71-80 (2011).

Huchet F., Richard P., Joniot J., Le Guen L., EPJ Web of Conferences 140, 02015 (2017), *8th Powder and Grains*, 1-7 july 2017 Montpelier, France. https://doi.org/10.1051/epjconf/201714002015

Asphalt materials

- Process modelling : a multi-scale approach

Indirect heat treatment



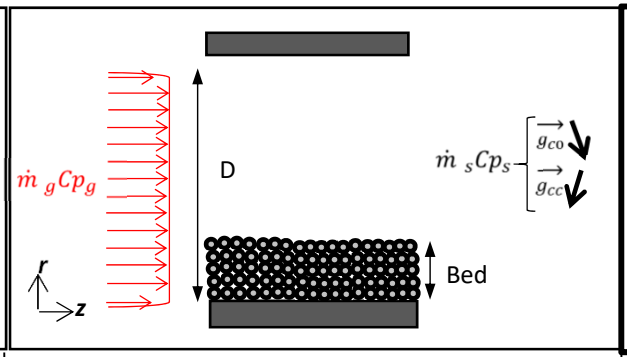
Mixing

Mellmann, Powder & grains 2001

Heat transfer grain to wall

Tcheng *et al.*, Canadian J Ch Eng, 1979
Herz *et al*. IJHMT, 2012

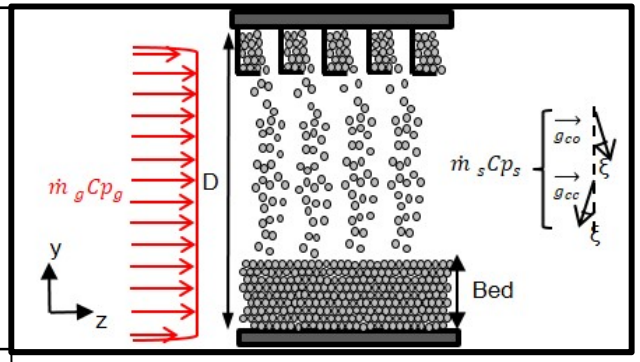
Direct heat treatment



Radiation and combustion

Gorog *et al.*, Metall trans. (1982)
Marias *et al*. Computer Chem. Eng. (2005)

Dry or Cohesive materials

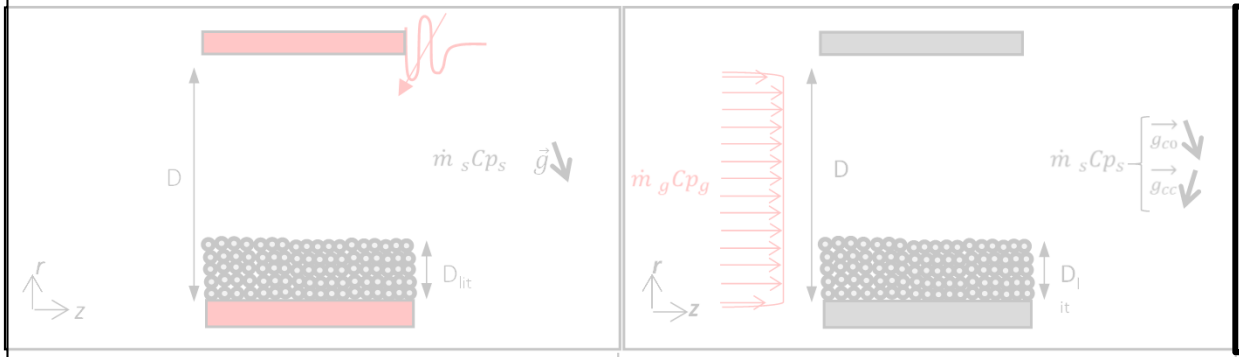


Asphalt materials

- Process modelling : a multi-scale approach

Indirect heat treatment

Direct heat treatment



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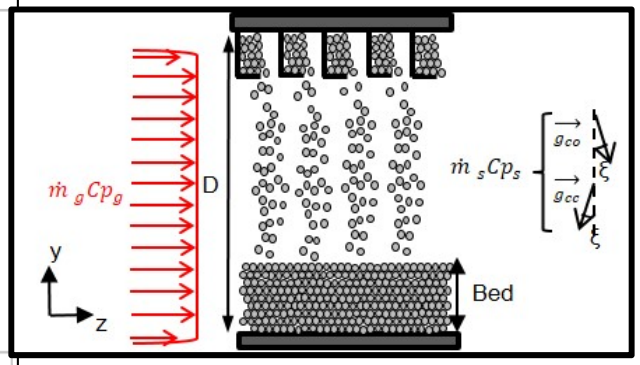
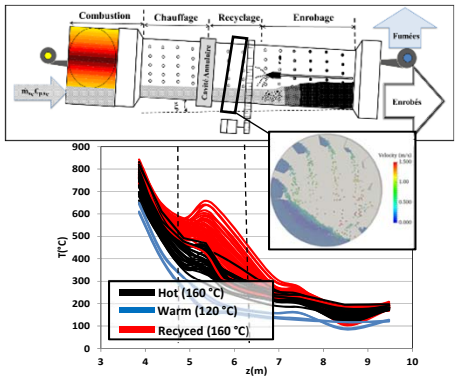


Granular cascading (3D - CFD+DEM)

Zhang *et al.* (2019), Constr. Building Mat.

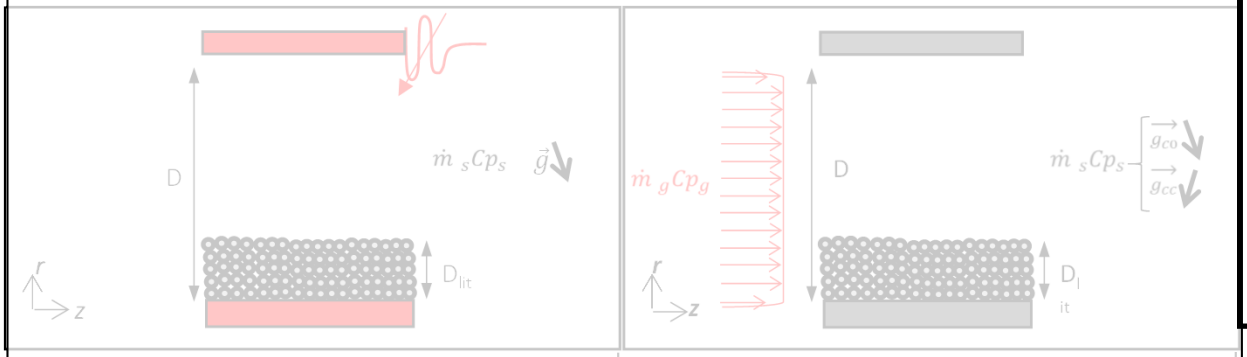


Asphalt materials

- Process modelling : a multi-scale approach

Indirect heat treatment

Direct heat treatment



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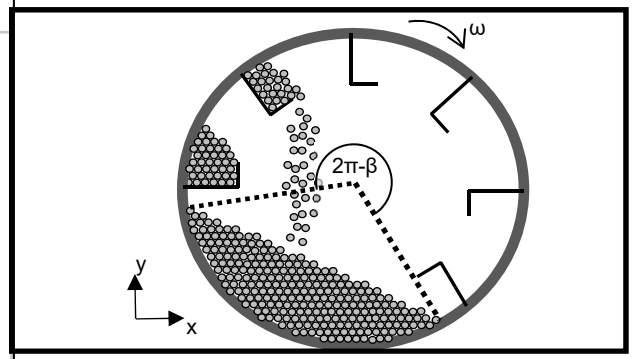


Discharging 2D model (continuous)

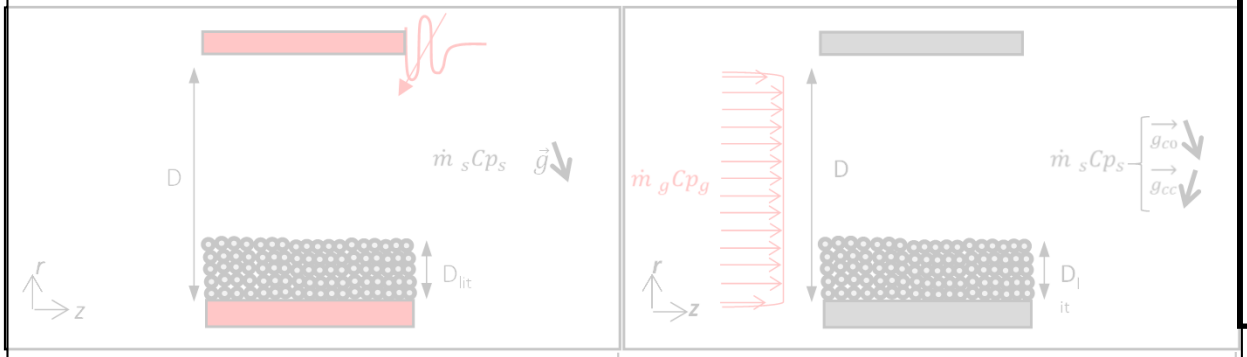
Sunkara *et al.*, CES, (2013)

Asphalt materials

- Process modelling : a multi-scale approach

Indirect heat treatment

Direct heat treatment



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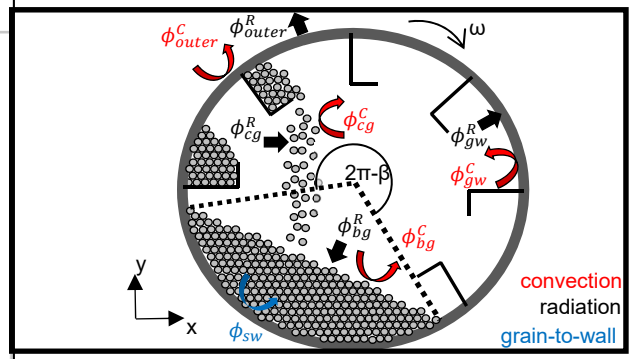


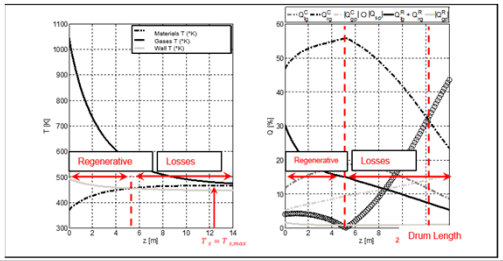
Discharging 2D model (continuous)

Sunkara *et al.*, CES, (2013)

Discharging model+Heat transfers

Piton M. *et al.* Applied Therm. (2015)

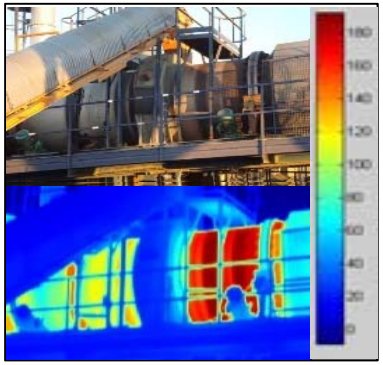
Le Guen *et al.* Canadian J. Chem. Eng. (2017)



Asphalt materials

- Waste heat recovery

Industrial-scale



Down-scaling 1/5

Annulus geometry

Scale 1/5

- Radius : **170** mm ; Size : **1750** mr
- Angular velocity **0 – 74** tr.min^{-1}
- Power **8,2** kW

Heat exchanger

- Radius : **210** mm
- Gap tickness : **40** mm
- Air flow passage **20 – 250** m^3.h^{-1}
- Longueur de **900** mm

Huchet F., Piton M., Del Barrio A. et al. Energy Conversion and Management (2017)

Asphalt materials

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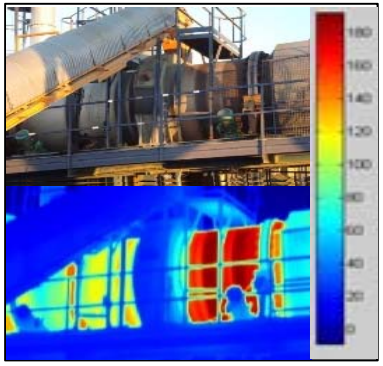

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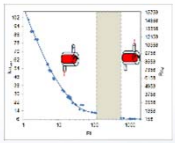
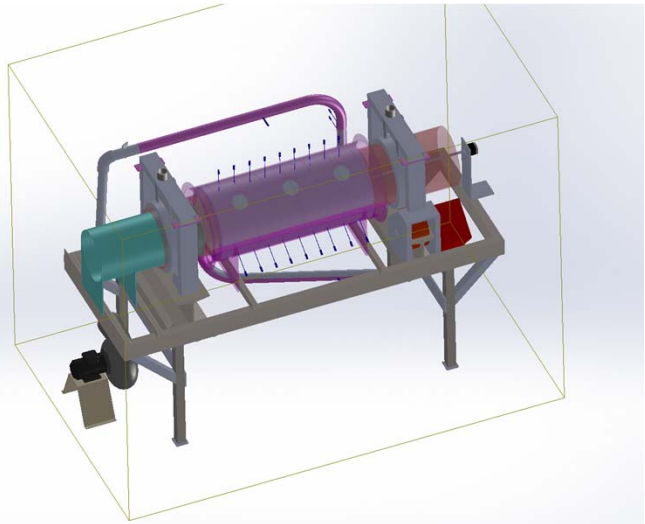
Heat convection regimes
Nu= f {Re,Ri}



2D model



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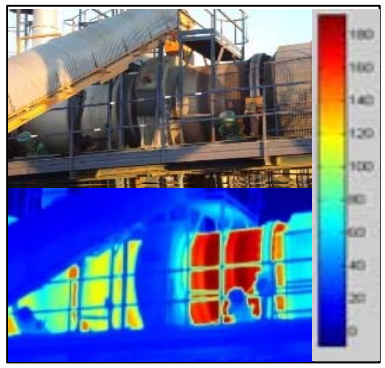

Down-scaling 1/5

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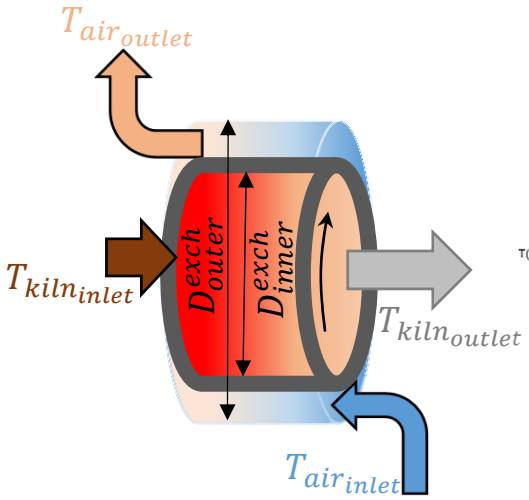

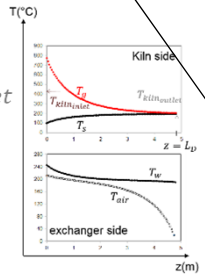

Heat convection regimes
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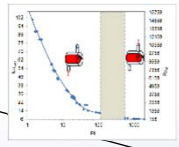
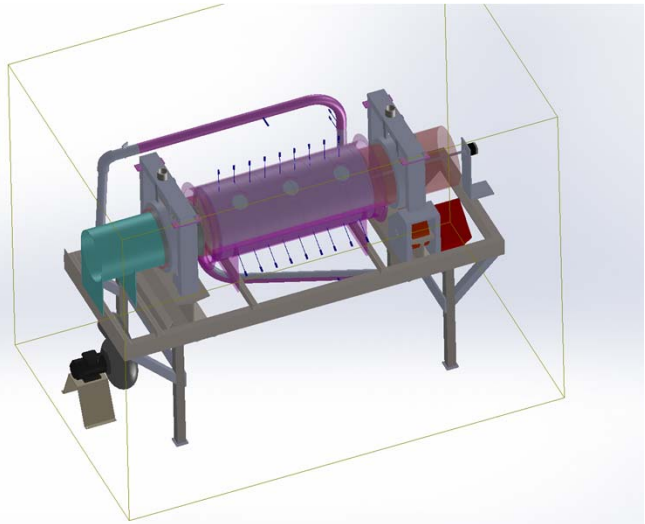
2D model



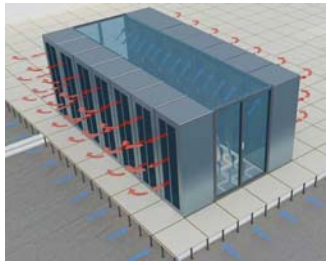


Le Guen L. , Huchet F. Quantitative InfraRed Thermography Journal (2019) https://doi.org/10.1080/17686733.2019.1611222

Project Eco-Datacenter« Reduction of the ecological print of datacenter ; Assessment of heat exchanger based on earth materials until to its scaling-up »

ADEME

Agence de l'Environnement et de la Maîtrise de l'Energie



- Large amount of earth materials stored in quarry site (~43 MTons around Paris)
- Low embodied energy due to the reversibility

- Thermal inertia
- Latent heat storage [1% to 3% of humidity in mass]

Data center energy consumption

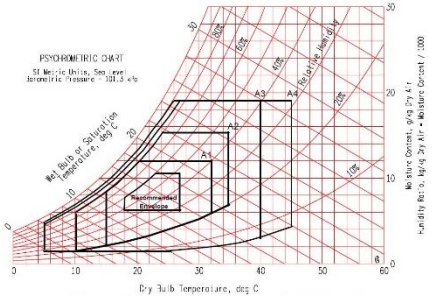
10 000 m^2≡ city of 50000 people

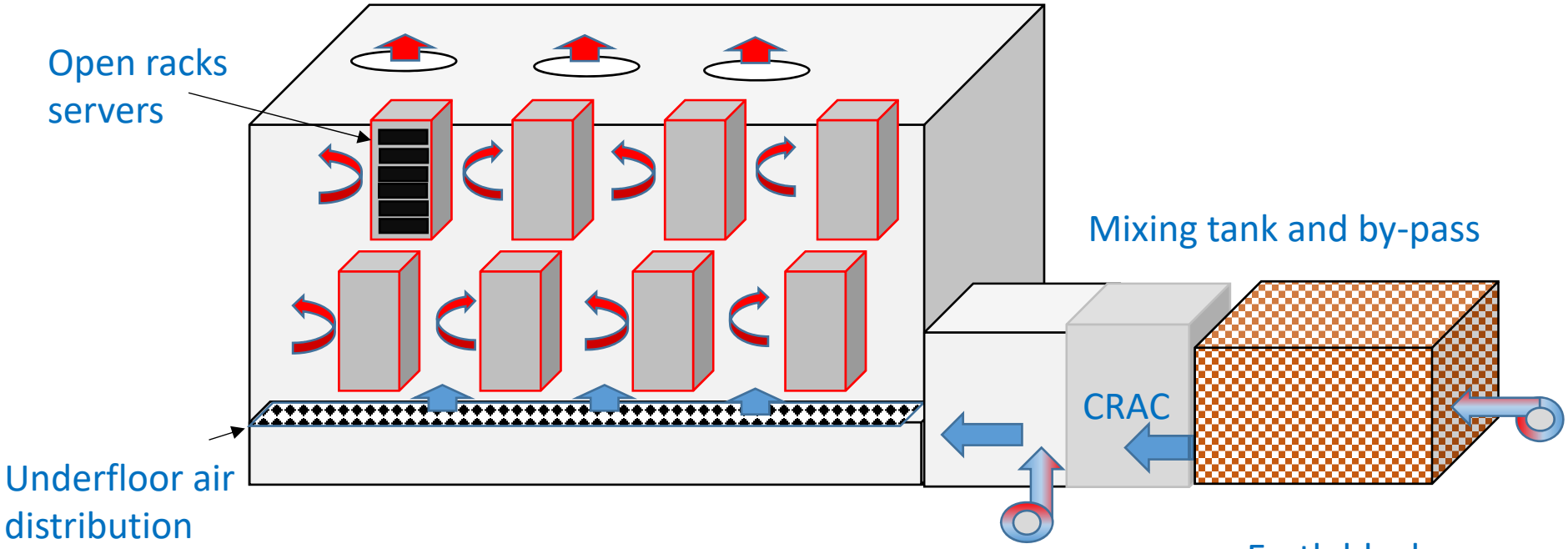
Bouchenna C., Huchet F., Le Guen L., Hamard E., Aramiou C., Dugelay S., Miceli N., Echangeur de chaleur conçu à partir d'un matériau en terre crue : application au refroidissement des data centre. French Congress of Chemical Engineering, 15-17th oct. 2019, Nantes, France.

Heat exchanger based on earth materials

- Data center issues

  - Respect the hydrothermal ASHARE standard





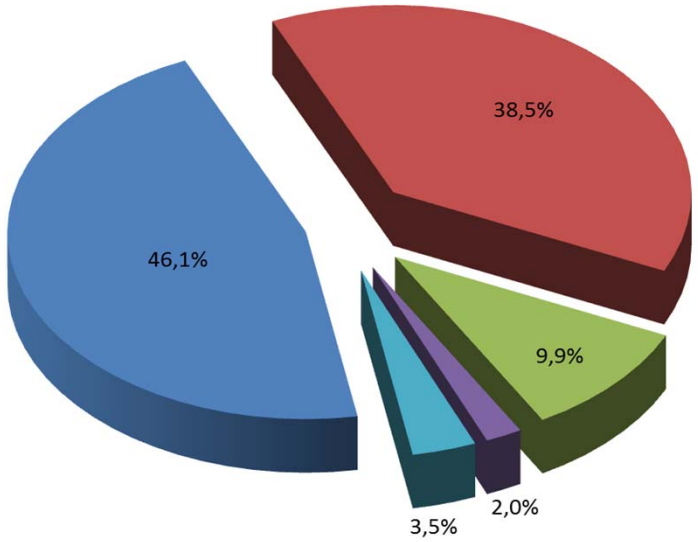
Heat exchanger based on earth materials

- Data center issues

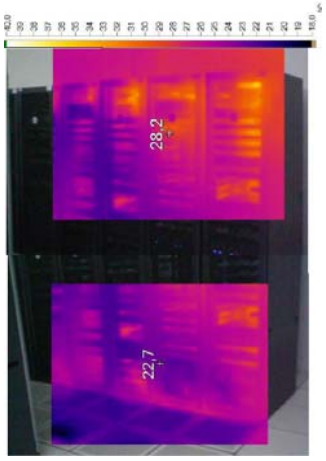
- Insertion of heat exchanger from sustainaible materials at low economical cost

- Extend the free cooling period {energy form natural origin}

- Reduce the energy consumption



IT Equipment
Cooling systems
Electric losses
Light
Power supply



Heat exchanger based on earth materials

- Packed bed design

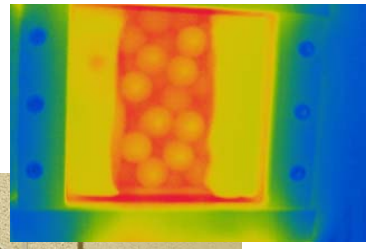
Formulation of the beads earth

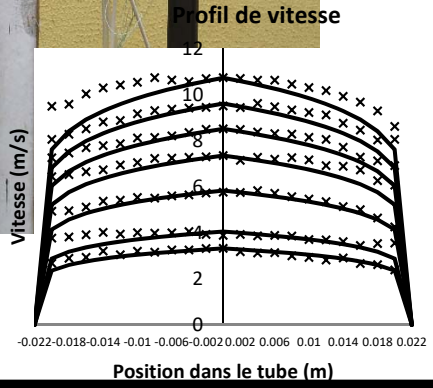
D

45 mm=H/6

32 mm=H/8

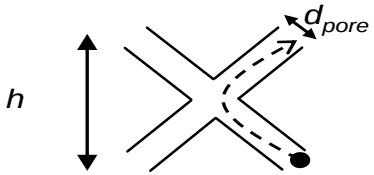
15 mm =H/18





Heat exchanger based on earth materials

- Flow regimes in packed bed : few definitions

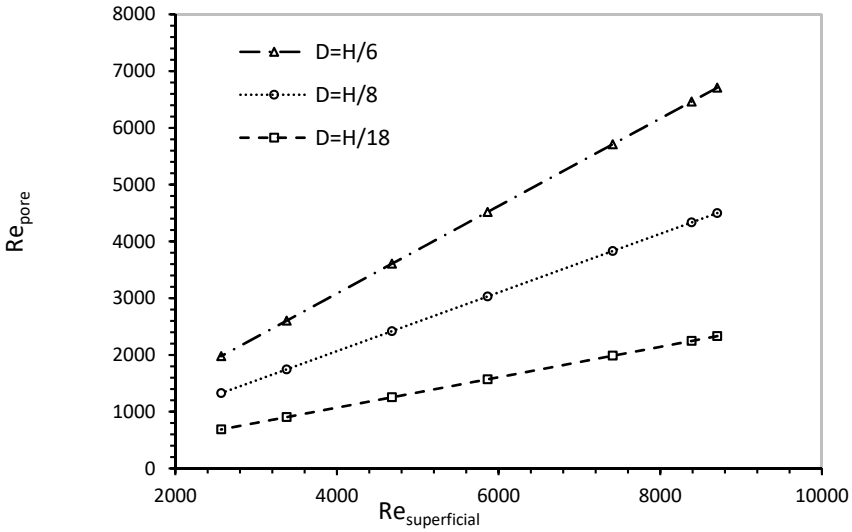


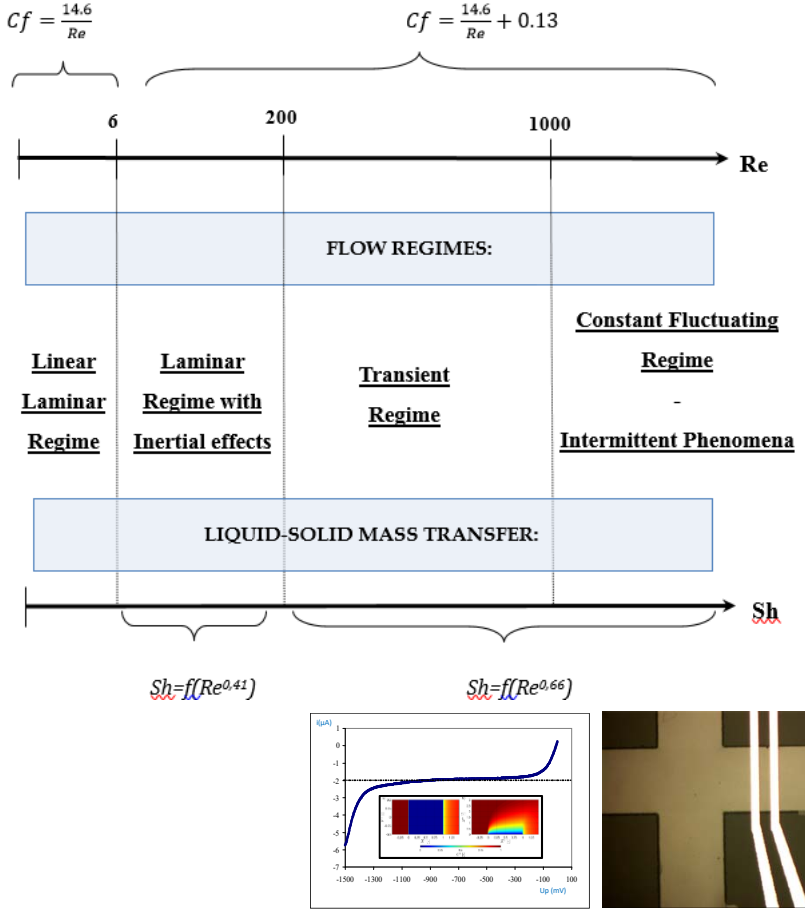
$$\tau = \frac{l}{h}$$

$$d_{pore} = 4\varepsilon/(1-\varepsilon)a_v$$

$$Re_{superficial} = \frac{\rho V d_{cylinder}}{\mu}$$

$$Re_{pore} = \frac{\rho V_{pore} d_{pore}}{\mu}$$



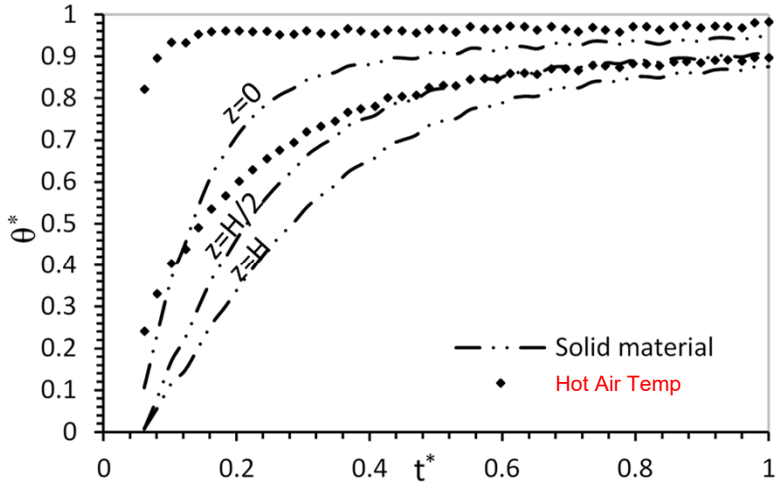


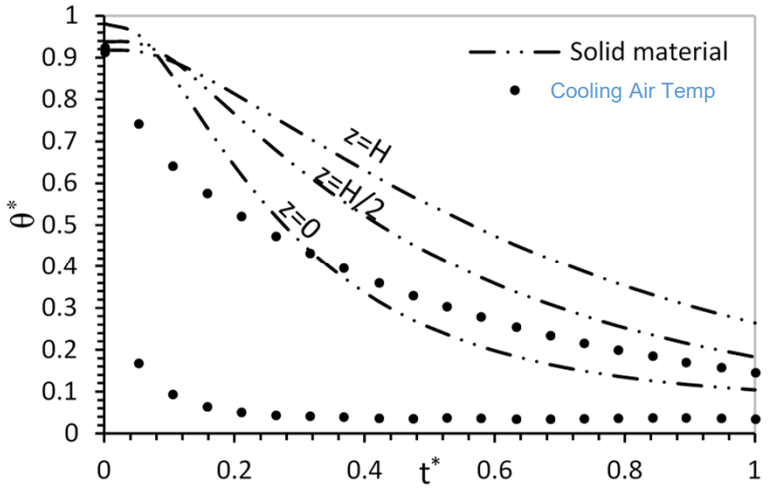
Huchet F. et al. Transport in Porous Media 104:299-313(2014)

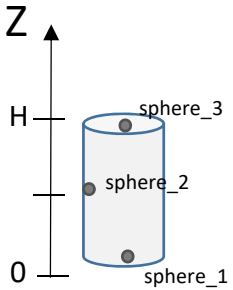
Huchet F., Kramolis D., Havlica J., French congress of Chemical Engineering, 15-17 oct. 2019, Nantes, France

Heat exchanger based on earth materials

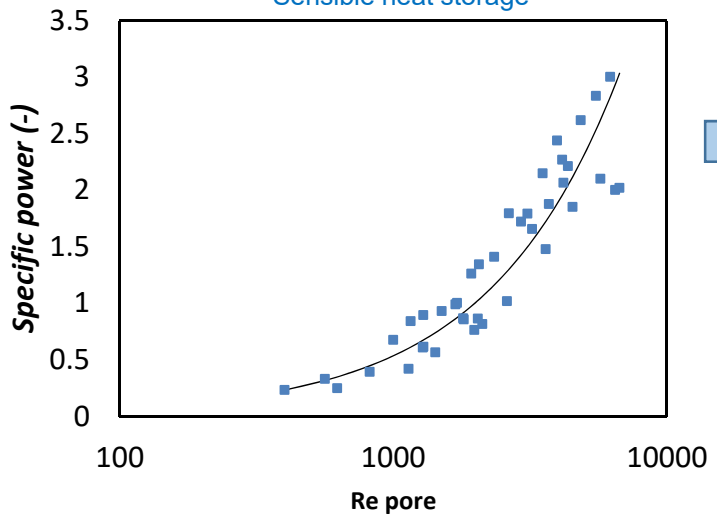
- Successive thermal cycles at Re_p=6708







Sensible heat storage



Next:

- Larger Re_{pore} range
- Latent heat storage
- Large-scale experience

General Conclusion

- Improve accuracy of the modelling : **transient phase**, **micro-scale to the system-scale**
- Transfer of knowledge and innovations to the **circular engineering concept**

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INVESTIR L'AVENIR

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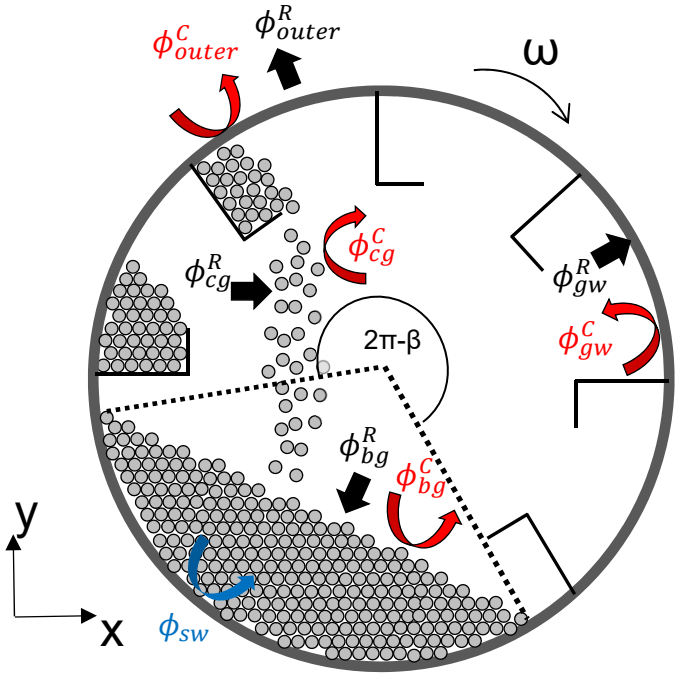
Asphalt materials

Process modelling : a multi-scale approach



convection $\phi^C_{ij} = h_{ij}\, l_{ij}(T_j - T_i)$

radiation $\phi^R_{ij} = \sigma E_{ij}\, l_{ij}(T_j^4 - T_i^4)$

grain-to-wall $\phi_{sw} = h_{sw} l_{sw}(T_w - T_s)$

$$\dot{m}_g c_{p_g} dT_g = \phi^C_{gw} + \phi^C_{cg} + \phi^C_{bg} + \phi^R_{gw} + \phi^R_{cg} + \phi^R_{bg} + \chi$$

$$\pm \dot{m}_s c_{p_s} dT_s = \phi_{sw} - \phi^C_{cg} - \phi^C_{bg} - \phi^R_{gw} - \phi^R_{cg} - \phi^R_{bg} + P$$

$$\phi_{sw} + \phi^C_{gw} + \phi^R_{gw} + \phi^R_{outer} + \phi^C_{outer} = 0$$

Asphalt materials

- Process modelling : a multi-scale approach

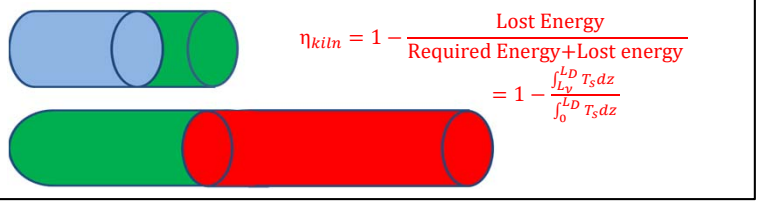
$\Rightarrow$ Optimal size L_v for $T_{s,max}$

$$T_s(z) = T_{s,\infty} + (T_{s,0} - T_{s,\infty})e^{-(z/\Lambda)^{\beta}}$$

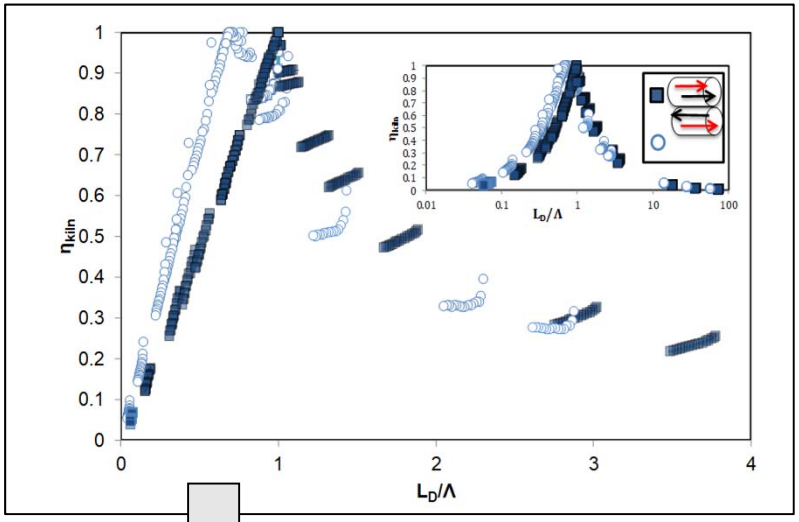
$$\Lambda \simeq \frac{\kappa}{h_{lg}l_{lg} + h_{rg}l_{rg}}$$

$$\kappa = \frac{\dot{m}_g C_{p,g} \dot{m}_s \; C_{p,s}}{\dot{m}_g C_{p,g} + \dot{m}_s \; C_{p,s}}$$

$$\eta_{kiln} = \frac{\text{Brought Energy}}{\text{Required energy}} = \frac{\int_0^{L_D} T_s dz}{\int_0^{L_v} T_s dz}$$



$$\eta_{kiln} = 1 - \frac{\text{Lost Energy}}{\text{Required Energy+Lost energy}} = 1 - \frac{\int_{L_v}^{L_D} T_s dz}{\int_0^{L_D} T_s dz}$$

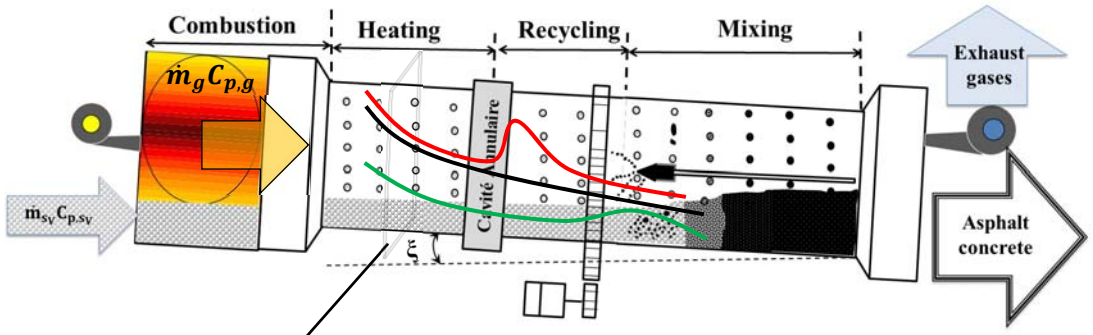


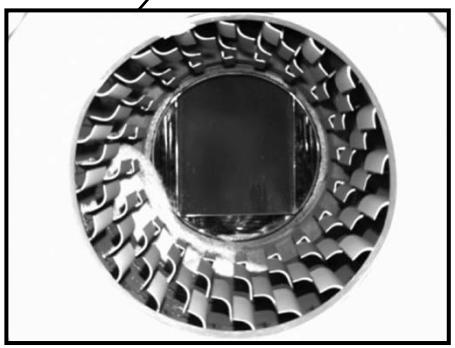
co − current $L_D/\Lambda \sim 1$

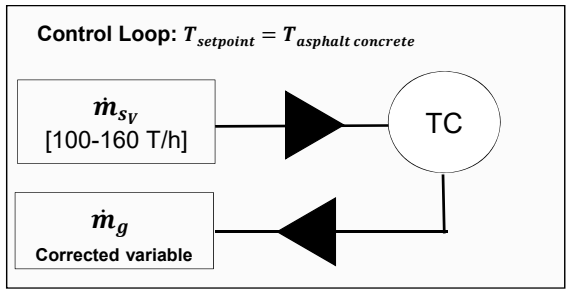
counter − curent $L_D/\Lambda \sim 0.7$

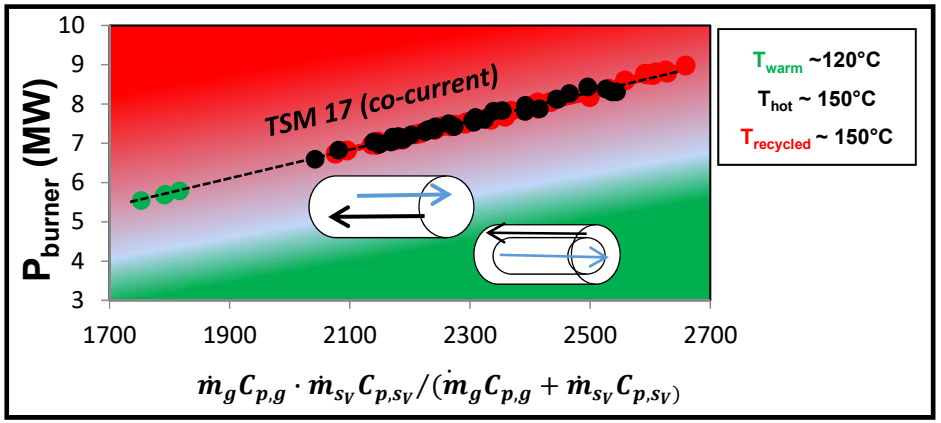
Asphalt materials

Process modelling : a multi-scale approach









⇒ Evolutive properties of the granular materials [Gases/Solids/Binder]

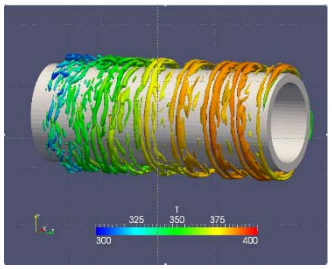
⇒ Fonction exponentielle décroissante :

$$\Lambda \simeq \frac{\kappa}{h_{lg} l_{lg} + h_{rg} l_{rg}}$$

⇒ Recyclage augmente l'énergie de consommation

Asphalt materials

3. Heat waste valorization

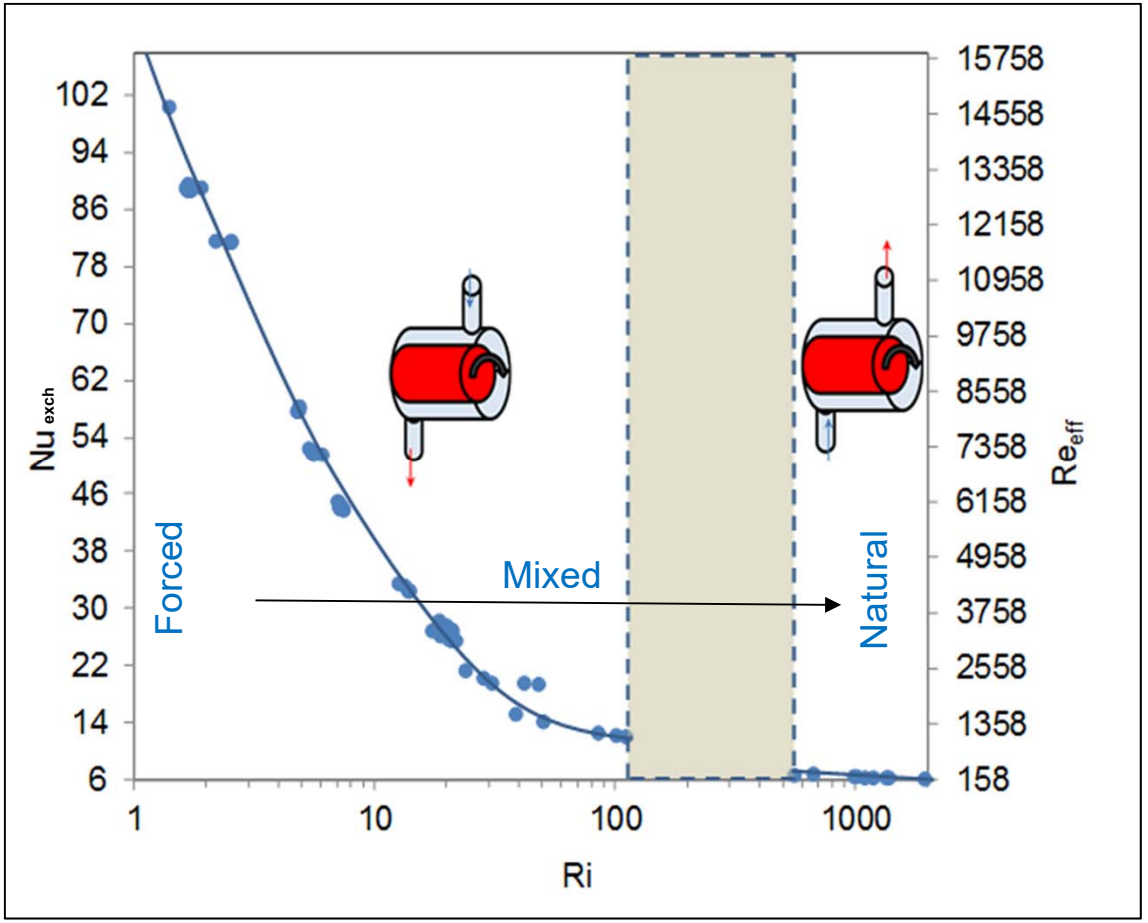


Iso-surface du critère Q
Re=370 –Ta=3,3 10^6

Forced draft /Natural updraft

$Nu_{exch} = 0.3\left[Re_{eff}(\alpha)\right]^{0.6}$ with $\alpha = 0.038$

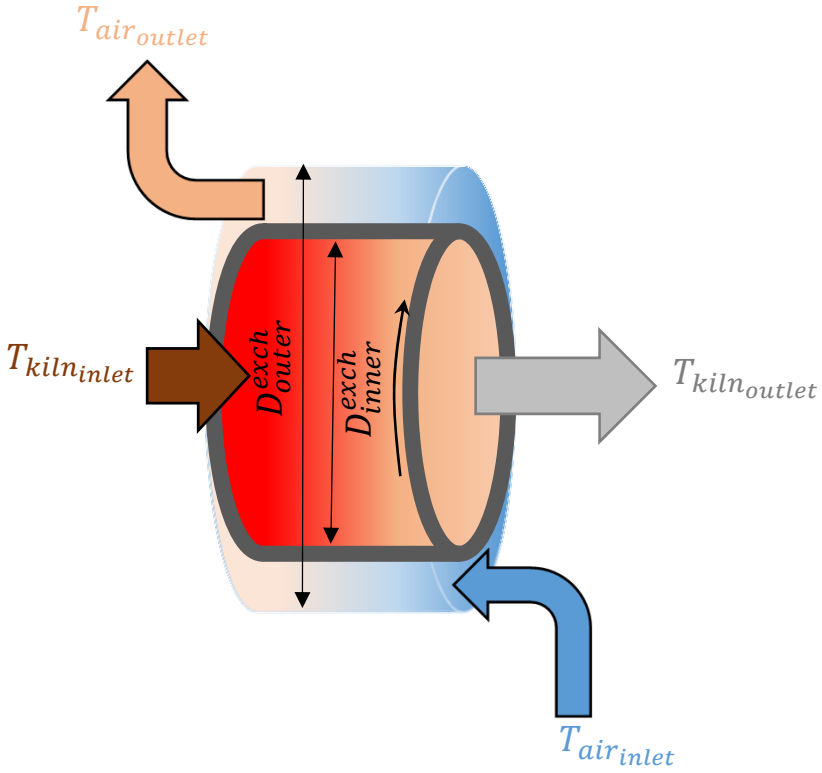
$Nu_{exch} = 0.0113Ra^{0.38}$

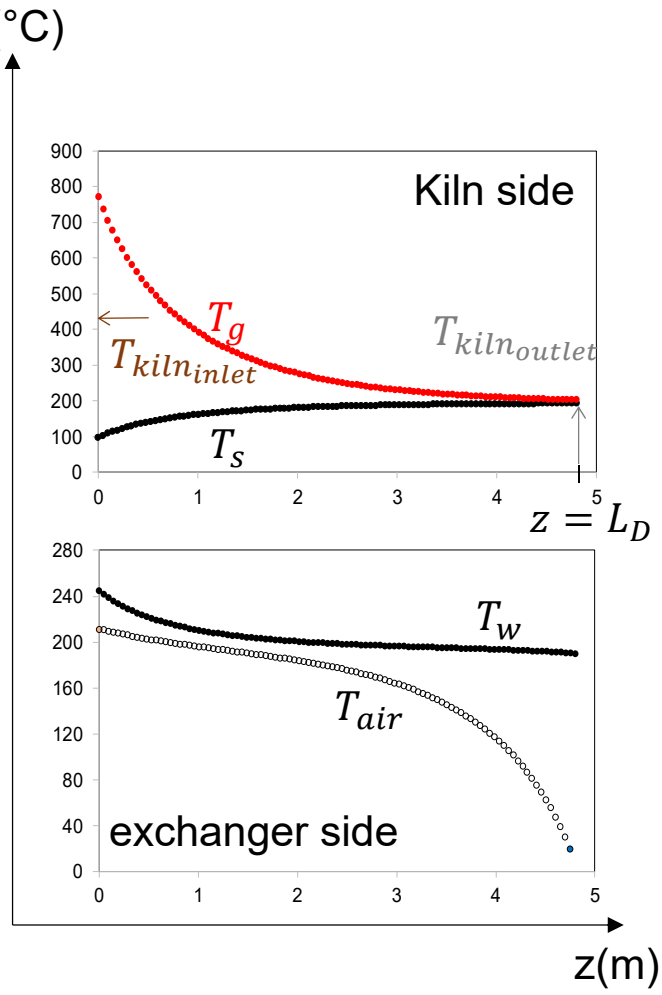


Asphalt materials

3. Heat waste valorization

$$\dot{m}_{air} c_{p\,air} dT_{air} = h_{exch} dS_{inner} (T_w - T_{air})$$

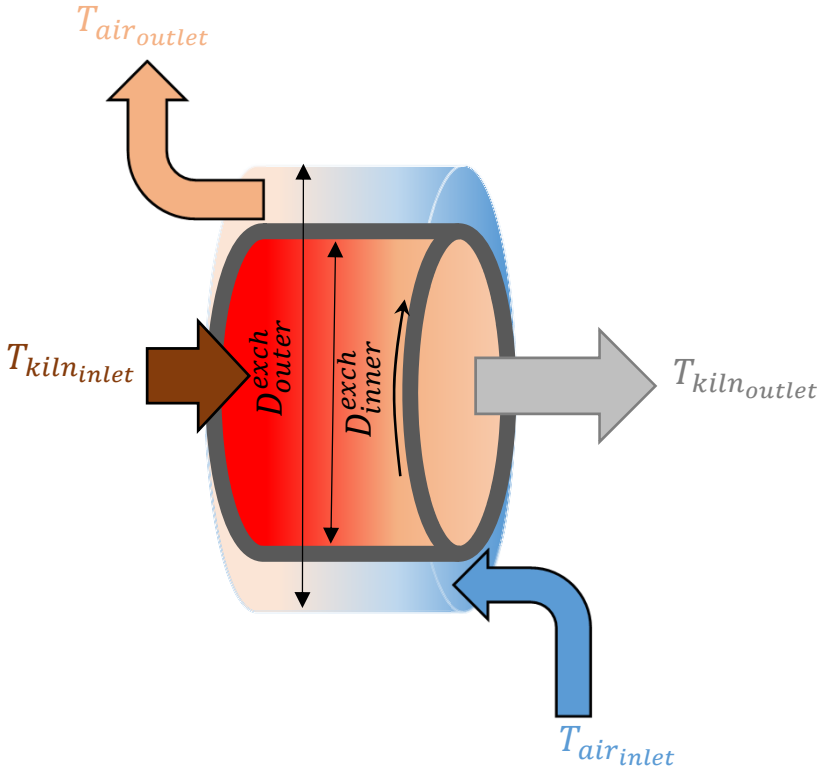


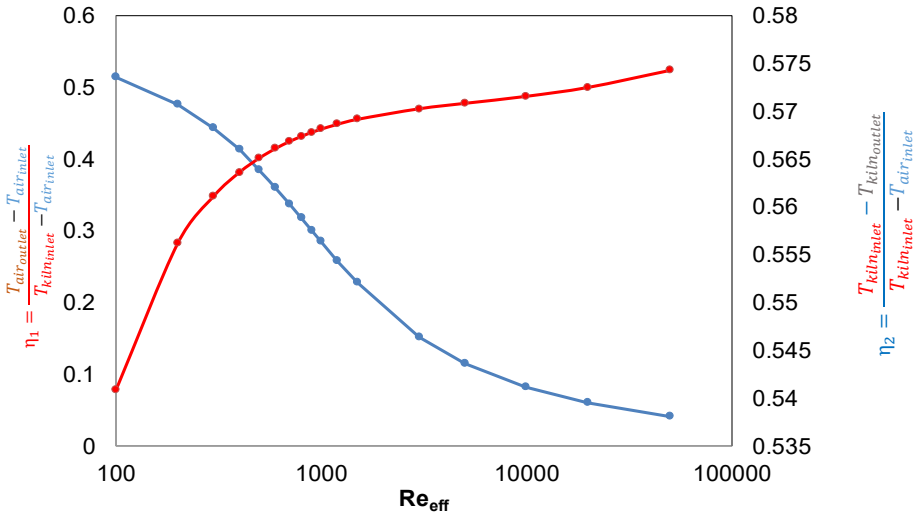


Asphalt materials

3. Heat waste valorization

$$\dot{m}_{air} c_{p\,air} dT_{air} = h_{exch} dS_{inner} (T_w - T_{air})$$

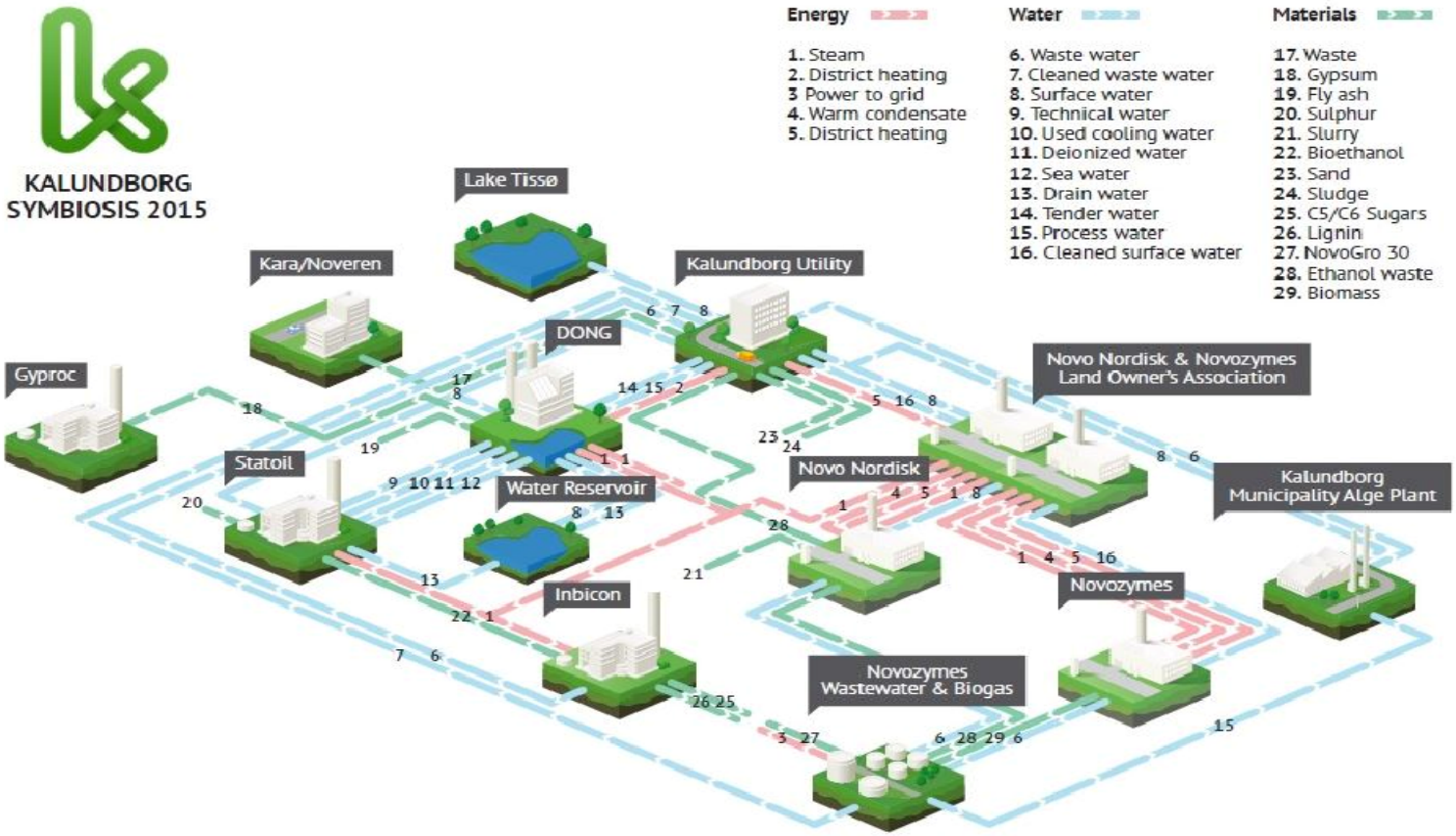




$$Re_{eff} = (V_{eff} \times D_h)/\nu$$

$$V_{eff} = \left(\bar{U}_a^2 + \alpha(\omega {R_i}^2)\right)^{1/2}$$

Toward better management of heat and mass fluxes at the city-scale



- District Heating management / Water / Materials
- Example of Gypsum valorization and Fly ash → plaster and cement production

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