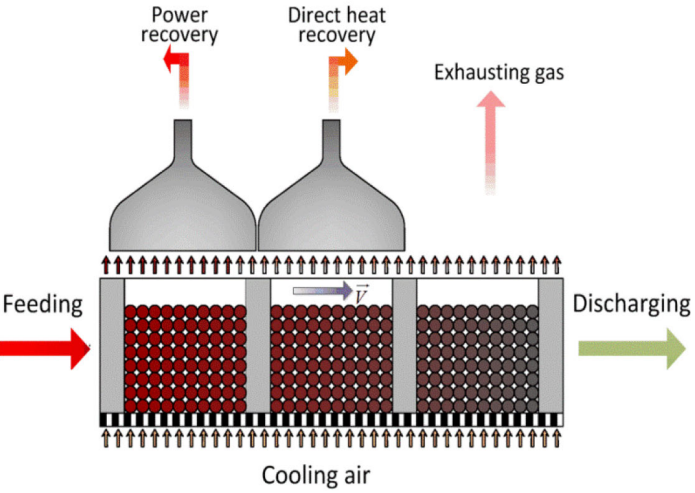
Journal of Zhejiang University-SCIENCE A

Pressure drop in a packed bed with sintered ore particles as applied to sinter coolers with a novel vertically arranged design for waste heat recovery

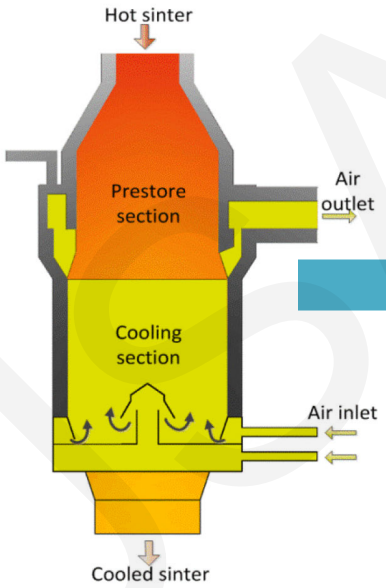
Fu-You TIAN, Lian-Feng HUANG, Li-Wu FAN, Hong-Liang QIAN, Jia-Xi GU, Zi-Tao YU, Ya-Cai HU, Jian GE, Ke-Fa CEN

Cite this as: Fu-you Tian, Lian-feng Huang, Li-wu Fan, Hong-liang Qian, Jia-xi Gu, Zi-tao Yu, Ya-cai Hu, Jian Ge, Ke-fa Cen, 2016. Pressure drop in a packed bed with sintered ore particles as applied to sinter coolers with a novel vertically arranged design for waste heat recovery. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 17(2):89-100. http://dx.doi.org/10.1631/jzus.A1500088

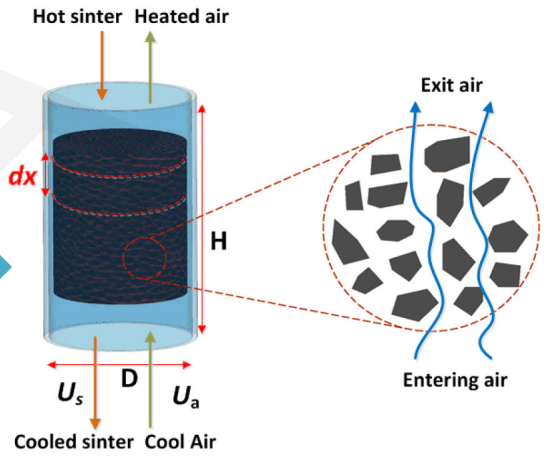
Background



Circular sinter cooler



Vertically arranged sinter cooler



Gas-particle flow of Cooling section

40-50 %	Leakage rate	0
150-450 °C	Waste air temperature	450-550 °C
40 %	Heat recovery efficiency	60-80 %

Moving bed

$U_s \approx (1\sim5)\times10^{-3}$ m/s

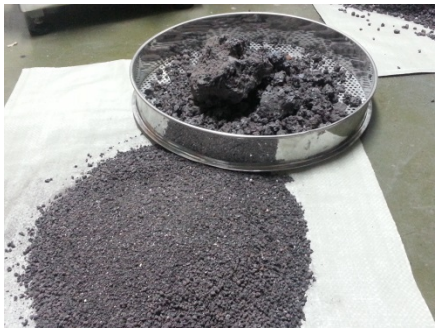
$U_a \approx 1\sim2$ m/s

Supposed $U_s=0$

Packed bed

Pressure drop in the packed bed (gas flow through packed bed)

Experimental - Characterization

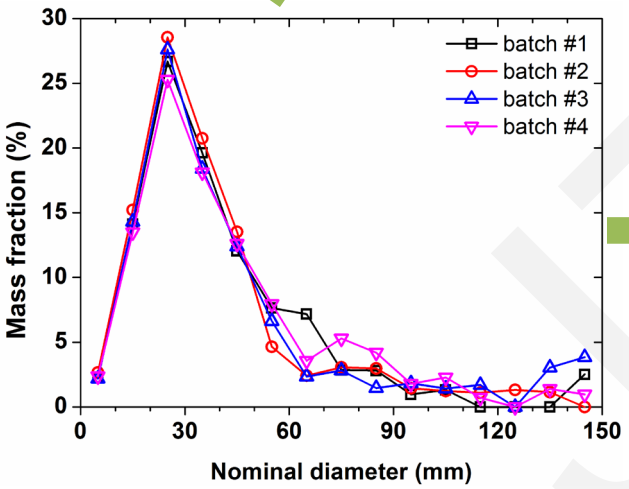


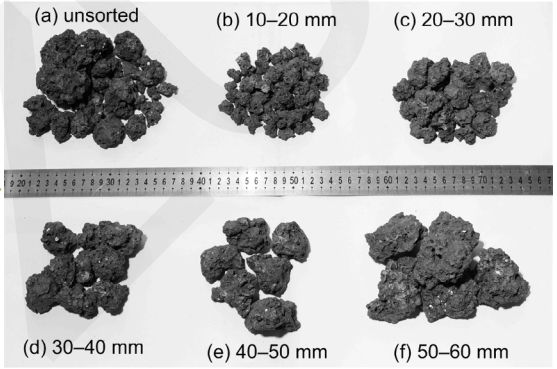
Sieving

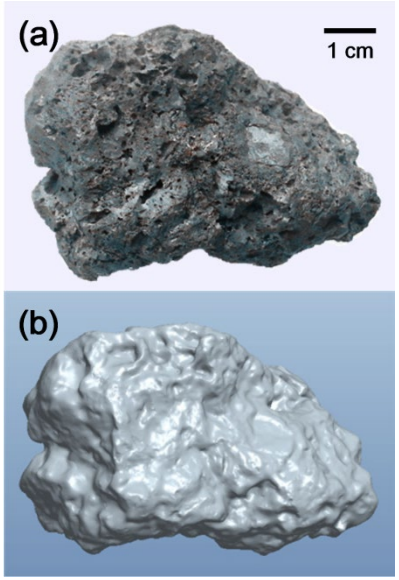
Bulk density

Apparent density

MaxSHOT 3D scanning



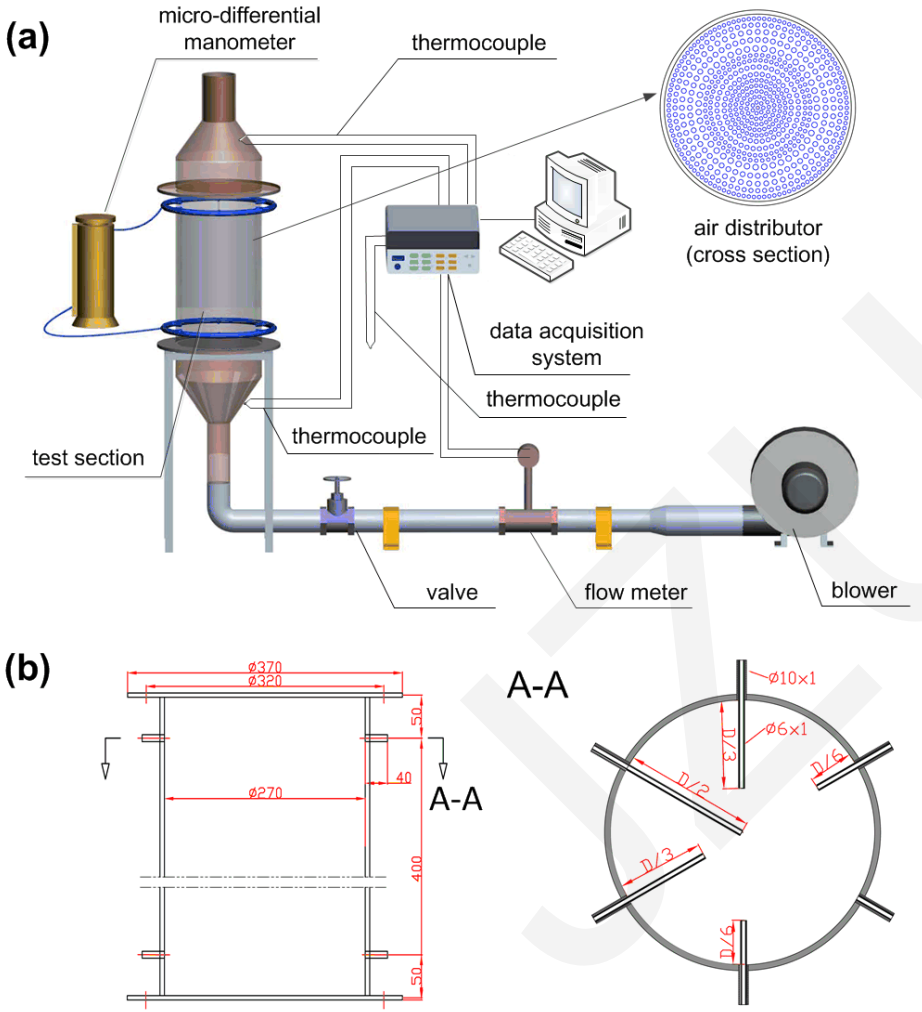




Mass fraction of 10-60 mm: ~80 %

d_p and ϕ

Experimental – Packed bed test setup



Apparatus or instruments	Type	Range	Accuracy
Blower	HTB 100-505	Flow range: 768 m^3/h Pressure: 7900 Pa	---
Vortex flow meter	FV10-FTLND1065	100–600 m^3/h	1%
Compensate-type manometer	YJB-2500	−2500–2500 Pa	±0.8Pa for $\|\Delta P\| < 1.5$ kPa; ±1.3Pa for $\|\Delta P\| \geq 1.5$ kPa
Digital manometer	DP1000III B	0–6000 Pa	50 Pa
Thermocouple	T-type, d_t = 0.3 mm	−200–350 °C	±0.1 °C

Data reduction

Forchheimer Equation

$$\frac{\Delta P}{L}=\frac{\mu}{K}U+\frac{\rho F}{K^{0.5}}U^2 \qquad (1)$$

Modification of Eq. (1)

$$\frac{\Delta P}{LU}=\frac{\mu}{K}+\frac{\rho F}{K^{0.5}}U \qquad (2)$$

Introducing bed characteristics,
Ergun equation

$$\frac{\Delta P}{L}=A\frac{\mu(1-\varepsilon)^2}{d_p^2\varepsilon^3}U+B\frac{\rho(1-\varepsilon)}{d_p\varepsilon^3}U^2 \qquad (3)$$

Modified friction factor

$$f_m=\frac{\Delta P}{L}\frac{d_p^2}{\mu U}\frac{\varepsilon^3}{(1-\varepsilon)^2} \qquad (4)$$

Linear form of Eq. (3)

$$f_m=A+B\mathrm{Re}_m \qquad (5)$$

$$\mathrm{Re}_m=\frac{\mathrm{Re}}{1-\varepsilon}=\frac{\rho U d_p}{\mu(1-\varepsilon)} \qquad (6)$$

Modification of of Eq. (5)

$$f_m=A+B\mathrm{Re}_m^n \qquad (7)$$

For wide range of Re_m

Inertial proportion in pressure drop

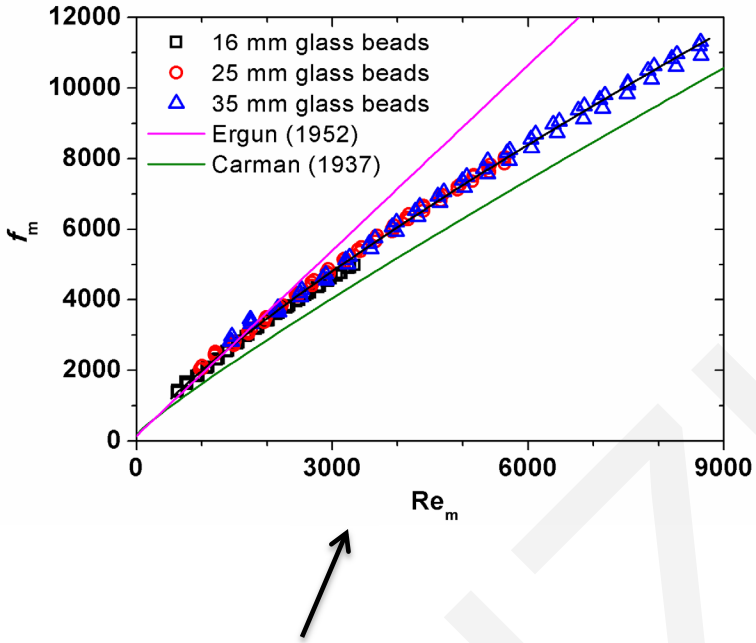
$$X=1-\frac{\mu U}{K}\frac{L}{\Delta P} \qquad (8)$$

***X*>0.71 Transition regime;**

***X*>0.91, Turbulent regime.**

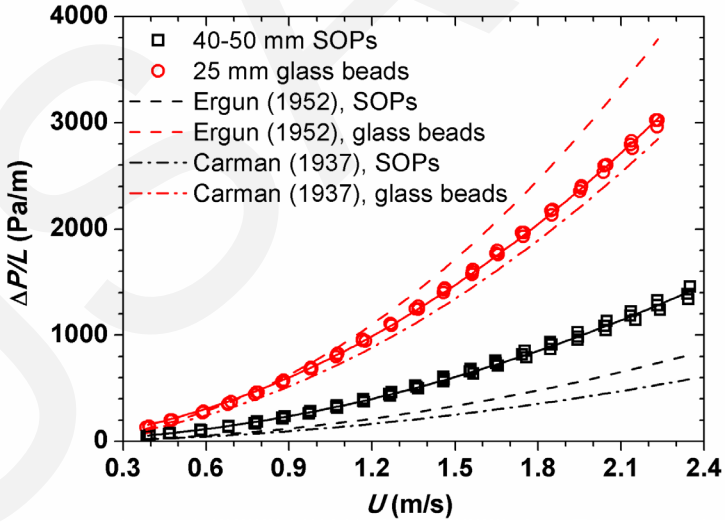
Pressure drop comparison

Glass beads VS. correlations



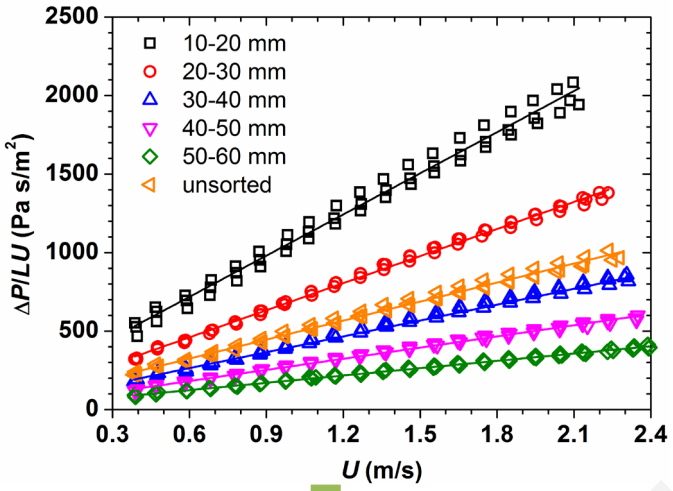
Verify the experimental setup

Sintered ore particles VS. glass beads



VS.

Packed bed parameters and flow regime

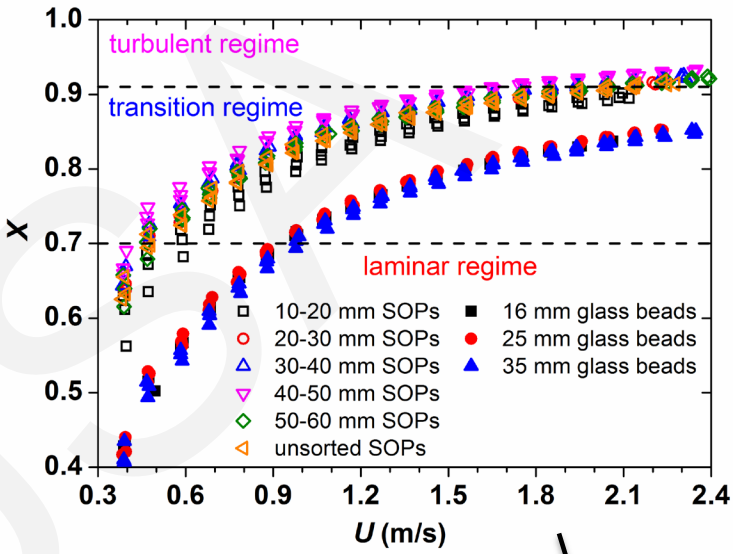


Pressure drop of SOP-filled beds

Particle	Size (mm)	K (10^{-8} m^2)	F
SOP	10–20	9.7	0.24
	20–30	16.1	0.20
	30–40	29.4	0.16
	40–50	47.0	0.14
	50–60	59.6	0.10
	unsorted	22.4	0.16
Glass bead	16	6.0	0.19
	25	11.5	0.14
	35	20.2	0.10

$K_{SOPs} \approx (2\sim3) K_{glass}$

$F_{SOPs} \approx F_{glass}$

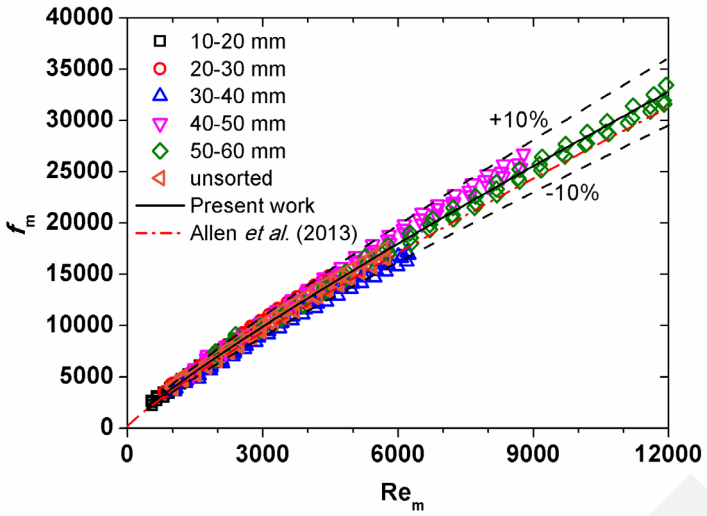


Flow regime

Flow in sinter ore particle bed is disordered and easy to transit.

Pressure drop correlation

Correlations



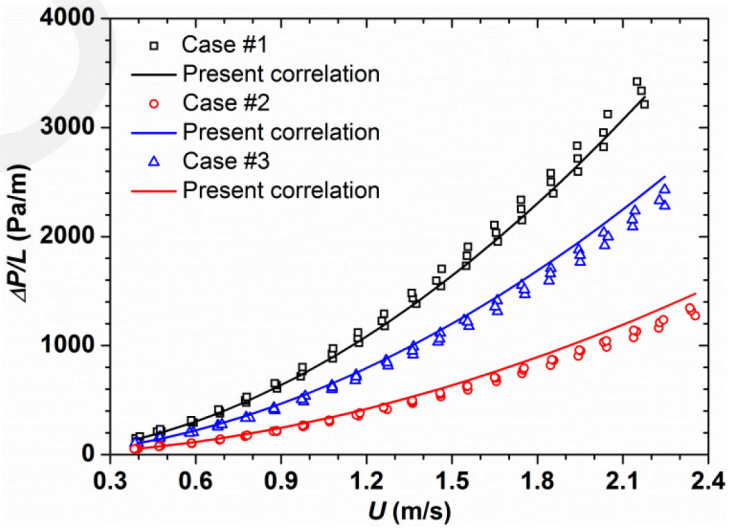
$$f_m = 213 + 8.8\,\mathrm{Re}_m^{0.87}$$

The correlation is comparable with that of Allen *et al.* for rock beds, which is

$$f_m = 200 + 8\,\mathrm{Re}_m^{0.88}$$

Verification

No.	Size (mm)	d_p (mm)	ε	ϕ	D/d_p
1	10–20 (50%), 30–40 (50%)	13.13 ± 4.70	0.562 ± 0.004	0.6383 ± 0.0612	20.5 7
2	30–40 (30%), 40–50 (30%), 50–60 (40%)	24.06 ± 5.98	0.595 ± 0.004	0.6348 ± 0.0554	11.2 2
3	equally-weighted for 10–60	16.81 ± 7.75	0.566± 0.004	0.6384 ± 0.0515	16.0 6



Within ±10 % range.

Summary and suggestions

- Main conclusions are
  - The original Ergun equation fails to predict the pressure drop over the packed bed with such highly irregularly shaped SOPs, with the underestimation by the Ergun equation being found to be ~40%.
  - The modified friction factor fit well to a scaled Ergun equation: $f_m = 213 + 8.8\,\mathrm{Re}_m^{0.87}$, which is valid for modified Re numbers ranging from 500 to 12,000.
- Future studies may focus on
  - the wall effect on the pressure drop of SOP-filled beds
  - the trickle flow of SOPs on the pressure drop
  - heat transfer between the SOPs and air flow