Experimental measurement of the heat transfer coefficients for gas flow through granular porous media

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Problem of interest

Local thermal non equilibrium equations (LTNE)

effective gas thermal conductivity

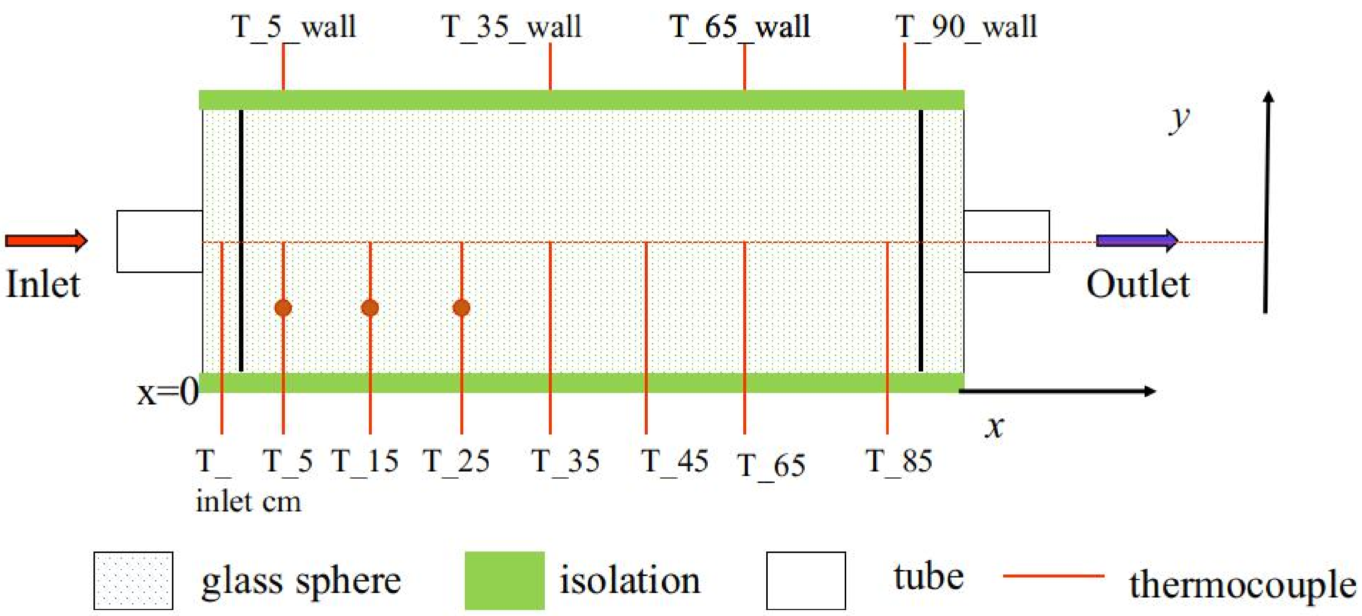
fluid phase $$\varepsilon(\rho c_p)_g \frac{\partial T_g}{\partial t} + (\rho c_p)_g u \cdot \nabla T_g = k_{g,eff} \nabla^2 T_g + h_v (T_s - T_g)$$

solid phase $$(1-\varepsilon)(\rho c_p)_s \frac{\partial T_s}{\partial t} = k_{s,eff} \nabla^2 T_s + h_v (T_g - T_s)$$

effective solid thermal conductivity

Heat transfer coefficients between flow and sphere

Experiment setup and test procedure



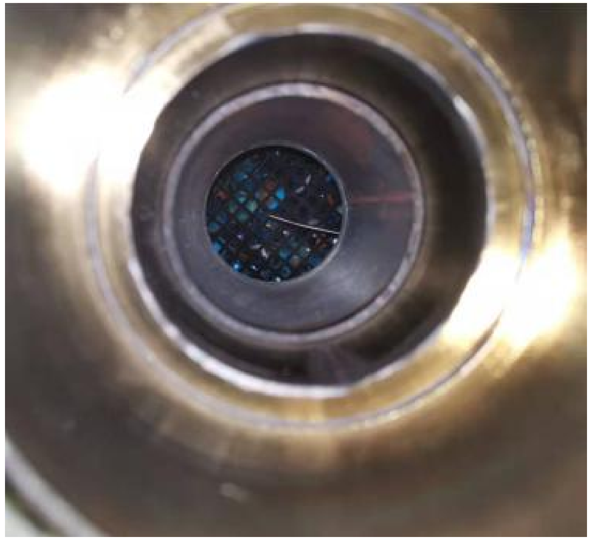
Tube size: 1000mm length, 194mm diameter, iron tube,

Measuring points: **seven central axis locations** (x =50, 150, 250, 350 ,450, 650, 850 mm),

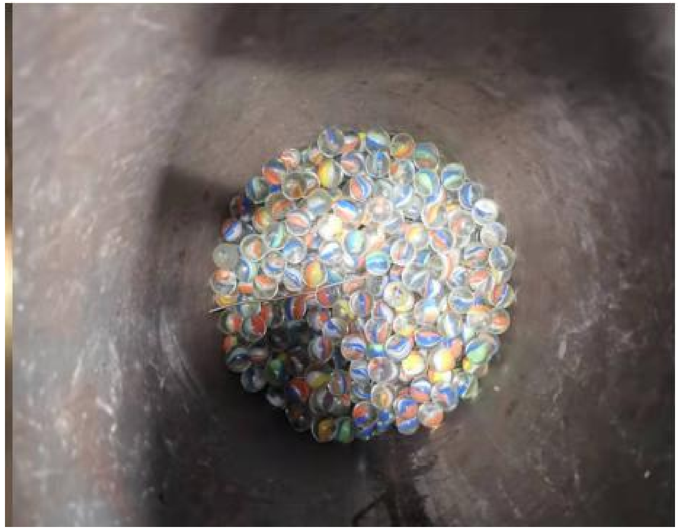
three radial locations (x=50mm, y=45 mm; x=150mm, y=45 mm; x=250mm, y=45 mm),

four wall surface locations (x = 5, 350, 650, 900 mm).

Experiment setup and test procedure



a). Thermocouple in the inlet part

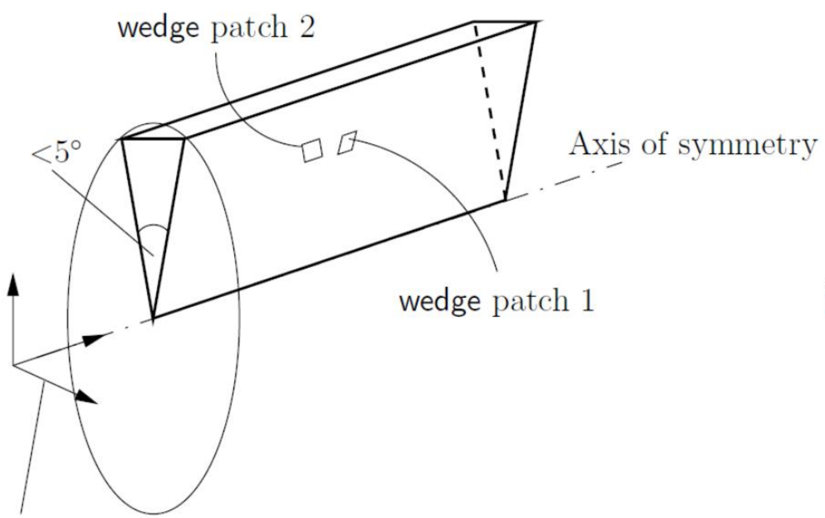


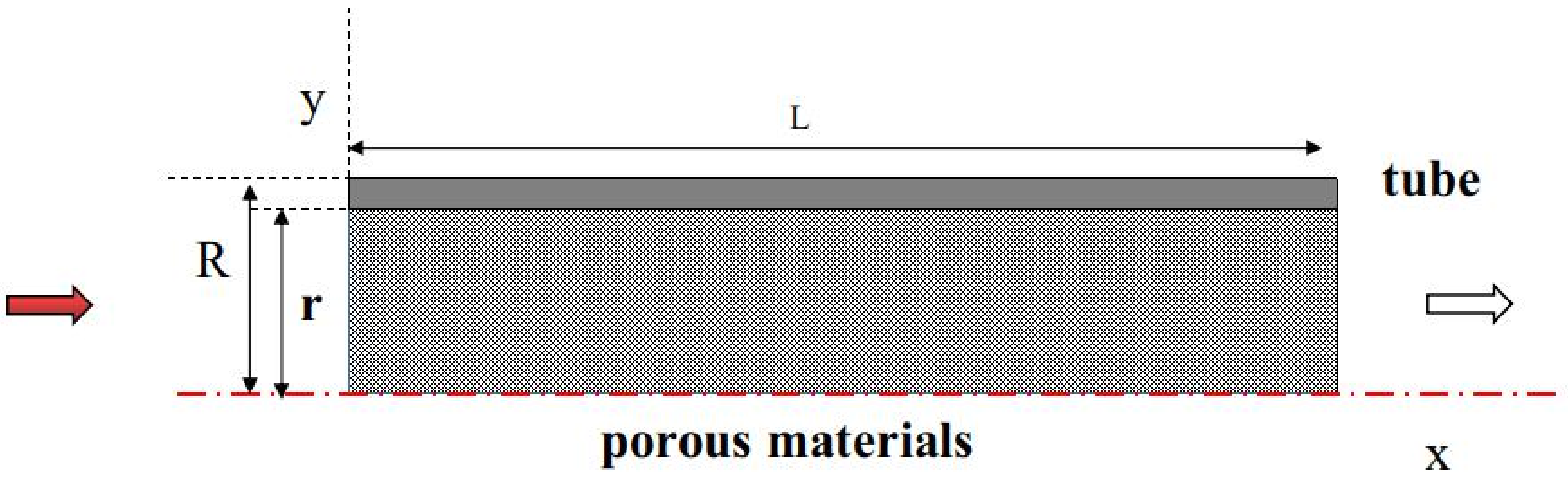
b). Thermocouple in the center part

c). Thermocouple measuring gas temperature

d). Rockwool insulation at outside of the tube

Numerical analysis



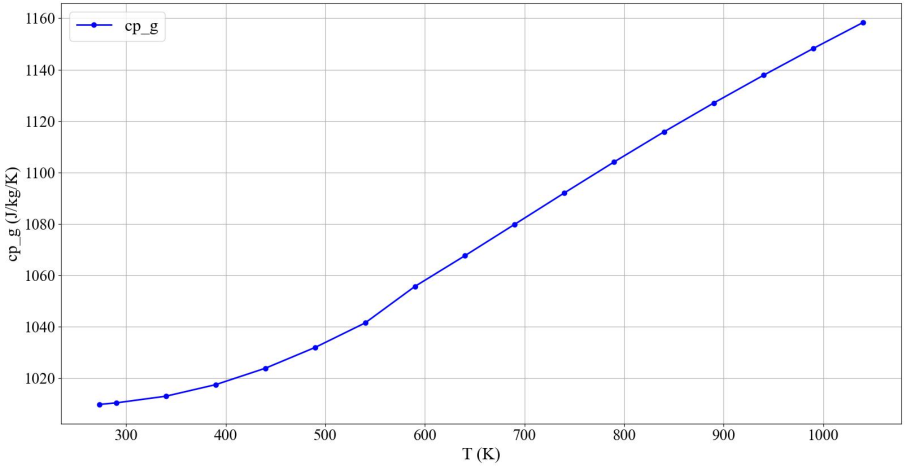


Mathematical model: LTNE model, Forchheimer's Law (porous region), Heat conduction (tube region)

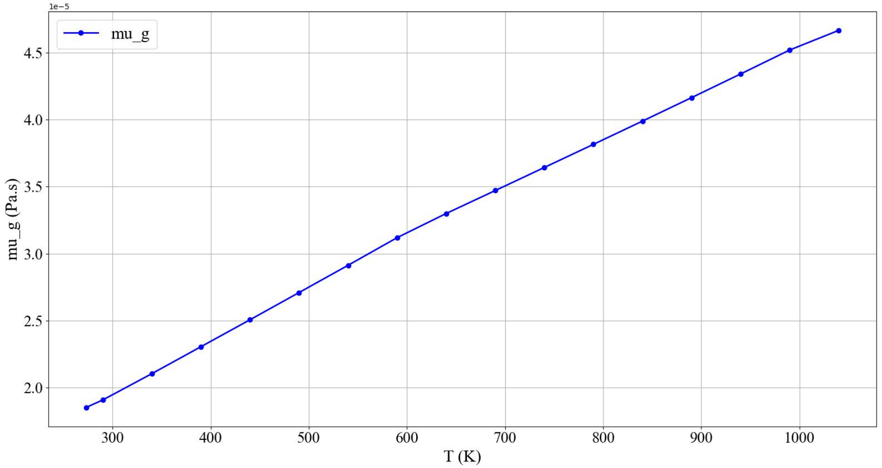
Forchheimer's Law: $\nabla p = -\mu \mathbf{K}_{\mathbf{s}}^{-1} \cdot (\mathbf{v}_g \cdot \varepsilon) - \beta \rho_g (\mathbf{v}_g \cdot \varepsilon)^2 + \rho_g \mathbf{g}$

Numerical analysis

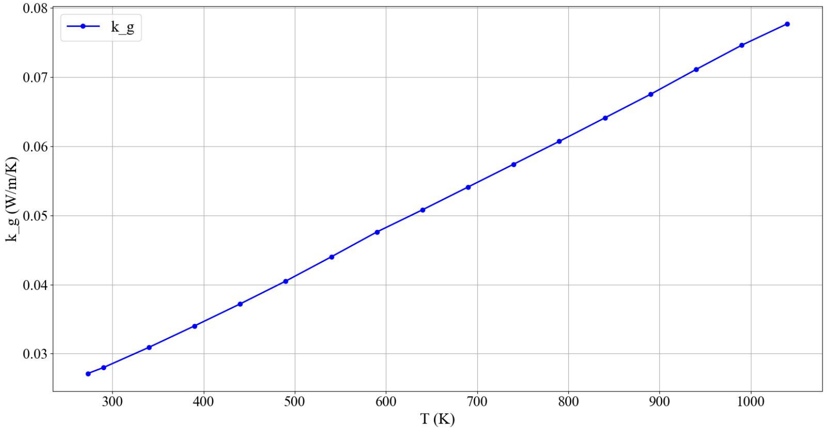
Temperature-dependent thermophysical properties of gas and solid



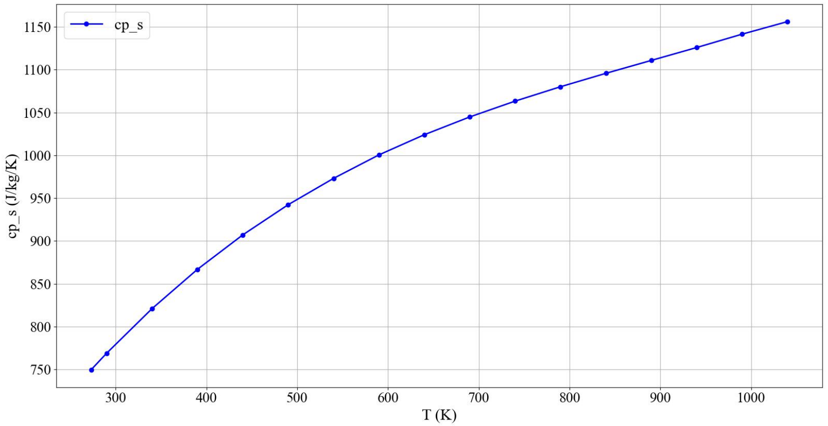
a) cp_{g} (J/kg/K)



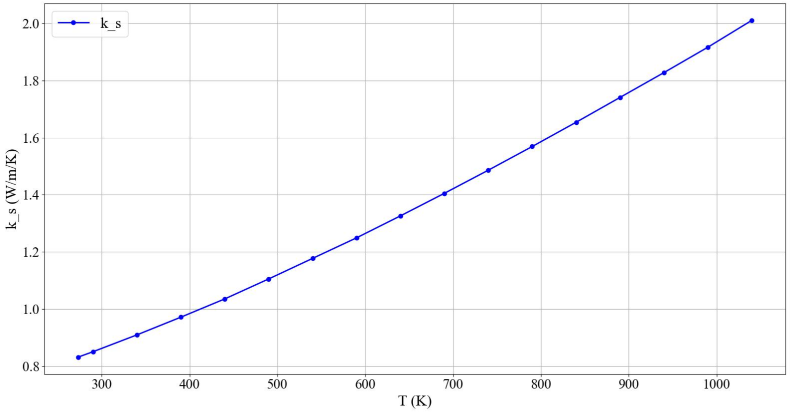
b) μ_{g} (Pa · s)



c) k_{g} (W/m/K)



d) cp_{s} (J/kg/K)



e) k_{s} (W/m/K)

Numerical analysis

Effective solid and gas thermal conductivity $k_{s,eff}$, $k_{g,eff}$, in LTNE model

$$k_s(T) = 0.59206 + 0.00062T + 1.0013 \times 10^{-6}T^2 - 2.778 \times 10^{-10}T^3$$ **Solid**

$$k_g(T) = 0.00825 + 6.662 \times 10^{-5}T$$ **Gas**

c1: $$\mathbf{k}_{\text{s,eff}} = (1-\varepsilon)k_s + \mathbf{k}_{\text{eff}}^{\mathbf{C}} + \mathbf{k}_{\text{eff}}^{\text{R}} = c1 \cdot k_s(T)$$ [1] **Solid**

c2: $$k_{g,eff,\parallel} = \varepsilon k_g + c2 \cdot d_p \cdot \varepsilon \cdot |\mathbf{v}_g| \cdot \rho_g \cdot cp_g$$ [2] parallel to flow direction

c3: $$k_{g,eff,\perp} = \varepsilon k_g + c3 \cdot d_p \cdot \varepsilon \cdot |\mathbf{v}_g| \cdot \rho_g \cdot cp_g$$ perpendicular to flow direction

f: $$h_v = \frac{6(1-\varepsilon)}{d} \cdot \frac{2 + f\,\text{Re}^{0.6}\,\text{Pr}^{1/3}\,k_g}{d}$$ [3] Wakao correlation

$\mathbf{k}^{\mathbf{C}}_{\mathbf{eff}}$: The contributions of contact conduction. $\mathbf{k}^{\mathbf{R}}_{\mathbf{eff}}$: The contributions of radiation between solids.

[1] Esence, T et al, 2017, Solar Energy 153, 628–654. [2] Wakao and Kaguei, 1982, Gordon and Breach Science Publishers, 364-368.

[3] Wakao and Kaguei, 1979, Chemical engineering science 34, 325–336.

Dakota Sensitivity analysis and optimization process

Design Analysis Kit for Optimization and Terascale Applications (Dakota)

1 Sensitivity analysis

Input parameters: *f, c1, c2, c3* **Output error:** *S*

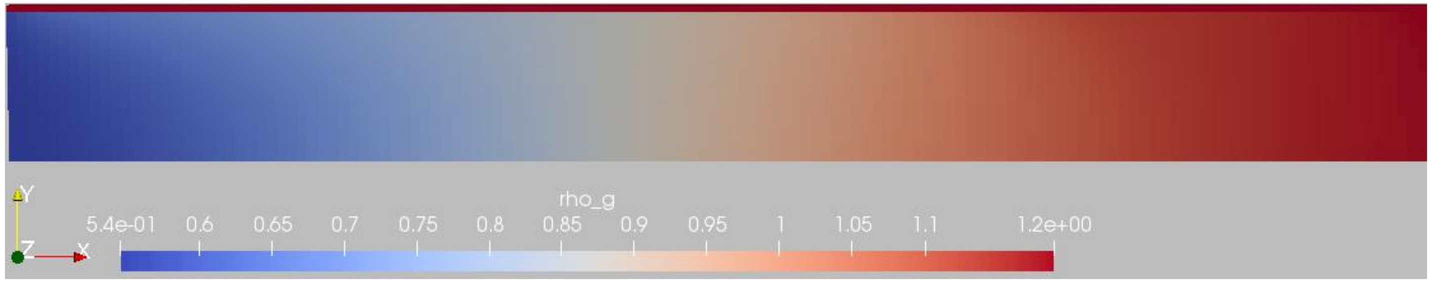
$$S=\frac{1}{8}\left(\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{T^i_{s1,num}-T^i_{s1}}{T^i_{s1}}\right)^2}+\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{T^i_{s2,\mathrm{num}}-T^i_{s2}}{T^i_{s2}}\right)^2}+\ldots\ldots+\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{T^i_{s8,num}-T^i_{s8}}{T^i_{s8}}\right)^2}\right)$$

2 Optimization process

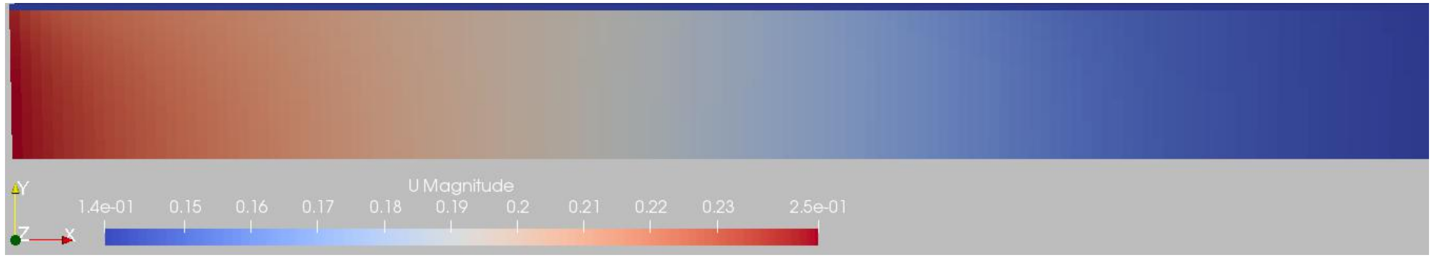
Input parameters: *f, c1, c2,* **Output error:** *S*

Numerical analysis

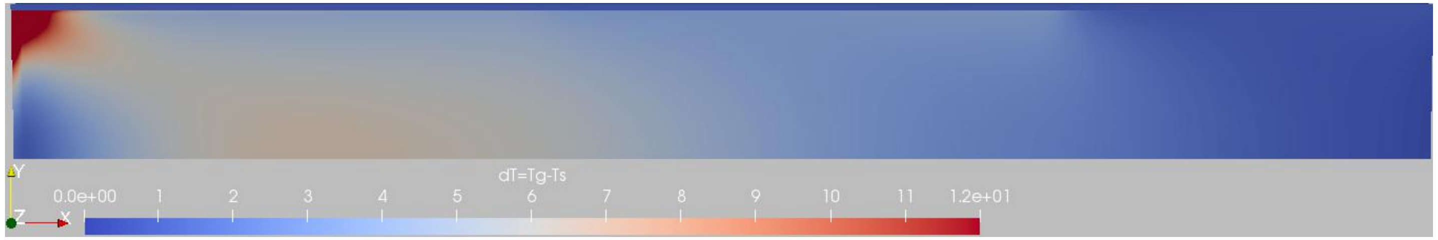
μ_g (Pa · s)



ρ_g (kg/m^3)



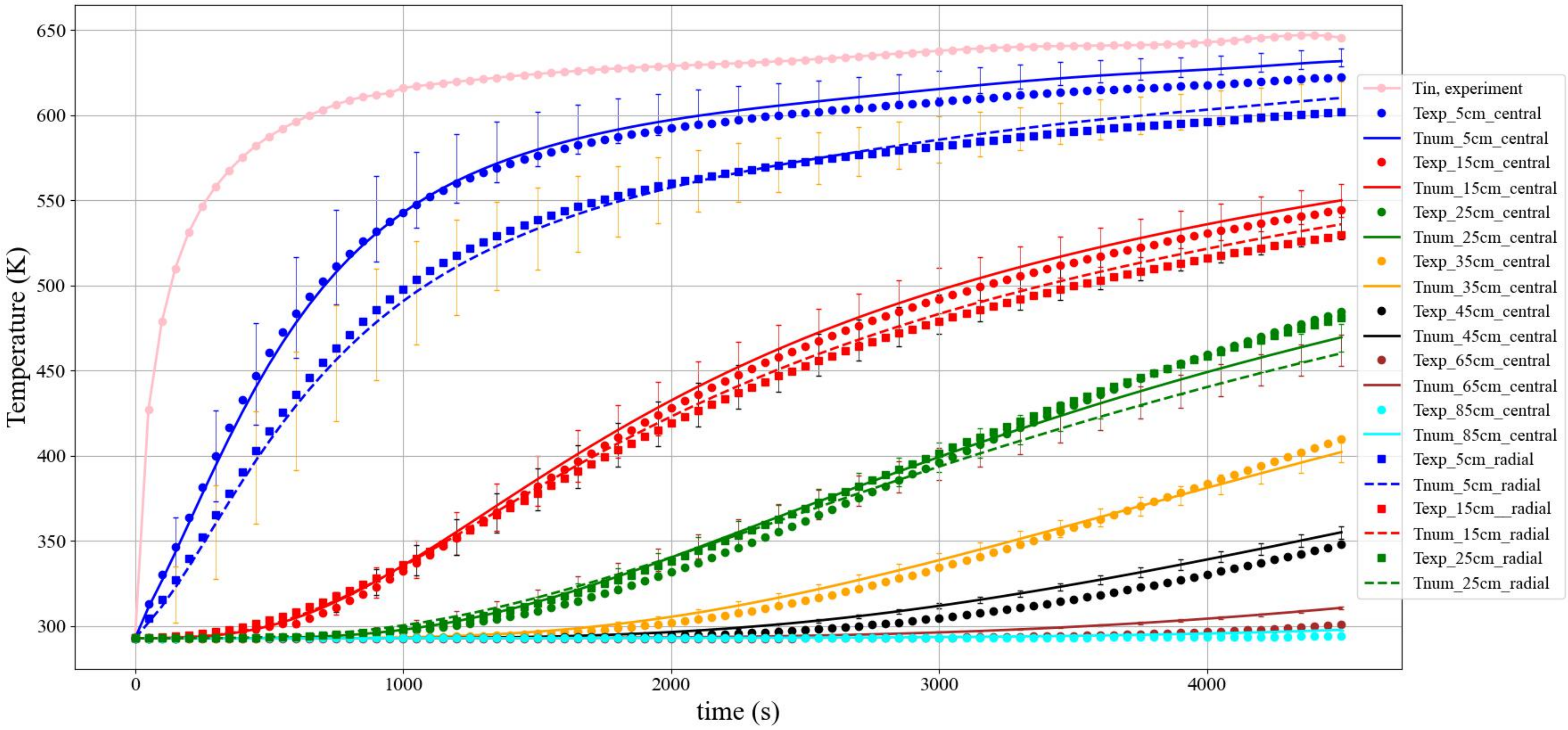
u (m/s)



dT= Tg-Ts (K)

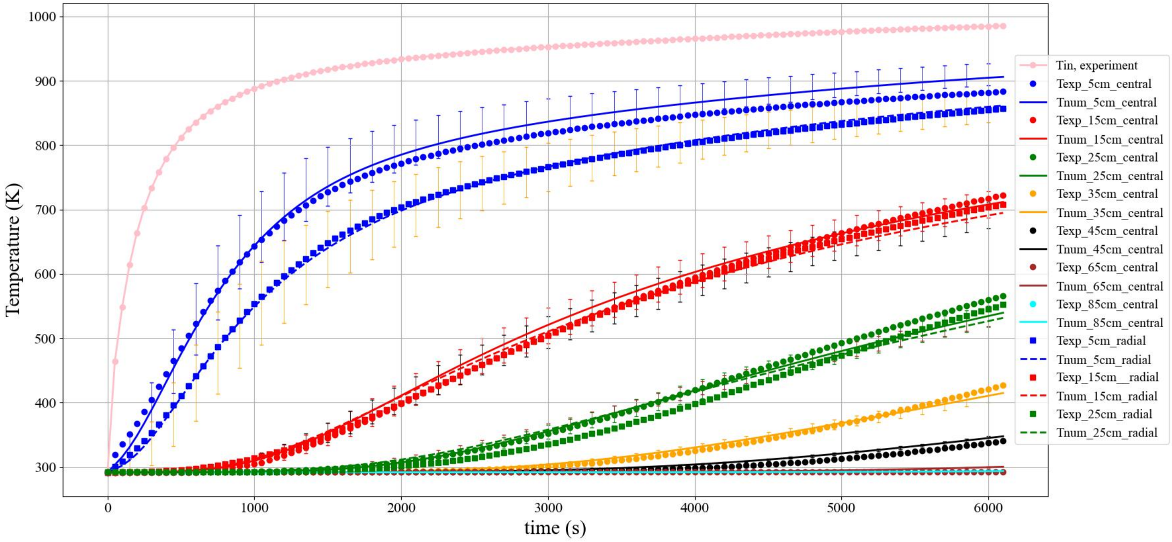
Results and discussion

Typical time variation of the temperature from experimental, numerical methods

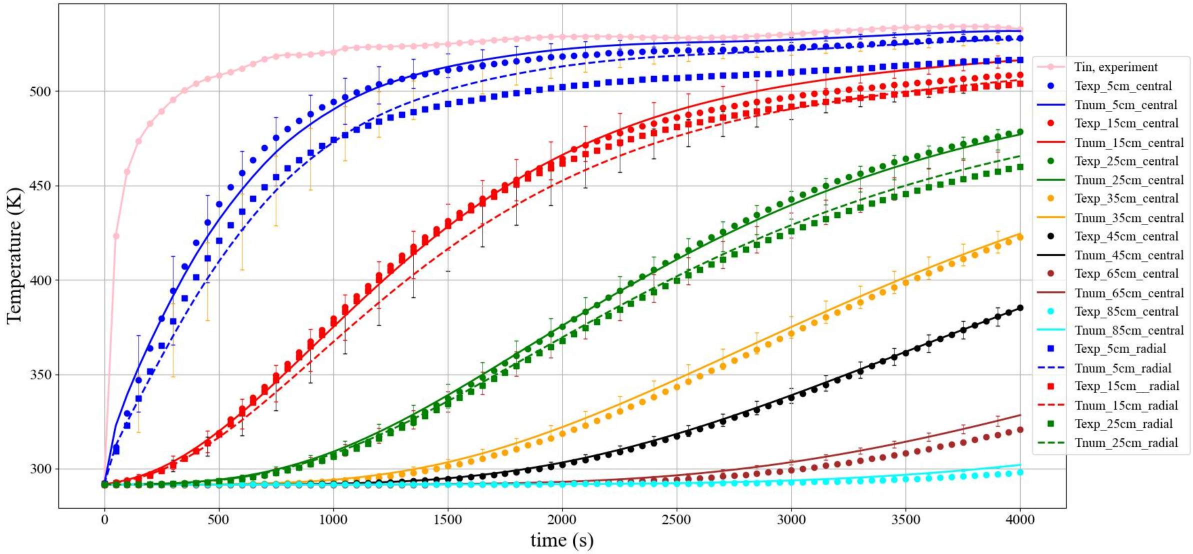


Point: experimental data **Line:** numerical data $\mathbf{T_{inlet}}$: 293- 650K **Re:** 58-100

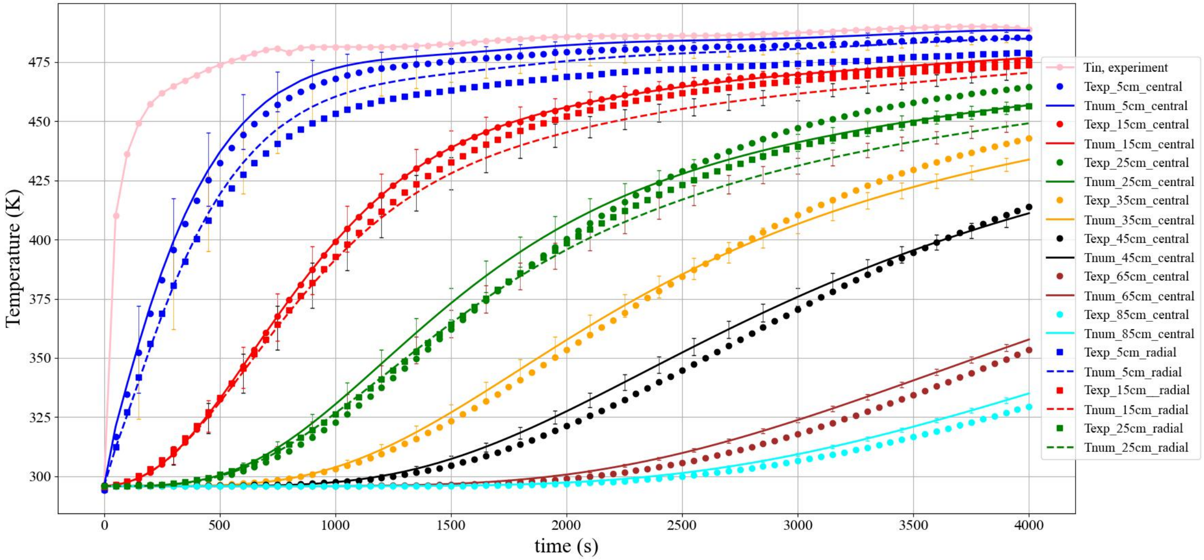
Results and discussion



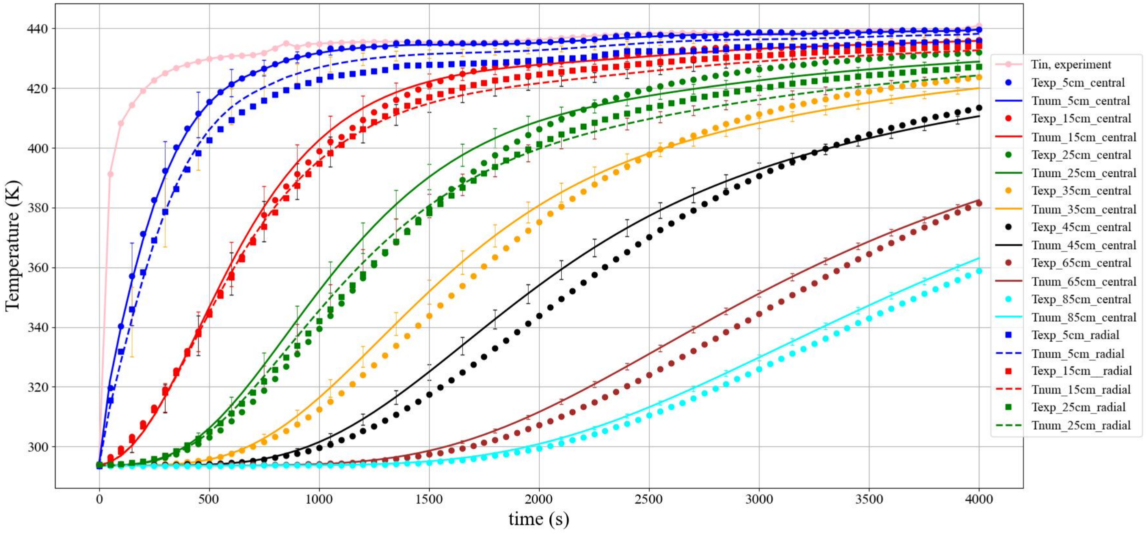
T_{inlet}: 293- 1000K **Re:** 32-54



T_{inlet}: 293- 540K **Re:** 100-151



T_{inlet}: 293- 480K **Re:** 150-190



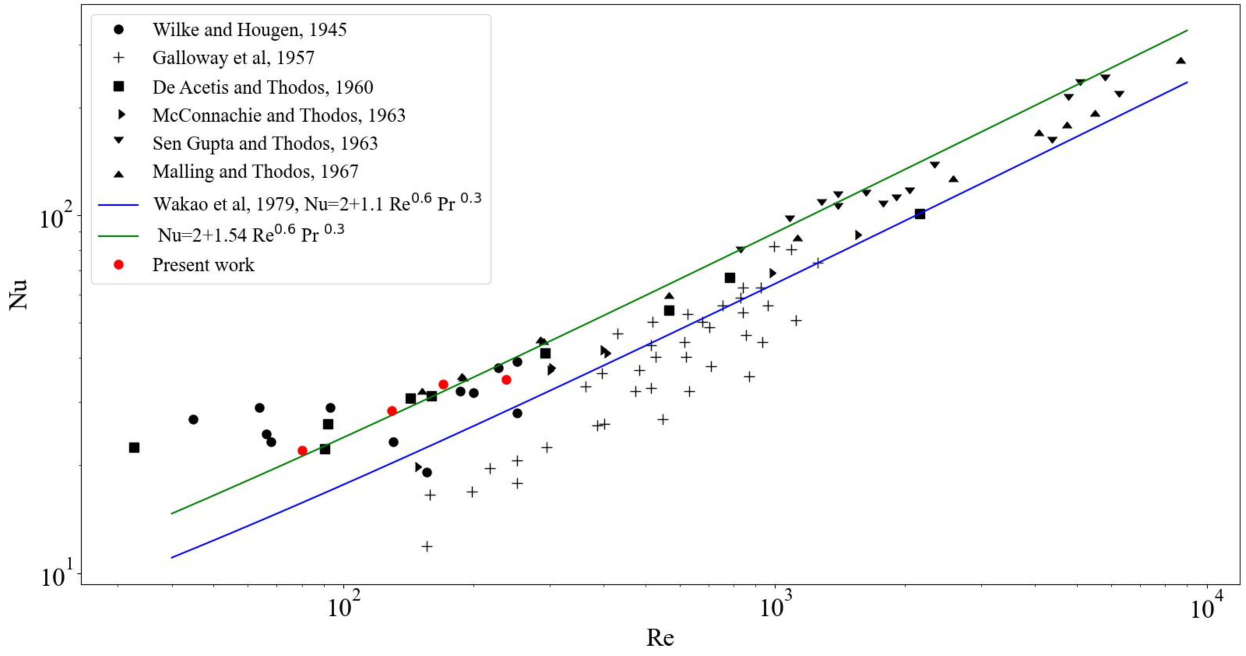
T_{inlet}: 293- 440K **Re:** 223-252

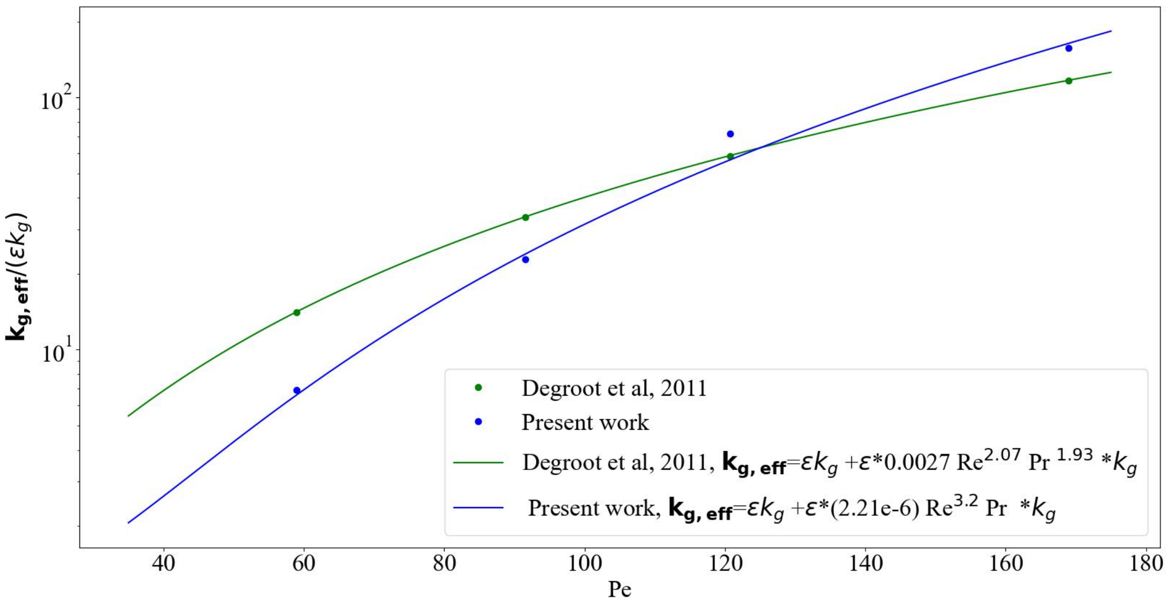
Results and discussion

The value of *f* , *c1* , *c2* obtained in the optimization process

	Case 1	Case 2	Case 3	Case 4
q_m (kg/s)	3.65e-3	5.97e-3	7.34e-3	1.02e-2
Re	58-100	100-151	150-190	223-252
f	1.61 ± 0.09	1.59±0.07	1.65±0.07	1.34±0.09
c1	1.22 ± 0.03	1.23±0.03	1.25±0.03	1.29±0.03
c2	0.039±0.004	0.09±0.008	0.24±0.02	0.38±0.03
hv (W/(m³ K))	1e4-1.3e4	1.15e4-1.45e4	1.54e4-1.83e4	1.72e4-1.95e4
$k_{g,eff,\parallel}$ (W/(m K))	0.083-0.094	0.29-0.31	0.98-1.08	2.14-2.22
$k_{s,eff}$ (W/(m K))	1.1-1.6	1.1-1.5	1.1-1.4	1.2-1.4
Bi	0.9-1.17	1.05-1.28	1.32-1.41	1.44-1.67
S	0.0117-0.0119	0.0137-0.0139	0.0102-0.0105	0.0098-0.01

Results and discussion





$$Nu = 2 + 1.54\, Re^{0.6}\, Pr^{0.3}$$

$$k_{g,eff} = \varepsilon\, k_g + \varepsilon\, (2.21e\text{-}6)\, Re^{3.2}\, Pr\, k_g$$

Conclusions

1 The variable gas and solid thermophysical properties are utilized over a wider range of temperature (273K to 1030K). This temperature-dependent thermophysical model is validated at different flow rates.

2 The results show that the value of h_v in the LTNE model is around 1.5e4 W/(m^3 K). Gas and solid temperatures are in LTNE within packed bed in the conditions of the experiment.

3 The dispersion term is added to the $k_{g,eff}$ in gas phase equation. A factor c2 is obtained in the flow direction. The $k_{g,eff,\parallel}$ changes from 0.012 W/(m K) to 0.096 -1.2 W/(m K) when *Pe* is in the range of 60 to 180.

Thank you for your attention

We would like to thank Loubna CHAHDAOUI for her assistance in experiments