



Fluid Dynamics and Transport Phenomena

Thermophoresis effects on gas-particle phases flow behaviors in entrained flow coal gasifier using Eulerian model



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ABSTRACT

A numerical model based on the Eulerian–Eulerian two-fluid approach is used to simulate the gasification of coal char inside an entrained flow gasifier. In this model, effects of thermophoresis of coal char particles are thoroughly investigated. The thermophoresis is due to the gas temperature gradient caused by absorbed heat of coal char gasification. This work, firstly, calculates the gas temperature gradient and thermophoretic force at 1100 °C, 1200 °C, 1300 °C and 1400 °C wall temperatures. Then, the changes of particle volume fraction and velocity in the gasifier are studied in the simulation with thermophoresis or not. The results indicate that considering the particle thermophoresis has some effects on the calculation of particle volume fraction in the gasifier, especially at wall temperature of 1400 °C, and the maximum particle volume fraction variance ratio reaches up to 1.38% on wall surface of the gasifier. These effects are mainly caused by large gas temperature gradient along the radial direction of the gasifier. For the particle velocity, the changes are small but can be observable along radial direction of the gasifier, which has good agreement with the distributions of radial gas temperature gradient and thermophoretic force. These changes above may have certain effects on gasification reaction rates in this Eulerian model. So the change of gasification reaction rates in the simulation with thermophoresis or not is studied finally.

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1. Introduction

The Study on the pulverized coal gasification has attracted interests of researchers. Improvements of experimental studies have laid a firm foundation for coal gasification study. Ahn *et al.* [1] studied the effects of gasification temperature pressure on gasification kinetics of coal-char with CO₂ at elevated pressure with a pressurized drop tube furnace reactor. Kajitani *et al.* [2,3] concluded the gasification rate of four different coal chars gasified with CO₂ using a PDT or TGA at high temperature and pressure.

In addition, establishing a coal gasification simulation model is also important for the investigation of coal gasification. Irfan *et al.* [4] reviewed the kinetics and the reaction rate equations for char-CO₂ gasification both in the reaction kinetic control region (low temperature) and the diffusion control region (high temperature) and at both low and high pressures. Their work facilitates the further improvement of the coal gasification model. As is known, coal gasification system is one of gas-particle phases flow reaction systems. Both Lagrangian and Eulerian models have been applied to simulating gas-particle phase flow system. Compared to the Lagrangian model, the Eulerian model treats all different phases mathematically as continuous and fully interpenetrating and reducing number of governing equations. Vicente

et al. [5] developed a coal gasification simulation model in entrained flow coal gasifier using Eulerian methods, considering gravity and drag in the model. Their results show good agreement for both the main and minor species, and temperature with experimental data. In this paper, a new Eulerian model based their work was established, considering particle thermophoretic force besides gravity and drag.

The particles suspended in a gas with a temperature gradient are subject to a force called thermophoretic force, directed in the opposite direction to the temperature gradient. Toda *et al.* [6] examined the relation between the diameter of particles and thermophoretic effect accurately by getting rid of the particle movement induced by the effects of natural convection and gravity. They found that smaller particles receive more remarkably the thermophoretic effect than larger ones and the effects are sensitive with the diameter especially for particles of small diameter and/or low thermal conductivity. Epstein [7] proposed a theoretical model for calculating thermophoretic force for small Knudsen numbers but their results show poor agreement between the experimental results obtained by Schadt and Cadled [8]. Brock [9] extended Epstein's analysis and obtained better agreement. Talbot *et al.* [10] studied velocity profiles of seed particles driven by thermophoretic force in the laminar boundary layer adjacent to a heated flat plate. They found that the theory of Brock, with an improved value for the thermal slip coefficient, gave the best agreement with experiment for low Knudsen numbers.

Char gasification could cause certain gas temperature gradients along both axial and radial two directions in the gasifier. So thermophoretic

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force may have some effects on migration of coal-char particles, especially sufficiently small ones. However, considering the effects of particle thermophoresis in coal gasification has not appeared in previous studies and this study is essential for coal gasification simulation.

This paper studied the temperature gradient and thermophoretic forces along both gasifier axial and radial two directions at wall temperatures of 1100 °C, 1200 °C, 1300 °C and 1400 °C. It also presented compared calculated results of particle volume fraction, velocity, and gasification reaction rate whether particle thermophoresis is considered in the gasification model. Talbot's theoretical model for particle thermophoresis is adopted in this paper, owing to its similar conditions with ours.

2. Char-CO₂ Entrained Flow Gasifier

The geometric model in this study is based on the experimental furnace adopted in Ref. [1] and its diameter is 52 mm. The geometry of the reactor is cylindrical. For a coal gasified in a gasifier, it is in a reducing environment and the temperature is not as high as that of fuel combustion. For these reasons, the following assumptions are adopted to simplify the physical problem. (1) The flow field is steady, axisymmetric, incompressible. (2) The wall temperature of the gasifier is uniform which has been adopted in other studies [11–13]. (3) The inlet temperature is heated to the size of corresponding wall temperature. Because of the assumption of axisymmetric flow, the three-dimensional gasifier can be reduced to a two-dimensional reactor in the simulation [14]. The geometric model is shown as Fig. 1 and the length is set as 500 mm

The mapped mesh method is adopted in this model which is helpful to reduce the calculating error. To validate the grid dependence, four grid sizes are adopted in this geometry to simulate a simply coupling problem of flow and heat transfer. The wall temperature is 1100 °C and the inlet temperature 25 °C. The inlet velocity is 0.1 m·s⁻¹ and CO₂ as the flow medium. As Fig. 2 shows, the grid size of 600 × 20 can meet the requirements of grid independence.

The conditions of char gasification are determined as Table 1. A mixture of reactant gas including CO₂ and N₂ gases is admitted into the gasifier at a flow rate of 0.5 m·s⁻¹. So the flow in the gasifier is streamline and the problems of turbulent flow are not considered through the course of this study. The ultimate analysis of coal and coal

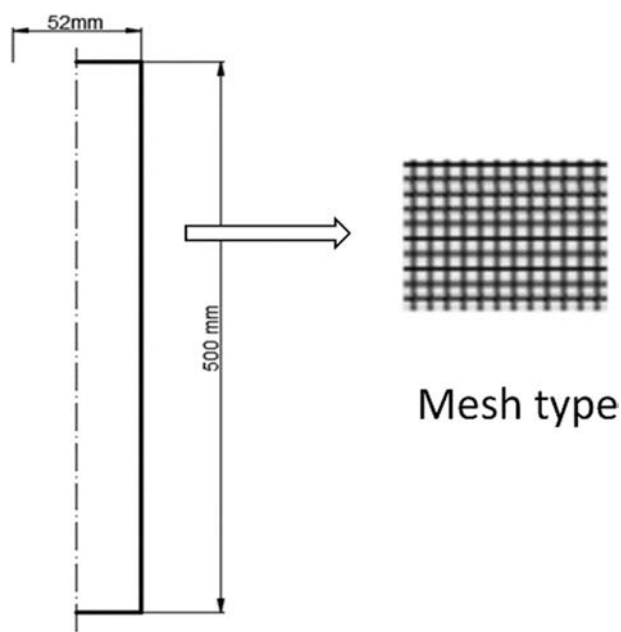


Fig. 1. The physical model of entrained flow coal gasifier.

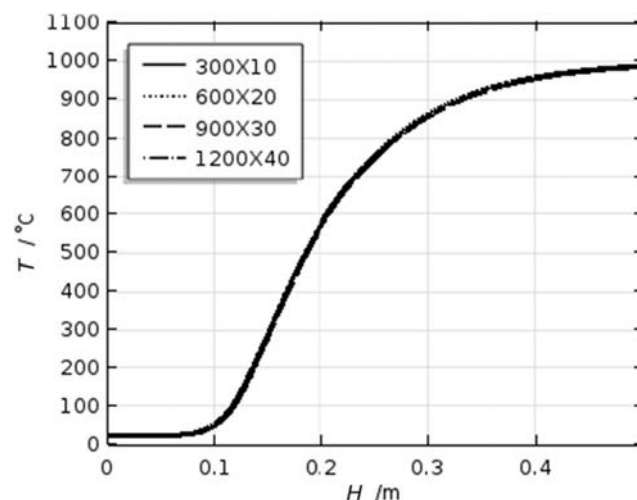


Fig. 2. The temperature distribution along the gasifier central axis with different grid sizes.

char used in the simulation is summarized in Tables 2 and 3. This paper needs to assume that only char density changes in the gasification reaction and the volume will keep constant. The way of the change of char density is given:

$$\frac{\partial \rho_p}{\partial t} + \nabla \mathbf{u}_p \cdot \nabla \rho_p = -R \quad (1)$$

where R is the value of the reaction rate expressed by carbon mass concentration, kg·m⁻³·s⁻¹. Moreover, the carbon conversion (X) in the gasification reaction is defined as Eq. (1):

$$X = 1 - \frac{C_x A_o}{C_o A_x} \quad (2)$$

where A is the mass fraction of ash and C is the mass fraction of carbon in the coal char at any time. The subscripts of “o” and “x” are the un-reacted coal char and the reacted coal char, respectively.

Table 1
Conditions of char-gasification [1]

Total pressure/MPa	1.0
CO ₂ partial pressure/MPa	0.2
Wall temperature/°C	1100, 1200, 1300, 1400
Gas inlet velocity/m·s ⁻¹	–0.5
Inlet temperature/°C	Wall temperature
Inlet volume fraction of coal char (1)	0.001
Density of coal char/kg·m ⁻³	1850
Diameter of coal char particle/μm	50
Convergence error	0.01

Table 2
Properties of Indonesian Rotor coal [1]

Ultimate analysis					Proximate analysis				Particle size/μm	
C	H	O	N	S	Mo.	VM	FC	Ash		
70.0	5.2	23.65	1.0	0.2	2.5	48.0	48.0	1.5	45–64	

Table 3
Ultimate analysis of Rotor coal char and chemical analysis of ash [1]

Ultimate analysis	C	H	O	N	S	Ash	Total	
Drybase/wt%	89	1.9	0.1	1.4	0.2	7.5	100	
Ash property	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	TiO ₂	CaO	MgO	K ₂ O	Na ₂ O
/wt%	15.15	37.93	21.47	0.73	0.2	12.02	2.57	0.98

In addition, the gasifier is heated up by the fixed wall temperature. It is assumed that the initial and inlet gas temperatures remain consistent with wall temperature. At the entrance of the gasifier, the difference between gas and particle temperature has been ignored, too.

3. Numerical Method

A Eulerian model was establishing in this paper based on the experimental equipment adopted in Ref. [1]. The particle thermophoresis model would be added to this model and the effects of particle thermophoresis on coal-char gasification was considered in the simulation in this study. The main governing equations include continuity equations, momentum equations along the gasifier axial and radial directions, and energy equations of gas and particle phases. Gasification chemical kinetic of coal char and the Eq. (1) also need to be coupled to this model. The numerical model is solved using COMSOL Multiphysics 5.0.

3.1. Continuity equations

In Eulerian model, both the particle and gas phases are solved using an Eulerian approach and an additional equation is solved the volume fraction of the particle phase locally. The two Continuity equations can be simplified for the incompressible flow, as follows [15]:

$$\nabla \cdot (\phi_p \mathbf{u}_p + \phi_g \mathbf{u}_g) = 0 \quad (3)$$

$$\frac{\partial \phi_p}{\partial t} + \nabla \cdot (\phi_p \mathbf{u}_p) = 0 \quad (4)$$

$$\phi_p + \phi_g = 1 \quad (5)$$

3.2. Momentum equations

The momentum equations for the continuous and dispersed phases, using the non-conservative forms of Ishii are as follows:

$$\rho_g \frac{\partial \mathbf{u}}{\partial t} + \rho_g \mathbf{u}_g \nabla \cdot \mathbf{u}_g = \nabla \cdot [-p\mathbf{I} + \boldsymbol{\tau}_g] + \frac{\nabla \phi_g}{\phi_g} \boldsymbol{\tau}_g + \rho_g \mathbf{g} + \frac{\mathbf{F}_{m,g}}{\phi_g} + \mathbf{F}_g \quad (6)$$

$$\rho_p \frac{\partial \mathbf{u}_p}{\partial t} + \rho_p \mathbf{u}_p \nabla \cdot \mathbf{u}_p = \nabla \cdot [-p\mathbf{I} + \boldsymbol{\tau}_p] + \frac{\nabla \phi_p}{\phi_p} \boldsymbol{\tau}_p + \rho_p \mathbf{g} + \frac{\mathbf{F}_{m,p}}{\phi_p} + \mathbf{F}_p \quad (7)$$

For fluid–solid mixtures, Eq. (7) is modified in the manner of Enwald [16]:

$$\rho_p \frac{\partial \mathbf{u}_p}{\partial t} + \rho_p \mathbf{u}_p \nabla \cdot \mathbf{u}_p = \nabla \cdot [-p\mathbf{I} + \boldsymbol{\tau}_p] + \frac{\nabla \phi_p}{\phi_p} \boldsymbol{\tau}_p \frac{-\nabla p_s}{\phi_p} + \rho_p \mathbf{g} + \frac{\mathbf{F}_{m,p}}{\phi_p} + \mathbf{F}_p \quad (8)$$

For the low particulate concentration in this model, the solid pressure could be ignored in this model [16]. So the Eq. (8) can be modified:

$$\rho_p \frac{\partial \mathbf{u}_p}{\partial t} + \rho_p \mathbf{u}_p \nabla \cdot \mathbf{u}_p = \nabla \cdot [-p\mathbf{I} + \boldsymbol{\tau}_p] + \rho_p \mathbf{g} + \frac{\mathbf{F}_{m,p}}{\phi_p} + \mathbf{F}_p \quad (9)$$

$\mathbf{F}_m$ is the drag term of drag force between two phases, where $\mathbf{F}_{m,g} = -\mathbf{F}_{m,p} = \beta \mathbf{u}_{slip}$, β is the drag force coefficient, where $\mathbf{u}_{slip} = \mathbf{u}_p - \mathbf{u}_g$. $\mathbf{F}_i$ ($i = g, p$) is the momentum transfer term which only includes particle thermophoretic force in this paper.

The drag force coefficient β in this study can be modeled for dilute flows as follows:

$$\beta = \frac{3\phi_p \rho_g C_d}{4d_p} |\mathbf{u}_p - \mathbf{u}_g| \quad (10)$$

In this model, the drag coefficient C_d can be computed from the Schiller–Neumann model, which is one of the most employed drag correlations in the last decades [17,18].

$$C_d = \begin{cases} \frac{24}{Re_p} (1 + 0.15 Re_p^{0.687}), & Re_p \leq 1000 \\ 0.44, & Re_p > 1000 \end{cases} \quad (11)$$

$$Re_p = \frac{\phi_g d_p \rho_g |\mathbf{u}_p - \mathbf{u}_g|}{\mu_g} \quad (12)$$

The viscous stress tensors are also needed to be defined in this paper. The dynamic viscosity of the respective phase can be expressed as a simple mixture viscosity, which is defined by Krieger [16] and given in Eq. (13). The Krieger type model can cover the entire range of particle concentrations and $\phi_{p, \max}$ is 0.62 in Eq. (11).

$$\boldsymbol{\tau}_g = \mu_g \left(\nabla \mathbf{u}_g + (\nabla \mathbf{u}_g)^T - \frac{2}{3} (\nabla \cdot \mathbf{u}_g) \mathbf{I} \right) \quad (13)$$

$$\boldsymbol{\tau}_p = \mu_p \left(\nabla \mathbf{u}_p + (\nabla \mathbf{u}_p)^T - \frac{2}{3} (\nabla \cdot \mathbf{u}_p) \mathbf{I} \right) \quad (14)$$

$$\mu_G = \mu_p = \mu_{\text{mix}} = \mu_g \left(1 - \frac{\phi_p}{\phi_{p, \max}} \right)^{-2.5\phi_{p, \max}} \quad (15)$$

In the end, Talbot's model [10] for particle thermophoresis is adopted for its similar conditions with that in this simulation.

$$\mathbf{F}_T = -\frac{6\pi\mu_g^2 d_p}{\rho_g} \frac{C_s(\Lambda + C_t K_n)}{(1 + 3C_m K_n)(1 + 2\Lambda + 2C_t K_n)} \frac{\nabla T}{T} \quad (16)$$

$$K_n = \frac{2l}{d_p}, l = \frac{2\mu_g}{\rho_g \bar{c}} \quad (17)$$

where K_n is Knudsen number, C_s , C_m and C_t are all numerical factors of order unity which must be obtained from kinetic theory, $C_s = 1.147$, $C_m = 1.146$, $C_t = 2.20$, $\bar{c}$ is the mean molecular speed, Λ is the gas-particle thermal conductivity ratio, $\Lambda = \lambda_g/\lambda_p$ [10,19,20].

3.3. Energy equations

There are convective, conductive and radiative heat transfers between the gases, particles and reactor walls in the gasifier. Two basic energy equations, for gas and particle phases are as follows.

$$\rho_g C_{p,g} \frac{\partial T}{\partial t} + \rho_g C_{p,g} \mathbf{u}_g \cdot \nabla T = \nabla \cdot (\lambda_g \nabla T) + Q + A_p \frac{\lambda_g Nu}{d_p} (T_p - T) \quad (18)$$

$$\rho_p C_{p,p} \frac{\partial T_p}{\partial t} + \rho_p C_{p,p} \mathbf{u}_p \cdot \nabla T_p = \nabla \cdot (\lambda_p \nabla T) - A_p \frac{\lambda_g Nu}{d_p} (T_p - T) + Q_r \quad (19)$$

$$Nu = 2 + 0.6 Re_p^{1/2} Pr^{1/3} \quad (20)$$

In this model, the gas phase is assumed to be transparent and radiative heat transfer to particles assumed to be isotropic. P1 model is used to solve the radiative heat transfers to particles. The basic parameters of radiative heat transfers to particles are summarized in Table 4 [11].

Table 4
Parameters of radiative heat transfer [11]

Wall emissivity	0.7
Particle absorption coefficient/m ⁻¹	0.3
Particle scattering coefficient/m ⁻¹	0.14

3.4. Chemical reaction

In this paper, only one Reaction (16) is coupled to the Eulerian model.



Q , heat of the reaction, is defined by enthalpy of reactants and resultants.

$$Q = -R_{\text{mol}}H \quad (22)$$

$$H = 2h_{\text{CO}} - h_{\text{CO}_2} \quad (23)$$

where R_{mol} is the reaction rate, mol·m⁻³·s⁻¹, H is the reaction enthalpy, J·mol⁻¹, and h_{CO} , h_{CO_2} are formation enthalpies, J·mol⁻¹.

The gasification reaction rate is obtained by fitting the experimental data [1].

$$\frac{dX}{dt} = kP_{\text{CO}_2}^{0.4}P^{0.65}\sqrt{1 - \ln(1-X)} \quad (24)$$

$$k = Ae^{\frac{E}{RT_p}} \quad (25)$$

where $A = 174.1 \text{ s}^{-1}$, $E = 71.5 \text{ kJ} \cdot \text{mol}^{-1}$ [1], P_{CO_2} is the size of the partial pressure of CO₂ and P is the size of the total pressure in the gasifier, based on the unit for MPa. The sign “ k ”, reaction rate constant, is defined by Arrhenius formula.

4. Results and Discussions

4.1. Validation of gasification reaction rate

To validate the developed chemical reaction rate equation, the predicted results of Eq. (19) are compared with the experimental data of Ahn [1]. As Fig. 3 shows, the gasification reaction rate equation is able to predict coal char gasification process accurately at wall temperatures of 1100 °C, 1200 °C, 1300 °C and 1400 °C.

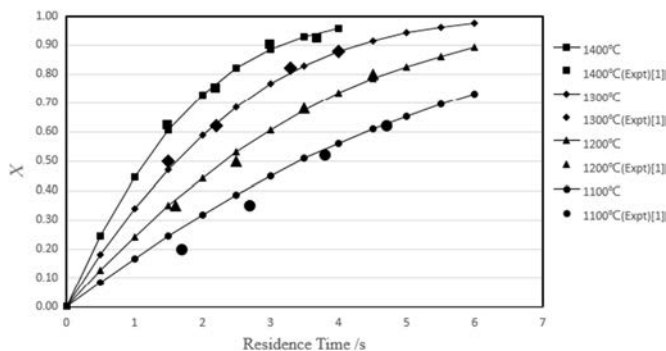
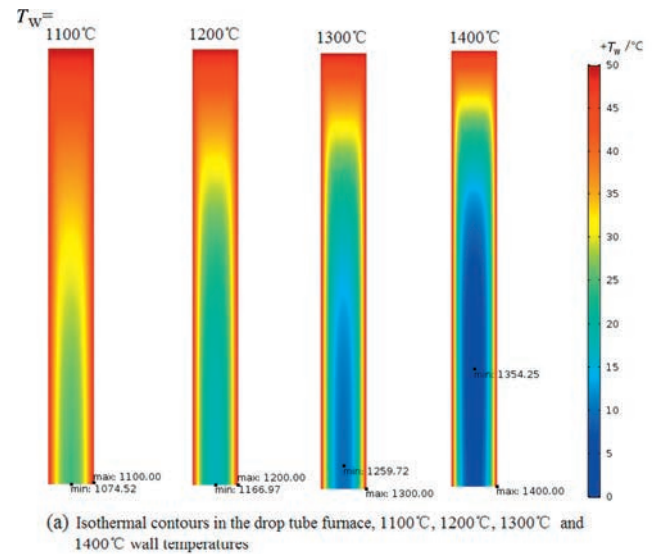


Fig. 3. Comparisons of carbon conversion vs reaction time between numerical predictions and experimental measurements [1].

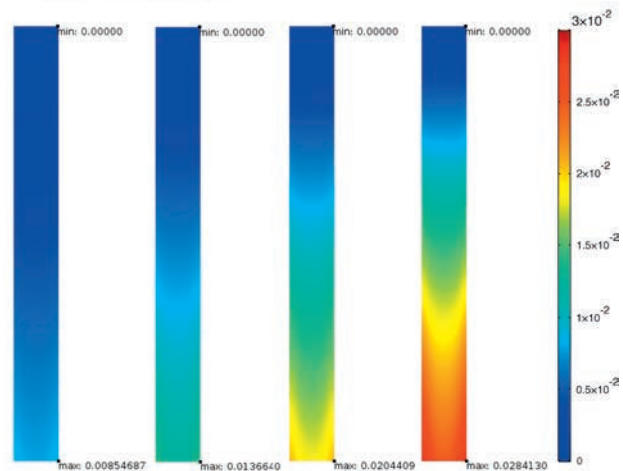
4.2. The particle thermophoresis

In this section, the gas temperature gradient and thermophoretic force are investigated. Firstly, the predicted isothermal contours in the entrained flow coal gasifier are shown in Fig. 4(a) and the maximum and minimum temperatures are also marked in the isothermal contours. The temperature difference increases with wall temperature increasing, which is caused by the increase of reaction rate. Fig. 4(b) demonstrates the conclusion by presenting the volume fraction contours of CO generated in the gasifier. The mass fraction of CO increases with wall temperature increasing and the maximum value is only 0.0284130, which has little effects on gas-particle phases flow behaviors.

Then, the characteristics in five cross sections are investigated to show the entire gasifier performance clearly. The five cross sections are built in the gasifier, 0.1 m, 0.2 m, 0.3 m, 0.4 m, and 0.5 m from the inlet. Figs. 5 and 6 present the gas temperature gradients and particle thermophoretic forces along both radial and axial directions of the gasifier in the five cross sections. The particle thermophoretic force has significant correlation with the gas temperature gradient and has the same trend and the opposite direction with the gas temperature



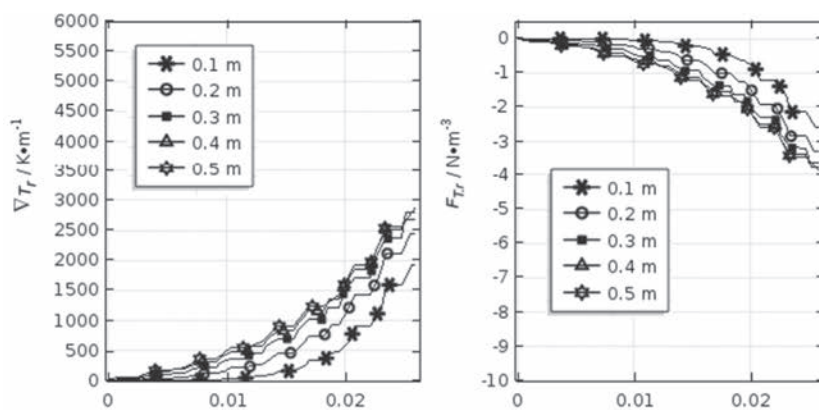
(a) Isothermal contours in the drop tube furnace, 1100 °C, 1200 °C, 1300 °C and 1400 °C wall temperatures



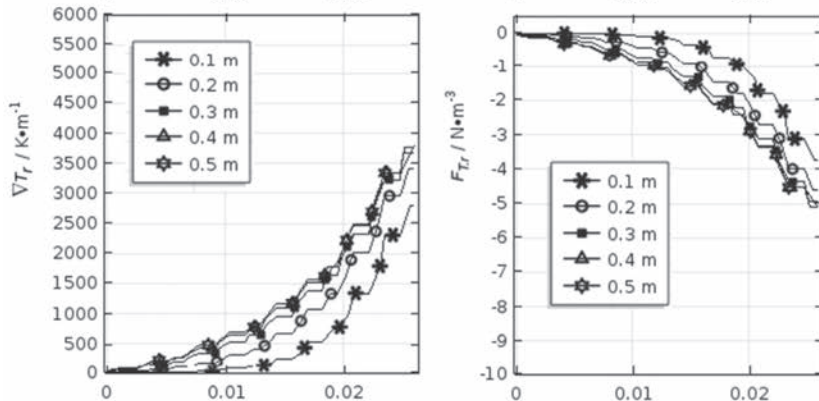
(b) Mass fraction contours of CO in the drop tube furnace, 1100 °C, 1200 °C, 1300 °C and 1400 °C wall temperatures

Fig. 4. Isothermal contours and CO mass fraction contours in the drop tube furnace.

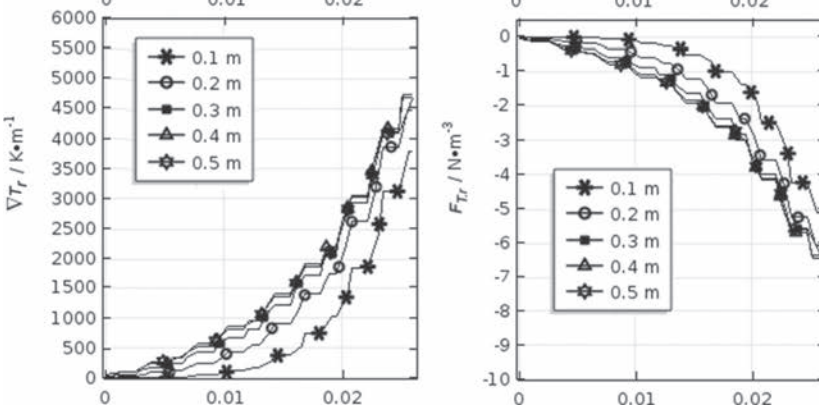
(1)
1100°C



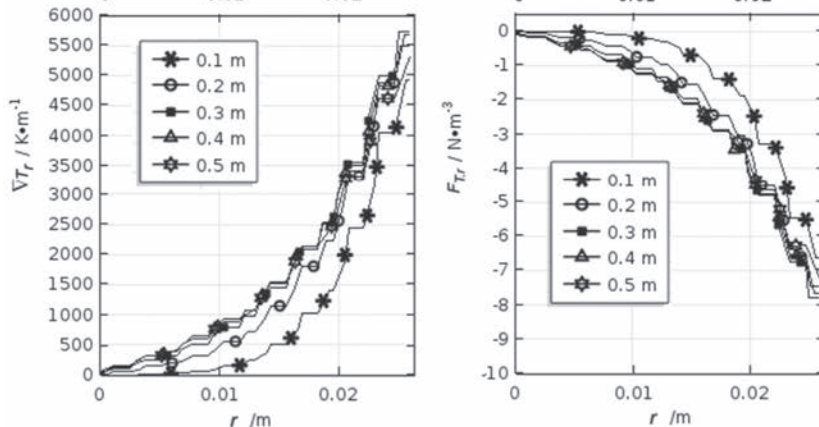
(2)
1200°C



(3)
1300°C



(4)
1400°C



(a) Gradient of gas temperature, r direction

(b) Thermophoretic force, r direction

Fig. 5. Gradient of gas temperature and thermophoretic force along the radial direction.

gradient has. They all increase with wall temperature increasing. As Fig. 5 shows, the radial gas temperature gradient and particle thermophoretic force reach the maximum values near the wall surface

of gasifier. Compared to the gas temperature gradient and particle thermophoretic force along the radial direction, those along axial direction are too small to be ignored.

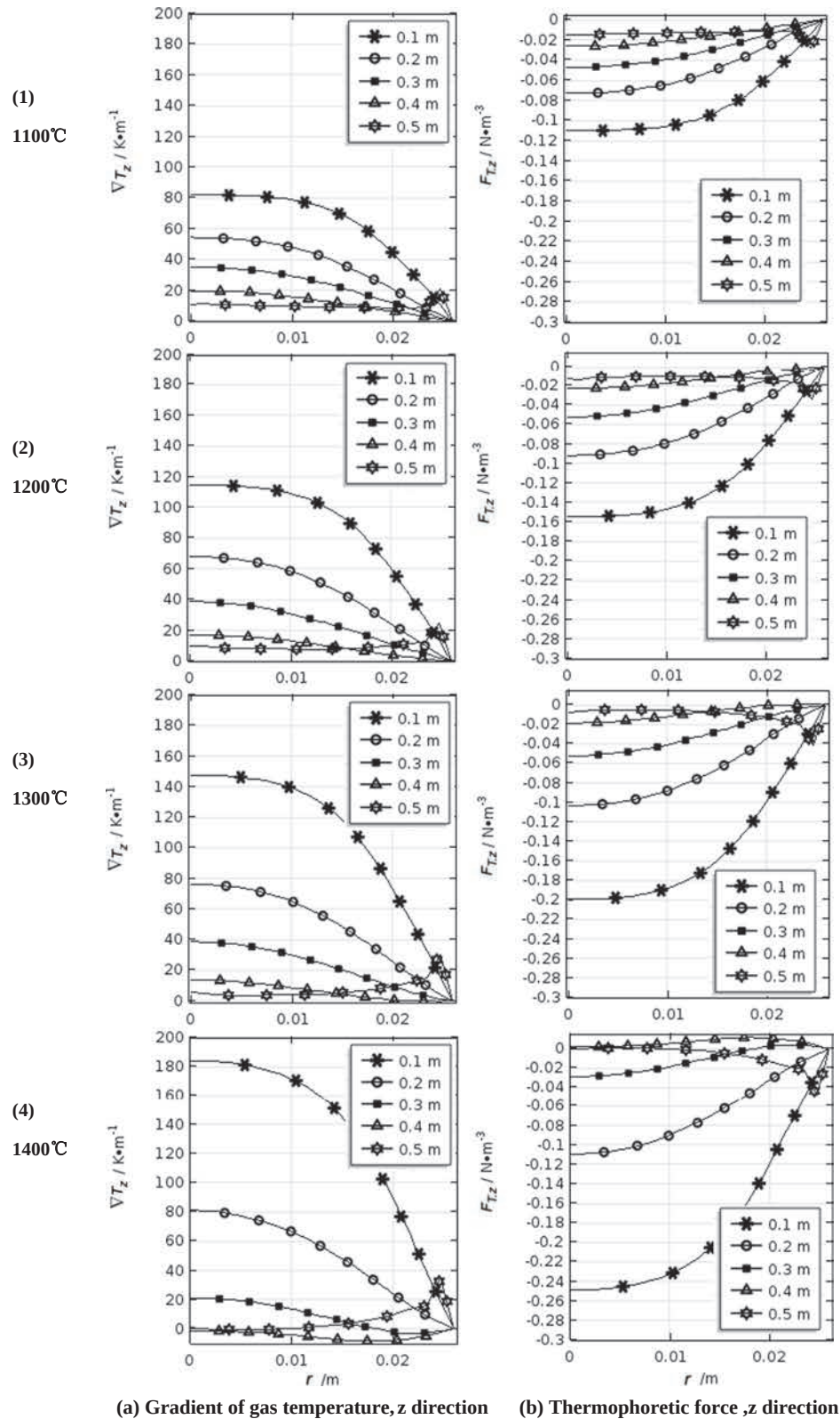


Fig. 6. Gradient of gas temperature and thermophoretic force along the axial direction.

4.3. Effects on particle distributions

This paper contrasts computational results of the particle volume fraction in five cross sections whether the particle thermophoresis is considered in this simulation model. The effects on the particle

distributions can be reflected. These effects are obvious near the wall surface of gasifier at all wall temperatures, where gas temperature gradient has the maximum value. The computational result of particle volume fraction with thermophoresis effects is lower than that without the effects, shown in Fig. 7. At 1400 °C wall temperature,

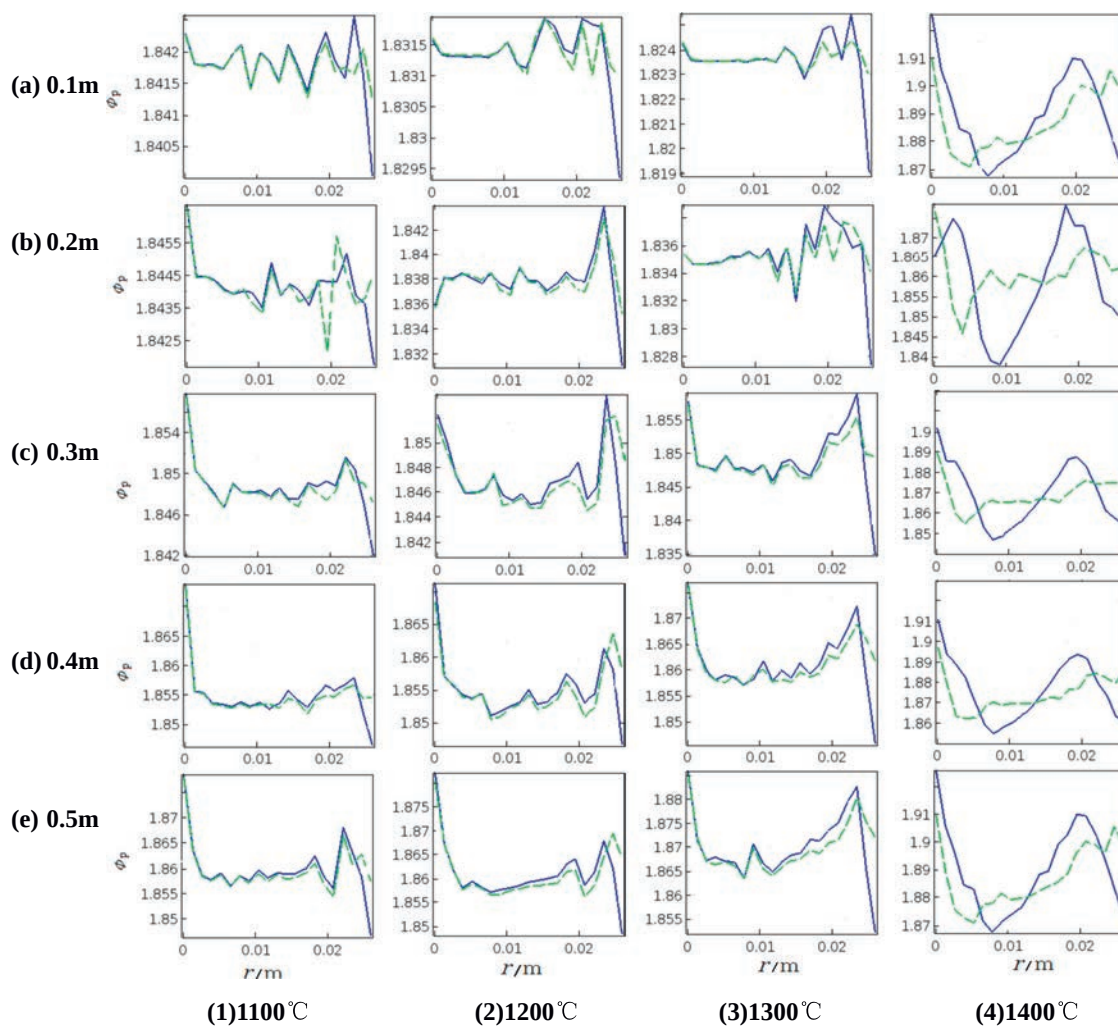
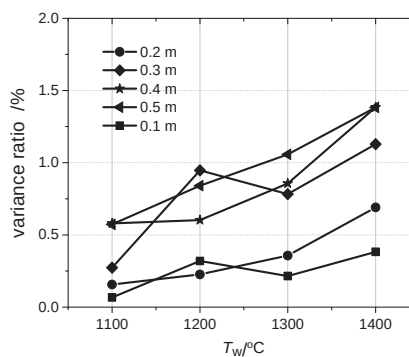
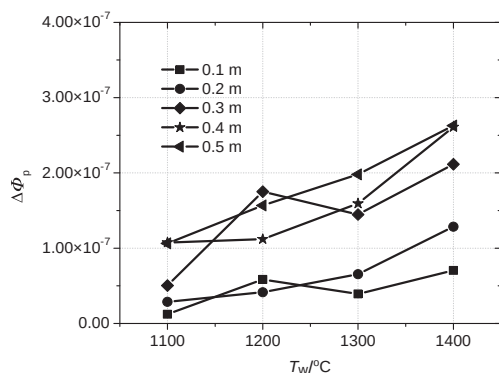


Fig. 7. Comparisons of coal char volume fraction with thermophoresis or not. — Talbot, ---- None.

the changes of particle volume fraction are becoming remarkable, which may be caused by higher gasification reaction rate or other factors.

For estimating thermophoresis effects on the computational results of particle volume fraction, Fig. 8 presents the trends of the difference

and variance ratio of particle volume fraction on wall surface with the wall temperature increases whether the particle thermophoresis is considered in this simulation model. The value of the particle volume fraction increases the wall temperature increases in all five cross sections. These trends are consistent with those of the radial gas



(a) the difference of particle volume fraction

(b) the variance ratio of particle volume fraction

Fig. 8. The trends of the difference and variance ratio of particle volume fraction on wall surface with increase of the wall temperature.

temperature gradients and the particle thermophoretic forces. The maximum variance ratio of particle volume fraction on wall surface reaches up to 1.38% whether the particle thermophoresis effects are considered in the simulation.

4.4. Effects on particle velocity

The changes of particle velocity are also need to be studied [6,10] because the thermophoresis will directly influence the particle velocity and the particle velocity change will affect the particle distance. The changes of axial velocity can be negligible in Fig. 9, which are associated with the small axial gas temperature gradients and thermophoretic forces presented in Fig. 5. However, the changes of radial velocity are observable, especially at wall temperature of 1400 °C as Fig. 10 shows, owing to the higher gas temperature gradients and thermophoretic forces along this direction presented in Fig. 3. So effects of particle thermophoresis are reflected in the changes along radial direction in this paper.

4.5. Effects on gasification reaction rate

The reaction rate is one of main characteristics of coal char gasification, which will affect the temperature field in the gasifier. So in this

section, it is investigated that the effects are on the calculation result of gasification reaction rate whether the particle thermophoresis is considered in the simulation model.

Fig. 11 presents the compared results of gasification reaction rate in the five cross sections whether the particle thermophoresis is considered in the model. At wall temperatures of 1200 °C and 1300 °C, the compared results are only observable near the wall surface of gasifier in five cross sections in Fig. 11(2),(3), which has the same trend with that particle volume fraction has. As Fig. 11(4) shows, the differences of the compared results become remarkable at 1400 °C wall temperature, which is also consistent with the changes the particle distribution has.

5. Conclusions

In this study, a numerical model was developed to investigate particle thermophoresis effect on gas-particle phases flow behaviors in entrained flow coal gasifier based on Eulerian method. Four wall temperatures was considered, including 1100 °C, 1200 °C, 1300 °C and 1400 °C. The main findings of the present study can be summarized as follows:

- (1) The gas temperature gradient and particle thermophoretic force along axial direction can be negligible in comparison to those

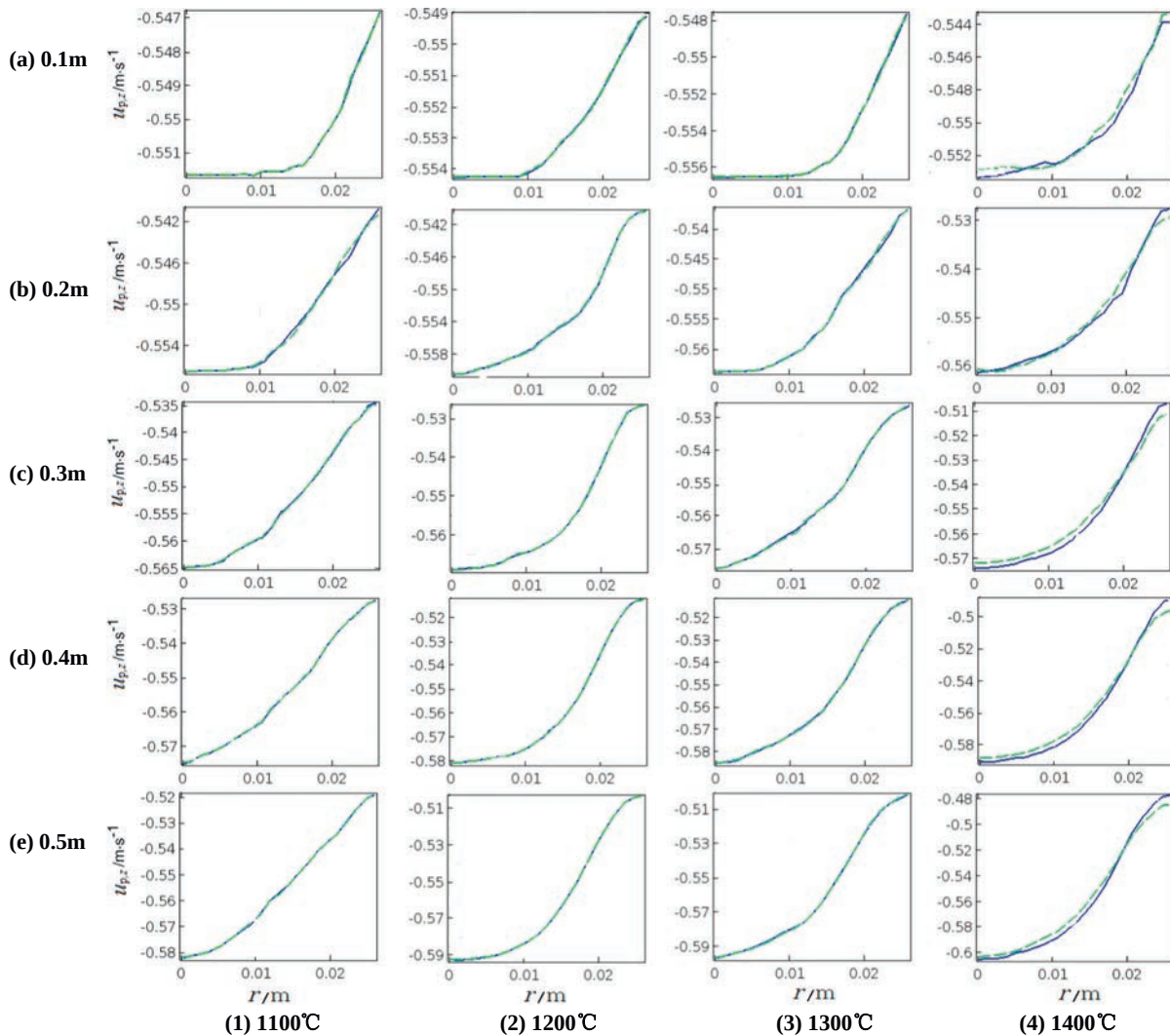


Fig. 9. Comparisons of coal char velocity along the axial direction with thermophoresis or not. — Talbot, ---- None.

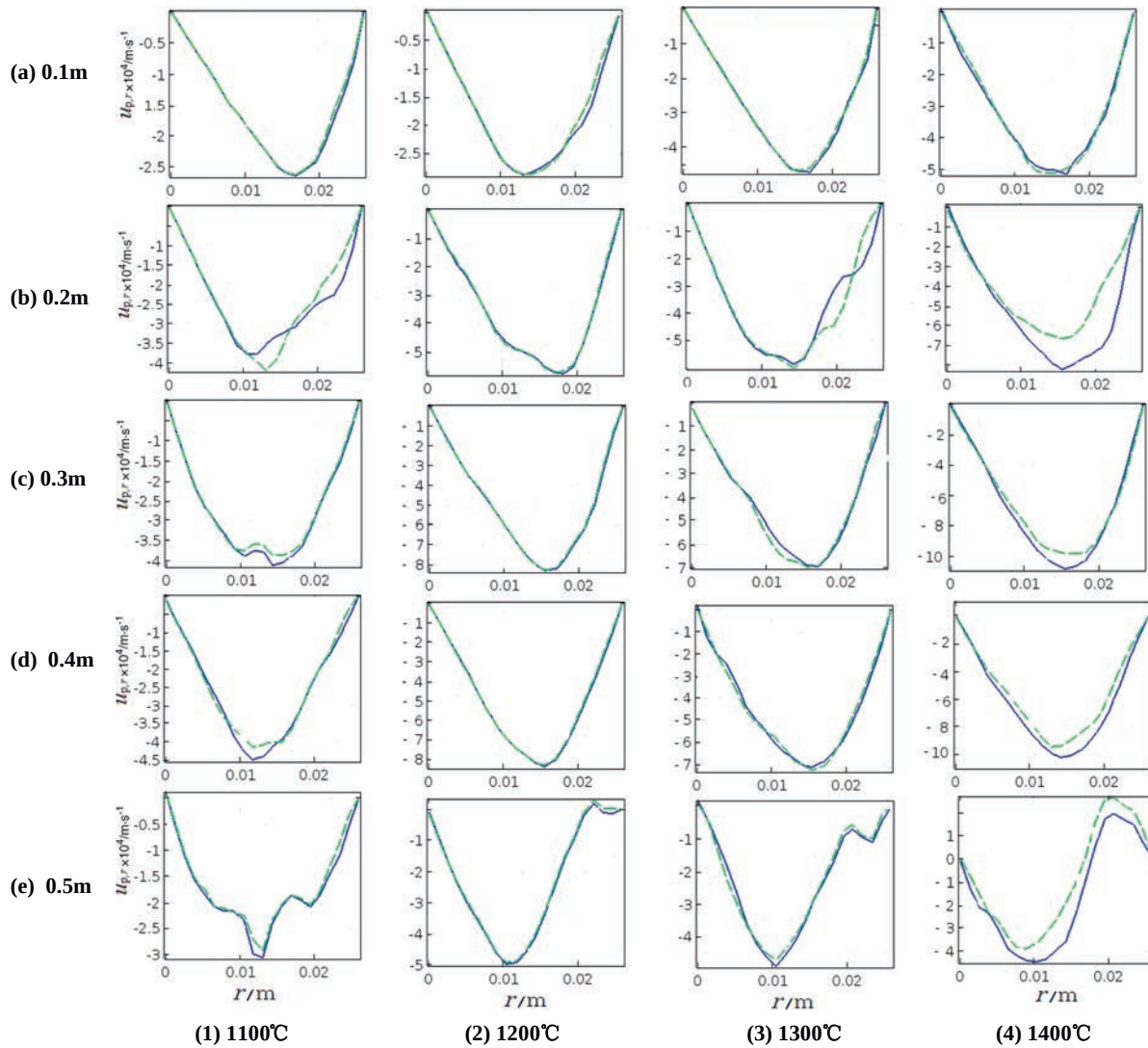


Fig. 10. Comparisons of coal char velocity along the radial direction with thermophoresis or not. — Talbot, ---- None.

along radial direction in the gasifier. Besides, the radial gas temperature gradient and particle thermophoretic force increase with the increase of wall temperature.

- (2) Considering particle thermophoresis had some effects on the distribution of particle volume concentration in simulation model, especially at wall temperature of 1400 °C. The effects were obvious near the wall surface of gasifier at all wall temperatures where the computational result of particle volume fraction with effects of particle thermophoresis is lower than that without the effects. Then the maximum particle volume fraction variance ratio reaches up to 1.38% on wall surface of the gasifier.
- (3) For the calculation of particle velocity in the gasifier, the change of axial velocity is too small to be ignored and that of radial velocity is observable, especially at wall temperature of 1400 °C.
- (4) There are few effects on calculation result of gasification reaction rate caused by particle thermophoresis, only the effects are significantly at wall temperature of 1400 °C.

With further decrease of particle size and further increase of reaction temperature the particle thermophoresis may have more effects on the investigation of gas-particle phases flow behaviors in entrained flow coal gasifier. So it is meaningful that more attention is paid to

develop the gasification model in which particle thermophoresis is considered.

Nomenclature

C_m	momentum exchange coefficient
$C_{p,g}$	gas specific heat capacity at constant pressure, $J \cdot kg^{-1} \cdot K^{-1}$
$C_{p,p}$	particle specific heat capacity at constant pressure, $J \cdot kg^{-1} \cdot K^{-1}$
C_s	thermal slip coefficient
C_t	temperature jump coefficient
d_p	particle diameter, m
$F_{T,r}$	thermophoretic force, r component, $N \cdot m^{-3}$
$F_{T,z}$	thermophoretic force, z component, $N \cdot m^{-3}$
K_n	Knudsen number, $2 L \cdot d^{-1}$
l	mean free path of gas molecules, m
Pr	Prandtl number
Re_p	Reynolds number
T	gas temperature, K
T_p	particle temperature, K
$u_{p,z}$	falling velocity of coal char particle
V_p	volume of a coal char particle
Λ	gas-particle thermal conductivity ratio, $\Lambda = \lambda_g / \lambda_p$
λ_g	gas thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
λ_p	particle thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
φ_p	volume fraction of particle

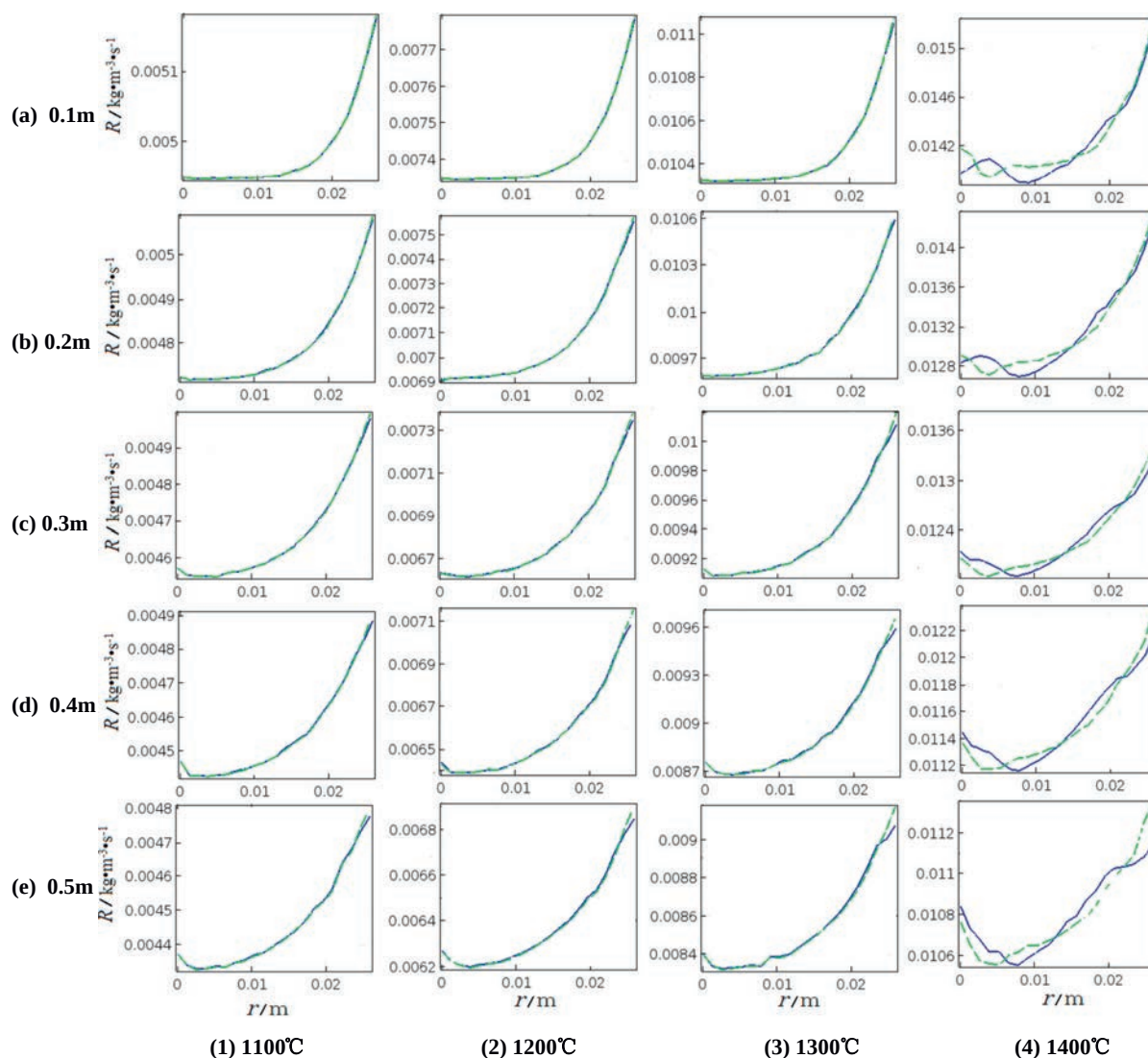


Fig. 11. Comparisons of the gasification reaction rate with thermophoresis or not. — Talbot, ---- None.

φ_g volume fraction of gas
 ρ_g gas density, $\text{kg} \cdot \text{m}^{-3}$
 ρ_p particle density, $\text{kg} \cdot \text{m}^{-3}$

Subscripts

g gas
 p particle
 r radial direction
 z axial direction

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