Numerical simulation of biomass fast pyrolysis in an auger reactor

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Abstract

Fast pyrolysis is an effective means of converting solid low-energy density biomass to intermediate energy products, such as bio-oil. In this study, computational fluid dynamics (CFD) simulations of the biomass fast pyrolysis processes in both the fluidized-bed and the auger reactors were conducted. The numerical results were validated by experimental data. Materials of all phases were modeled as interpenetrating continua by use of a multi-fluid model. Chemical reactions were simulated using a multi-step reaction mechanism that considers multiple compounds in biomass and various gaseous species in the reactor. In the study of biomass fast pyrolysis in the fluidized-bed reactor, CFD simulation results were analyzed to obtain the average residence time of materials in the reactor. This residence time was used as the time for chemical reactions in estimating the final product yields. The estimated product yields agreed well with the experimental data. To simulate the complex geometry and fluid dynamics in the auger reactor, a numerical approach based on a rotating

reference frame was incorporated into the multi-fluid model to account for the auger rotation. Good levels of agreement between the predicted and measured product yields were obtained. A parametric study was conducted to characterize the effects of operating conditions on product yields. The study shows that the optimal wall temperature for maximum tar production was approximately 823 K. The tar yield decreased with increased pre-treatment temperature of the biomass feedstock. It was also found that increased inlet nitrogen flow rate was beneficial to tar yield, while increased biomass feed rate had a negative effect on tar production.

Keywords: Biomass fast pyrolysis; multi-fluid model; rotating reference frame; fluidized bed; auger reactor

1. Introduction

Developing alternative and clean energy sources has become increasingly urgent because of environmental concerns. Biomass, because of its abundant supply and low life-cycle carbon emissions, is an important renewable energy source. Fast pyrolysis, a thermochemical process that decomposes low-energy density organic materials in the absence of oxygen, is a promising approach to converting raw biomass into high-energy density bio-oil and combustible gases [1]. Because of this attractive feature, biomass fast pyrolysis has received great attention from both industry and the scientific community [2]. However, because of the complex nature of biomass fast pyrolysis in chemical reactors, current technologies for converting biomass to bio-oil via fast pyrolysis still face many

challenges. The multiphase flow in the biomass fast pyrolyzer is highly complex, and it is rather difficult to optimize the reactor operating conditions for desirable product yields [3]. In addition, because of the multiscale nature of the biomass feedstock, the performance of a reactor depends significantly on the geometrical characteristics of the biomass particles [4].

Computational fluid dynamics (CFD) simulations, in which conservation laws and equations are employed to describe the complicated multiphase fluid dynamics and chemical reactions, has helped develop understanding of the complex biomass fast pyrolysis process [5-22]. Compared with experimental approaches [23-25], CFD can effectively provide detailed information on the processes occurring in the reactor. Considerable costs and time can be saved by use of CFD for reactor design, optimization, and scaling up. Moreover, CFD has the advantage of being useful in exploring detailed processes occurring in harsh reactor environments that have posed great challenges to researchers.

For biomass fast pyrolysis simulation, CFD has been applied mainly to the fluidized-bed reactor because of the simple geometry and widespread applications of this reactor [26-36]. Fluidized beds can provide excellent gas-solid mixing and heat transfer. Because of the simple geometry, temperature control and operation of fluidized beds are more straightforward than for other types of reactors. Therefore, in the research discussed in this paper, we continued our previous studies [37-39] on CFD simulation of biomass fast pyrolysis in a bubbling fluidized-bed reactor and conducted further analyses of the simulation results to characterize the pyrolysis product yields.

The auger reactor, a novel type of reactor, has attracted much interest for biomass fast pyrolysis application [40, 41]. Auger reactors can be operated continuously with little or no carrier gas. Along with the rotation of one or multiple screw conveyors in the reactor, materials of different phases are mixed to enhance heat transfer among solids, gases, and the reactor wall. The resulting biochar particles are mechanically transported toward the reactor exit by the rotating screw to empty the reactor such that subsequent biomass particles can be fed and pyrolyzed. Because of the rather complex geometry and motion of the screw, the numerical analysis of biomass fast pyrolysis in auger reactors is very rare in the literature. It appears that there has been no report on multi-dimensional CFD simulation of biomass fast pyrolysis in auger reactors using comprehensive numerical models. Nonetheless, CFD simulation is highly important for the design and optimization of auger reactors to achieve effective biomass fast pyrolysis, since it is very costly to conduct comprehensive experiments. Therefore, in this paper, numerical models are introduced for simulating a laboratory-scale auger reactor using CFD.

In this work, a multi-fluid model (MFM) was employed to simulate the multiphase fluid dynamics and a multi-component multi-step reaction kinetics mechanism was applied to describe the biomass fast pyrolysis reactions. The rotation of the screw in the auger reactor was simulated based on the concept of a rotating reference frame. The numerical results were compared with experimental data, and the effects of operating conditions were quantified.

2. Numerical models

2.1 Multi-fluid model

On the basis of our previous studies [37–39], a multi-fluid model was used to simulate the hydrodynamics and heat transfer in the fast pyrolysis reactor. In a MFM, all phases are treated as interpenetrating continua, and the governing equations for mass, momentum, and energy conservations are solved to obtain the spatiotemporal evolutions of the phase volume fraction, velocity, temperature, and species mass fraction. The conservation equations are summarized in Table 1. Various numerical models for gas-solid drag force and heat transfer are summarized in Table 2. A detailed description of the model used in this study can be found in previous publications [37, 39].

2.2 Rotating reference frame

The motion of the rotating screw in the auger reactor was modeled using the so-called rotating reference frame (RRF) [42]. In a RRF, the velocity and acceleration of a rotating object in an inertial coordinate can be expressed by the corresponding velocity and acceleration obtained from a rotating coordinate. The idea of RRF can be described as follows. For a rotating axis with a constant angular velocity ω , the velocity and acceleration of a point at a distance $\mathbf{r}$ from the rotating axis can be expressed in the following.

$$\begin{aligned} \mathbf{U}_{inertial}(\mathbf{r}, t) &= \mathbf{U}_{rotating}(\mathbf{r}, t) + \omega \times \mathbf{r} \\ \frac{d\mathbf{U}_{inertial}(\mathbf{r}, t)}{dt} &= \frac{d\mathbf{U}_{rotating}(\mathbf{r}, t)}{dt} + 2\omega \times \mathbf{U}_{rotating}(\mathbf{r}, t) + \omega \times (\omega \times \mathbf{r}) \end{aligned} \quad (1)$$

Based on Eq. (1), the momentum equation, as listed in Table 1, for the gas phase in the rotating coordinate can be written as

$$\begin{aligned}
102 \quad & \alpha_g \rho_g \left[\frac{d\mathbf{U}_{g,rotating}}{dt} + 2\boldsymbol{\omega} \times \mathbf{U}_{g,rotating} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) \right] = \\
& \nabla \cdot \boldsymbol{\tau}_g - \alpha_g \nabla p + \beta_{gsm} (\mathbf{U}_{sm,rotating} - \mathbf{U}_{g,rotating}) + \alpha_g \rho_g \mathbf{g}
\end{aligned} \tag{2}$$

103 It is worth noting that $\mathbf{D}_g$ in $\boldsymbol{\tau}_g$ also needs to be rewritten as

$$104 \quad \mathbf{D}_g = \frac{\nabla(\mathbf{U}_{rotating}(\mathbf{r}, t) + \boldsymbol{\omega} \times \mathbf{r}) + \nabla(\mathbf{U}_{rotating}(\mathbf{r}, t) + \boldsymbol{\omega} \times \mathbf{r})^T}{2}. \tag{3}$$

105 Other conservation equations to be solved within the rotating coordinate can be formulated
106 similarly.

107 The cylindrical wall of the auger reactor remained fixed and its motion was solved
108 within the inertial coordinate. A cylindrical zone with a radius slightly larger than the outer
109 radius of the screw was set as the RRF solution region, as shown in Fig. 1. The solutions
110 within the rotating coordinate and inertial coordinate were coupled at the boundary of the
111 RRF zone.

112 **2.3 Reaction kinetics of biomass fast pyrolysis**

113 A lumped multi-component multi-step reaction kinetics mechanism [43] was used to
114 model biomass fast pyrolysis reactions. This reaction mechanism was chosen because it has
115 been shown to be able to predict the biomass fast pyrolysis products when used in CFD
116 simulations [38, 43]. Note that comprehensive reaction kinetic schemes [44] can provide
117 more detailed information, but their use in multi-dimensional CFD simulation may be
118 computationally prohibitive.

In this study, the raw biomass was assumed to be composed of cellulose, hemicellulose, and lignin with different mass fractions,

$$\text{Biomass} = \alpha \text{Cellulose} + \beta \text{Hemicellulose} + (1.0 - \alpha - \beta) \text{Lignin} \quad (4)$$

where α and β are the mass fraction of cellulose and hemicellulose, respectively. In the present reaction mechanism, biomass is first elevated to an active state. Then the active biomass is decomposed into tar, noncondensable gases (referred as “syngas” hereafter), and biochar in competitive reaction steps. Some tar will be cracked into syngas if temperature and time permit. In practice, tar will be condensed to form liquid bio-oil. The overall reaction paths are shown in Fig. 2. All reactions were modeled using the first-order irreversible Arrhenius rate

$$\frac{dC}{dt} = -Ck, \quad k = A \exp(-E / RT) \quad (5)$$

where A and E are the pre-exponential constant and activation energy, respectively. C is the concentration of a component. The reaction constants in this reaction mechanism are listed in Table 3.

The coupling between the solution of MFM and chemical reactions were accomplished by use of the so-called time-split scheme [45]. The governing equations in MFM were solved first without incorporating the source terms from chemical reactions. Chemical reactions were then solved in each computational cell, and finally the relevant field variables were updated according to the predicted reaction rates and heat releases.

3. Results and discussion

3.1 Analysis of the fast pyrolysis process in a fluidized-bed reactor

The present CFD code was applied to simulate a laboratory-scale bubbling fluidized-bed reactor located at Iowa State University [46]; and results have been presented previously [46]. Effects of operating conditions on product yields were also investigated [50]. Detailed information about the reactor geometry, operating conditions, and comparisons between experimental data and numerical predictions can be found in our previous publications and thus are not repeated here. However, these results will be analyzed here, since further analyses have showed that the residence time is an important factor in determining the product yields. On one hand, if the residence time is too short, biomass particles will not be completely converted to products. On the other hand, if the residence time is too long, a large portion of tar will be converted to syngas, resulting in a significant reduction in bio-oil production. In principle, the residence time is mainly determined by the fluid dynamics in the reactor. For a typical fluidized bed, its characteristic residence time may vary from a fraction of second to a few seconds. In this section, further analyses of the effects of residence time on final product yields will be conducted by use of the results from CFD simulations.

In the present analysis, product yields were calculated by considering only the residence time and chemical reactions. In this approach, chemical reactions and fluid dynamics were decoupled. The chemical reactions were simulated by solving a system of ordinary differential equations (ODEs) described in Fig. 2 and Eq. (5). To determine how long the chemical reactions progress, the residence time was evaluated on the basis of the

fluid dynamics predicted by the CFD code. By taking into account the reactor geometry and the average gas phase velocity at steady state conditions, the residence time is evaluated as

$$t_{res} = \frac{H_{reactor}}{V_g} \quad (6)$$

where $H_{reactor}$ and V_g are the height of the reactor and the domain-averaged axial component of the gas velocity, respectively. As a result, the residence time was evaluated 0.88 s for the present operating conditions.

Using the methodology already described, the temporal evolution of product yields were calculated by integrating a system of ODEs. It was assumed that the reaction temperature was 773 K and the reaction time was 0.88 s. Fig. 3 shows the temporal evolution of product yields. It can be seen that the biomass mass fraction decreased rapidly. The model had predicted that biomass would decompose almost completely by about 0.3 s, a rate attributed to the high decomposition rate of pure cellulose. It can be found that at 0.2 s, the tar yield reached its maximum, which was about 90% of the total products. After this point, the secondary tar cracking reaction became dominant, resulting in a decrease in tar and an increase in syngas. At 0.88 s, the final product yields agreed with the experimental results reasonably well. It can be concluded that the present chemical kinetic analysis is useful in estimating the final product yields, although chemical reactions were not simulated simultaneously with CFD. However, it is worth noting that in order to obtain the residence time, the steady-state gas velocity is required, from either experiments or CFD simulations.

3.2 Auger reactor

An auger reactor with one rotating screw was simulated using the present 3-D CFD code to study the characteristics of biomass fast pyrolysis in this type of reactor. In this approach, chemical reaction equations were solved in the context of CFD, i.e., reactions and fluid dynamics were coupled. The schematic diagram of the reactor and the operating parameters are shown in Fig. 4. The experiments were conducted at Iowa State University [47], and the experimental data were used for model validation. The biomass feedstock used in the experiment was red oak that consisted of 41% cellulose, 32% hemicellulose, and 27% lignin. The initial size of biomass particles was between 250 and 400 μm . The length (L) and diameter (D) of the reactor are 0.16 m and 0.04 m, respectively. The pitch (p_c), blade thickness (t_c), shaft diameter (d_{in}), flight diameter (d_{out}), and length (L_s) of the screw are 0.0317 m, 0.003 m, 0.008m, 0.03 m, and 0.14 m, respectively. Biomass with a feed rate (F_{s0}) of 0.5 kg/h was injected continuously from the top inlet, while nitrogen with a volume flow rate (F_{g0}) of 75 L/h was supplied from the left inlet, both at 300 K. The distance from the center of the biomass inlet to the gas inlet (L_{in}) is 0.0015 m. The reactor wall was maintained at a constant temperature of 848 K. The screw rotated at a speed of 60 rpm, and adiabatic boundary conditions were used for the screw surface.

3.2.1 Characterization of the fast pyrolysis process

The predicted outflux of solid particles, including biochar and unreacted biomass, at the reactor exit was monitored and its temporal evolution is shown in Fig. 5. It can be seen that the solid outflux was negligible until 2 s after injection, which was approximately the time for solid particles to arrive at the reactor exit. Between 2 s and 5 s, the solid outflux drastically increased and reached statistically steady state at about 15 s. Therefore, the

simulation was run for 25 s and the data obtained in the last 10 s were used for analysis. The temporal evolutions of the product yields are shown in Fig. 6. It can be seen that biomass particles rapidly decomposed to pyrolysis products within 6 s, and that the CFD prediction of final product yields agreed well with the experimental data.

Fig. 7 shows the spatial distributions of the volume fraction and velocity of the solid phase. It can be seen that biomass decomposed quickly after injection. After the rapid initial decomposition, the solid volume fraction decreased more gradually as the particles moved toward the reactor exit. Moreover, because of gravity, the unreacted biomass and biochar tended to stay at the bottom of the reactor. However, as shown in Fig. 7, the rotation of the screw caused the biomass particles to swirl, increasing contact between biomass particles and the heated walls.

Fig. 8 shows that because of heat absorption by the pyrolysis reactions, the temperatures of the solid and gas phases were low near the inlet. Overall, the temperatures of both phases increased downstream of the reactor because of heat transfer from the heated walls. In addition, in auger reactors, because of the centrifugal effects caused by screw rotation, contact between biomass particles and the heated walls is more frequent than in fluidized beds, a feature that also increases the heating of biomass particles.

The spatial distributions of the mass fractions of tar and syngas are shown in Fig. 9. It can be seen that because of the fast biomass decomposition, the tar mass fraction was high near the biomass inlet. Because of the combined effects of tar cracking and diffusion, the tar mass fraction was reduced as it moved downstream. In contrast, the syngas mass fraction increased downstream, since a portion of tar was cracked into syngas. At regions

near the walls, more syngas was formed because of the high wall temperature. It can also be seen that more tar was found at the bottom of the reactor because its density is higher than that of nitrogen and syngas. It is worth noting that because of the low rotation speed of the screw, the spatial distributions of tar and syngas appeared to be relatively homogeneous.

3.2.2 Parametric study

The reactor temperature is an important parameter that affects the pyrolysis reactions. In this study, the temperature of the reactor wall was varied to characterize its effects on product yields. It can be seen from Fig. 10 that the initial increase in the wall temperature favored tar production. However, if the wall temperature exceeded 823 K, tar yield decreased. For the temperature range studied, syngas yield increased with temperature while the amount of unreacted biomass decreased. The biochar yield appeared to be insensitive to changes of the wall temperature. These findings are consistent with experimental results [41, 48] and confirmed that with an increase in wall temperature, more biomass will be converted to tar, syngas and biochar, resulting in a decrease in unreacted biomass. However, because of the secondary cracking of tar at high temperature, the amount of tar decomposed into syngas was larger than the amount of tar produced from biomass if the wall temperature was above a critical point. Therefore, there existed an optimal wall temperature for maximum tar production. The rapid increase of syngas yield at extremely high temperatures (~900 K) represented the combined effects of temperature on biomass decomposition and tar cracking.

Thermal pre-treatment of biomass is a common practice to improve the quality of pyrolysis products. The simulated effects of thermal pre-treatment of biomass on product

yields in the range of temperature between 350 K and 673 K are shown in Fig. 11. It can be seen that, with an increase of pre-treatment temperature, a slight increase in syngas and a decrease in tar were found. These results are consistent with the experimental data on auger reactors by Liaw et al. [49], in which a decrease in the tar yield was observed when biomass was thermally pre-treated.

In practical applications, nitrogen is used to purge gas products out of a reactor, and its flow rate will influence the residence time and final product yields. Fig. 12 shows the variations of product yields with changes in the inlet nitrogen flow rate. It can be seen that increasing the inlet nitrogen flow rate resulted in more tar yield and hindered syngas formation; this is because product yields are affected by the residence times of materials in the reactor. Increasing the inlet nitrogen velocity will reduce the tar residence time, and thus less tar will be converted to syngas. Biochar formation and unreacted biomass yields were not significantly affected by the change of inlet nitrogen velocity, because in an auger reactor, the solids are mainly conveyed by the screw and the residence time of biomass is almost unaffected by the inlet nitrogen flow rate.

The present CFD code was also used to explore the capacity of the current auger reactor, i.e., the maximum amount of biomass that can be pyrolyzed effectively. The variations of product yields with respect to the biomass feed rate is shown in Fig. 13, in which it can be seen that product yields were highly sensitive to the biomass feed rate. In contrast to the situation with bubbling fluidized beds, where product yields were relatively insensitive to the biomass feed rate [50], in the auger reactor as the biomass feed rate increased from 0.1 kg/h to 2 kg/h, more unreacted biomass exited the reactor. While in bubbling fluidized bed reactors heat transfer is mainly accomplished through solid-gas

interactions, in auger reactors heat transfer to biomass particles largely results from direct contact between the particles and the wall. A large biomass feed rate will reduce the percentage of biomass particles that directly contact the wall, resulting in less biomass being pyrolyzed. In the present reactor, fast pyrolysis became ineffective if the biomass feed rate exceeded 1 kg/h.

Conclusion

A comprehensive CFD code was applied to simulate biomass fast pyrolysis in an auger reactor. Additionally, the effects of the residence time on final pyrolysis product yields were investigated for a previously simulated bubbling fluidized-bed reactor. Reactor fluid dynamics were modeled by use of a multi-fluid model, and biomass fast pyrolysis was simulated by a multi-component, multi-step chemical reaction mechanism. The rotating reference frame approach was employed to take into account the screw rotation in the auger reactor. Chemical kinetic analysis of the biomass fast pyrolysis in the bubbling fluidized bed reactor was conducted by considering chemical reactions and the residence time, the latter obtained from CFD simulations. The predicted product yields were found to agree well with the experimental data, showing that such simplified analysis can be useful in estimating product yields if the residence time can be evaluated reasonably well.

The characteristics of biomass fast pyrolysis in the auger reactor were investigated using multi-dimensional CFD. In the auger reactor, the screw stirred up the biomass particles and increased the frequency of direct contact between biomass particles and heated wall, promoting pyrolysis reactions. The biochar produced was rapidly entrained out of the reactor by the partial slip between the biochar particles and the screw surface. The

predicted product yields agreed well with the experimental data. The parametric study shows that the optimal wall temperature for tar production was around 823 K. High pretreatment temperature of the biomass particles can slightly decrease the tar yield and increase the syngas yield. A higher nitrogen inlet velocity resulted in higher tar yield because of the shorter residence time of vapor, which prevented tar from cracking into syngas. It was also found that more unreacted biomass exited the reactor if the biomass feed rate was excessive, indicating the limitation of the auger reactor at high biomass feed rate.

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Table 1 Governing equations of the MFM in this study

Gas phase	Solid phase
Continuity equation	Continuity equation
$\frac{\partial \alpha_g \rho_g}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{U}_g) = R_g$	$\frac{\partial \alpha_{sm} \rho_{sm}}{\partial t} + \nabla \cdot (\alpha_{sm} \rho_{sm} \mathbf{U}_{sm}) = R_{sm}$
Momentum equation	Momentum equation
$\frac{\partial (\alpha_g \rho_g \mathbf{U}_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{U}_g \mathbf{U}_g) =$ $\nabla \cdot \boldsymbol{\tau}_g - \alpha_g \nabla p + \sum_{m=1}^M \beta_{gsm} (\mathbf{U}_{sm} - \mathbf{U}_g) + \sum_{m=1}^M \boldsymbol{\psi}_{gsm} + \alpha_g \rho_g \mathbf{g}$	$\frac{\partial (\alpha_{sm} \rho_{sm} \mathbf{U}_{sm})}{\partial t} + \nabla \cdot (\alpha_{sm} \rho_{sm} \mathbf{U}_{sm} \mathbf{U}_{sm}) =$ $\nabla \cdot \boldsymbol{\tau}_{sm} - \alpha_{sm} \nabla p + \beta_{gsm} (\mathbf{U}_g - \mathbf{U}_{sm}) + \sum_{l=1, l \neq m}^M \beta_{slm} (\mathbf{U}_{sl} - \mathbf{U}_{sm}) + \boldsymbol{\psi}_{gsm} + \alpha_{sm} \rho_{sm} \mathbf{g}$
Stress-strain tensor:	Stress-strain tensor:
$\boldsymbol{\tau}_g = 2\alpha_g \mu_g \mathbf{D}_g + \alpha_g \lambda_g \text{tr}(\mathbf{D}_g) \mathbf{I}$	$\boldsymbol{\tau}_{sm} = -p_{sm} \mathbf{I} + 2\alpha_{sm} \mu_{sm} \mathbf{D}_{sm} + \alpha_{sm} \lambda_{sm} \text{tr}(\mathbf{D}_{sm}) \mathbf{I}$
	Solid phase properties obtained using KTGF [51]
Energy equation	Energy equation
$\frac{\partial (\alpha_g \rho_g C_{pg} T_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g C_{pg} T_g \mathbf{U}_g) =$ $\nabla \cdot \mathbf{q}_g + \sum_{m=1}^M h_{gsm} (T_{sm} - T_g) + H_g$	$\frac{\partial (\alpha_{sm} \rho_{sm} C_{psm} T_{sm})}{\partial t} + \nabla \cdot (\alpha_{sm} \rho_{sm} C_{psm} T_{sm} \mathbf{U}_{sm}) =$ $\nabla \cdot \mathbf{q}_{sm} + h_{gsm} (T_g - T_{sm}) + H_{sm}$
Conductive heat flux:	Conductive heat flux:
$\mathbf{q}_g = \alpha_g \kappa_g \nabla T_g$	$\mathbf{q}_{sm} = \alpha_{sm} \kappa_{sm} \nabla T_{sm}$
Species equation	Species equation
$\frac{\partial \alpha_g \rho_g Y_{gk}}{\partial t} + \nabla \cdot (\alpha_g \rho_g Y_{gk} \mathbf{U}_g) = j_{gk} + R_{gk}$	$\frac{\partial \alpha_{sm} \rho_{sm} Y_{smk}}{\partial t} + \nabla \cdot (\alpha_{sm} \rho_{sm} Y_{smk} \mathbf{U}_{sm}) = R_{smk}$
Diffusive flux:	
$j_{gk} = \alpha_g \rho_g D_{gk} \nabla Y_{jk}$	

Table 2 Empirical interphase transport correlations for the MFM in this study

Gas-solid drag correlation [51]	Gas-solid heat transfer correlation [52]
$\beta_{gsm} = \begin{cases} \frac{3}{4} C_D \frac{\rho_g \alpha_g \alpha_{sm} U_g - U_{sm} }{d_{sm}} \alpha_g^{-2.65} & \alpha_g \geq 0.8 \\ 150 \frac{\alpha_{sm} (1 - \alpha_g) \mu_g}{\alpha_g d_{sm}^2} + \frac{7}{4} \frac{\rho_g \alpha_{sm} U_g - U_{sm} }{d_{sm}} & \alpha_g < 0.8 \end{cases}$	$h_{gsm} = \frac{6 \alpha_{sm} \kappa_g Nu_m}{d_{sm}^2}, \quad \text{Pr} = \frac{C_{pg} \mu_g}{\kappa_g}$
where	where
$C_D = \begin{cases} \frac{24}{\text{Re}} (1 + 0.15 \text{Re}^{0.687}) & \text{Re} < 1000 \\ 0.44 & \text{Re} \geq 1000 \end{cases}$	$Nu_m = (7 - 10\alpha_g + 5\alpha_g^2)(1 + 0.7 \text{Re}_m^{0.2} \text{Pr}^{1/3}) + (1.33 - 2.4\alpha_g + 1.2\alpha_g^2) \text{Re}_m^{0.7} \text{Pr}^{1/3}$
$\text{Re} = \frac{\rho_g d_{sm} U_g - U_{sm} }{\mu_g}$	

Table 3 Rate constants of the reaction kinetics used in this study

Components	Reaction	Y	A, s^{-1}	$E, \text{kg}\cdot\text{m}^2\cdot\text{mol}^{-1}\cdot\text{s}^{-2}$	$H, \text{m}^2\cdot\text{s}^{-2}$
Cellulose	k_{1c}		2.8×10^{19}	2.424×10^5	0
	k_{2c}		3.28×10^{14}	1.965×10^5	2.55×10^5
	k_{3c}	0.35	1.3×10^{10}	1.505×10^5	2.55×10^5
Hemicellulose	k_{1h}		2.1×10^{16}	1.867×10^5	0
	k_{2h}		8.75×10^{15}	2.024×10^5	2.55×10^5
	k_{3h}	0.6	2.6×10^{11}	1.457×10^5	2.55×10^5
Lignin	k_{1l}		9.6×10^8	1.076×10^5	0
	k_{2l}		1.5×10^9	1.438×10^5	2.55×10^5
	k_{3l}	0.75	7.7×10^6	1.114×10^5	2.55×10^5
Tar	k_4		4.28×10^6	1.08×10^5	-4.2×10^4

Fig. 1 Schematic of the coupling between the rotating reference frame and inertial frame in the auger reactor

Fig. 2 The multi-component multi-step reaction mechanism for biomass fast pyrolysis

Fig. 3 Temporal evolutions of product yields for pure cellulose at 773 K in the present bubbling fluidized-bed reactor

Fig. 4 Schematic of the auger reactor and its operating parameters

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Fig. 5 Temporal evolution of the simulated solid outflux at the exit of the [auger reactor](#)

Fig. 6 Temporal evolutions of the predicted product yields in the auger reactor

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Fig. 7 Spatial distributions of solid volume fraction (depicted by color) and velocity (depicted by length of vector) in the auger reactor at $t = 20$ s

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485 Fig. 8 Temperature fields of the solid and gas phases in the middle plane of the auger

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reactor at $t = 20$ s

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490 Fig. 9 Mass fractions of tar and syngas in the middle plane of the auger reactor at $t = 20$ s

Fig. 10 Simulated variations of product yields with respect to reactor wall temperature in the auger reactor

Fig. 11 Simulated variation of product yields with respect to biomass pre-treatment temperature in the auger reactor

Fig. 12 Simulated variation of product yields with respect to nitrogen flow rate in the auger reactor

Fig. 13 Simulated variation of product yields with respect to biomass feed rate in the auger reactor