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Modelling of the flow and heat transfer of microalgae slurry in a parabolic trough collector driven by solar energy

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ABSTRACT

In this paper, flow and heat transfer characteristics of microalgae slurry in the absorber tube of a solar-driven parabolic trough collector was studied numerically. Several viscosity models were introduced to describe the rheological property which would determine the flow pattern. Meanwhile the proposed model accomplished with the temperature term was optimized by the experimental data. Different thermal conductivities were employed to improve the heat transfer process which was described in the cases of different microalgae concentrations and heat fluxes. The relevant results reveal that the temperature field dominates the viscosity discrepancy in the dilute microalgae slurry while the shear thinning effect will be enhanced with the increasing microalgae condensation. The established model is supposed to represent the non-Newtonian pseudo-plastic fluid flow in the hydrothermal pretreatment system which will introduce a direct method to investigate the heat transfer process. Hence the enhanced heat transfer techniques could be applied to accelerate the recovery techniques of solar energy by microalgae hydrothermal utilization.

Keywords: solar energy, microalgae-based biofuels, micro-channel, flow and heat transfer, parabolic trough collector

ONMENCLATURE

Abbreviations	
DNI	Direct Normal Irradiation
Symbols	
φ	Volume fraction
ρ_{ms}	Density of microalgae slurry
$C_{\rho ms}$	Specific heat capacity of microalgae slurry
λ_{ms}	Thermal conductivity of microalgae slurry
ρ_s	Density of microalgae cells
C_{ps}	Specific heat capacity of microalgae cells
λ_s	Thermal conductivity of microalgae cells
ρ_w	Density of water
C_{pw}	Specific heat capacity of water
λ_w	Thermal conductivity of water
T	Temperature
H	Apparent viscosity
k	Consistency coefficient
n	Power law index
γ	Shear rate
α	Ratio of activation energy to the thermodynamic constant

1. INTRODUCTION

Microalgae biomass is a kind of single-celled organisms with small volume, simple structure and rapid growth, which has a wide distribution range and strong environmental adaptability [1]. By the algae photosynthesis, solar energy transforms into chemical energy efficiently together with the progress of carbon capture and storage. Hence, Carbon-neutral can be expected in the life cycle of algae biomass as biofuels [2]. At present, the typical approaches for converting microalgae biomass into biofuels include the thermochemical and biochemical conversions [3]. Anaerobic digestion of algae biomass is a promise approach due to the mild reaction condition, low energy consumption and full conversion of organic matters [4]. However, the cell wall structure of microalgae cells slows down the efficiency of fermentation bacteria on the transformation and

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utilization of organic matters [5]. Hydrothermal pretreatment is an efficient method to enhance the hydrolysis rate by accelerating the release of organic matters from microalgae cells [6]. In regards to the pretreatment cost, a pretreatment system driven by solar energy was proposed , which was a kind of energy saving technology and the maximum output of proteins and carbohydrates were improved for 3.7 and 7.4 times, respectively [7]. In the solar-driven pretreatment system, the microalgae slurry was heated by solar energy in a parabolic trough collector. In the previous study, the microalgae slurry behaved as a non-Newtonian pseudo-plastic fluid when the microalgae concentration was in a specific range [8]. Nevertheless, the viscosity of the pseudo-plastic fluid was also determined by the fluid temperature [9]. The microalgae slurry viscosity was investigated by considering the combined effect of the temperature, algae concentration and shear rate experimentally [10]. In the view of heat transfer process, the non-uniform heat flux of the parabolic trough collector was emphasized and the natural convection driven by the temperature gradient was performed numerically [11]. As mentioned in the literature above, microalgae slurry has the complex flow characteristics due to its rheological properties. Numerical simulation is a common method to study the fluid heat and mass transfer. The influence of generalized Reynolds number on flow resistance and flow state was reported based on the different microalgae concentrations in the slurry [12]. A numerical model was introduced to describe the flow and heat transfer characteristics of microalgae slurry in tubular reactors where the effect of the shear flow on the heat transfer characteristics was discussed [13].

In summary, a series of studies had been carried out on the conversion of microalgae biomass into biofuels by considering the potential of solar energy storage and recovery and the efficiency of carbon capture and storage. In the previous work, a hydrothermal treatment experiment system had been established by imitating the digestive function of termites[7], where the solar energy was used to solve the problem of low conversion efficiency of microalgae biomass due to the compact cell wall structure of microalgae cells. In this system, the flow and heat transfer processes were supposed to dominate the hydrothermal treatment process, significantly. Therefore, flow and heat transfer characteristics of the microalgae slurry in a micro-channel system need to be comprehensively studied by numerical and experimental methods. Compared to the studies of Fu et al [14], a viscosity model based on kinetic theory rather than the experimental correlations was established to describe the rheological properties of microalgae slurry in the solar-driven parabolic trough collector. Furthermore, the cases based on the optimized thermal conductivity, different microalgae concentrations and heat fluxes were also established to investigate the heat transfer process of microalgae slurry, thoroughly. The proposed model would aid the design and optimization of the solar-driven parabolic trough collector in the hydrothermal pretreatment system.

2. PHYSICAL AND MATHEMATICAL MODELS

2.1 Physical model

Schematic diagram of the parabolic trough collector employed in the previous work [7] was given in Fig. 1. The inner size of the absorber tube is 32 mm in diameter (D) and 6 m in length (L), which was specified in the numerical models. Based on the actual heat flux through the absorber tube, the equivalent heat flux with the uniform heating around the absorption tube was given. Therefore, the direct normal irradiation (DNI) calculated by Monte Carlo Ray-Trace method was converted into uniform heat fluxes of 9930, 11100, and 13000 W/m^2 for simulations.

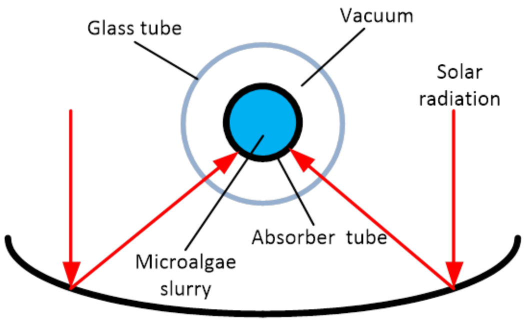

Fig.1. Schematic diagram of the parabolic trough collector

Microalgae slurry was prepared by mixing microalgae biomass powder with water at the volume fraction (φ) of 5%, 10%, or 15%. Density (ρ_{ms}) and specific heat capacity (C_{pms}) of the microalgae slurry were calculated by Eqs.(1-2) while the thermal conductivity (λ_{ms}) can be calculated by two methods. Considering the microalgae slurry as the fluid with suspending particles, Eq.(3) was applicable [15]. Meanwhile, the relevant values would be calculated based on the empirical correlations. Eqs.(4-6) proposed in the previous work [16] defined the thermal conductivity of microalgae slurry under the volume fraction of 5, 10, and 15%, respectively.

$$\rho_{ms} = \varphi\rho_s + (1-\varphi)\rho_w \tag{1}$$

$$C_{\rho ms} = \varphi C_{\rho s} + (1-\varphi)C_{\rho w} \tag{2}$$

$$(\lambda_{ms}/\lambda_s - 1)/(\lambda_w/\lambda_s - 1) = (\lambda_{ms}/\lambda_w)^{1/3}(1-\varphi) \tag{3}$$

$$\lambda_{ms} = 6.9 - 5.6\times10^{-2}T + 2\times10^{-4}T^2 - 2\times10^{-7}T^3 \tag{4}$$

$$\lambda_{ms} = -1 + 3\times10^{-2}T - 8\times10^{-5}T^2 + 7\times10^{-8}T^3 \tag{5}$$

$$\lambda_{ms} = 4.4 - 2.1\times10^{-2}T + 7\times10^{-5}T^2 - 8\times10^{-8}T^3 \tag{6}$$

where ρ_s, C_{ps} and λ_s are the density(kg/m^3), specific heat capacity(kJ/(kg K)) and conductivity(W/(m K)) of microalgae cells; ρ_w, C_{pw} and λ_w are the density, specific heat capacity and conductivity of water; T is the temperature of microalgae slurry(K).

To describe the rheological property of microalgae slurry, the Power-law model for viscosity(Eq.(7)) was defined to analyze the influence of shear rate on the flow pattern while the temperature dependence term was present in Eq.(8) to consider the connection between temperature and viscosity.

$$\eta = k\gamma^{n-1} \tag{7}$$

$$\eta = k\gamma^{n-1} * exp\left[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_\alpha - T_0}\right)\right] \tag{8}$$

where η is the apparent viscosity of microalgae slurry(Pa s), k is the consistency coefficient(Pa s), n is the power law index, and γ is shear rate(s^{-1}). T_0 is the lowest temperature that is thermodynamically acceptable and T_α is the reference temperature(K). α is the ratio of the activation energy to the thermodynamic constant(K) and the activation energy value is derived by experimental data.

2.2 Governing equations

It was assumed that the microalgae slurry was homogeneous, incompressible and steady state in the absorber tube meanwhile the laminar convection heat transfer is mainly considered for the flow and heat transfer. The governing equations can be written as Eqs.(9-11).

$$\frac{\partial}{\partial x_j}\left(\rho_{ms}u_j\right) = 0 \tag{9}$$

$$\frac{\partial}{\partial x_j}\left(\rho_{ms}u_iu_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\eta\frac{\partial u_i}{\partial x_j}\right) - \rho_{ms}g_i \tag{10}$$

$$\frac{\partial}{\partial x_j}\left(\rho_{ms}u_jC_{\rho ms}T\right) = \frac{\partial}{\partial x_j}\left(\lambda_{ms}\frac{\partial T}{\partial x_j}\right) \tag{11}$$

where u_i and u_j are the velocity components, p and g_i are the static pressure and gravitational acceleration.

2.3 Numerical strategy

In the current work, no-slip boundary condition was used on the inner wall. The flow rate of microalgae slurry was set as 60L/h. Initial temperature of microalgae slurry was given as 313.15 K. The governing equations were discretized by the finite volume method and the second upwind scheme was used to discretize the convective terms.

2.4 Grid independence

A 3-d geometry model was built bases on the actual size of absorber tube and the computational domain was meshed by 143880, 191840, 270570 or 638048 cells to improve the simulation. The calculation results are shown in Fig. 2. Referring to the results, no obvious difference would be introduced and then the grid system of 191840 cells was selected in the following studies to ensure the computational accuracy and economics.

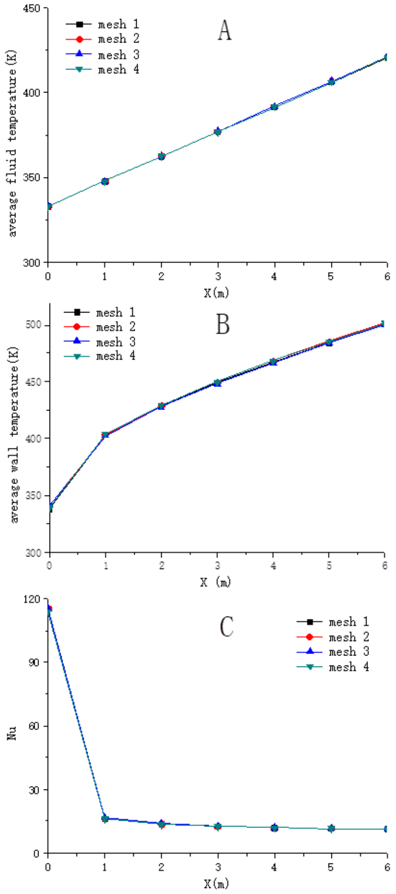

Fig. 2. Comparison of the fluid(A) and wall(B) temperature and local Nu(C) with different grid sizes

3. RESULTS AND DISCUSSION

3.1 Comparison of viscosity models

Fig. 3 shows the curves of wall and fluid temperature, local Nu, and near wall viscosity in absorber tube by different viscosity models. Model 1 assumed the initial constant viscosity to microalgae slurry where the influences of shear rate and temperature were ignored. Models 2 and 3 were established based on Eqs.(7) and (8), respectively.

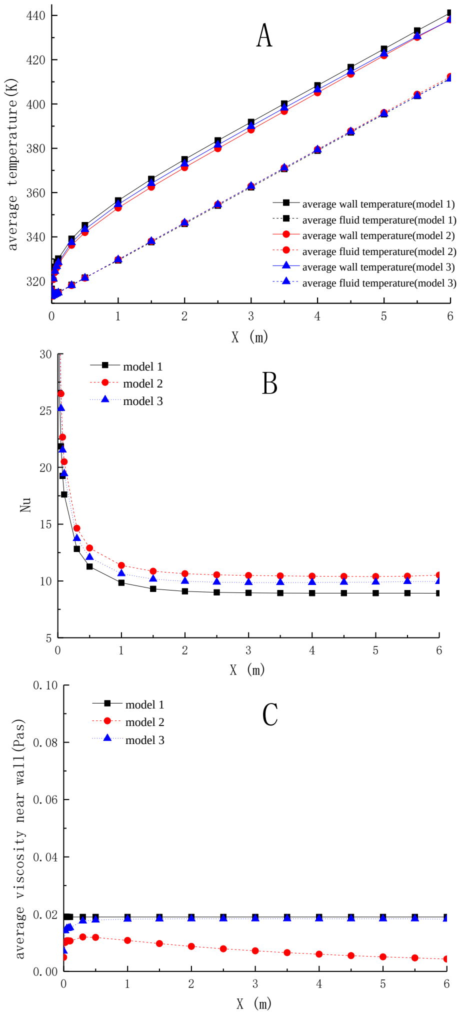

Fig. 3. Plots of wall and fluid temperature(A), local Nu(B), and average viscosity(C) under different viscosity models

By applying different viscosity models, there is no obvious deviation on temperature prediction can be observed meanwhile the distribution curves of Nu number along the axial direction of the absorber tube follow the similar tendency as shown in Fig. 3 (A and B). It should be noticed that the highest Nu numbers are performed when the influence of temperature on slurry viscosity is considered. The constant viscosity model delivers the lowest Nu numbers.

Compared to the constant viscosity model in Fig. 3C, the shear-thinning effect by applying models 2-3 can be observed due to the large velocity gradient at the entrance region. The phenomenon could be neglected with the flow developing by applying model 2. Considering the effect of temperature by applying model 3, the continuous decrease of viscosity is delivered which indicates that temperature field dominates the viscosity discrepancy in the developing flow region.

3.2 Comparison of thermal conductivity models

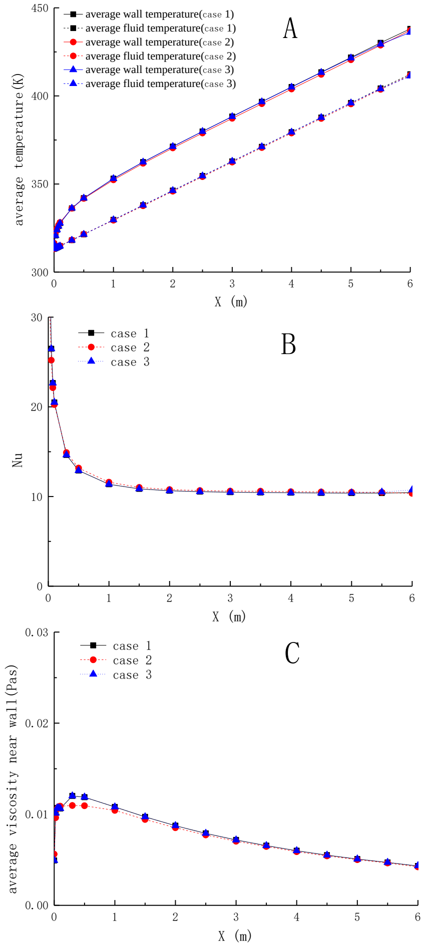

Fig. 4. Plots of wall and fluid temperature (A), local Nu (B), and viscosity(C) under different thermal conductivity models

Fig.4 shows the variation of the average temperature of wall and microalgae slurry, local Nu number and near-wall viscosity of microalgae slurry under different thermal conductivity models. Case 2 adopted the thermal conductivity calculated by Eq.(3). The thermal conductivity model (Eqs.(4-6)) based on experimental data was defined as case 1. In case 3, a constant value was given to the thermal conductivity of microalgae slurry. The calculated results showed that the given thermal conductivity models would vary the calculation result slightly meanwhile the empirical correlation derived by experiment date delivered almost the same temperature, Nu and viscosity distributions.

3.3 Consideration of microalgae concentration

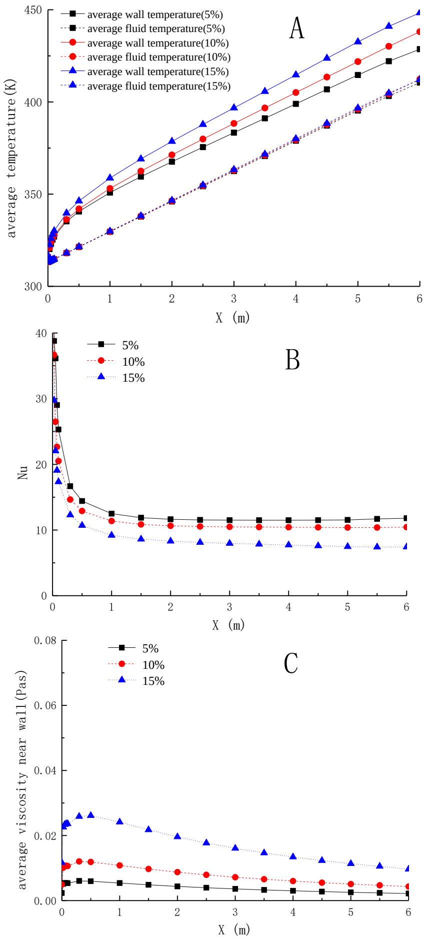

Fig. 5. Plots of wall and fluid temperature (A), local Nu (B), and average viscosity(C) under different microalgae concentrations

By increasing the microalgae concentration from 5% to 15%, the fluid temperature distribution behaved with no variation in Fig.5A but the wall temperature changed a lot, which can be attributed to the heat transfer deterioration with the lower Nu number as shown in Fig.5B. Curves in Fig.5C showed that the thinning effect was enhanced at higher microalgae concentration. In other words, the discrepancy would be emphasized more if dense microalgae slurry was applied.

3.4 Consideration of heat flux

Fig. 6A shows the variation of average temperature of microalgae slurry and wall on axial direction at a flow rate of 60L/h and a volume fraction of 10% under different heat fluxes. It is obvious that the average temperature of microalgae slurry and wall increases with the enlarged heat flux, nevertheless the heat transfer coefficient would not vary in Fig.6B. As shown in Fig.6C, smaller local viscosity is delivered when the heat flux increased from 9930 W/m^2 to 13000 W/m^2. It is consist with the result above which indicated the effect of temperature on the viscosity discrepancy.

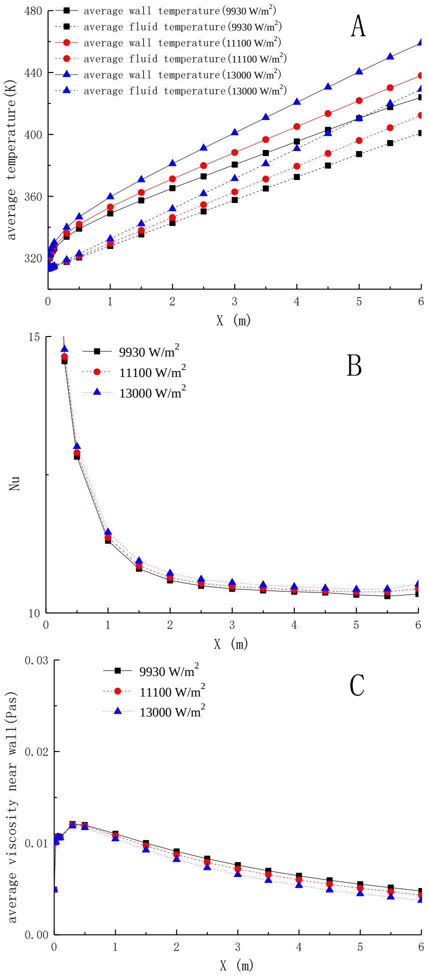

Fig. 6. Plots of wall and fluid temperature (A), local Nu (B), and average viscosity (C) under different heat fluxes

4. CONCLUSIONS

Flow and heat transfer characteristics of microalgae slurry in a micro-channel were investigated numerically by applying different sub-models including viscosity models, thermal conductivity models while the influences of different microalgae concentrations and heat fluxes were also discussed. The relevant results revealed that the viscosity discrepancy of dilute microalgae slurry was mainly influenced by the temperature field meanwhile the shear-thinning effect would behave positively in the entrance region due to the steep velocity gradient; for dense microalgae slurry, the lower wall heat transfer coefficient would increase the wall temperature which delivered the enhanced thinning effect.

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