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Effect of turbulent fluctuation on the ignition of millimeter particle: Experimental studies and numerical modelling with a new correlation of nusselt number

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ABSTRACT

Understanding the influencing mechanism of turbulent fluctuation on the ignition characteristics of millimeter coal particles is essential. In this work, to study the effect of turbulent fluctuation on ignition time, millimeter coal particles are subjected to a specific flow field, generated in a furnace with symmetric fans. A one-dimensional model with the new proposed correlation and the Ranz-Marshall (R-M) correlation for *Nu* (Nusselt number) is established to simulate the coal ignition process. In addition, the effects of fan speed, temperature, particle diameter, particle distance and coal type on the ignition time are investigated. It is found that an increase in fan speed from 0 to 3000 rpm leads to a particle Reynolds number Re_p increase from 0 to 22.5, and a turbulent particle Reynolds number Re_t* increase from 0 to 71.5. With a consideration of the fluctuation effect, the new correlation of *Nu* gives a better prediction of ignition time compared to the R-M correlation. Moreover, the ignition time is revealed to decrease with an increasing fan speed and an elevating temperature. While the ignition time shows merely an initial boost with enlarging particle distance, it exhibits a linearity with the term of particle diameter $d_p^{1.3-1.7}$ and Reynolds numbers $(Nu^*/Nu)^{-0.6}$ (Nu^* is turbulent Nusselt number). Based on this relationship, the difference of predicted ignition time is calculated at different Re_p and Re_t*. It is shown that at low Re_p or high Re_t* values, the new correlation should substitute for the R-M correlation.

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1. Introduction

Ignition is an essential part of the entire coal combustion process, which significantly affects the combustion stability and the reactor safety (Bai et al., 2017; Kim et al., 2014). Substantial research has been conducted on the ignition behavior of coal particles (Davini et al., 1996; Faundez et al., 2005), which generally concludes that the convective heat transfer plays a vital role in ignition time (Khatami et al., 2012; Liu et al., 2014; Lu et al., 2010). However, the existing studies are usually focused on low Reynolds numbers, for which the effect of turbulent fluctuation is negligible, corresponding to the traditional combustion conditions. In recent years, nonetheless, new combustion technologies with intense turbulent fluctuation are emerging. For example, the circulating fluidized bed boiler is developing toward large scale and high parameters, with secondary air speed up to 120 m/s, inducing an intense turbulent flow field with a large fluctuating velocity (Zhou et al., 2019). Research has shown that turbulence exerts a non-negligible effect on the heat transfer, ignition and combustion of solid particles (Moran & Glicksman, 2003; Sung et al., 2011; Zhou et al., 2021), especially for millimeter particles (Huang et al., 2019). Thus, understanding the influencing mechanism of turbulent fluctuation on the ignition characteristics of millimeter coal particles is necessary and of practical importance.

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It is well known that the fluctuating velocity of round jet is usually 20% lower than the time-averaged velocity. Therefore, studying the effect of turbulent fluctuation on coal ignition necessitates the establishment of an experimental system which is capable of generating a flow field with a low time-averaged velocity but a high fluctuating velocity (Ahmed & Mastorakos, 2006; Birouk & Fabbro, 2013; Chaudhuri et al., 2013; Coppola et al., 2009; Hadi et al., 2019; Wang & Maxey, 1993; Xia et al., 2021; Zhou & Frank, 2021). Among the various methods, the "counter flow fan" method is widely regarded as the most effective, wherein a symmetrical placement of the fans generates an isotropic turbulence flow field. For instance, in an attempt to study the effect of turbulent fluctuation on coal and gas flame propagation speed, Hadi et al. (Hadi et al., 2019) and Chaudhuri et al. (Chaudhuri et al., 2013) used a dual-fan and four-fan facility, respectively. Birouk and Fabbro (Birouk & Fabbro, 2013) designed an isotropic turbulent flow field in a three-dimensional space through the symmetrical placement of eight fans. The flow field characteristic was measured, and the turbulence intensity effect on droplet evaporation was studied. In general, there is some interesting and inspiring work in the literature on investigating the effect of turbulent fluctuation. The coal ignition in turbulent environments, nevertheless, remains experimentally unresolved.

Alternatively, researchers resorted to numerical simulation methods to study the turbulent fluctuation effect on the ignition behavior. In accordance with the dimension of the models, three types of numerical models had been employed to simulate the convective effect on the mass and heat transfer in particles, namely the zero-dimensional model (Zhang et al., 2005), the 0.5-dimensional model (Sijercic & Hanjalic, 1994), and the three-dimensional model (Bagchi & Kottam, 2008; Tufano et al., 2018; Wissink & Rodi, 2011). The current zero-dimensional and 0.5-dimensional models emphasize on calculating the effect of forced convection, with an inability to consider the effect of turbulent fluctuation. Therefore, to study the turbulent effect on particle heat transfer and combustion, many researchers utilized direct numerical simulation (DNS) (Tufano et al., 2018). For example, Bagchi and Kottam (Bagchi & Kottam, 2008) examined the heating rate on single spherical particle in an isotropic turbulent field, and discovered a maximum difference of 20% between the instantaneous Nusselt number and the time-averaged Nusselt number. In studying the heat transfer behavior of a single cylinder in a turbulence field, Wissink and Rodi (Wissink & Rodi, 2011) revealed that increasing turbulence intensity significantly enhanced the phenomenon of heat transfer. In these studies, the Ranz-Marshall (R-M) correlation was usually adopted to calculate the Nusselt number for particle heat transfer (Ranz & Marshall, 1952), which is proved to be applicable under low turbulent fluctuating velocity. However, Raithby and co-worker Eckert (Raithby & Eckert, 1968) reported that at a high Reynolds number the instantaneous variation of velocity outnumbers the slip velocity between gas and the particle, rendering the Ranz-Marshall correlation a compromised predictability of the Nusselt number.

To simulate the homogeneous and isotropic turbulence, in the previous work (Feng et al., 2022) we designed and manufactured an experimental apparatus for studying the heating process of copper particles (diameters of 2 mm and 4.4 mm) under different ambient temperatures. And the experimental findings were used to calibrate the Ranz-Marshall correlation to account for the turbulent effect. In particular, an additional term, Nu_t (turbulent effect term) was added, as shown in Eqs. (1)–(3). The new correlation was validated by comparing the simulation results with experimental data for heat transfer of a copper particle with a Biot number smaller than 0.1. However, the conductivity of coal is far smaller than that of copper, thus the Biot number of millimeter coal particle would substantially exceed 0.1. Hence, extending the new *Nu* correlation to the modeling of the millimeter coal particle requires further investigation.

$$Nu = 2 + 0.6Re_p{}^{1/2}Pr^{1/3} \tag{1}$$

$$Nu_t = 0.0024\left(\mathrm{Re}_t^*\right)^{1.488}\left(\frac{\rho_f\mu_f}{\rho_w\mu_w}\right)^{-6.755} \tag{2}$$

$$Nu^* = 2 + 0.6Re_p{}^{1/2}Pr^{1/3} + 0.0024(Re_t{}^*)^{1.488}\left(\frac{\rho_f\mu_f}{\rho_w\mu_w}\right)^{-6.755} \tag{3}$$

where, Nu^* is turbulent Nusselt number, Re_p is particle Reynolds number, Pr is Prandtl number, Re_t^* is particle turbulent Reynolds number, ρ is density, μ is viscosity, the subscripts w and f represent particle surface and fluid.

The particle Reynolds number Re_p and particle turbulent Reynolds number Re_t^* are defined as

$$Re_p = \frac{\rho u_{slip} d}{\mu} \tag{4}$$

$$Re_t{}^* = \frac{\rho u_{rms} d}{\mu} \tag{5}$$

where u_{slip} is gas-solid slip velocity, u_{rms} is turbulent fluctuation velocity, d is characteristic length.

In summary, in the emerging new combustion technologies, the fluctuating velocity deviates emphatically from the traditional conditions. Therefore, there is an urgent need to study the effect of turbulent fluctuation on the heat transfer and ignition of millimeter coal particle. On the other hand, there exists a scarcity of work devoted to measuring the coal ignition time in a specific flow field with a low time averaged velocity but a high fluctuating velocity. Besides, the traditional R-M correlation for *Nu* is unfeasible to conditions of a high fluctuating velocity, while the new copper-based correlation proposed by the authors has not been validated for coal particles. Moreover, it remains unresolved with respect to the value range of the Reynolds number for which the R-M correlation holds valid. It is thus the aim of this work to address those relevant uncertainties.

First, millimeter coal particles are subjected to a specific flow field to probe the effect of turbulent fluctuation on the ignition time. A one-dimensional (1D) model with the new proposed correlation and the R-M correlation for *Nu* is then used to simulate the coal ignition process. In addition, the effects of temperature, particle diameter, particle distance and coal type on the ignition time are investigated. The predicted ignition times with the new proposed correlation and the R-M correlation are compared at different Reynolds numbers. This work helps shed light upon understanding the coal ignition in flow field with an intense turbulence, and provides a proper correlation for calculating the particle heat transfer.

2. Methodology

2.1. Experimental system

A schematic of the experimental system is shown in Fig. 1. The 220 mm-deep inner chamber of the electric heating furnace features an octagonal prism shape, and the vertical section is a regular octagon with an inscribed circle diameter of 200 mm. An

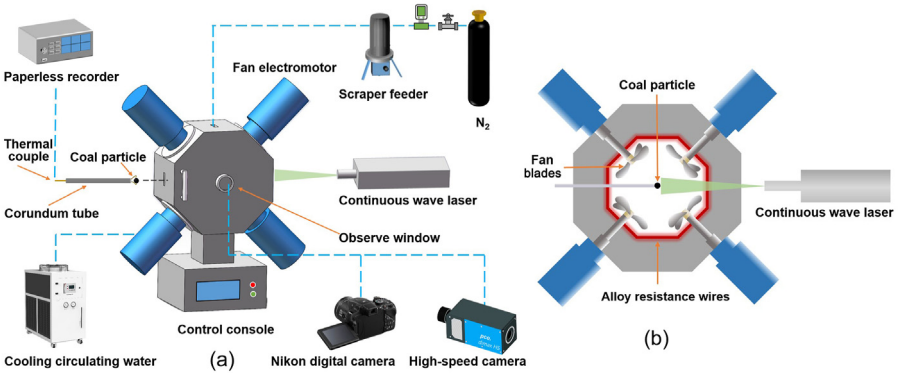


Fig. 1. (a) Schematic diagram of the experimental system; (b) Cross-section view of the furnace.

observation window, positioned at the center of the furnace's front door, was used for image acquisition; a Nikon digital camera was used to capture flame images, with a recording interval of 0.1 s. The furnace features a rated power of 3 kW, and a heating range of 0–973 K. To generate an isotropic turbulent flow field, four fans are symmetrically installed in the furnace, each of which was controlled by an independent frequency converter. The coal particle is fixated by a K-type thermocouple into a corundum tube, with a through hole of 0.4 mm in the center of the particle. The thermocouple boasts a measurement accuracy of ±2.5 °C. The flow field under different fan speeds was measured using Particle Image Velocimetry (PIV). The SiC particles with an average size of less than 1 μm were adopted as tracer particles. The planar laser with a wavelength of 532 nm is located through the laser channel of the electric furnace. The frequency was 7 Hz, and the exposure time was 20 μs. Approximately 1000 frames were captured by PIV to ensure the accuracy of the measured results. The software Insight 4G was applied to post-process the captured images. The local flow velocity was calculated based on the displacement of tracer particles between two adjacent frames. According to the PIV analysis of the flow field characteristic in our previous work, the fluctuation velocity at any points in the central region is close to each other, and the components of time-averaged velocity and fluctuation velocity in two directions are also close to each other. Therefore, the experiment is considered to be conducted in a homogeneous isotropic turbulent flow field. Since the particle is stationary and fixed at the center of furnace. Therefore, the solid-gas velocity is the gas velocity at the center of the furnace obtained through PIV.

Zuoyun bituminous coal was used in the experiment, with a diameter of 4.5 ± 0.1 mm. The analysis results are shown in Table 1. In this work, the experiments were conducted at three different fan speed (0, 1000 and 2000 rpm) with a fixed ambient temperature 773 K.

2.2. Numerical model

In this work, a 1D coal combustion model was adopted to study the coal particle ignition behavior under a turbulent flow field, as shown in Fig. 2. The gray region represents the computational domain, and the red circle outlines the radiation wall. This model

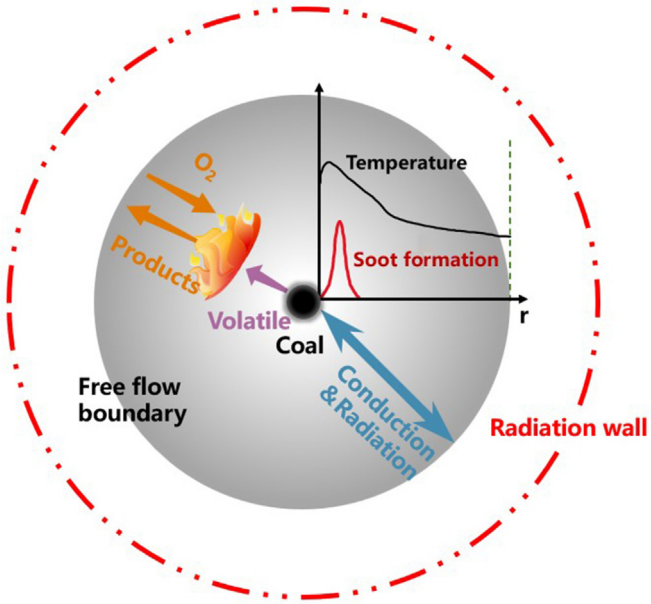


Fig. 2. Schematic of mass transport and heat transfer in the computational domain.

assumes that the coal particle heat-transfers with the ambient hot gas via conduction, and with the hot wall surface through thermal radiation. This 1D coal combustion model does not consider the convection effect, the heat and mass transfer between particles and surrounding hot gas are carried out through the conductive process on the surface of the particle. To account for the turbulence effect on the mass and heat transfer in the 1D model, assumed that the increase in mass and heat transfer due to turbulence can be described by an increase in the mass diffusivity D and conductivity λ from Eqs. (6) and (7). In the calculation of the convective heat transfer, the apparent conductivity (λ') was used instead of the real conductivity (λ_0), and $\lambda' = Nu/Nu_0 \times \lambda_0$, wherein Nu is the real Nusselt number, while Nu_0 takes a value of 2, implying that the conduction predominates the heat transfer event. Considering the

Table 1
Proximate and ultimate analysis of the Zuoyun bituminous coal.

Proximate analysis, dry base (%)			Ultimate analysis (%)				
Volatile	Ash	Fixed carbon	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
26.84	34.77	38.39	70.36	5.34	21.54	1.60	1.14

comparability of mass transfer and heat transfer, the apparent mass diffusivity (D') is expressed as $D' = Nu/Nu_0 \times D_0$, wherein D_0 is the real diffusivity. The new proposed and the R-M correlation are employed to compute the real Nu and the corresponding apparent conductivity and mass diffusivity.

The governing equations are expressed as follows:

Mass balance:

$$\frac{\partial \rho_g}{\partial t} + \frac{1}{r^2}\frac{\partial \rho_g r^2 u_r}{\partial r} - \dot{S}_g = 0 \tag{6}$$

Species balance:

$$\rho_g \frac{\partial \varphi}{\partial t} + \rho_g u_r \frac{\partial \varphi}{\partial r} + \dot{S}_g \varphi - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho_g D_\varphi \frac{\partial \varphi}{\partial r}\right) - \dot{S}_\varphi = 0 \tag{7}$$

Energy balance:

$$\left(\rho_g c_g + \rho_g Y_s c_s + \rho_g Y_{tar} c_{tar}\right)\left(\frac{\partial T}{\partial t} + u_r \frac{\partial T}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \lambda_g \frac{\partial T}{\partial r}\right) - \dot{S}_h = 0 \tag{8}$$

In Eqs. (6)–(8), $\dot{S}_g$ is the source term of gas mass; φ represents the mass fraction of gas species (Y_i), tar (Y_{tar}), and soot (Y_s); and N_s signifies the number density of soot; D_φ is the mass diffusivity of the corresponding species, tar or soot; c_g, c_s and c_{tar} are the heat capacity of gas, soot, and tar, respectively; λ_g symbolizes the thermal conductivity of gas; and $\dot{S}_h$ is the source term from reactions.

The internal thermal conductivity is obtained by solving Eq. (9),

$$\rho C \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\lambda r^2 \frac{\partial T}{\partial r}\right) \tag{9}$$

The surface temperature of the particle is obtained by solving Eq. (10),

$$m_{coal} c_{coal} \frac{dT_{coal}}{dt} = 4\pi {r_0}^2 \lambda_g \left.\frac{\partial T}{\partial r}\right|_w + \dot{m}_{char} \Delta H_{char} + \left(\dot{m}_g + \dot{m}_{tar}\right)\Delta H_{pyro} + 4\pi {r_0}^2 \varepsilon_{coal} \sigma \left({T_{rad}}^4 - {T_{coal}}^4\right) \tag{10}$$

where ΔH_{char} and ΔH_{pyro} represent the reaction enthalpy of char reaction and coal pyrolysis. The detailed reaction pathways and chemical kinetics can be found elsewhere (Feng et al., 2020).

To investigate the interactions of surrounding particles on the combustion of a single coal particle in group combustion, the Neumann boundary condition is applied at the outer boundary of the calculating domain, as shown in Eq. (11). Varying particle distance is equivalently obtainable via a change in the size of the calculating domain. The applicability analysis of the boundary conditions can be referred to our previous work (Feng et al., 2020).

$$\frac{\partial \varphi}{\partial r}_{r=r_m} = 0, \frac{\partial T}{\partial r}_{r=r_m} = 0 \tag{11}$$

The aforementioned set of equations, along with the corresponding initial and boundary conditions, were solved by the Differential Algebraic System Solver in the FlameMaster code (Pitsch & Bollig, 1994). Three coal types, i.e., Zuoyun coal shown in Table 1, Hancheng coal and Columbia coal shown in Table 2, were researched in the numerical simulation to reveal the impact of coal types.

3. Results and discussion

3.1. Experimental results and model validation

PIV is applied to measure the gas velocity field at different fan speeds based on the statistical analysis, of which the time-averaged velocity and the fluctuating velocity are determined. In addition, the particle Reynolds number (Re_p) and turbulent particle Reynolds number (Re_t*) are calculated, as shown in Fig. 3. As fan speed increases from 0 to 3000 rpm, Re_p increases from 0 to 22.5, while Re_t* increases from 0 to 71.5. It illustrates in the plots that an increasing fan speed contributed to Re_t* further outnumbering Re_p, indicating an intense fluctuation.

The measured ignition time for coal particles with ambient temperature was 773 K is shown in Fig. 4, along with the modelling results by different correlations of the Nusselt number. Since the ignition time is an important index in this work, the criterions for ignition identification in both the experiment and the simulations are as follow. In the experiment, based on the flame images, the ignition time t_i was recorded when the volatile flame increased rapidly. For the simulations, the homogeneous ignition criterion was adopted to determine the ignition time (Annamalai & Durbetaki, 1977). At the fan speed of 0, 1000 and 2000 rpm, the high-speed camera computed the ignition time as 44 s, 30 s and 15 s, respectively. A shortening ignition time with an increasing fan speed is the result of a strengthened heat transfer from surrounding hot gas to the coal particle, as substantiated in the plots in Fig. 3, wherein higher Re_p and Re_t* values are obtained at a faster fan speed. Both the R-M correlation and the new correlation (see Eqs. (1) and (2)) are shown to be able to predict the trend of ignition time with increasing fan speed. However, with the ability to consider a turbulent effect, Fig. 4 clearly implies that the new model boosts a better predictive accuracy. In general, both the R-M correlation and the new correlation are practically applicable at low fluctuation conditions, while the new model is highly recommended when the fluctuation is intense.

To further reveal the effect of turbulent fluctuation on the ignition of a single millimeter coal particle, the predicted coal mass was procured at different fan speeds with the two correlations, as shown in Fig. 5, with the ambient temperature at 773 K. At 1000 rpm, according to the R-M correlation the particle begins to shed weight (denoted as pyrolysis time) at 28 s, while the pyrolysis time is predicted to be 22 s in the new correlation. At 2000 rpm, the pyrolysis time from the R-M correlation and the new correlation is 24 s and 15 s, respectively. Hence, the predicted pyrolysis time difference of the two correlations increased from 6 s to 9 s during this fan speed boost process. It is inferred that the fluctuation enhanced the heat transfer and shortened the pyrolysis time, leading to a significant difference in predicted coal mass curves between the R-M correlation and the new correlation, especially at a high fan speed. Furthermore, Fig. 5 exhibits that the correlations derived mass curves of the coal particle deviate moderately at 1000 rpm, whereas they differ prominently at 2000 rpm.

It is suggested in Figs. 4 and 5 that the predictability of the R-M correlation and the new correlation on the ignition time is less distinct than on the change in mass of the coal particle. In other words, although the new correlation gives a better prediction on particle heat transfer than the R-M correlation, it might be acceptable in some cases to assess the ignition time with the traditional R-M correlation. It thus becomes an uncertainty with respect to the conditions under which the R-M correlation holds acceptable, as well as the conditions which justifies the use of the new correlation because the traditional correlation will introduce a significant error. Aiming to address this concern, the following section covers the analysis of the effects of heat transfer

Table 2
Proximate and ultimate analysis of Hancheng coal and Columbia coal.

Coal type	Proximate analysis, dry base (%)			Ultimate analysis (%)				
	Volatile	Ash	Fix carbon	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
Columbia coal	26.84	34.77	38.39	70.36	5.34	21.54	1.60	1.14
Hancheng coal	14.52	42.24	43.25	77.25	4.18	1.26	14.10	3.90

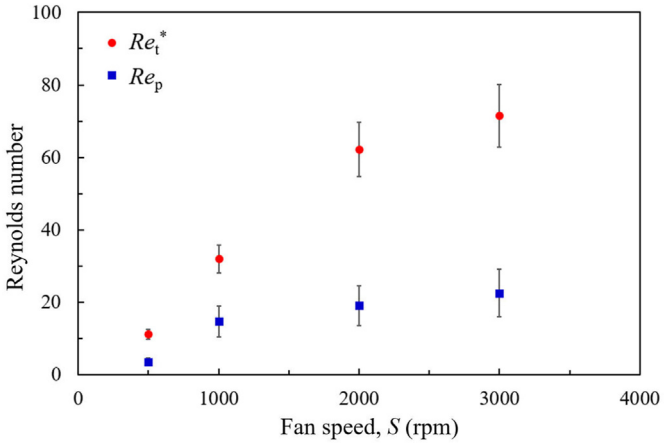


Fig. 3. Reynolds numbers based on measured gas velocity.

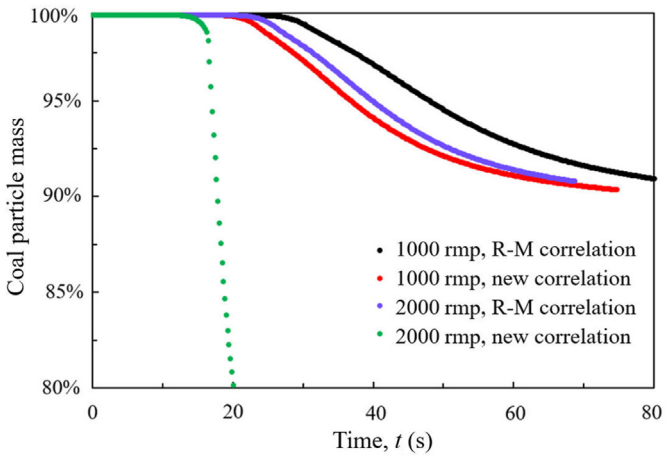


Fig. 5. Predicted coal mass at different fan speeds with different correlations.

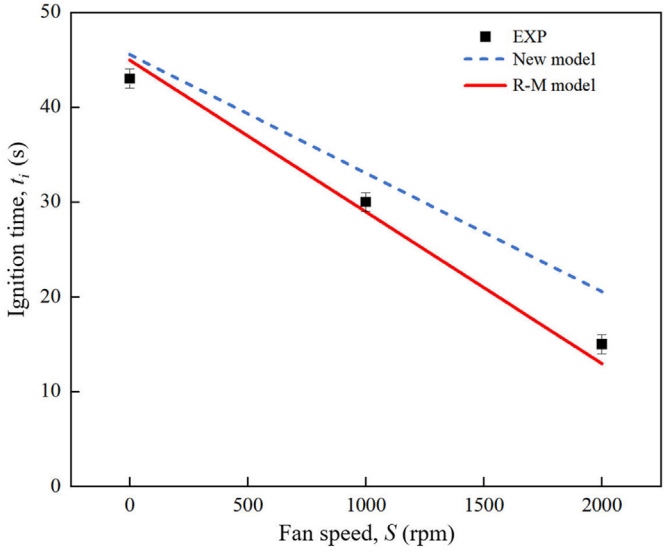


Fig. 4. Comparison of measured and simulated ignition time.

enhancement on the ignition time at different ambient temperatures, particle diameters and particle distances.

3.2. Effect of heat transfer enhancement on ignition time

Fig. 6 presents the predicted ignition time (t_i) of single coal at different ambient temperatures (T_a). It clearly shows that as T_a increases, t_i decreases dramatically since the convective heat transfer rate is proportional to the temperature difference between the particle and the surrounding gas. However, the proportionality between the decreasing ignition time with increasing temperature features a watershed at about the mid-value of the tested temperature range, i.e. approximately 1200–1300 K, at which the momentum of decrease largely levels off. The finding pertaining to the relationship of ignition time with temperature is consistent with experimental results. For example, Yang et al. (Yang et al., 2021) measured the ignition time of 2 mm coal particle in the temperature range of 920–1070 K, and reported a decrease of ignition time with the increase of temperature. Furthermore, Kuznetsov et al. (Kuznetsov et al., 2023) measured the ignition time of millimeter wood particles in the temperature range of 870–1270 K, and found the ignition time decreases fast initially and then slowly when the temperature increases. This phenomenon is in high consistency with the trend in Fig. 6, indicating that the simulated results is reliable.

The effects of Nusselt number on the ignition time are analyzed in the form of Nu^*/Nu, where Nu is fixed at 2, corresponding to the heat transfer without convection. Thus, an increase in the value of Nu^*/Nu amounts to an enhancing turbulence. It implies in Fig. 6 that t_i decreases with increasing Nu^*/Nu due to a stronger turbulence boosted heat transfer to the particle. It should be noted that the ignition time is not inversely proportional to the Nusselt number.

The impact of particle size on the ignition time of single coal particle can be disclosed in Fig. 7, with ambient temperature at 773 K. wherein the predicted ignition time varies with particle diameter under various Nu^*/Nu values. It shows that at all Nu^*/Nu values a big particle diameter leads to a longer ignition time t_i. This finding is sensible because in general the convective heat transfer rate is proportional to the surface area of particle (d_p^2), while the thermal inertia is proportional to the volume of particle (d_p^3). In addition, Fig. 7 demonstrates that an enhanced turbulence/heat transfer, represented by a bigger Nu^*/Nu value, results in a shorter ignition time. However, it is revealed that the influence of Nu^*/Nu on the ignition time dwindles on small-size particles. A quantitative analysis on the data in Fig. 7 exhibits that t_i is approximately proportional to $d_p^{1.3-1.7}$. Katalambula et al. (Katalambula et al., 1996) measured the coal ignition time with the particle diameter in the range of 0.6–1.8 mm, and reported that t_i is proportional to $d_p^{0.5-0.6}$.

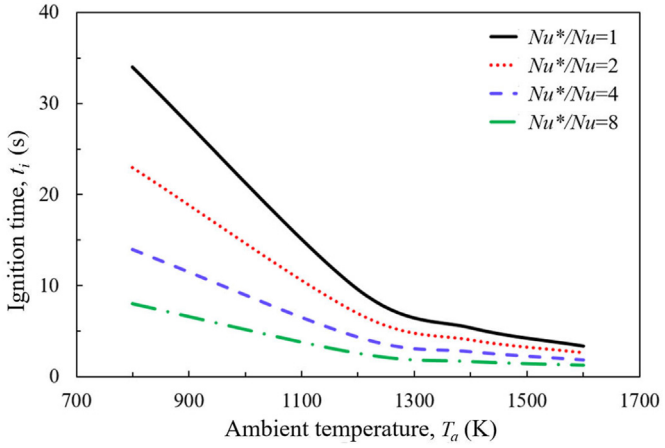


Fig. 6. Effect of ambient temperature on ignition time.

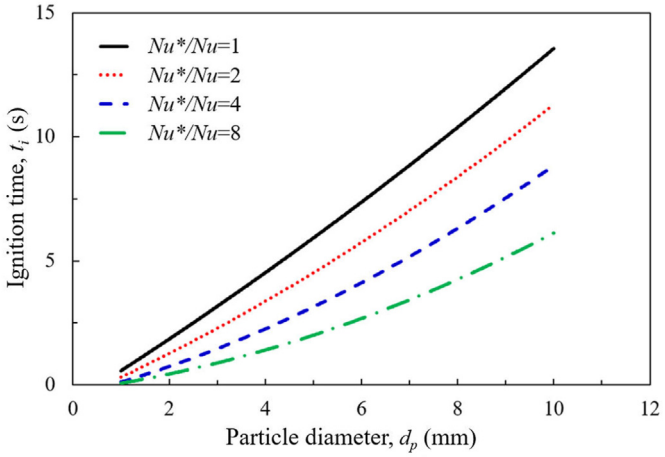


Fig. 7. Effect of particle diameter on ignition time.

It is well known that for small particles with a Biot number smaller than 0.1, t_i is nearly proportional to d_p^2. Both this work and the work of Katalambula et al. (Katalambula et al., 1996) show that the power exponent of d_p is smaller than 2, indicating that the prediction is likely to overestimate the ignition time when the particle diameter is large. This overestimation is attributable to a notable temperature difference inside the millimeter particle. Therefore, at a low average temperature, the surface temperature might be very high, leading to a shorter-than-predicted ignition time.

The predicted ignition time at different particle distance is shown in Fig. 8, with the ambient temperature at 773 K. It shows that the ignition time increases with L/d_p substantially until L/d_p reaches 5, after which the L/d_p exerts a negligible impact. Therefore, at large L/d_p values, the effect of particle interaction is minimal, namely the particle is in individual combustion mode. Conversely, when the L/d_p gets smaller, each particle is surrounded with less gas, and thus a faster accumulation of heat from oxidization and species from devitalization leads to a shorter ignition time. Similar to previous analysis, the impact of Nu^*/Nu in this regard is consistent that an enhanced heat transfer helps reduce the ignition time.

Based on the simulated data in Figs. 6–8, it can be concluded that t_i is proportional to $(Nu^*/Nu)^{-0.6}$ when other parameters are fixed. In order to further validate this relationship, Colombian coal and Hancheng coal are used in the simulation to predict their

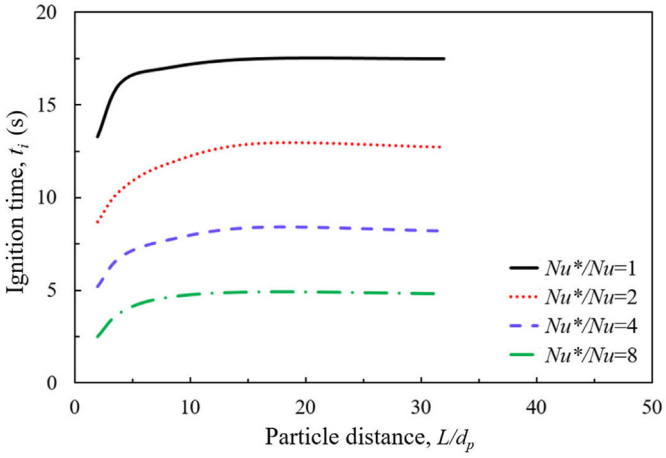


Fig. 8. Effect of particle distance on ignition time.

ignition time under the effect of heat transfer enhancement, which is plotted in Fig. 9. As shown, there is a nearly proportional relationship between t_i and $(Nu^*/Nu)^{-0.6}$. Therefore, for the millimeter coal particles simulated in this work, it is reasonable to apply this proportional relationship to estimate the variation of ignition time when the heat transfer is enhanced.

3.3. Applicability of different correlations

With the consideration of the effect of turbulent fluctuation on particle heat transfer, the new correlation is slated to predict a higher particle temperature than that with the R-M correlation. However, the difference of the predicted ignition time by the two correlations can be insignificant in many cases. In view of the importance of the ignition time of coal particle on the combustor safety and combustion stability, it is necessary to clear the uncertainties with respect to the conditions where the new correlation should substitute for the R-M correlation.

Based on the relationship between t_i and $(Nu^*/Nu)^{-0.6}$ as revealed in the abovementioned analysis and combining Eqs. (1) and (2), the difference of predicted t_i between the R-M correlation and the new correlation is calculated with different Re_p and Re_t^*, as shown in Fig. 10. It illustrates that, at a big Re_p and a small Re_t^*, the difference of predicted t_i is acceptable; when Re_p is small or Re_t^* is large, the difference grows prominent and thus

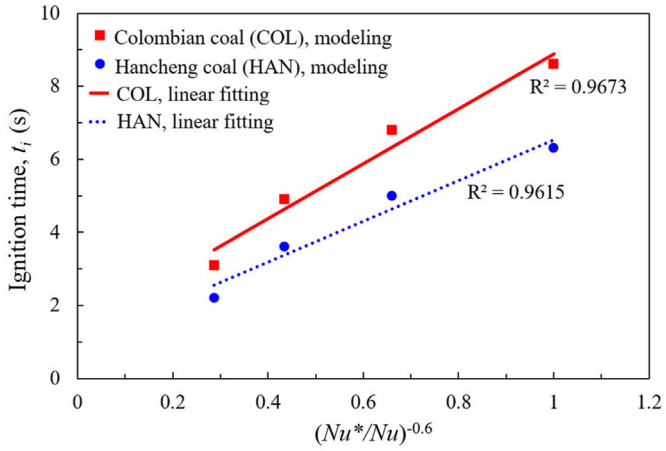


Fig. 9. Proportional relationship between t_i and $(Nu^*/Nu)^{-0.6}$.

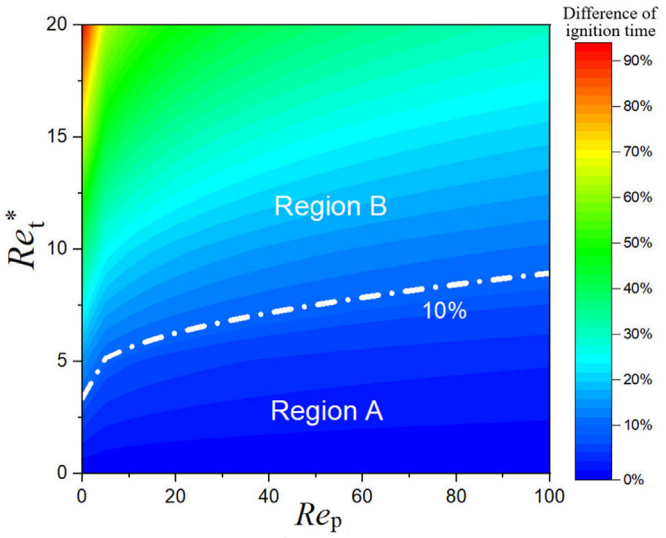


Fig. 10. Comparison of different correlations at different Re_p and Re_t*.

unacceptable. The white line in Fig. 10 is corresponding to the difference value of 10%. In Region An under the white line, both the R-M correlation and the new correlation give a reasonable prediction of the particle heat transfer, while in Region B above the white line, the new correlation is recommended.

4. Conclusions

In this work, the effect of turbulent fluctuation on the ignition of millimeter coal particle is investigated through experiment and simulation. The traditional R-M correlation and newly proposed correlation are compared when applied to calculate the Nusselt number for particle heat transfer. The main conclusions are as follows.

(1) The furnace with symmetric fans is capable of generating a flow field with high a fluctuating velocity and a low time averaged velocity. As the fan speed increases from 0 to 3000 rpm, Re_p increases from 0 to 22.5, while Re_t* increases from 0 to 71.5. The ignition time decreases when the fan speed increases.
(2) With the inclusion of the effect of fluctuation, the newly proposed correlation of *Nu* gives a better prediction of ignition time compared to the R-M correlation. However, it is to note that the predicted difference of the two correlations on the particle mass is more significant.
(3) The ignition time of the millimeter coal particle is revealed to be nearly proportional to $(Nu^*/Nu)^{-0.6}$ when other parameters are fixed. Based on this relationship, the difference of predicted ignition time is calculated at different Re_p and Re_t*, which manifests that at a small Re_p or a large Re_t*, the newly proposed correlation should substitute for the R-M correlation.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature of kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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