Particuology 91 (2024) 168–175

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

# 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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A R T I C L E I N F O

*Article history:*
Received 7 January 2024
Received in revised form
25 February 2024
Accepted 7 March 2024
Available online 19 March 2024

Handling editor: Lifang Wu

*Keywords:*
Turbulent fluctuation
Particle heat transfer
Empirical correlation
Coal ignition

A B S T R A C T

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.


## 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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https://doi.org/10.1016/j.partic.2024.03.002
1674-2001/

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.

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

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

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

where, $Nu^*$ is turbulent Nusselt number, $Re_p$ is particle Reynolds number, $Pr$ is Prandtl number, $Re_t^*$ is particle turbulent Reynolds number, $\rho$ is density, $\mu$ 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

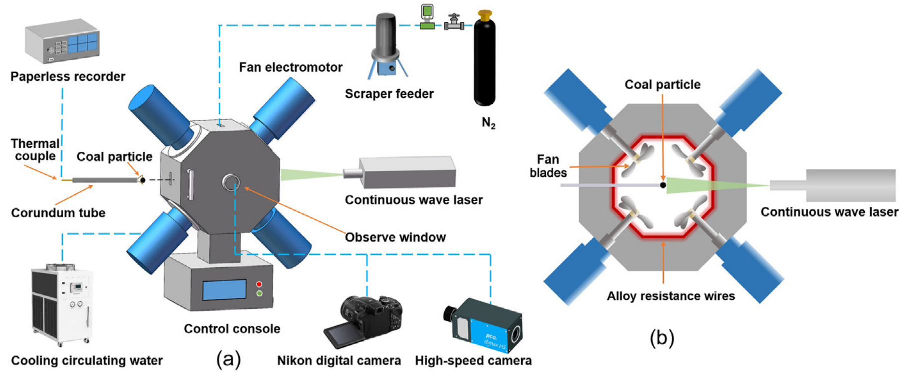


**Fig. 1.** (a) Schematic diagram of the experimental system; (b) Cross-section view of the furnace.

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 $\pm 2.5$ °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 $4.5 \pm 0.1$ 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 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 $\lambda$ from Eqs. (6) and (7). In the calculation of the convective heat transfer, the apparent conductivity ($\lambda'$) was used instead of the real conductivity ($\lambda_0$), 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

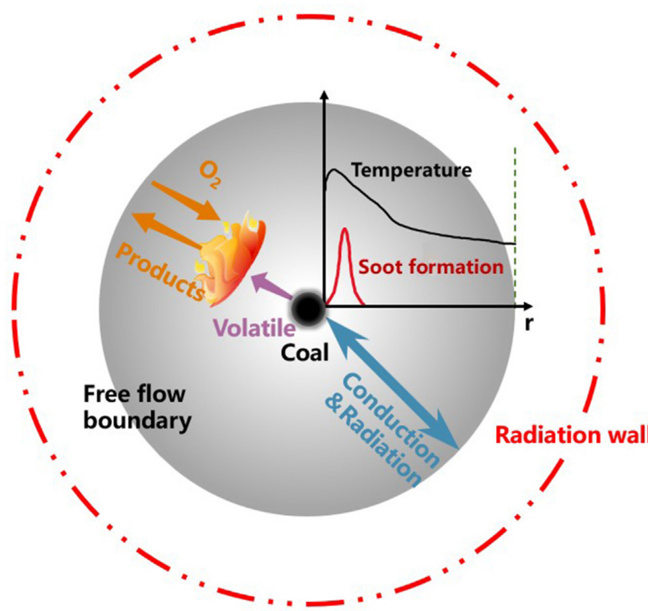


**Fig. 2.** Schematic of mass transport and heat transfer in the computational domain.

**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:

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

Species balance:

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

Energy balance:

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

In Eqs. (6)–(8), $\dot{S}_g$ is the source term of gas mass; $\varphi$ 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; $D_\varphi$ 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; $\lambda_g$ 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),

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

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

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

where $\Delta H_{char}$ and $\Delta H_{pyro}$ 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).

$$\frac{\partial \varphi}{\partial r_{r=r_m}} = 0, \frac{\partial T}{\partial r_{r=r_m}} = 0 \quad (11)$$

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 |

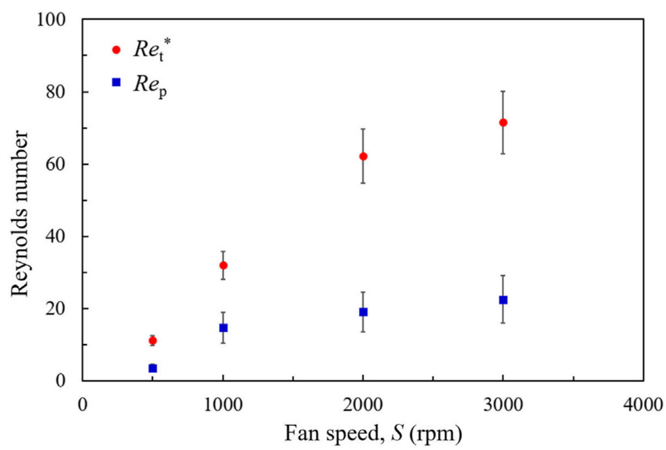

**Fig. 3.** Reynolds numbers based on measured gas velocity.

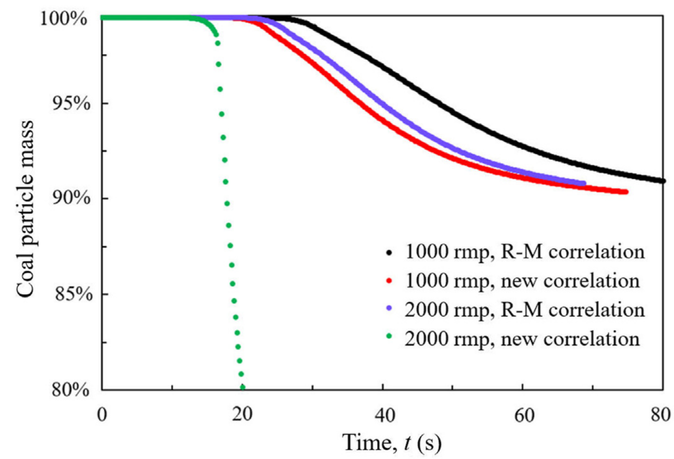

**Fig. 5.** Predicted coal mass at different fan speeds with different correlations.

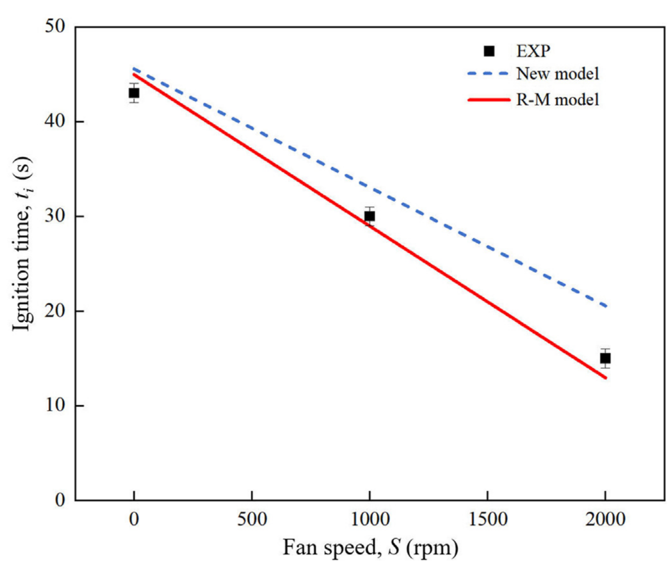

**Fig. 4.** Comparison of measured and simulated ignition time.

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 $d_p^{0.5-0.6}$.

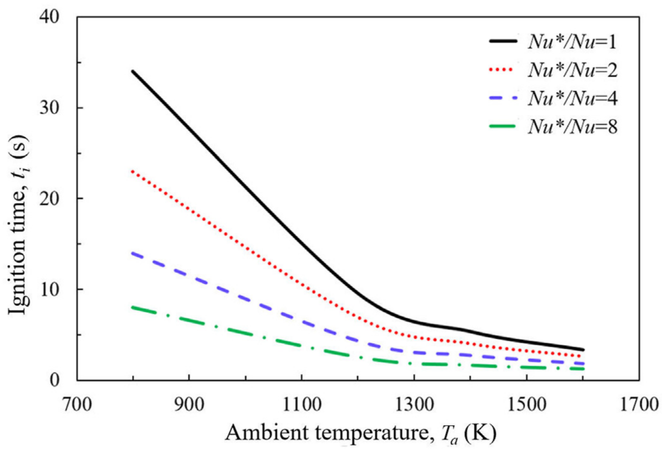


**Fig. 6.** Effect of ambient temperature on ignition time.

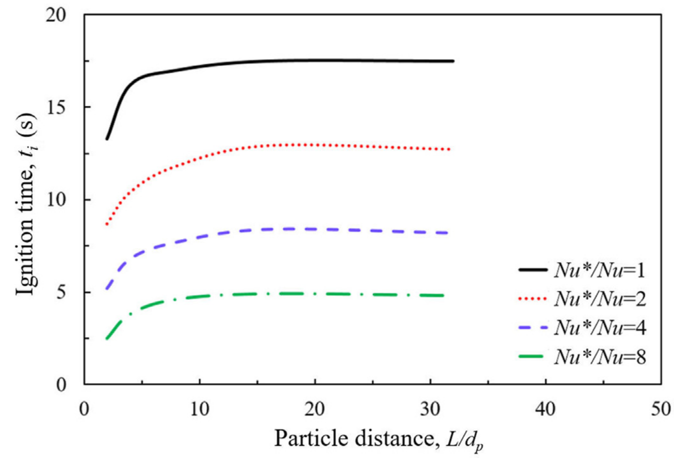


**Fig. 8.** Effect of particle distance on ignition time.

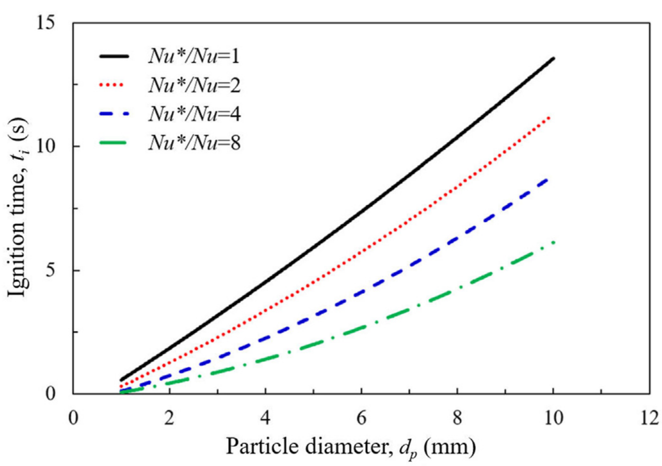


**Fig. 7.** Effect of particle diameter on ignition time.

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 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

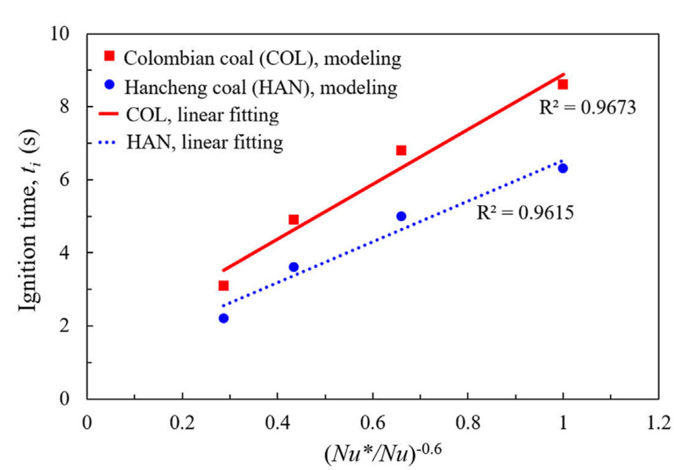


**Fig. 9.** Proportional relationship between $t_i$ and $(Nu^*/Nu)^{-0.6}$.

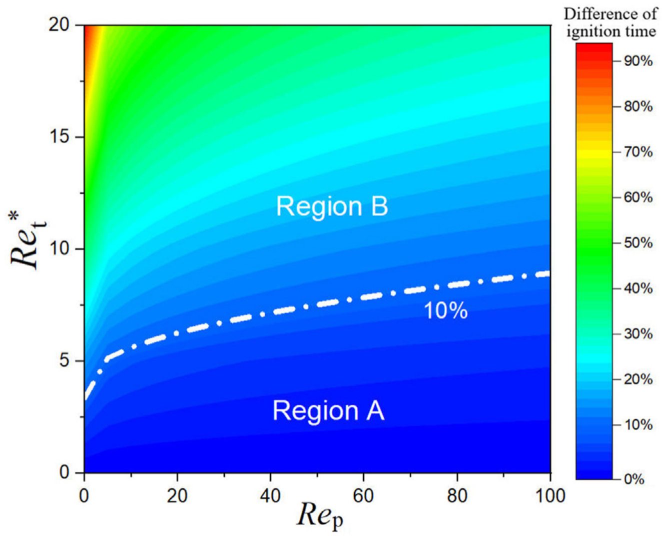


**Fig. 10.** Comparison of different correlations at different $Re_p$ and $Re_t$*.

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.

## Acknowledgements

The supports provided by the National Natural Science Foundation of China (grant Nos. 52106189 and 52174220) are highly appreciated. The support provided by the Shuangchuang Doctor Project of Jiangsu Province (grant No. 202131196) is also appreciated. This research was also financially supported by fund from Key Laboratory of Hubei Province for Coal Conversion and New Carbon Materials, Wuhan University of Science and Technology (grant No. WKDM202302) This research was also funded by "Double First Class" Construction Project to Enhance Independent Innovation Ability of China University of Mining & Technology (grant No. 2022ZZCX03K06).

## References

Ahmed, S. F., & Mastorakos, E. (2006). Spark ignition of lifted turbulent jet flames. *Combustion and Flame, 146*(1–2), 215–231. https://doi.org/10.1016/j.combustflame.2006.03.007
Annamalai, K., & Durbetaki, P. (1977). A theory on transition of ignition phase of coal particles. *Combustion and Flame, 29*, 193–208.
Bagchi, P., & Kottam, K. (2008). Effect of freestream isotropic turbulence on heat transfer from a sphere. *Physics of Fluids, 20*(7), Article 073305. https://doi.org/10.1063/1.2963138
Bai, X., Lu, G., Bennet, T., Sarroza, A., Eastwick, C., Liu, H., & Yan, Y. (2017). Combustion behavior profiling of single pulverized coal particles in a drop tube furnace through high-speed imaging and image analysis. *Experimental Thermal and Fluid Science, 85*, 322–330. https://doi.org/10.1016/j.expthermflusci.2017.03.018
Birouk, M., & Fabbro, S. C. (2013). Droplet evaporation in a turbulent atmosphere at elevated pressure - experimental data. *Proceedings of the Combustion Institute, 34*, 1577–1584. https://doi.org/10.1016/j.proci.2012.05.092
Chaudhuri, S., Wu, F. J., & Law, C. K. (2013). Scaling of turbulent flame speed for expanding flames with Markstein diffusion considerations. *Physical Review E, 88*(3), Article 033005. https://doi.org/10.1103/PhysRevE.88.033005
Coppola, G., Coriton, B., & Gomez, A. (2009). Highly turbulent counterflow flames: A laboratory scale benchmark for practical systems. *Combustion and Flame, 156*(9), 1834–1843. https://doi.org/10.1016/j.combustflame.2009.03.017
Davini, P., Ghetti, P., Bonfanti, L., & DeMichele, G. (1996). Investigation of the combustion of particles of coal. *Fuel, 75*(9), 1083–1088. https://doi.org/10.1016/0016-2361(96)00073-7
Faundez, J., Arenillas, A., Rubiera, F., Garcia, X., Gordon, A. L., & Pis, J. J. (2005). Ignition behaviour of different rank coals in an entrained flow reactor. *Fuel, 84*(17), 2172–2177. https://doi.org/10.1016/j.fuel.2005.03.028
Feng, L. L., Wu, Y. X., Guo, H. N., Hu, Z. K., Zhang, S. Y., & Zhou, H. (2022). Effect of fluctuation on heat transfer enhancement of a spherical particle. *International Communications in Heat and Mass Transfer, 133*, Article 105981. https://doi.org/10.1016/j.icheatmasstransfer.2022.105981
Feng, L. L., Wu, Y. X., Xu, K. L., Zhang, H., & Zhang, Y. (2020). Effect of particle distance on combustion behaviors through 1-D model with Neumann boundary condition. *Fuel, 276*, Article 117974. https://doi.org/10.1016/j.fuel.2020.117974
Hadi, K., Ichimura, R., Hashimoto, N., & Fujita, O. (2019). Spherical turbulent flame propagation of pulverized coal particle clouds in an $O_2/N_2$ atmosphere. *Proceedings of the Combustion Institute, 37*(3), 2935–2942. https://doi.org/10.1016/j.proci.2018.09.021
Huang, Z. Q., Zhang, C., Jiang, M., Wang, H. Z., & Zhou, Q. (2019). Effects of particle velocity fluctuations on inter-phase heat transfer in gas-solid flows. *Chemical Engineering Science, 206*, 375–386. https://doi.org/10.1016/j.ces.2019.05.047
Katalambula, H. H., Kitano, K., Ikeda, K., & Chiba, T. (1996). Mechanism of ignition of single coal particle: Effect of heating rate on particle size dependence of ignition temperature. *Journal of Chemical Engineering of Japan, 29*(3), 523–530. https://doi.org/10.1252/jcej.29.523
Khatami, R., Stivers, C., & Levendis, Y. A. (2012). Ignition characteristics of single coal particles from three different ranks in $O_2/N_2$ and $O_2/CO_2$ atmospheres. *Combustion and Flame, 159*(12), 3554–3568. https://doi.org/10.1016/j.combustflame.2012.06.019
Kim, R.-G., Li, D., & Jeon, C.-H. (2014). Experimental investigation of ignition behavior for coal rank using a flat flame burner at a high heating rate. *Experimental Thermal and Fluid Science, 54*, 212–218. https://doi.org/10.1016/j.expthermflusci.2013.12.017
Kuznetsov, G. V., Syrodoy, S. V., Borisov, B. V., Kostoreva, Z. A., Gutareva, N. Y., & Kostoreva, A. A. (2023). Influence of homeomorphism of the surface of a wood particle on the characteristics of its ignition. *Renewable Energy, 203*, 828–840. https://doi.org/10.1016/j.renene.2022.12.097
Liu, B., Zhang, Z. Z., Zhang, H., Yang, H. R., & Zhang, D. K. (2014). An experimental investigation on the effect of convection on the ignition behaviour of single coal particles under various $O_2$ concentrations. *Fuel, 116*, 77–83. https://doi.org/10.1016/j.fuel.2013.07.112

Lu, H., Ip, E., Scott, J., Foster, P., Vickers, M., & Baxter, L. L. (2010). Effects of particle shape and size on devolatilization of biomass particle. *Fuel, 89*(5), 1156–1168. https://doi.org/10.1016/j.fuel.2008.10.023

Moran, J. C., & Glicksman, L. R. (2003). Mean and fluctuating gas phase velocities inside a circulating fluidized bed. *Chemical Engineering Science, 58*(9), 1867–1878. https://doi.org/10.1016/s0009-2509(02)00683-8

Pitsch, H., & Bollig, M. (1994). *Flamemaster, a computer code for homogeneous and one-dimensional laminar flame calculations*. Institut für Technische Mechanik, RWTH Aachen.

Raithby, G. D., & Eckert, E. R. G. (1968). Effect of turbulence parameters and support position on heat transfer from spheres. *International Journal of Heat and Mass Transfer, 11*(8), 1233–1252. https://doi.org/10.1016/0017-9310(68)90194-4

Ranz, W., & Marshall, W. (1952). Evaporation from drops. *Chemical Engineering Progress, 48*, 41–146.

Sijercic, M., & Hanjalic, K. (1994). Application of computer simulation in a design study of a new concept of pulverized coal gasification. Part 2: Model of coal reactions and discussion of results. *Combustion Science and Technology, 97*(4–6), 351–375. https://doi.org/10.1080/00102209408935385

Sung, Y. M., Moon, C. E., Kim, J. R., Kim, S. C., Kim, T. H., Il Seo, S., Choi, G. M., & Kim, D. J. (2011). Influence of pulverized coal properties on heat release region in turbulent jet pulverized coal flames. *Experimental Thermal and Fluid Science, 35*(4), 694–699. https://doi.org/10.1016/j.expthermflusci.2011.01.003

Tufano, G. L., Stein, O. T., Wang, B., Kronenburg, A., Rieth, M., & Kempf, A. M. (2018). Coal particle volatile combustion and flame interaction. Part II: Effects of particle Reynolds number and turbulence. *Fuel, 234*, 723–731. https://doi.org/10.1016/j.fuel.2018.07.054

Wang, L. P., & Maxey, M. R. (1993). Settling velocity and concentration distribution of heavy-particles in homogeneous isotropic turbulence. *Journal of Fluid Mechanics, 256*, 27–68. https://doi.org/10.1017/s0022112093002708

Wissink, J. G., & Rodi, W. (2011). Heat transfer from the stagnation area of a heated cylinder at $Re_D$=140,000 affected by free-stream turbulence. *International Journal of Heat and Mass Transfer, 54*(11–12), 2535–2541. https://doi.org/10.1016/j.ijheatmasstransfer.2011.02.008

Xia, Z., Han, X., & Mao, J. (2021). Very large eddy simulation of turbulent jet diffusion flame based on FGM. *Journal of Engineering and Thermophysics, 42*(2), 529–533.

Yang, W. T., Zhang, Y., Hu, L. L., Lyu, J. F., & Zhang, H. (2021). An experimental study on ignition of single coal particles at low oxygen concentrations. *Frontiers in Energy, 15*(1), 38–45. https://doi.org/10.1007/s11708-020-0692-1

Zhang, M. C., Yu, J., & Xu, X. C. (2005). A new flame sheet model to reflect the influence of the oxidation of CO on the combustion of a carbon particle. *Combustion and Flame, 143*(3), 150–158. https://doi.org/10.1016/j.combustflame.2005.05.010

Zhou, B., & Frank, J. H. (2021). Experimental study of vorticity-strain interactions in turbulent premixed counterflow flames. *Proceedings of the Combustion Institute, 38*(2), 2909–2916. https://doi.org/10.1016/j.proci.2020.06.182

Zhou, H., Ring, T. A., & Sutherland, J. C. (2021). Additional criteria for MILD coal combustion. *Proceedings of the Combustion Institute, 38*(3), 4233–4240. https://doi.org/10.1016/j.proci.2020.06.175

Zhou, H., Tu, Q. Y., & Wang, H. G. (2019). Investigation of the complex gas-solids flow characteristics in a fluidized bed with a Wurster tube by process tomography and CFD simulation. *Powder Technology, 357*, 117–133. https://doi.org/10.1016/j.powtec.2019.08.099