

## THE EFFECT OF FUEL PYROLYSIS ON THE COAL PARTICLE COMBUSTION – AN ANALYTICAL INVESTIGATION

by

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*The aim of this work is to analytically investigate the symmetrical combustion of an isolated coal particle with the fuel pyrolysis effect. The modelling concept of coal particles is similar to that of the liquid droplet combustion but in the case of coal devolatilization, the particles do not shrink like droplet does due to evaporation of liquid fuel. The rate of devolatilization of volatiles can be calculated using the equation that is similar to Arrhenius equation. This model is based on an assumption of combined quasi-steady and transient behaviour of the process and especially focuses on predicting the variations of temperature profile, radius of pyrolysis and transfer number. It is revealed that the entrance of pyrolysis effect into the governing equations leads to the reduction in the film radius and consequently a reduction in the stand-off ratio and transfer number.*

Key words: *analytical model, pyrolysis effect, coal combustion, devolatilization rate*

### Introduction

The ignition of droplets has attracted considerable interest because of its fundamental and practical importance. Within droplet combustion researches, one of the important aims is to utilize the available droplet models for determining a new model for the combustion of organic dust particles in many applications. Several studies on the effect of fuel droplets on a propagating flame have been carried out during the recent decades. One of the fundamental investigations was performed by Aouina *et al.* [1] who developed a computer code based on a 2-D model for the simulation of heating, vaporization, ignition, and subsequent combustion of cold droplets injected in a hot uniform gas flow. Both methanol droplets in hot air as well as liquid oxygen droplets in gaseous hydrogen were studied in this research. Another important parameter in the droplet combustion is the role of cooled wall. Also Okai *et al.* [2] performed reduced-gravity experiments with heptane droplets burning near cool walls. Dombrovsky and Sazhin [3] formu-

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lated the boundary-value problem for calculation of differential absorption of thermal radiation on a spherical droplet. The solution of this problem was supplemented by simple analytical approximations for the normalized absorbed radiation power. Miliauskas [4] presented a mathematical model of unsteady heat transfer in evaporating semitransparent droplets of non-isothermal initial state and the numerical research method, evaluating selective radiation absorption and its influence on interaction of transfer processes. Shaw *et al.* [5] experimentally investigated the combustion characteristics of droplet streams in the vicinity of a cooled wall. The experiments indicated that burning rates decreased significantly when droplets were in the vicinity of the wall. Also in another study [6], he developed the symmetrical combustion of an isolated fuel droplet to account for the fuel pyrolysis. Fuel pyrolysis was modeled as a high activation-energy process that occurred within a thin zone between the droplet and the flame. Tseng and Viskanta [7] claimed that the fuel droplet evaporation was relevant to spray combustion in technologically important devices and must be understood to develop reliable combustion methods for hydrocarbon fuels. A model based on radiative transfer theory was used to calculate the local volumetric rate of radiation absorption. Then, Atzler *et al.* [8] used a combustion vessel for fundamental studies of aerosol combustion, under strictly controlled conditions of pressure, temperature, and equivalence ratio. Ghassemi *et al.* [9] experimentally studied the evaporation characteristics of single and multi component droplets at the different environmental conditions under normal gravity. In the first step, the evaporation of single component droplet of both fuels was examined separately. In the next step the evaporation of several blends of these two fuels, as a binary component droplet was studied. It was revealed that the evaporation of the binary droplet at low pressure was accompanied with bubble formation and droplet fragmentation and led to incomplete micro explosion. Consequently, Ulzama [10] presented an analytical model based on an assumption of combined quasi-steady and transient behavior of the process to exemplify the unsteady, spherically-symmetric single droplet combustion under microgravity.

Moreover, there are few numerical investigations corresponding to the pyrolysis effect of coal particles. Ulloa *et al.* [11] used a multiple reaction model to characterize the kinetics of pyrolysis of single coals and binary blends. Chern and Hayhurst [12] followed the previous experimental work showing that the shrinking-core model applies to the pyrolysis of coal particles. These experimental facts were in accord with the production of volatile matter being endothermic and not thermo neutral, as often assumed. In addition, Jimenez and Ballester [13] discussed the factors influencing the evolution of particle size during the combustion of pulverized coal, as well as their consequences for the interpretation of burnout curves. In this research, the effect of pyrolysis is not considered. Higuera [14] numerically investigated the devolatilization of an isolated coal particle moving relative to the surrounding gas using a competing reaction model of the pyrolysis and assuming that the released volatiles burn in an infinitely thin diffusion flame around the particle. The temperature of the particle was assumed to be uniform and the effects of the heat of pyrolysis, the intraparticle mass transfer resistance, and the variation of the particle radius are neglected. Yu *et al.* [15] developed a model that takes into account chemical reactions, heat and mass transfers in the boundary layer of the particle simultaneously for simulating the combustion of a pulverized coal particle. Sadhukhanet *et al.* [16] studied the combustion of a single-particle of high ash coal at elevated pressure. They employed a transient shrinking reactive core model which includes heat and mass transfer phenomena as well as reaction kinetics and intra-particle details such as transportation of gaseous reactants and products.

Furthermore, since fuel particle size has an essential role in combustion problems, Shah *et al.* [17] described an adaption of a kinetic population balance model for predicting parti-

cle size evolution during pulverized fuel combustion. They derived the fragmentation and burning rate constants from lab-scale experiments and implemented them into the model. Liakos *et al.* [18] presented a 2-D, two-phase combustion model of pulverized coal char. The aim of their study was to predict the diffusion and reaction rates and also to evaluate the effect of coal particle size on the performance of the burner. In their model the equations of conservation of mass, energy, momentum, and chemical species are solved taking into consideration turbulent flow, interphase mass and heat transfer, radiative heat transfer and operational conditions such as coal feed and primary and secondary air.

Marek and Swiatkowski [19] accomplished experimental studies of single particle combustion in air and different oxy-fuel atmospheres. Combustion of coal and char particle in different gases mixtures has been studied and the influence of atmosphere composition on combustion process and on the comparison between combustion in air-like vs. oxy-fuel dry and oxy-fuel wet conditions has been investigated. Kim and Jeon [20] used a novel technique to measure the coal char particle temperature in order to obtain the intrinsic reaction kinetics of the particles. Coal char ignition was found to begin at a spot on the particle's external surface and then moved across the entire particle. Moreover, the ignition point determined according to the minimum of  $dT/dt$  is a spot point and not a full growth point. The ignition temperature of the spot point rises as the particle diameter increases. They also developed a spot ignition model to evaluate the intrinsic kinetics and predict the ignition temperature of the coal char.

The current research group previously worked on the flame propagation mechanism and a number of investigations were carried out on the effects of radiation, particle size and heat loss on the pyrolysis of biomass particles [21-23]. More specifically, attention of the current research group was focused on the flame propagation through lycopodium dust particles at different Lewis and Damkohler numbers, while the effects of initiation of particles vaporization, radiation and heat loss on the combustion properties of the latter particles were also investigated [24-27].

In this research, a novel analytical model based on the current presented model Ulzama [10] is developed in this research with the emphasis on the role of pyrolysis effect on the devolatilization of a single coal particle. In order to achieve this objective, similar approach for the droplet combustion developed is used considering a point that in the case of coal devolatilization, particles don't shrink due to the evaporation (like liquid fuel) and therefore a first order Arrhenius equation is used to calculate the rate of devolatilization. In order to simulate the pyrolysis heat, the coal particle combustion process is extended into three zones with a pyrolysis sheet located between droplet (zone I) and flame sheet (zone II). Finally the combustion characteristics obtained by this mathematical model are depicted.

### Analytical model

In this analytical model, the combustion process consists of three zones as shown in fig. 1.

The first zone is located between the char surface and the fuel pyrolysis sheet, as well, zone II is a narrow interval between the pyrolysis sheet and the flame sheet and finally, zone III is between the flame

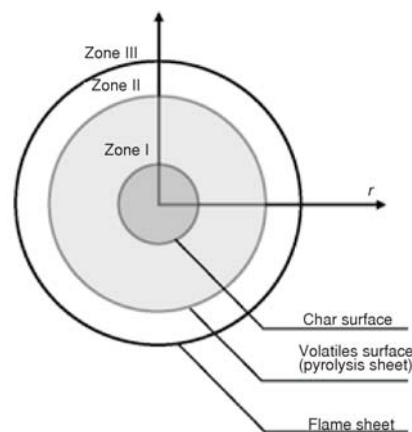


Figure 1. Schematic of the coal combustion with a fuel pyrolysis sheet

sheet and the environment. In order to simplify the process of solving the governing equations, it is assumed that all endothermic chemistry occurs in a thin sheet, denoted here as a fuel pyrolysis sheet. It is worthwhile noting that the pyrolysis product is transported both inward toward the char (by diffusion) and outward toward the flame (from advection and diffusion). In the present model, the pyrolysis product is not allowed to dissolve into the char, so there is no net flux of pyrolysis product between the char and the pyrolysis sheet. However, the pyrolysis product is transported to the flame sheet, where it is consumed. The following assumptions are considered in this research:

- the gas phase is quasi-steady,
- the ratio  $\lambda/c_p$  is constant,
- the Lewis number is considered unity, and
- pyrolysis sheet is assumed between char and flame.

Under these conditions, the equations for conservation of energy and species between the char and the environment (zone III) can be expressed:

$$4\pi r^2 \lambda \frac{dT}{dr} = \dot{m}[c_p(T - T_{sp}) + \Delta\tilde{H}_v + H - Q] \quad (1)$$

$$4\pi D \rho r^2 \frac{dy_i}{dr} = \dot{m}(y_i - \varepsilon_i) \quad (2)$$

where  $r$ ,  $\dot{m}$ ,  $T_{sp}$ ,  $\Delta\tilde{H}_v$ ,  $H$ ,  $Q$ ,  $y$ , and  $\varepsilon$  are the radial co-ordinate, mass flow rate off the char surface, char surface temperature, devolatilization enthalpy obtained by Chern and Hayhurst[12], enthalpy change associated with fuel pyrolysis, heat of combustion for the fuel-related species reaching the primary oxidation zone, mass fraction and mass-flux fraction, respectively, and the subscript  $i$  represents species where  $i$  is the oxidizer, fuel, pyrolysis product, combustion product, or inert. The heat of devolatilization ( $\Delta\tilde{H}_v$ ) is defined:

$$\Delta\tilde{H}_v = \Delta H + [\Delta H_w + C_{p,w}(T_f - 373)] \frac{W_\infty}{Y_\infty} + \frac{C_{p,c}(T_f - T_0)}{Y_\infty} \quad (3)$$

where  $W_\infty$  and  $Y_\infty$  are the masses of water and volatile material, respectively, per unit mass of moisture-free original coal. In addition,  $H_w$  is the latent heat of vaporization per unit mass of water at 373 K. In the combustion of coal dust particles, according to the aforementioned model Ulzama [10], term  $\dot{m}$  should be replaced by  $\rho_v(dV/dt)$  because in the case of coal devolatilization, the particle does not shrink like droplet does due to evaporation of liquid fuel. Thus, the rate of devolatilization can be calculated by a first order Arrhenius reaction:

$$\frac{dV}{dt} = (V_\infty - V)k_{v0} \exp\left(-\frac{E_v}{RT_{sp}}\right) \quad (4)$$

Here,  $V$ ,  $V_\infty$ ,  $k_{v0}$ ,  $E_v$ , and  $R$  are the total of volatiles evolved up to time  $t$ , the total volatile content of coal, pre-exponential factor, activation energy, and the universal gas constant, respectively. For the pre-exponential factor and activation energy, various values are reported in different references for instance Goldberg and Essenhigh [28] reported the quantities of these parameters as  $k_{v0} = 5.5 \cdot 10^5$ ,  $E_v = 78.7$  KJ/mol, while Badzich and Hawksley [29] determined the amount of these parameters by  $k_{v0} = 1.34 \cdot 10^5$ ,  $E_v = 74$  kJ/mol. Substituting  $\rho_v(dV/dt)$  instead of  $\dot{m}$  into eqs. (1) and (2) yields the expressions:

$$4\pi r^2 \lambda \frac{dT}{dr} = \rho_v \frac{dV}{dt} [C_p(T - T_{sp}) + \Delta\tilde{H}_v + H - Q] \quad (5)$$

$$4\pi D\rho r^2 \frac{dy_i}{dr} = \rho_v \frac{dV}{dt} (y_i - \varepsilon_i) \quad (6)$$

The mass-flux fraction is defined as the ratio of the mass flux of species  $i$  to the total mass flux, *i. e.*,  $\varepsilon_i + \rho_i v_i / (\rho v) = \dot{m}_i / \dot{m}$  where  $v = \dot{m} / (4\pi r^2)$  is velocity. Integrating eq. (5) using a needed boundary condition ( $T_{(\infty)} = T_{\infty}$ ) yields:

$$T = T_{sp} - \frac{\Delta\tilde{H}_v + H - Q}{c_p} + \left[ T_{\infty} - T_{sp} + \frac{\Delta\tilde{H}_v + H - Q}{c_p} \right] e^{-\frac{\phi}{r}} \quad (7)$$

where, the variable  $\phi$  is defined as  $(\rho_v c_p dV/dt) / (4\pi\lambda)$ . It is worth noting that this variable can be considered to provide a length scale over which convective effects are important. For example, the exponential in eq. (7) can be expanded in a Taylor series. Retaining the first two terms yields a solution of the form:

$$T = T_{\infty} - \left( T_{\infty} - T_{sp} + \frac{\Delta\tilde{H}_v + H - Q}{c_p} \right) \frac{\phi}{r} \quad (8)$$

Integrating eq. (6) using the required boundary condition,  $y_o(\infty) = y_{o,\infty}$ , yields eq. (9):

$$y_o = \varepsilon_o + (y_{o,\infty} - \varepsilon_o) e^{-\frac{\phi}{r}} \quad (9)$$

The flame sheet radial location is determined by the initial condition  $y_o(r_f) = 0$ , *i. e.*, oxygen vanishes at the flame sheet. Thus, eq. (9) culminates in the following expression for the flame location:

$$e^{\phi/r_{sp}} = 1 + v \quad (10)$$

where, the variable  $v$  is described by  $v = -y_{o,\infty} / \varepsilon_o$ . Typically,  $v \ll 1$  indicates that transport processes in the vicinity of the flame are dominated by diffusion. It is needed to noted that according to eq. (10), associates with  $\phi/r_f \ll 1$ . Equation (10) is substituted into eq. (7) and the following expression for the flame temperature in zone III is extracted:

$$T_f = T_{sp} - \frac{\Delta\tilde{H}_v + H - Q}{c_p} + \left( T_{\infty} - T_{sp} + \frac{\Delta\tilde{H}_v + H - Q}{c_p} \right) \frac{1}{1+v} \quad (11)$$

It is noted that  $Q = Q_0 + H$ , where  $Q_0$  is the enthalpy of combustion for parent fuel leaving the droplet. Differential equations for energy conservation in zones I and II are written as eqs. (12) and (13), respectively:

$$4\pi r^2 \lambda \frac{dT}{dr} = \rho_v \frac{dV}{dt} [C_p (T - T_{sp}) + \Delta\tilde{H}_v] \quad (12)$$

$$4\pi r^2 \lambda \frac{dT}{dr} = \rho_v \frac{dV}{dt} [C_p (T - T_{sp}) + \Delta\tilde{H}_v + H] \quad (13)$$

Equations (12) and (13) are integrated under the boundary conditions,  $T(r_{sp}) = T_{sp}$  and  $T(r_f) = T_f$ , are represented:

$$T = T_{sp} - \frac{\Delta\tilde{H}_v}{C_p} + \frac{\Delta\tilde{H}_v}{C_p} e^{-\phi \left( \frac{1}{r} - \frac{1}{r_{sp}} \right)} \quad (14)$$

$$T = T_{sp} - \frac{\Delta\tilde{H}_v + H}{C_p} + \left[ (T_f - T_{sp}) + \frac{\Delta\tilde{H}_v + H}{C_p} \right] e^{-\phi \left( \frac{1}{r} - \frac{1}{r_{sp}} \right)} \quad (15)$$

In order to determine the radial location of the pyrolysis sheet, the aforementioned temperature profile must match at the pyrolysis sheet. After applying this matching condition, the pyrolysis sheet is extracted by the expression:

$$e^{\frac{\phi}{r_p}} = \frac{C_p}{H} \left[ \left( T_f - T_{sp} + \frac{\Delta\tilde{H}_v + H}{C_p} \right) e^{\frac{\phi}{r_f}} - \frac{\Delta\tilde{H}_v}{C_p} e^{\frac{\phi}{r_{sp}}} \right] \quad (16)$$

Inserting eqs. (10) and (11) into eq. (16) yields:

$$e^{\frac{\phi}{r_p}} = \frac{C_p(T_\infty - T_{sp}) + \Delta\tilde{H}_v + H + Qv}{C_p(T_p - T_{sp}) + \Delta\tilde{H}_v + H} \quad (17)$$

where  $T = T_p$  at  $r = r_p$  in eq. (14). Substituting eq. (17) into eq. (16) yields the following expression:

$$e^{\frac{\phi}{r_{sp}}} = \left[ B_0 + \frac{H}{\Delta\tilde{H}_v} (1 + \nu) + 1 \right] \frac{B_1 + 1}{B_1 + \frac{H}{\Delta\tilde{H}_v} + 1} \quad (18)$$

where  $B_0$  and  $B_1$  are the transfer numbers defined in eqs. (19) and (20). It is noted that  $B_0$  is a classical transfer number for droplet combustion as reported by Borman and Ragland [30]:

$$B_0 = \frac{C_p(T_\infty - T_{sp}) + \nu Q_0}{\Delta\tilde{H}_v} \quad (19)$$

$$B_1 = \frac{C_p(T_p - T_{sp})}{\Delta\tilde{H}_v} \quad (20)$$

It is worth noting that the quasi-steady flame stand off ratio can be extracted by combining eqs. (10) and (18) as shown in eq. (21):

$$\frac{r_f}{r_{sp}} = \frac{\ln \left\{ \left[ B_0 + \frac{H}{\Delta\tilde{H}_v} (1 + \nu) + 1 \right] \frac{B_1 + 1}{B_1 + \frac{H}{\Delta\tilde{H}_{v\infty}} + 1} \right\}}{\ln(1 + \nu)} \quad (21)$$

Replacing eq. (3) into eq. (21) results to:

$$\frac{r_f}{r_{sp}} = \frac{\ln \left[ \left( B_0 + \frac{H}{\Delta H + [\Delta H_w + C_{p,w}(T_f - 373)]W_\infty / Y_\infty + C_{p,c}(T_f - T_0) / Y_\infty} (1 + \nu) + 1 \right) \right]}{\ln(1 + \nu)} + \ln \left[ \frac{B_1 + 1}{B_1 + \frac{H}{\Delta H + [\Delta H_w + C_{p,w}(T_f - 373)]W_4 / Y_4 + C_{p,c}(T_f - T_0) / Y_4} + 1} \right] \quad (22)$$

An effective transfer number can be defined by rewriting eq. (18) as shown in eq. (23):

$$e^{r_p} = \frac{C_p(T_\infty - T_{sp}) + \Delta\tilde{H}_v + H + Qv}{C_p(T_p - T_{sp}) + \Delta\tilde{H}_v + H} \quad (23)$$

Thus, the effective transfer number is represented:

$$B_{\text{eff}} = B_0 \frac{1 + \frac{H}{\Delta\tilde{H}_v} \frac{B_1}{B_0} \left( \frac{1}{1+B_1} + \frac{v}{B_1} \right)}{1 + \frac{1}{1+B_1} \frac{H}{\Delta\tilde{H}_v}} \quad (24)$$

Inserting eq. (3) into eq. (24) culminates in:

$$B_{\text{eff}} = B_0 \frac{1 + \frac{H}{\Delta H + [\Delta H_w + C_{p,W}(T_f - 373)]W_\infty / Y_\infty + C_{p,c}(T_f - T_0) / Y_\infty} \frac{B_1}{B_0} \left( \frac{1}{1+B_1} + \frac{v}{B_1} \right)}{1 + \frac{1}{1+B_1} \frac{H}{\Delta H + [\Delta H_w + C_{p,W}(T_f - 373)]W_\infty / Y_\infty + C_{p,c}(T_f - T_0) / Y_\infty}} \quad (25)$$

Equation (24) shows that  $B_{\text{eff}} \rightarrow B_0$  for  $H/\Delta\tilde{H}_v \rightarrow 0$  because the classical transfer number  $B_0$  should be recovered for  $H/\Delta\tilde{H}_v \rightarrow 0$ . It can also be shown that  $B_{\text{eff}} \rightarrow B_0$  for  $T_p \rightarrow T_f$ , which corresponds to the case where fuel pyrolysis occurs in the fuel oxidation zone. In this case, fuel pyrolysis endothermicity does not influence combustion behaviours. Hence, the combustion properties are definitely influenced by  $H/\Delta\tilde{H}_v$  and pyrolysis sheet location. The pyrolysis sheet stand-off ratio is determined:

$$\frac{r_p}{r_{sp}} = \frac{\ln[1 + B_{\text{eff}}]}{\ln \left[ 1 + \frac{c_p(T_f - T_{sp}) + \Delta\tilde{H}_v}{H} (1 + B_{\text{eff}})^{r_{sp}} - \frac{\Delta\tilde{H}_v}{H} (1 + B_{\text{eff}}) \right]} \quad (26)$$

Also the pyrolysis sheet stand-off ratio can also be expressed as shown in eq. (27):

$$\frac{r_p}{r_{sp}} = \frac{\ln[1 + B_{\text{eff}}]}{\ln \left\{ \left[ (B_0 + 1) \frac{\Delta\tilde{H}_v}{H} + 1 + v \right] \left[ (B_1 + 1) \frac{\Delta\tilde{H}_v}{H} + 1 \right]^{-1} \right\}} \quad (27)$$

Inserting eq. (3) into eq. (27) results to:

$$\frac{r_p}{r_{sp}} = \frac{\ln[1 + B_{\text{eff}}]}{\ln \left[ (B_0 + 1) \frac{\Delta H + [\Delta H_w + C_{p,W}(T_f - 373)]W_\infty / Y_\infty + C_{p,c}(T_f - T_0) / Y}{H} + 1 + v \right.} \\ \left. \frac{(B_1 + 1) \frac{\Delta H + [\Delta H_w + C_{p,W}(T_f - 373)]W_\infty / Y_\infty + C_{p,c}(T_f - T_0) / Y}{H}}{H} \right]} \quad (28)$$

## Results and discussions

The temperature profile as a function of radius is shown in fig. 2. The temperature profile is composed of three zones. In the first zone, the flame temperature approximately reaches 870 K corresponding to eq. (14). Then it sharply goes up in the pyrolysis zone (zone II) and finally the remarkable turnaround is observed in the last zone (zone III). Figure 3 shows the variations in the normalized transfer number ratio  $B_{\text{eff}}/B_0$  as a function of  $H/\Delta\tilde{H}_v$  for different quantities of  $T_p$ . As seen, the rate of decreasing of  $B_{\text{eff}}/B_0$  by increasing in  $H/\Delta\tilde{H}_v$  becomes slower and in addition, it is revealed that  $B_{\text{eff}} \rightarrow B_0$  when  $T_p$  increases to flame temperature ( $T_p \rightarrow T_f$ ), which corresponds to the case where fuel pyrolysis occurs in the fuel oxidation zone.

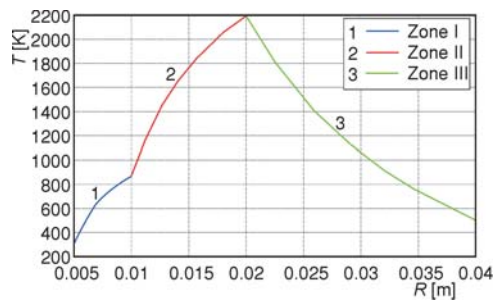


Figure 2. Temperature diagram as a function of radius

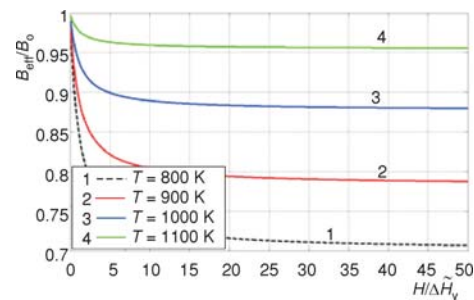


Figure 3. Variation of the normalized transfer number ratio  $B_{\text{eff}}/B_0$  with  $H/\Delta\tilde{H}_v$

Figure 4 indicates the variations of the normalized flame stand-off ratio  $(r_f/r_{\text{sp}})/(r_f/r_{\text{sp}})_0$  as a function of  $H/\Delta\tilde{H}_v$ . The trend of this diagram for different  $T_p$  is akin to fig. 3 which demonstrates that the flame location should be near the droplet in order to provide the needed energy for fuel pyrolysis.

Figure 5 illustrates the variation of the normalized pyrolysis zone stand-off ratio  $(r_p/r_{\text{sp}})/(r_p/r_{\text{sp}})_0$  as a function of  $H/\Delta\tilde{H}_v$ . As perceived, higher  $H/\Delta\tilde{H}_v$  leads to increase in the ratio  $(r_p/r_{\text{sp}})/(r_p/r_{\text{sp}})_0$  implies that the pyrolysis zone shifts towards the flame while  $H/\Delta\tilde{H}_v$  increases.

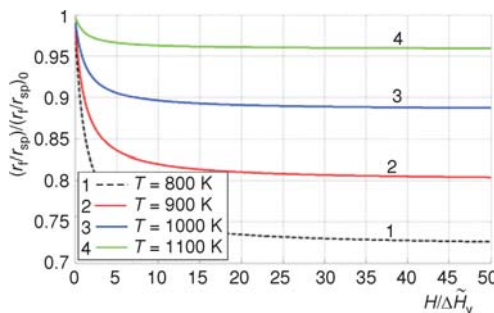


Figure 4. Variation of the normalized flame stand off ratio  $(r_f/r_{\text{sp}})/(r_f/r_{\text{sp}})_0$  with  $H/\Delta\tilde{H}_v$

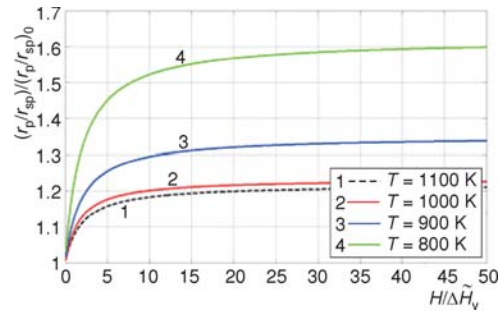


Figure 5. Variation of the normalized pyrolysis zone stand off ratio  $(r_p/r_{\text{sp}})/(r_p/r_{\text{sp}})_0$  with  $H/\Delta\tilde{H}_v$

Figure 6 depicts the variations in the normalized transfer number ratio  $B_{\text{eff}}/B_0$  as a function of  $H/\Delta\tilde{H}_v$  for coal and droplet at 900 K. As shown, smaller loss is seen in the transfer number of the coal compared to the droplet, while the chemical pyrolysis is considered in either coal or droplet combustion.



The novelty of this research is to propose the new analytical model to indicate the role of pyrolysis effect on the devolatilization of a single coal particle. Hence this model does not require time consuming calculations and has a practical application in the numerical simulations.

### Conclusions

In this research, the attempt has been made to develop an analytical model for coal devolatilization based on the available model for the liquid droplet combustion. The rate of devolatilization is simulated by the Arrhenius equation. Moreover, the effect of pyrolysis, which is assumed to be a high activation-energy process that occurs in a thin zone between the char and the flame, on the combustion properties of a single coal particle is investigated. From this research, it is revealed that the fuel pyrolysis effect becomes incredibly important as  $H/\Delta\tilde{H}_v$  increases in magnitude due to either increase in  $H$ , corresponding to stronger levels of endothermic chemistry, or decrease in  $\Delta\tilde{H}_v$ . It is elucidated that increasing in  $T_p$  associates with  $B_{\text{eff}} \rightarrow B_0$  which corresponds to the case where fuel pyrolysis occurs in the fuel oxidation zone. Furthermore, the variation in stand-off ratio  $(r_p/r_{\text{sp}})/(r_p/r_{\text{sp}})_0$  demonstrates that the pyrolysis zone moves towards the flame front. Consequently, the normalized transfer ratio obtained by this analytical model is calculated for coal and droplet and it is declared that the smaller loss is observed in the transfer number of the coal in comparison with droplet.

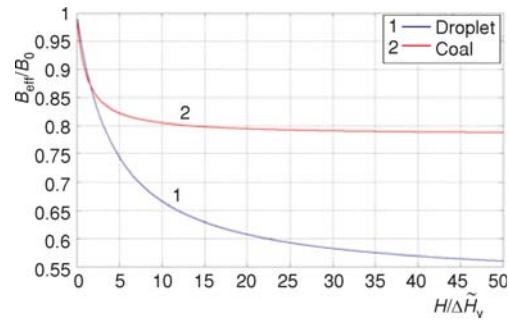


Figure 6. Variation of the normalized transfer number ratio  $B_{\text{eff}}/B_0$  with  $H/\Delta\tilde{H}_v$  for coal and droplet at 900 K

### Nomenclature

$B_{\text{eff}}$	– effective transfer number, defined in eq. (24) [–]
$B_0$	– transfer number, defined in eq. (19), [–]
$B_1$	– transfer number, defined in eq. (20), [–]
$C_p$	– specific heat capacity, [ $\text{JKg}^{-1}\text{K}^{-1}$ ]
$D$	– fuel diffusivity in the gas phase, [ $\text{m}^2\text{s}^{-1}$ ]
$E_V$	– activation energy, [ $\text{kJmol}^{-1}$ ]
$H$	– enthalpy change associated with fuel pyrolysis per unit mass, [ $\text{Jkg}^{-1}$ ]
$\Delta\tilde{H}_v$	– devolatilization enthalpy per unit mass, [ $\text{Jkg}^{-1}$ ]
$k_{V0}$	– pre-exponential factor, [–]
$\dot{m}$	– mass flow rate of the char surface, [ $\text{kgs}^{-1}$ ]
$Q$	– heat of combustion for fuel, [ $\text{Jkg}^{-1}$ ]
$Q_0$	– enthalpy of combustion for parent fuel leaving the char per unit mass, [ $\text{Jkg}^{-1}$ ]
$R$	– universal gas constant, [ $\text{Jmol}^{-1}\text{K}^{-1}$ ]
$r$	– radial co-ordinate, [m]
$r_f$	– flame radius, [m]
$r_p$	– pyrolysis sheet radius, [m]
$r_{\text{sp}}$	– char surface radius, [m]
$T$	– temperature, [ $^{\circ}\text{C}$ ]
$T_{\text{sp}}$	– char surface temperature, [ $^{\circ}\text{C}$ ]
$t$	– time, [s]

$V$	– total of volatiles evolved up to time, [ $\text{m}^3$ ]
$V_{\infty}$	– total volatile content of coal, [ $\text{m}^3$ ]
$v$	– defined in eq. (10), [–]
$W_{\infty}$	– mass of water content per unit mass of moisture-free original coal, [–]
$Y_{\infty}$	– mass of volatile material released from unit mass of moisture-free coal, [–]
$y$	– mass fraction, [–]

### Greek symbols

$\varepsilon$	– mass-flux fraction, [–]
$\lambda$	– thermal conductivity, [ $\text{Wm}^{-1}\text{K}^{-1}$ ]
$\rho$	– density, [ $\text{kgm}^{-3}$ ]
$\nu$	– mass flow rate per area, [ $\text{kgm}^{-2}\text{s}^{-1}$ ]
$\phi$	– defined in eq. (7), [m]

### Subscripts

$c$	– of or pertaining to coal
$i$	– subscript that refer to species
$O$	– subscript that refer to oxygen
$V$	– of or pertaining to volatile material
$w$	– of or pertaining to water
$0$	– initial value
$\infty$	– denotes conditions at $r = \infty$

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