B. TECH. PROJECT REPORT

On

Laser Ignition of Pulverized Coal

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Laser Ignition of Pulverized Coal

A PROJECT REPORT

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Requirement for the award of the degrees

Of
BACHELOR OF TECHNOLOGY

In
MECHANICAL ENGINEERING

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

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CANDIDATE’S DECLARATION

We hereby declare that the project entitled **“Laser Ignition of Pulverized Coal”** submitted in partial fulfilment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Dr. D.L. Deshmukh (Assistant Professor, Mechanical Engineering),** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Rahil Kote

Bhaben patir

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of our knowledge.

Dr. D.L Deshmukh
Associate prof. Mechanical Engineering
IIT Indore

<u>Preface</u>

This report on **“Laser Ignition of Pulverized Coal"** is prepared under the guidance of **Dr. D.L. Deshmukh (Associate Professor).**

Through this report we have tried to give a detailed analysis of the concept of laser ignition of pulverized coal. We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added MATLAB code and Graphs for better understanding.

Rahil Kote
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Acknowledgement

We wish to thank our guide **Dr. D.L. Deshmukh** for his kind support and valuable guidance and giving us an opportunity to work for the B.Tech project under his supervision. We owe profound gratitude to him who took a keen interest in our project work and we are extremely fortunate to have his guidance.

It is his help and support, due to which we became able to complete the review and technical report.

We would like to thank Discipline of Mechanical Engineering and in total IIT Indore for providing us the necessary equipment and environment. We are thankful to get constant encouragement support and guidance from B.Tech project evaluation committee.
Without their support, this report would not have been possible.

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Abstract

This report is a review of the study of ignition of pulverized coal. A dilute stream of particles is dropped into a laminar, upward-flow wind tunnel with a quartz test section. The gas stream is not preheated. A single pulse from a Nd:YAG laser is focused through the tunnel and ignites the fuel. The transparent test section and cool walls allow for optical detection of the ignition process. In this report we describe the experiment and demonstrate its capabilities by observing the ignition behaviour of spherical, amorphous-carbon particles and two coals: anthracite is a high-volatile bituminous coal. The ignition behaviours of the carbon spheres and the anthracite are as expected for heterogeneous ignition, while the mechanism of the bituminous coal is uncertain. Calculations are also presented to describe the physical behaviour of a laser-heated particle, and the heat transfer and chemistry of heterogeneous ignition.

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Nomenclature

A_o	pre exponential factor in Arrhenius rate constant
C_p	particle specific heat
D	binary self-diffusion coefficient of oxygen
D_l	diameter of laser beam at ignition point
D_p	particle diameter
E	activation energy in Arrhenius rate constant
E_{laser}	energy of laser pulse
h	convective heat transfer coefficient
k	particle thermal conductivity
K_g	Thermal conductivity of the gas in the boundary layer
M_c	molecular weight of carbon
n	order of reaction
P	pressure
Q_g	rate of heat generation
Q_l	rate of heat loss
Q_{laser}	fraction of average laser power which is intercepted by the particle
R	universal gas constant
R	radial coordinate
S	external surface area of the particle
T	temperature
t	time
V	particle volume
y	molar ratio of molar carbon consumption to oxygen oxygen consumption

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ΔH_c	Heat of reaction per mass of carbon consumed
ε	particle emissivity
X	oxygen mole fraction
A	wavelength of laser
P	particle density
σ	Stefan-Boltzmann constant
τ	laser pulse duration
ω	molar flux of oxygen at the particle surface

1. INTRODUCTION

The ignition behaviour of clouds of pulverized coal and its related study is gaining great interest both due to its economic scope and preventions of disaster like gas explosions in coal mines or grain elevators, for example) and with flame stability in coal-fired combustors.

But such systems are difficult to analyze because of the coupling of solid-to-gas, solid-to-solid, and gas-to-gas in heat transfer and chemical reactions. This coupling is known as the "cooperative mechanism". To analyze the results from cloud experiments and to extend them to other systems, it is first necessary to measure reaction parameters in single-particle or dilute-suspension experiments in order to eliminate the cooperative mechanism.

Here, we review on a experiment that relies on pulsed-laser ignition of a dilute suspension. Laser ignition experiments offer the distinct advantage of easy optical access to the particles (because of the absence of a furnace or radiating walls), and thus permit direct observation and particle temperature measurement. At present, however, reaction parameters have not been reported from these experiments.

We know that pulverized fuel combustion system is widely used in thermal plants. Plants performance varies with solid fuel properties, but it is difficult to evaluate the fuel properties using large scale facilities. Fundamental experiment techniques are required to evaluate the effect of actual systems.

1.1. Experimental setups:

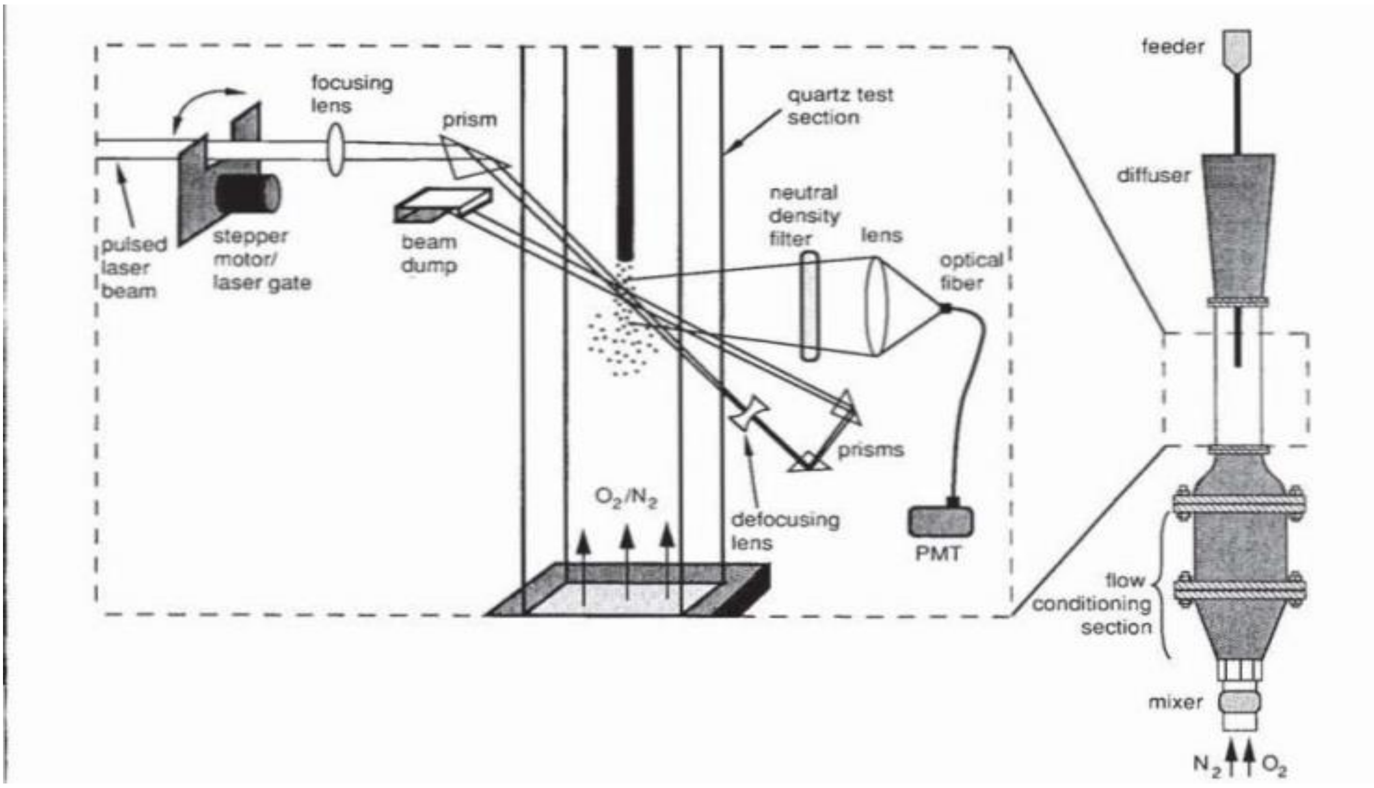


Figure 1

- The laser used in this experiment is YAG laser which operates at 5Hz and emits a nearly collimated beam (8mm diameter) in the infrared.
- The laser pulse duration is 150µs.
- The energy is variable up to 740mJ per pulse.

1.2. Why Pulverized Coal?

- Cost efficiency
- Less time required to obtain result
- Less fuel required (less wastage)
- Simple design or processing

In today’s world of high energy uses and dwindling natural resources, efficient and smart methods are required to keep tract of unnecessary wastes. we should be able to use the available resources in a such a way that can guarantee to increase its capacity of producing energy and at the same time increase its longibility.

When using pulverized coal instead of ordinary coal we are able to extract more energy from the given coal and the storage and supply also becomes easier.

Also studying of pulverized coal is much easier which is really important.

Figure 2

2. Analysis of a Laser Heated Particle

In this review the study is about a single cola particle heated by laser pulse. Even though the analysis is about one single particle, it is applicable to a dilute suspension of particles. By that we mean that the behaviour of each particle is independent of the others in the suspensions. In this review we are neglecting any kind of chemical reactions happening in the particle and its fluid surrounding the particles. Here we are taking the approximation that the time prior to ignition is too short for significant reaction to occur.

2.1. Thermal Behaviour of a single Particle heated by a Laser Pulse

The temperature distribution within a spherical particle is described by the conduction heat equation:

$$\frac{1}{r^2}\frac{d}{dr}(kr^2\frac{dT}{dr}) = \rho c\frac{dT}{dt} \quad \text{-----}\ (1)$$

In Eq. 1 we have assumed temperature T varies only in the radial direction r and no heat generation in the particle.

Boundary conditions:

$$T(r\ ,t\ =\ 0\ )\ =\ T_o\ =\ 300\ \ K \quad \text{----- (2)}$$

$$\left.\frac{\partial T}{\partial r}\right|_{(r\ =\ R)}\ =\ 0 \quad \text{---- (3)}$$

Equation 2 states that at time t= 0, the initial temperature distribution is uniform throughout the particle.

Eq. 3 is the symmetry condition at the centre of the particle.

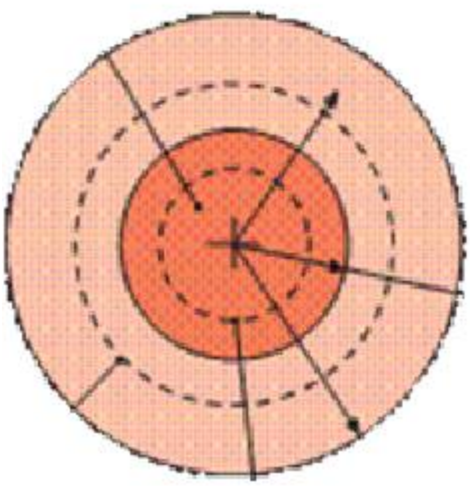


Figure 3

2.2. Heat Balance Equation:

$$Q_{\text{laser}} - kS\frac{dT}{dR}\bigg| - hS(T_r - T_\infty) - S\varepsilon\sigma(T_r{}^\wedge 4 - T_\infty{}^\wedge 4) = \rho C_p V\frac{dT}{dt}\bigg|$$

-----(4)

Equation- 4 states that the power input from the laser pulse minus the rate of energy loss (by conduction into the particle, and by convective and radiative heat loss) equals the rate of energy storage.

The values of variables used in the calculation are:

Ɛ= 0.8; ρ = 1300 kg m-3 ;

Once the particle diameter is specified. Q(laser)is affected only by E(laser) and laser beam diameter (D1). For the present calculations we use $Q_{laser}/\Pi d^2{}_p = 2.37 \times 10^8 Wm^{-2}$. This corresponds to the experimental condition with the laser energy at 700 mJ per pulse.

2.3. <u>After solving these equations we get the solution as</u>:

1) When k(thermal conductivity of the particle) is constant

Solution:

$$T = r[\frac{Q_{asee}}{Sk} - \frac{h}{k}(T_R - T_\infty) - \varepsilon\sigma(T_R{}^4 - T_\infty{}^4) - \frac{6VK}{R^2}(T - 300)]$$

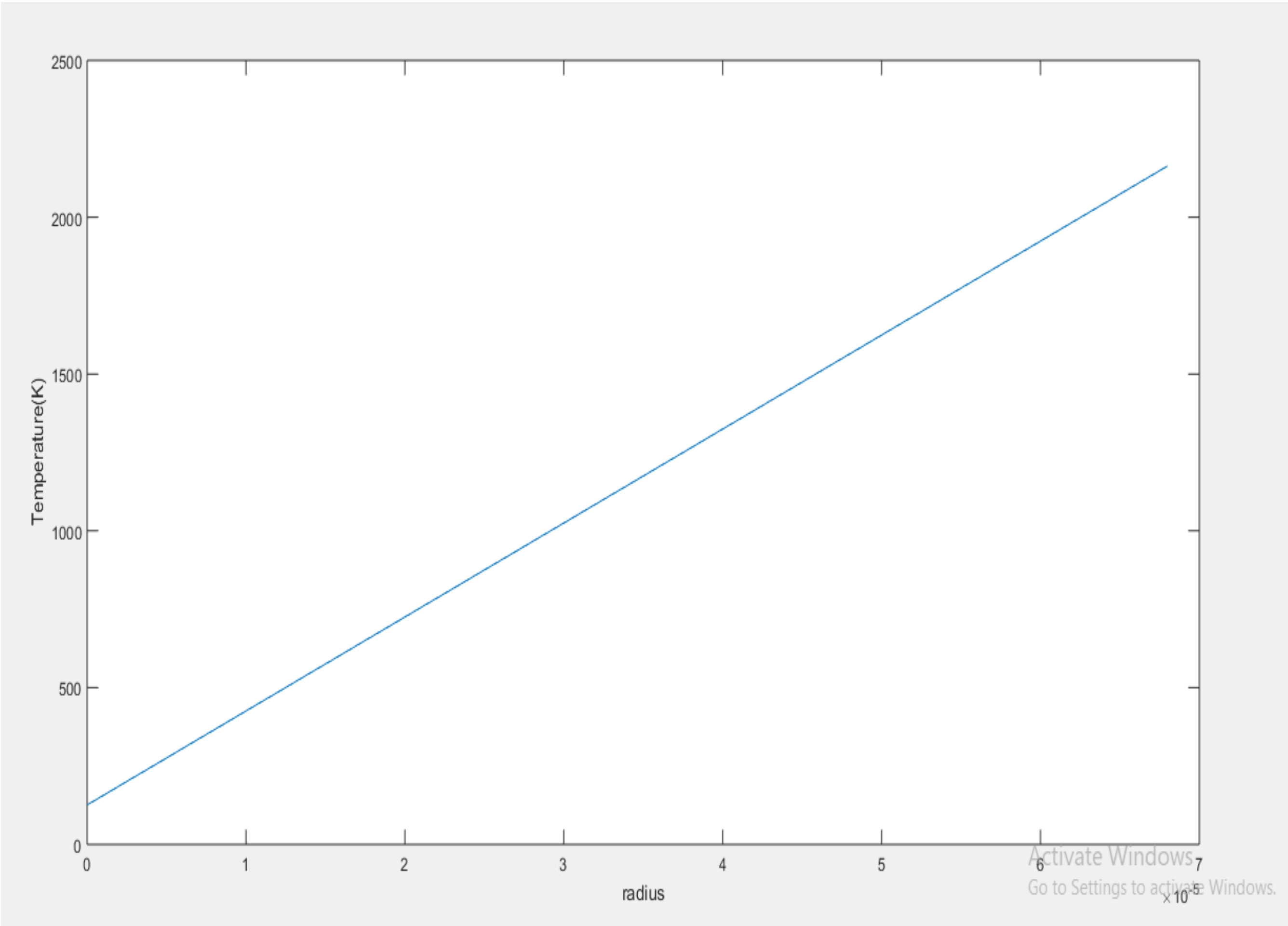
<u>MATLAB code</u>

```
Q=2.37*10^8;
e=0.8;
k=4.8;
sigma=5.67*10^(-8);
v=10.51*10^(-12);
T2=300;
R=68*10^(-6);
h=70.58*10^3;
r=0:1*10^(-6):68*10^(-6);
T1=1600;

for i=1:69
   T(1,i)=(r(1,i)*((Q/k)-(h/k)*(T1-T2)-e*sigma*(T1^4-T2^4)+(6*v*k*300/(R^2))))/(1+6*v*k*r(1,i)/(R^2));
end

plot(r,T);
xlabel('radius');
ylabel('Temperature(K)');
```

<u>Graph 1</u>



Graph 1 shows the temperature distribution across the radius of the coal particle when thermal conductivity of the particle is constant.

The temperature distribution is linear across radius r. At the centre of the coal particle temperature is around 150K and on the surface temperature is around 2100K.

2) When k (thermal conductivity of the particle) is variable

$$k = 1.412 \times 10^{-3} T + 1.245 (Wm^{-1} K^{-1})$$

Solution:

$$\frac{a}{2} T^2 + bT = r \frac{(1300 \times h - 11.73 \times 10^7)}{(1 - 9972r)}$$

MATLAB code

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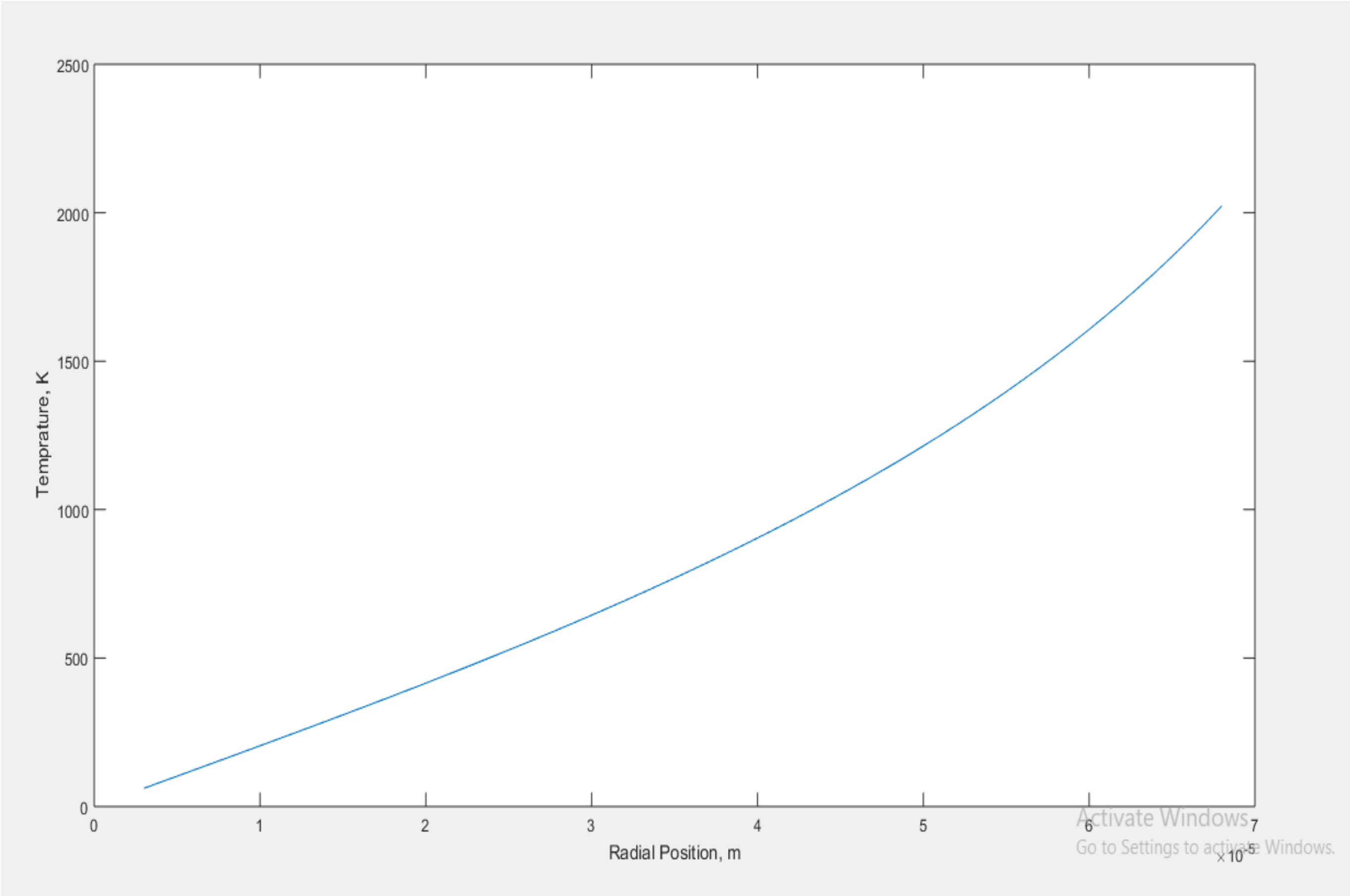
```
r=3*10^(-6):1*10^(-6):68*10^(-6);
h=70.58*10^3;
a=1.412*10^(-3);
b=1.245;

for i=3:68
    c = ((1300*h - 117350000)*r(1,i-2))/(1-9972*r(1,i-2));
    p = [a/2 b c];
   T(1:2,i-2) = roots(p);
end

plot(r, T(2,:));
```

Graph 2



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Graph 2 shows the temperature distribution within a 136µm carbon particle uniformly heated on its surface by a laser pulse for 150µs.

At the end of the heating phase the surface attains a temperature of 2000 K, while the particle center is at around100 K.

The heat is conducted into the particle from the surface.

3. Theory of Heterogeneous Ignition

Till now we reviewed the experiment and the particle behaviour when particle heated for some time. Here we solved the temperature distribution within the coal particle with the help of the heat transfer equation and few boundary conditions.

And then with the help of MATLAB we wrote a code for the same to see its graphical representation which we obtained.

From the graph we can see that a particle can be rapidly heated by a laser pulse. Also the graph shows a large temperature gradient is sustained within the particle and the internal temperature equilibrates rapidly. This can be explained by the fact that the heat conduction is much higher within the particle then the heat loss rate to the surrounding from the particle.

How the experiment proceeds?

A particle or collection of particles in a dilute suspension is instantaneously heated to some higher temperature by the laser pulse. (This simplification is justified by the short time needed to achieve temperature equilibration, which also justifies the neglect of reactions during this period,) The temperature attained is uniform throughout the particle and corresponds to that achieved after temperature equilibration within the particle.

4. Heat loss and heat generation

Heat Losses:

The heat loss from the surface of a particle at temperature Tr is the sum of the losses due to convection and radiation:

Q1=Q1(convection)+ Q1(radiation)

$$Q_1 = hS\ (T_r - T_\infty) + \varepsilon\sigma\ S\ (T_r{}^\wedge 4 - T_\infty{}^\wedge 4)$$

The radiative loss term is easily determined and is relatively unimportant until the particle temperature exceeds - 1500 K.

Heat Generation:

Heat generated by a spherical Carbon particle undergoing oxidation on its external surface is determined by the kinetic expression**:**

$$\boxed{\frac{Q_g}{S} = \Delta H_c\ \chi_R{}^\wedge n\ A_o \exp(-\frac{E}{\Re T})}$$

<u>And the oxidant diffusion expression</u>:

$$\frac{Q_g}{S} = \Delta H_C M y \frac{5P\alpha}{4\Re d_P} \left(\frac{T_R\text{^}2 - T_\infty\text{^}2}{T_R\text{^}1.25 - T_\infty\text{^}1.25} \right) \times (\chi_\infty - \chi_R)$$

Parameters used to generate Graphs 3, 4, 5 and 6.

T_∞ =300K

$A_o = 100\ kg\ m^{-2}\ s^{-1}$

$d_p = 136\mu m$

$E = 83.7\ kJ\ mol^{-1}$

$\varepsilon = 0.8$

$P = 10^5\ Pa$

$\chi_\infty = 1.0$

$y = 2\ mol\ C\ mol\ O_2^{-1}$

$D = 2\times 10^{-5} (\frac{TR}{300})^{1.75}\ m^2 s^{-1}$

$kg = 1.04\times 10^{-2} + 5.56\times 10^{-5} (\frac{TR + T\infty}{2}) W\ m^{-1}\ K^{-1}$

$\Delta HC = 9210 kJ\ kg^{-1}$

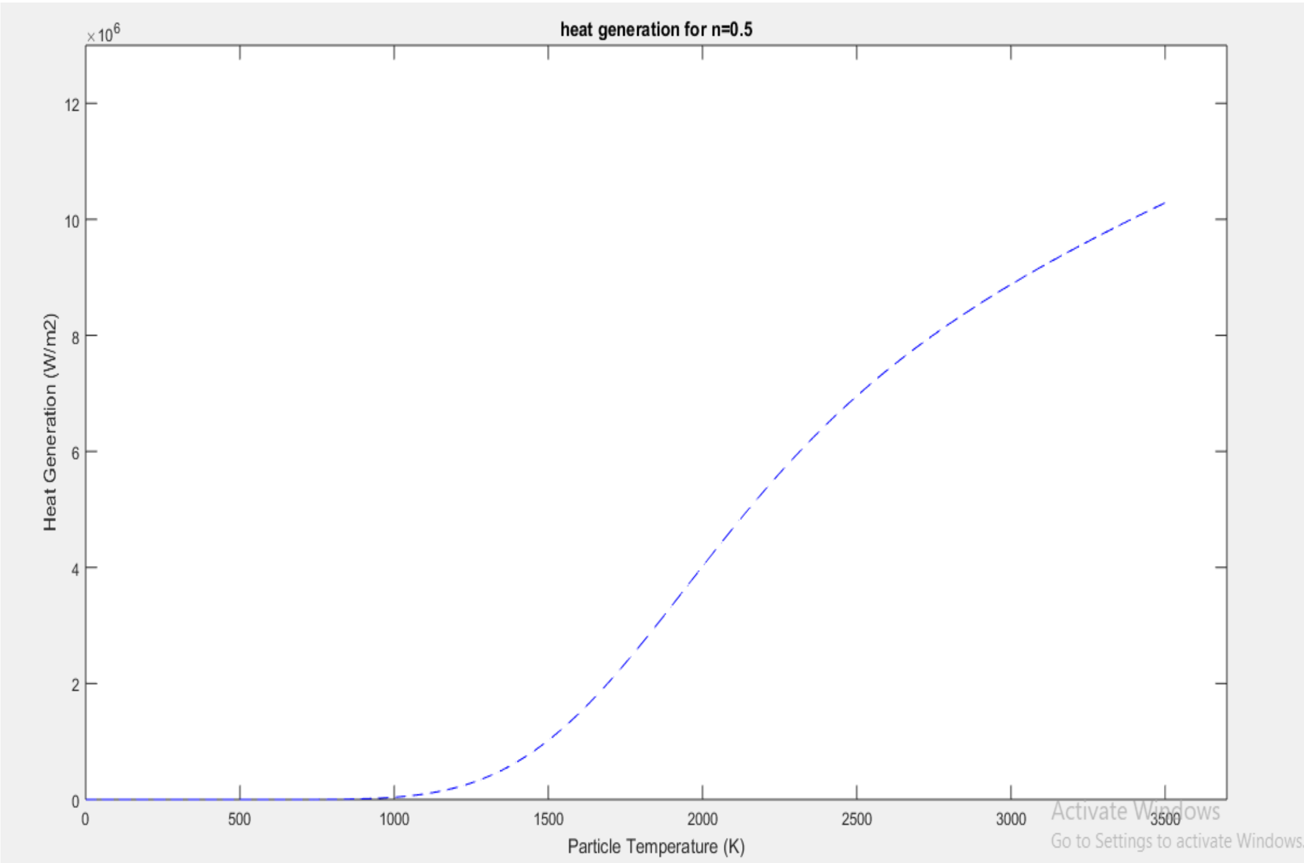
$(\ for\ the\ reaction\ of\ C + \frac{1}{2}\ O2 \rightarrow\ CO)$

Heat generation Vs Particle Temperature curve for n= 0.5

MATLAB code


```
T1 = 300;
P = 10^5;
Tr = 1:2:3501;
d = 136*10^(-6);
e = 0.8;
D = 2*10^(-5)*(Tr/300).^1.75;
x = 1;
k = 1.04*10^(-2)+5.56*10^(-5).*((Tr+T1)/2);
y = 2;
H = 9210*10^3;
A = 100;
E = 83.7*10^3;
R = 8.314;
S = 5.81*10^(-8);
n = 0.5;
alpha = 9.25*10^(-10);
M = 12*10^(-3);



a = A*exp(-E./(R*Tr));
b = M*y*(5/4)*(P*alpha/(R*d))*((Tr.^2-T1^2)./(Tr.^(1.25)-T1^(1.25)));

X1 = zeros(2,length(Tr));


for i=1:length(Tr)
    % for n=0.5
    X1(:,i) = roots([b(i) a(i) -b(i)]);
    Q(i)=(H*A*X1(2,i).*exp(-E./(R*Tr(i))));

end
```

Graph 3



Graph 3 shows rate of heat Generation inside the coal particle per external surface area as a function of particle temperature, for n=0.5

The heat generation inside the particle takes place after the particle temperature reaches around 1000K, after this temperature heat generation curve increases rapidly up to around 2200K, later heat generation inside the particle slow down. This is because of radiative heat loss is greater after 2000K.

For n=0.5, we can achieve a greater heat generation (10*10^6) compared to n=1(9*10^6, refer graph 4).

And heat generation has the sigmoid shape.

Heat generation Vs Particle Temperature curve for n= 1

MATLAB code

```
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T1 = 300;
P = 10^5;
Tr = 1:2:3501;
d = 136*10^(-6);
e = 0.8;
D = 2*10^(-5)*(Tr/300).^1.75;
x = 1;
k = 1.04*10^(-2)+5.56*10^(-5).*((Tr+T1)/2);
y = 2;
H = 9210*10^3;
A = 100;
E = 83.7*10^3;
R = 8.314;
S = 5.81*10^(-8);
n = 0.5;
alpha = 9.25*10^(-10);
M = 12*10^(-3);



a = A*exp(-E./(R*Tr));
b = M*y*(5/4)*(P*alpha/(R*d))*((Tr.^2-T1^2)./(Tr.^(1.25)-T1^(1.25)));

X = zeros(length(Tr));

for i=1:length(Tr)
    % for n=1
    X = b./(a+b);
    Q1(i)=(H*A*X(i).*exp(-E./(R*Tr(i))));
end

plot (Tr, Q1,'m--');
axis([0 3700 0 13*10^6]);
xlabel('Particle Temperature (K)');
ylabel('Heat Generation (W/m2)');
title('heat generation for n=1');
```
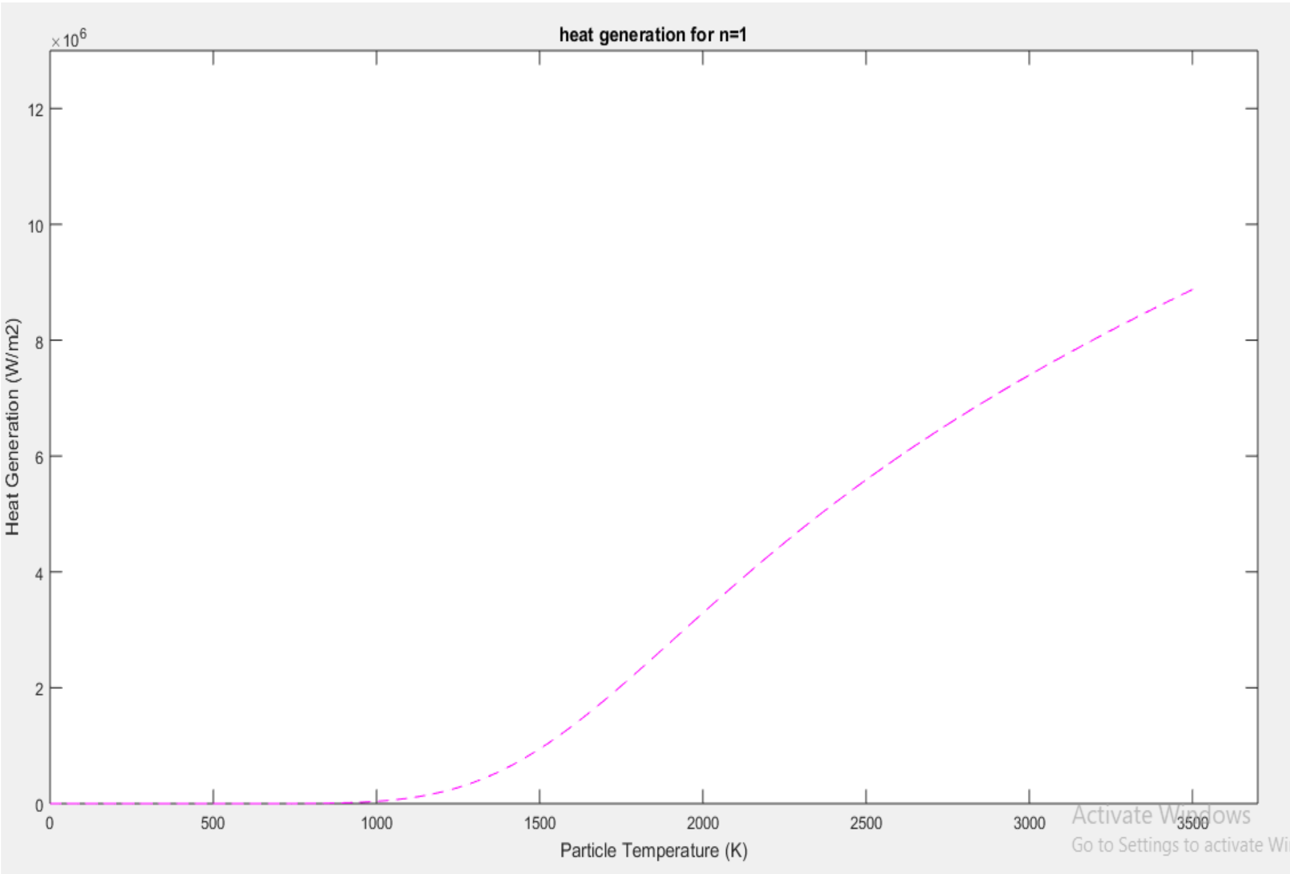

Graph 4



Graph 4 shows rate of heat Generation inside the coal particle per external surface area as a function of particle temperature, for n=1.

Heat loss Vs Particle Temperature curve

MATLAB code

```
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T1 = 300;
P = 10^5;
Tr = 1:2:3501;
d = 136*10^(-6);
e = 0.8;
sigma = 5.67*10^(-8);
D = 2*10^(-5)*(Tr/300).^1.75;
x = 1;
k = 1.04*10^(-2)+5.56*10^(-5).*((Tr+T1)/2);
y = 2;
H = 9210*10^3;
A = 100;
E = 83.7*10^3;
R = 8.314;
S = 5.81*10^(-8);
n = 0.5;
alpha = 9.25*10^(-10);
M = 12*10^(-3);

a = A*exp(-E./(R*Tr));
b = M*y*(5/4)*(P*alpha/(R*d))*((Tr.^2-T1^2)./(Tr.^(1.25)-T1^(1.25)));

for i=1:length(Tr)

    % heat loss
    Q2(i) = 2*(k(i)/d).*(Tr(i)-T1) + e*sigma*(Tr(i).^4 - T1^4);
end

plot (Tr, Q2,'k-');
axis([0 3700 0 13*10^6]);
xlabel('Particle Temperature (K)');
ylabel('Heat Loss (W/m2)');
title('heat loss');
```
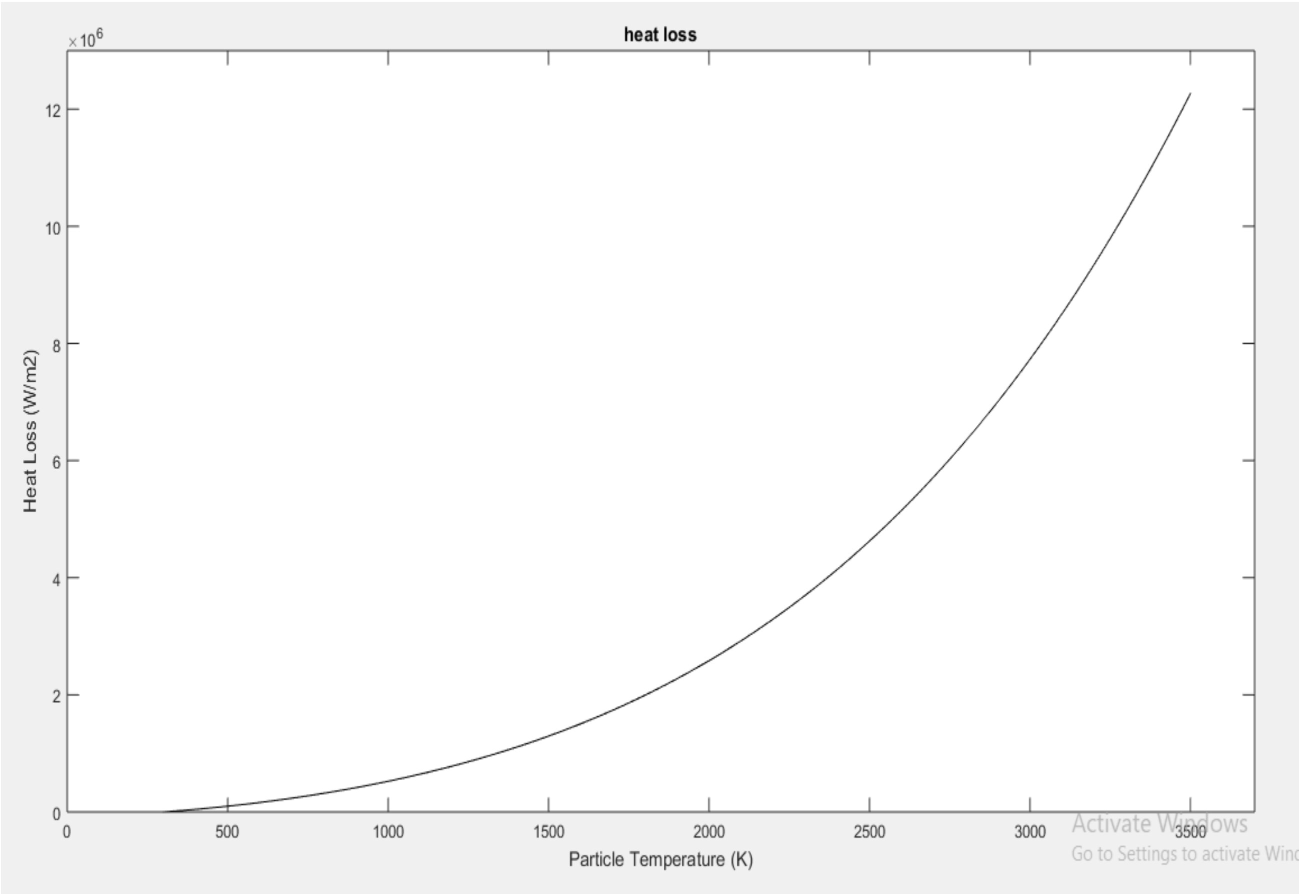

Graph 5



Graph 5 shows rate of heat loss per external surface area by the particle as a function of particle temperature.

5. Critical Ignition criteria

We shall now examine the behaviours of $\frac{Q_g}{S} = \frac{Q_1}{S}$, since this will guide us in establishing the ignition criteria. The critical ignition temperature is the temperature at which the particle is ignited or combustion occurs. The critical ignition temperature obtained from the graph is important so we don’t waste unnecessary energy by providing only the amount of energy required to ignite the pulverized coal in industries and other places. This will save both time and capital.

Heat generation or loss Vs Particle Temperature curve

MATLAB code


```
T1 = 300;
P = 10^5;
Tr = 1:2:3501;
d = 136*10^(-6);
e = 0.8;
sigma = 5.67*10^(-8);
D = 2*10^(-5)*(Tr/300).^1.75;
x = 1;
k = 1.04*10^(-2)+5.56*10^(-5).*((Tr+T1)/2);
y = 2;
H = 9210*10^3;
A = 100;
E = 83.7*10^3;
R = 8.314;
S = 5.81*10^(-8);
n = 0.5;
alpha = 9.25*10^(-10);
M = 12*10^(-3);
```

```
a = A*exp(-E./(R*Tr));
b = M*y*(5/4)*(P*alpha/(R*d))*((Tr.^2-T1^2)./(Tr.^(1.25)-T1^(1.25)));

X1 = zeros(2,length(Tr));
X = zeros(length(Tr));

for i=1:length(Tr)
    % for n=0.5
    X1(:,i) = roots([b(i) a(i) -b(i)]);
    Q(i)=(H*A*X1(2,i).*exp(-E./(R*Tr(i))));

    % for n=1
    X = b./(a+b);
    Q1(i)=(H*A*X(i).*exp(-E./(R*Tr(i))));

    % heat loss
    Q2(i) = 2*(k(i)/d).*(Tr(i)-T1) + e*sigma*(Tr(i).^4 - T1^4);
end
figure
hold on
axis([0 3700 0 13*10^6]);
plot(Tr,Q,'b--',Tr,Q1,'m--',Tr,Q2,'k-');
xlabel('Particle Temperature (K)');
ylabel('Heat Generation/Loss (W/m2)');
legend('n=0.5','n=1','heat_loss','Location','NorthEastOutside')
```

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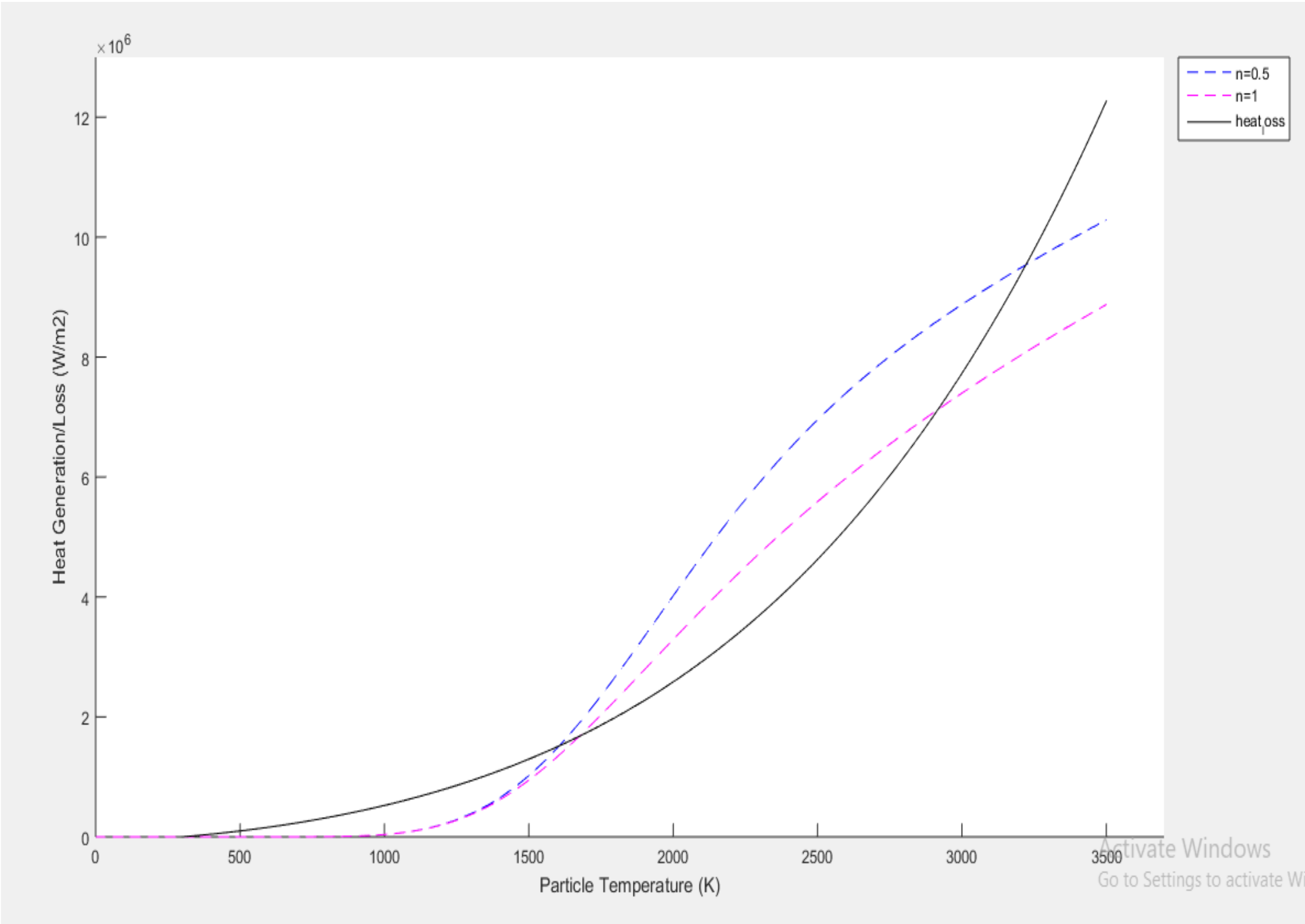
Graph 6



Graph 6 shows the rates of heat loss (solid curve) and heat generation (dashed curves) per external surface area as a function of particle temperature.

Also from graph 6 we can see that heat loss increase in a steady rate with temperature up to a certain temperature but above 2000 K it accelerates rapidly because of strong temperature dependence of radiative loss.

For curve corresponding to n=0.5, a particle heated uniformly to a final temperature below 1600 K will cool off immediately because below 1600 K, the heat generation is less then the heat loss by the particle.

But when the particle is heated above 1600 K, the temperature curve will keep on increasing because the heat generation is greater than the heat loss of the particle. The curve will keep on increasing until the curve will meet at a temperature (3200 K for this condition),at which point the rate are just balanced.

Thus we can say **ignition** occurs when the particle is heated at a temperature above 1600 K.

Like this by equating $\frac{Q_g}{S} = \frac{Q_1}{S}$ we can find out the critical ignition condition.

6. Conclusion

- The objective of this project work is to find t he critical ignition temperature for a single coal particle and temperature distribution within it in laser ignition of pulverized coal.
- We solved the required equations with appropriate assumptions for temperature distributions in the coal particle.
- We wrote MATLAB code to verify this and represent it in graphical form and to find the ignition temperature sand characteristics of the coal
- The temperature distribution curve when K is constant is straight line with constant slope while for K=variable is exponential curve and graph are always positive.
- The ignition temperature for the coal particle is found to be 1600 K.
- This finding will help in reducing energy wastage and valuable time.

7. FUTURE SCOPE OF WORK

The very task of ignition of coal or pulverized coal is a difficult one and to provide the required amount of heat is more difficult. Through this project we know exactly how much heat to provide and its characteristics.

We can further work to minimize the heat looses from the coal particles.

We can take more accurate assumptions to find more accurate values of critical ignition.

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