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Effect of Particle-Size and Air Flow Rates on the Ignition Temperature of Sub-Bituminous Coal

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***Abstract**: S*pontaneous ignition and combustion of coal are the major problems for its mining, transportation and usage. The temperature of ignition or combustion of the coal mainly depends upon its rank. Generally, coals having lower ranks are more prone to the spontaneous ignition or combustion than the coal having higher ranks. But many times, as an exception, as the rank increases, the coal becomes more susceptible to spontaneous ignition. To check the variables which affect the susceptibility of the ignition of the coal, practical experimentation can be carried with some proper combustion setup. Bituminous coal is generally used in many applications. But to reduce the use of it, sub-bituminous coal may be examined.

Index Terms: *Coal, Bituminous Coal, Sub-bituminous Coal, Volatile Material, Particle Size, air flow rate, air temperature Ignition Temperature.*

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I. Introduction

A. *Combustion of coal in burner*

Combustion process can be done by different methods such as fluidized bed combustion(FBC), pulverised coal combustion, integrated coal gasification combined cycle (IGCC). In FBC, fuel particles are suspended in a hot, bubbling fluidity bed of ash and other particulate materials (sand, limestone etc.) through which jets of air are blown to provide the oxygen required for combustion or gasification. The resultant fast and intimate mixing of gas and solids promotes rapid heat transfer and chemical reactions within the bed.

In pulverised combustion, the basic idea of a firing system using pulverised fuel is to use the whole volume of the furnace for the combustion of solid fuels. Coal is ground to the size of a fine grain, mixed with air and burned in the flue gas flow. Biomass and other materials can also be added to the mixture. Coal contains mineral matter which is converted to ash during combustion. The ash is removed as bottom ash and fly ash. The bottom ash is removed at the furnace bottom.

B. *Coal Contents*

The classification of coal is generally based on the content of volatiles. Other deciding contents in the coal are Carbon, Hydrogen, Oxygen, Sulphur and its heat content. Other than these, maceral content in the coal is also a deciding parameter in the classification of coals. Maceral in the coal is analogues to the minerals in rocks. Examples of maceral are inertinite, vitrinite, and liptinite

1) *Inertinite:* Inertinite is oxidized organic material or fossilizedcharcoal. It is found as tiny flakes within sedimentary rocks. The presence of inertinite is significant in the geological record, as it signifies that wildfires occurred at the time that the host sediment was deposited. It is also an indication of oxidation due to atomospheric exposure or fungal decomposition during deposition. Inertinite is a common maceral in most types of coal.

2) *Vitrinite:* Vitrinite is one of the primary components of coals and most sedimentary kerogens. It is derived from the cell-wall material or woody tissue of the plants from which coal was formed. Chemically, it is composed of polymers, cellulose and lignin

3) *Liptinite:* Liptinite is the finely-ground and macerated remains found in coal deposits. Liptinites were originally formed by spores, pollen, dinoflagellate cysts, leaf cuticles, and plant resins and waxes

C. *Purpose of using Sub-Bituminous coal*

In India, Bituminous coal is being used widely. To check the effects on the overall results, different types of coal can be used. In the following discussion we will see the overall comparison of the Sub-Bituminous coal and Bituminous coal.

1) *Comparison with Bituminous coal*

Table1: Comparison of bituminous and sub-bituminouos coal

Parameter	BituminousCoal	Sub-Bituminous
GCV (kJ/kg)	19,000 to 29750	18840 to 23000
Carbon content	43 to 75%	43 to 75%
Moisture Content	Less than 12%	12 to 25%

Volatile matter in Sub-bituminous coal is always higher than the Bituminous coal. Hence the ignition takes place earlier. The ignition point of sub-bituminous coal is slightly lower than the bituminous coal.

II. Previous Studies

A. *Effect of Particle Size*

From the study done the coal in theparticle size range of 1mm < particle size < 6 mm is most susceptible to spontaneous combustion. As the particle size increases, the Tg value required to induce a sudden jump in runaway temperature value also increases. The influence of particle size upon the concentration required for a lower-limit mixture diminishes as particle size decreases, and below about 60 microns, the effect of particle size becomes inappreciable[3]. Different types of coal from different parts have different glow-points[4]. They also have different ash and moisture content. The glow point is probably affected by the oxygen content of the coal. Particle size appears to have a small effect on coal ignition. Overall, the <53µm fraction behaved very similar to the whole coal. However, the large size fractions (>53µm) of a coal were generally slightly more difficult to ignite and always resulted in a significantly lower weight loss compared to its corresponding small size fraction (<53µm).

To find out the effect of coal particle size on the combustion properties, the TG, DTG and DSC data were compared[6]. It was found that the peak temperatures of the three coal particles <63 µm, 63 - 100 µm and 100 - 200 µm are 514, 530 and 561oC, respectively. The exothermic heats for the particles <63 µm and 63 - 100 µm in the temperature range of 300 - 450^{o}C are higher than that for 100 – 200 µm because of the heterogeneous reactions of volatiles and char.

B. *Effect of Air Flow Rate*

To determine the effects of air flow temperature, T = 493 K was chosen since a sudden jump in runaway temperature was observed at this temperature. The runaway temperature shows a parabolic dependence on the air flow rates[1]. Increasing the gas temperature dramatically decreased the ignition delay time. It was concluded from the research that[2], ignition delay depends strongly on the gas temperature.

Ray Arms[4] considered three different cases of air supply to observe the effect of air and oxygen on coal ignition. Inthe first case, the coal was heated in an ordinary manner by of a very small stream of oxygen. In the second case, the stream was cut off at 300^{o}C and in the third case; the blast of the oxygen was played on the sample. It was observed that the glow point is largely dependent upon the air supply, but that the actual temperature of the glow point, no matter how it is approached, is not altered.

Man and Gibbins[5] concluded from their study that, almost all the coals ignited in O2 in CO2 at some point. The concentration of O2 in CO2 that gave a similar ignition comparable to that in air was established to be between 30 and 35%. This is consistent with recentdata reported by CANMET, which concluded that the heat flux from oxyfuel experiments between 28 and 35% O2 in CO2 was comparable to that carried out in air.

Brikci-Nigassa, Garbett and Hedley[7] studied three different samples of coal of 6.3, 9.5 and 12.5mm. An increase in carbon combustion efficiency is achieved with the increase of air up to about 20-25%, a further increase in excess air beyond this value does not improve the carbon combustion efficiency significantly.

III. Experimental Setup

A. *Construction*

A circular chamber is designed with a diameter of 300mm and height 300mm with 80mm thick inside wall.The heater is placed all around its periphery inside the wall. The chamber is filled with the sand which is then heated electrically by using the heater.Within the sand a nickel crucible is placed in which the coal is being burnt.Two cylinders, one containing oxygen another, containing nitrogen are placed near the chamber.The crucible is provided with a cap which has three holes, out of which 1 is to feed oxygen and another for nitrogen. The third hole works as a vent.Two flow meters are connected between the flow lines of oxygen and nitrogen to measure the volume flow rate. Two thermocouples are connected near the crucible to measure the temperature.Temperatures are shown in the temperature indicator.

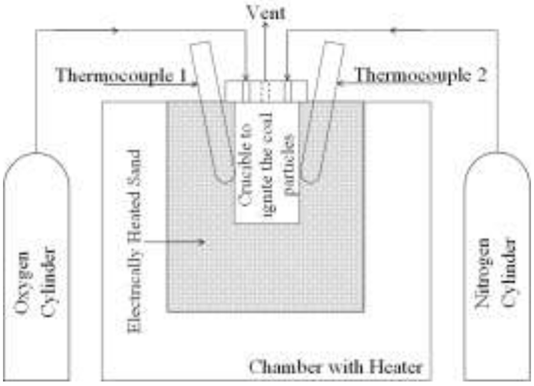

Fig 1: Schematic of coal combustion Setup

Fig 2: Experimental Setup

B. *Working*

The coal sample of required size is kept inside the crucible and the cap is kept to cover it. After switching the heater on, the stopwatch is being started. Oxygen and nitrogen are the allowed to flow from the cylinder to the crucible through the flow meter. The flow is set according to the requirements.

The coal follows a series of following phenomena

1) Commencement of visible active combustion, glowing of the mass

2) Ignition as manifested by an explosion or production of flame and the visible combustion.

Out of these the special points noted were the time interval before visible combustion. Explosion or production of flame can be hazardous in the environment of the setup or experiment, hence not observed. And the experiment was stopped before the temperature could reach this point.

The progress, of the combustion was watched through a central hole in the lid and the residue after visible combustion had ceased was examined preparatory to the introduction of a fresh charge. Tests were made on the same coal under various temperature conditions in the apparatus.

Table2: Dimensions of Setup

Dimensions of the chamber:	
Outer diameter	36 cm
Thickness	8 cm
Height	48 cm
Dimensions of the crucible	
Outer diameter	8 cm
Thickness	1.2 cm
Height	12 cm
Thermocouple Type	Type K (Chromel- Alumel)
Thermocouple Range	−200 °C to +1350 °C
Dimensions of pipeline	
Diameter	6mm
Total length	195mm
Heater Capacity	1Kw

IV. OBSERVATIONS

Coal particles were distributed in three parts according to their sizes. 120 to 150 µm, 151 to 200 µm and 251 to 500 µm. Air flow rate is varied from 0.75LPM to 1.2LPM. Time for each reading was measured. Practical data and analytical data was then checked.

A. *Observation Table*

Out of all the readings taken, 9 readings are shown in the research. Coal particles are divided into three catagories. For each category, air flow is kept constant as shown below. All the readings taken are tabulated as below.

Table 3 : Observation Readings

Particle (µm)	Air Flow LPM	Time	Thermomet T_1	T_2	Ignition °C	K
120 to150	1.2	2hrs 37mins	417	401	409	682
	0.9	2hrs 45mins	425	405	415	688
	0.75	2hrs 59mins	429	411	420	693
151 to 200	1.2	3hrs 16mins	364	352	358	631
	0.9	3hrs 34mins	369	357	363	636
	0.75	3hrs 57mins	376	360	368	641
201 to 250	1.2	3hrs 30mins	353	333	343	616
	0.9	3hrs 42mins	356	340	348	621
	0.75	4hrs 03mins	362	342	352	625

V. ANALYTICAL MODEL

A. *Mathematical Model*

Heat Transfer from the heater as well as the oxygen+nitrogen gases is equal to the heat absorbed by the coal particles. Considering the basic heat transfer laws and the setup, we can draw a mathematical model as,

Heat absorbed by coal particles = Conductive heat transfer from heater to crucible + Convective heat transfer from air to crucible

$$m.C_P\left(\frac{dT}{dt}\right) = R * (T_H - T) + h*A_S(T - T_G)$$

where,

m is the mass of coal particles; C_P is the specific heat capacity of coal; R is the resistance in conduction for heat transfer from cylindrical chamber, sand and crucible; T_H is the heater temperatre; T is the coal ignition temperature; h is the convective heat transfer coefficient; A_S is the surface area of coal; T_G is the air temperature.

$$m.C_P\left(\frac{dT}{dt}\right) = 0.1167 * (973 - T) + h.A_S(T - 623)$$

m = Density * volume
Density for coal = 833 kg/m^3
Considering the particle size are approximately spherical in shape, volume= $4\pi.r^3/3$
A_S is the surface area of the particle which can be formulates as, $4\pi.r^2$
Integrating this function, and taking the condition at t=0, T=303K (room temperature), we get the final equation as

$$T = [\exp [\{ (h.A_S - 0.1167) t / m * C_P \} + \ln (80.5229 - 320*h.A_S)] - (115.833 - 623 * h.A_S) \} / (h.A_S - 0.1167)$$

h is the convective heat transfer which can be found from the basic equation of the Nusselt Number
Nu= (hd/k)
Where,
Nu is a function of Reynolds No. and Prandle which are found out from the propertt table of air; d is the diameter of the pipeline and k is the thermal conductivity of air at 623K.
For Reynolds No, velovity needs to be found out.
Flow rate = velocity * area
Area = $\pi*(0.006)^2$

B. *Analytical results*

At 1.20LPM, h = 554.49 W/m^2K
At 0.90LPM, h = 488.93 W/m^2K
At 0.75LPM, h = 422.57 W/m^2K

Calculations are done for the particle size from 120 to 250 separately. Results are shown for sizes between 120µm TO 150µm. Time taken for the analytical results is the time taken by coal particles in the experimental readings.

Table 4: Analytical results for 120-150µm

Size µm	M ($x10^{-4}$)	$m.C_P$ kJ/K	A_S ($x10^{-8}$)	T (K) h =554.49 W/m^2.K	h = 488.93 W/m^2.K	h = 422.57 W/m^2.K
120	7.53	1.00	4.52	777.14	777.98	784.12
121	7.72	1.02	4.60	772.16	773.15	779.28
122	7.92	1.05	4.67	767.42	768.54	774.64
123	8.11	1.07	4.75	762.88	764.12	770.19
124	8.31	1.10	4.83	758.55	759.90	765.93
125	8.51	1.13	4.91	754.42	755.86	761.84
126	8.72	1.16	4.99	750.46	751.98	757.92
127	8.93	1.18	5.06	746.67	748.27	754.15
128	9.14	1.21	5.14	743.04	744.70	750.54
129	9.36	1.24	5.23	739.56	741.28	747.06
130	9.58	1.27	5.31	736.23	738.00	743.71
131	9.80	1.30	5.39	733.03	734.84	740.49
132	10.03	1.33	5.47	729.96	731.81	737.39
133	10.26	1.36	5.55	727.01	728.89	734.41
134	10.49	1.39	5.64	724.18	726.09	731.53
135	10.73	1.42	5.72	721.46	723.38	728.76
136	10.97	1.45	5.81	718.84	720.78	726.09

137	11.21	1.49	5.89	716.32	718.27	723.51
138	11.46	1.52	5.98	713.89	715.85	721.02
139	11.71	1.55	6.07	711.55	713.52	718.62
140	11.96	1.58	6.15	709.29	711.27	716.30
141	12.22	1.62	6.24	707.12	709.10	714.05
142	12.48	1.65	6.33	705.02	707.01	711.89
143	12.75	1.69	6.42	703.00	704.98	709.79
144	13.02	1.72	6.51	701.05	703.02	707.76
145	13.29	1.76	6.60	699.16	701.13	705.80
146	13.57	1.80	6.69	697.34	699.30	703.90
147	13.85	1.83	6.79	695.58	697.53	702.07
148	14.13	1.87	6.88	693.88	695.82	700.28
149	14.42	1.91	6.97	692.23	694.16	698.56
150	14.71	1.95	7.07	690.64	692.56	696.89

From the results obtained, the average of the ignition temperature for the particle size ranging between 120 to 150µm to compare it with the practical data obtained. Similarly, temperature for the samples between 151-200µm and 251-500µm are calculated and taken the average as tabulated below.

Table5: Average temperature readings for different particle sizes

Coal Particle Size (µm)	Air Flow Rate (LPM)	h (W/m^2.K)	T (K)
120-150	1.2	554.48	723.53
	0.9	488.93	725.30
	0.75	422.57	730.58
151-200	1.2	554.48	670.20
	0.9	488.93	671.79
	0.75	422.57	674.47
251-500	1.2	554.48	651.69
	0.9	488.93	652.36
	0.75	422.57	653.44

VI. Result And Discussion

From various readings and observations, graphs are plotted for various relations. To show the effect of particle size, time and air flow rate on temperatures, the relevant figures, the results are shown graphically as follows.After these graphical presentations, comparison between practical and analytical readings is checked.

A. Results from Practical Data

1) Effect of Particle size on temperature

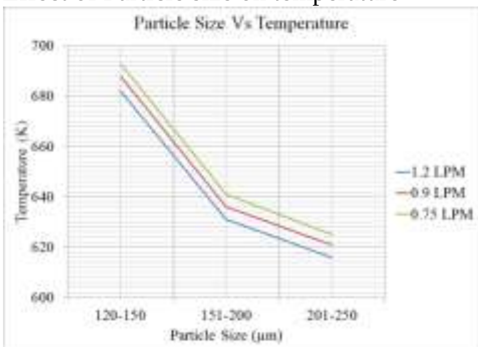

Fig 3: Effect of Particle size on temperature

2) Effect of Particle Size on Time

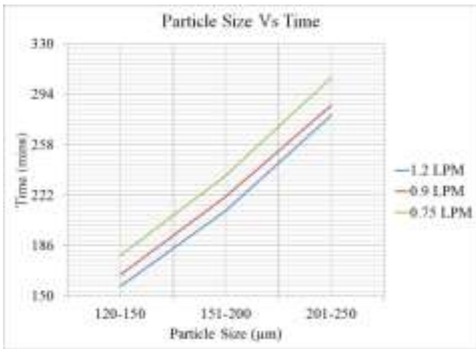

Fig 4: Effect of Particle size on time

3) Effect of Air Flow rate on temperature

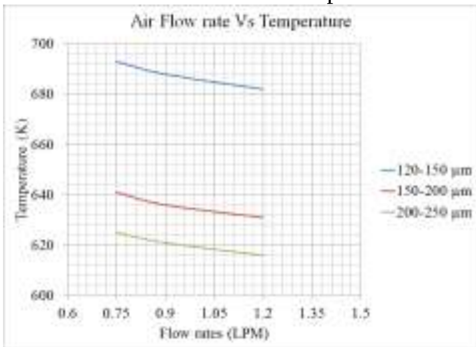

Fig 5: Effect of Air Flow Rate on temperature

4) Effect of Air Flow rate on time

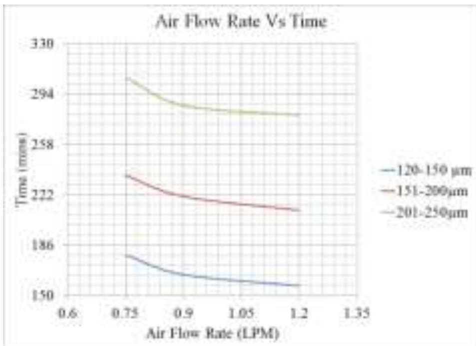

Fig 6: Effect of Air Flow Rate on temperature

5) Effect of time for variable particle size

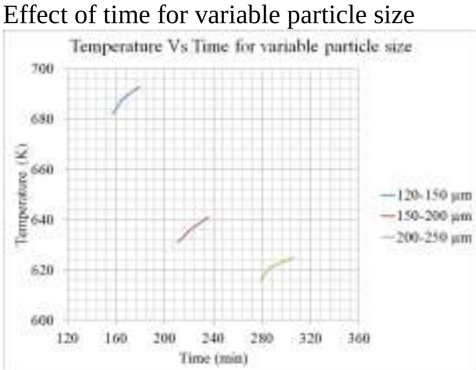

Fig 7: Effect of time for variable particle size

6) Effect of time for variable air flow rates

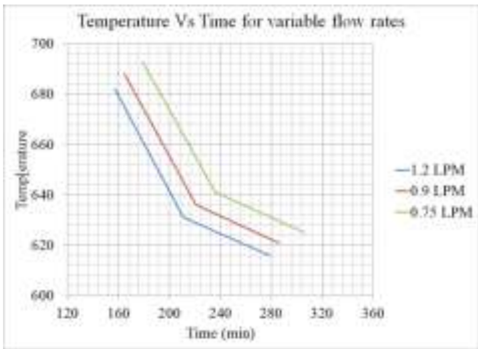

Fig 8: Effect of time for variable air flow rates

B. *Comparison of Practical and Analytical Data*

1) For Different Particle sizes

For 120-150 µm

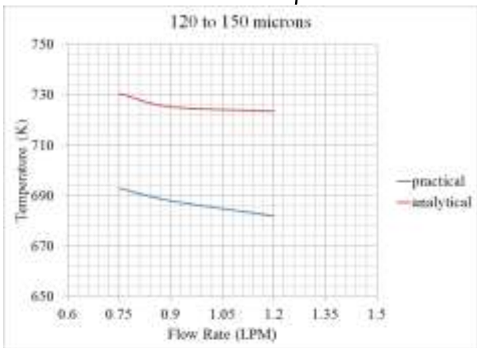

Fig 9: Analytical and practical comparison for 120-150µm

For 151-200 µm

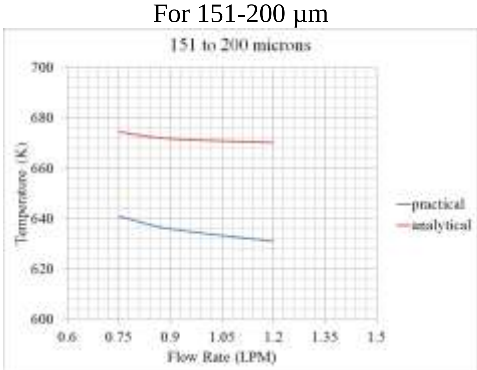

Fig 10: Analytical and practical comparison for 151-200µm

For 251-500 µm

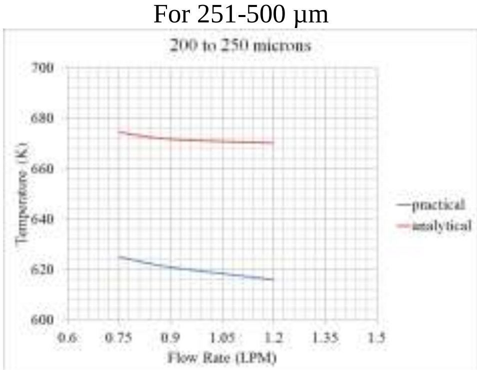

Fig 11: Analytical and practical comparison for 201-250µm

2) *For Different Particle sizes*

For 1.2LPM

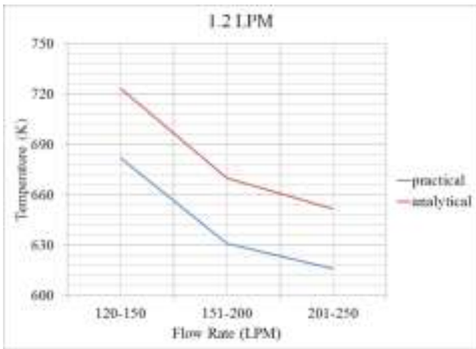

Fig 12: Analytical and practical comparison for 1.2LPM

For 0.9LPM

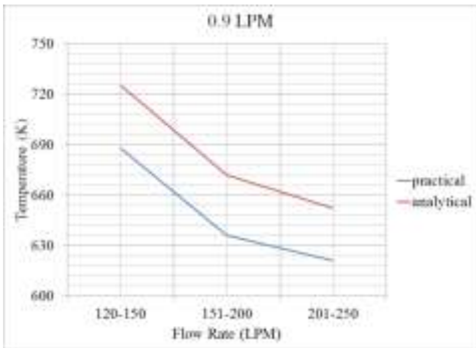

Fig 13: Analytical and practical comparison for 0.9LPM

For 0.75LPM

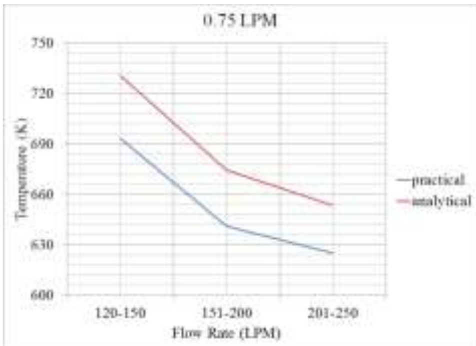

Fig 14: Analytical and practical comparison for 0.75LPM

VII. CONCLUSION

1) Ignition temperature decreases as the particle size increases. For the same coal particle size, temperature decreases for the lower flow-rate. This is because of the more area exposure of the particle. As the area of the particle increases, the susceptibility of ignition increases.

2) For particle size ranging from 120 to 150µm, ignition temperature is, from experimental data, 682K for 1.2LPM, 688K for 0.9LPM and 693K for 0.75LPM. whereas from analytical data that is 723.53K for 1.2LPM, 725.3K for 0.9LPM and 730.58K for 0.75LPM.

3) For particle size ranging from 151-200µm, ignition temperature is, from experimental data, 631K for 1.2LPM, 636K for 0.9LPM and 641K for 0.75LPM. whereas from analytical data that is 670.20K for 1.2LPM, 671.79K for 0.9LPM and 674.47K for 0.75LPM.

4) For particle size ranging from 251-500µm, ignition temperature is, from experimental data, 616K for 1.2LPM, 612K for 0.9LPM and 625K for 0.75LPM. whereas from

analytical data that is 651.69K for 1.2LPM, 652.36K for 0.9LPM and 653.44K for 0.75LPM.

5) Ignition temperature increases as the air flow rate decreases. For the same flow rate, coal with a lower dimension has a higher value of ignition temperature. As the air flow rate decreases, the velocity decreases which leads to a lower value of convective heat transfer coefficient. This results in slower ignition of the coal.

6) For air flow rate of 1.2LPM, ignition temperature is, from experimental data, 682K for 120-150 µm, 631K for 151-200µm and 616K for 251-500 µm. whereas from analytical data that is 723.53K for 120-150 µm, 670.20K for 151-200µm and 651.69K for 251-500 µm

7) For air flow rate of 0.9LPM, ignition temperature is, from experimental data, 688K for 120-150 µm, 636K for 151-200µm and 621K for 251-500 µm. whereas from analytical data that is 725.30K for 120-150 µm, 671.79K for 151-200µm and 652.36K for 251-500 µm

8) For air flow rate of 0.75LPM, ignition temperature is, from experimental data, 693K for 120-150 µm, 641K for 151-200µm and 625K for 251-500 µm. whereas from analytical data that is 730.58K for 120-150 µm, 674.47K for 151-200µm and 653.44K for 251-500 µm

9) Time taken by the coal particles ranging between 120 to 150 µm is lesser than time taken by the coal particles ranging between 151 to 200 µm which is further lesser than time taken by the coal particles ranging between 251 to 500 µm. Again, this is because of the area exposure of the coal particles. More the area available, more the time taken to ignite.

10) But for the same flow rate, increase in the particle size takes lesser time to ignite.

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