Journal of Engineering and Computer Sciences
Qassim University, Vol. 4, No. 1, pp. 63-81 (January 2011/Moharram 1432H)

Pyrolysis and Combustion Rates of Solid Fuel

Bahgat K. Morsy
Mechanical Engineering Department, College of Engineering, Qassim University
bahgat52@yahoo.com

(Received 28/2/2010; accepted for publication 2/6/2010)

Abstract: A knowledge of the product distribution from the pyrolysis of coal when particles are heated is of considerable importance in understanding the process involved in both the production of gaseous and liquid fuels from coal and the combustion of coal. Studies of decomposition of Sinai coal and combustion rates have been undertaken because the rate and extent of volatilization play an important part in the ignition process of coal particles in circulating fluidized bed. There is a little information available in the literature on the rate of decomposition occurring under the very rapid heating characteristics of Sinai coal firing. This is due to incomplete knowledge about the phenomenon of combustion of Sinai coal in circulating fluidized involved in special care operations. That is why this work is continued to bring new technical solutions and sake knowledge in this scope more profound.

Keywords: Pyrolysis, combustion, solid fuel

List of Symbols

A^d	Quantity of ash determine in standard conditions	A_c^d	quantity of ash remaining in char after coal pyrolysis
C_{O2}	local concentration of oxidizer	D	coal particle diameter
E	activation energy	k_O	frequency factor
M	True reaction order	N	apparent reaction order
Q	degree of devolatilization	Q	char reactivity
R_g	universal gas constant	T_g	ignition temperature
T_s	particle temperature	V^{dav}	quantity of volatile matter (V.M.) determine in standard conditions
V_c^{dav}	Quantity of volatile matter (V.M.) remaining in char after coal pyrolysis	ΔV^{dav}	change in quantity of volatile matter (V.M.)
ΔM^{dav}	actual coal mass loss	ρ_{O2}	density of oxygen
β	stoichiometric coefficient	λ	heat transfer coefficient
ε	Porosity	daf	dry ash free

1. Introduction

The combustion of most solid fuels involves two major steps:

(i) The thermal decomposition (pyrolysis, devolatilization) that occurs during the initial heating, accompanied by drastic physical and chemical changes which usually involve the particle become plastic then rehardening, and

(ii) The subsequent combustion of pores solid residue (char) from the first step. The burning rate of the solid depends in part-on the size of char particle and the natural of its pore structure. These physical properties, together with important chemical properties, are affected by changes during the first step. The first step is rapid, the second is slow. In pulverized flames the time for devolatilization to take place is of the order of 0.1s and for char burn.-out the time is 1s; for particles burning in fluidized bed combustors the corresponding orders are 10s and 1000 s. Therefore the burning of the char has a major effect on the volume of the combustion chamber required to attain a given heat release.

Actually, when necessity of burning low grade fuels, has arisen, there is a demand to find adequate technologies to burn them effectively and with as low emission of pollutants as possible. Circulating fluidized bed may provide the solution. The gas/solid mixing and heat transfer properties of fluidized beds have been utilized in combustion systems for burning low grade coal, but it that the advantages have been appreciated of the high heat transfer rates occurring at surfaces immersed within the bed. Sufficient heat is extracted in this way to maintain the temperature of the bed in the average 700-800 ^{o}C. The high heat transfer rates which result in high combustion intensities and a reduction the weight of expensive tube materials-leading to a substantial saving in the capital cost of steam generation.

Prospecting for coal in Egypt, can be considered to data from early in 1844, when a well near Edfu (Southern Egypt) shown some iodination of bituminous carbonaceous material. Further prospecting for call carried out in 1958-1962 resulted in the discovery of the coal deposits of Ayun Musa, Wadi Thorn and Maghara in Sinai Peninsula. The Safa mine was opened in 1964 and was about to start production in 1967, when it was then abandoned due to Israeli invasion. It is planned to resume production in April 1986. A call-for tender is now being issued for studding the possibility of erecting a coal-fired power plant on the Gulf of Suez (initial) capacity 300 MW, to be followed by other coal fired power stations.

2. Pyrolysis of Coal Particles

Prior studies in which finely-ground coal was heated very rapidly have shown that the fraction of the coal that can be volatilized increases with both the rate of heating and the final temperature to which the coal is heated. For example, Eddinger, *et a1* [1], have presented data from an entrained flow reactor which show that volatile products amounting to 49.9 percent of the coal fed may be produced from a finely-ground coal having an AS'IM volatility of only 35.5 percent, even though maximum reactor temperature was less than the 1223 K reached in the standard volatility test.

Mustafa *et al* [2] studied the effect of particle size on coal pyrolysis by thermogravimetry (TG/DTG). All the experiments were conducted at non-isothermal heating conditions with a heating rate of 10°C $\min^{-1}$. in the temperature range of 20–600ºC, under nitrogen atmosphere. Different fractions of Çayırhan coal showed differences in TG/DTG curves, peak temperatures and residue values. The Arrhenius model is applied to determine the kinetic parameters from TG/DTG curves.

Kinetic analysis of rapid coal devolatilization in a spot heater apparatus was made for Tatong coal by [3]. A multiple-stage measuring technique was devised to provide the change of total volatiles with time/temperature during the devolatilization. On the basis of the analyses of the total volatiles yield and measured temperature of coal particle, the kinetic parameters of the rapid devolatilization for Tatong coal were estimated by applying Distributed Activation Energy Model (DAEM).

A poly-generation process of simulated circulating fluidized bed (CFB) combustion combined with coal pyrolysis was developed in a laboratory scale by [4]. Pyrolysis characteristics of three bituminous coals with high volatile contents were investigated in a fixed bed with capacity of 10 kg solid samples. The effects of initial temperature of solid heat carrier, pyrolysis holding time, blending (ash/coal) ratio and coal particle size on gas and tar yields were studied experimentally. The results indicate that the initial temperature of the heat carrier is the key factor that affects the gas and tar yield, and the gas composition. Most of the gas and the tar are released during the first few minutes of the pyrolysis holding time. For caking coal, the amount of char agglomerating on the pyrolyzer inner wall is reduced by enhancing the blending ratio. The experimental results may provide basic engineering data or information for the process design of CFB combustion combined with coal pyrolysis in a large scale.

An experimental apparatus was set up for batch simulation of coal pyrolysis with solid heat carrier in a fixed bed. by [5] Quartz sand as heat carrier preheated to about 700–800°C was mixed with Datong bituminous coal by an agitator. The thermal history of the coal particle has been followed by a K-type thermocouple. The effects of particle size, pyrolysis time and temperature on the gas yield during pyrolysis of coal with solid heat carrier were examined for different conditions. The experimental results showed that a dominant percentage of the gas product is produced during the first 1–3 min, although gas evolution would last for as long as 10 min. The total gas yield, insensitive to particle size of the heat carrier, depends on carrier temperature and coal particle size under tested conditions. The contact heat transfer of cold and hot particles was analyzed.

The authors of the works [6, 7, and 8] observed that heating the coal particles at the rate higher than 10000 K/s substantially influences the quantity of evolutes volatile matters. Rapid heating results in greater quantity of volatile products of pyrolysis than slow heating does. Another feature differentiating pyrolysis in high rate of heating from slow heating is qualitatively different composition of evoluted gaseous products [10].

Complex processes occurring during thermal decomposition of coal are not well known or quantitatively described. Model allowing for more than one reaction are presented in work [6, 7, 8, and 9]. References [7 and 8] propose that pyrolysis may be described by two parallel reactions. The review of pyrolysis models [6, 7, 8, and 9] of volatile matters evolution is presented in tables (1).

Table (1). Review of Pyrolysis models

Author	Model	Commentary
Badzioch and Hawksley [6]	$\frac{dV}{dt} = \mathrm{k}(\mathrm{V}^* - V)$	K: constant rate of chemical reaction
Kobayshi *et al*. [7]	Coal $\rightarrow x_1 v_1 + R_1(1 - x_1)$	V : gas
Ubkayakar *et al*. [8]	Coal $\rightarrow x_2 v_2 + R_2(1 - x_2)$	R; solid phase
Solomon [9]	$\frac{dV_i}{dt} = \mathrm{k}_{\mathrm{i}}(\mathrm{V}^* - V_i)$	V^* : emitted quantity of volatile matters (% daf)

Pyrolysis converts coal into volatile products and solid residue. The rate of volatile evolution may be controlled by either chemical decomposition of the coal or gaseous flow through the solid matrix Knowledge of the kinetics of pyrolysis is required for under standing the combustion of coal particles. Volatile evolution is known to influence the combustion of solid particle, and the influence of pre-ignition volatile generation on flame speed. [11 to 18]

The report has determined the degree of devolatilization of SINAI coal in the range of temperature from 923 K to 1323 K for particle diameter from 250 μm to 750 μm, ignition temperature, and reactivity.

2.1. Coal size

A high percentage of coal mined today is by mechanical coal cutters; in most countries the days of pick- and shoved mining disappeared, and mechanical conveying, cleaning and screening the coal is now widely adopted. As a result, there is a much smaller amount of large coal available and generally coal is much cleaner with less dirt and ash. In stoker fired boilers coal size is important. Although large coal is usually the most expensive, it is not the most uitable for use in mechanical stokers. Most large coal suppliers grade their coal into a range of sizes in which both the minimum and maximum particle sizes are stipulated. For example, British coal grade their bituminous and anthracite coal into groups as shown in Table (2). Other industrial countries have their own systems for classifying coal by average particle size, and use their own descriptive names for the various grades.

Table (2). British coal grade of bituminous and anthracite coal

Bituminous coal grading			**Typical size groups for graded low, volatile coal**			
Range of screen sizes			**Welsh anthracite**		**Welsh dry steam coal**	
Description	**Max, mm**	**Min. mm**	**Description**	**Mm**	**Description**	**mm**
Large Cobbles	150	75	Cobbles	125-80	Cobbles	125-80
Cobbles	100-150	50-100	French nuts	80-63	Large nuts	80-56
Trebles/large nuts	63-100	38-63	Stoves nuts	63-36	Small	56-18
			Stoves	36-2--16	Nuts	18-16
Doubles/nuts	38-63	25-38	Beans	20-10	Beans	18-10
Singles	25-38	12.5-18	Peas	16-10	Peas	10-0
			Grains	10.5	Washed duff.	
			Washed duff.	5-0		

2.2. Coal analysis

SINAI coal was the raw material used for pyrolysis research. The analysis was listed in Table (3) and Table (4). The coal was preheated, milled and divided into groups of particles of diameters by sieving in the range from 250 μm to 750 μm. The samples for proximate and ultimate analysis were carried out according to obligatory Polish Standards. The content of carbon was determined in the examined samples by means of Radmacher–Hoverth method.

Table (3). Analysis of SINAI coal

Proximate Analysis (dry ash free % by weight)			
Moisture	Ash	Volatile matter.	Fixed Carbon
2.9	13.7	54.45	8.95

Table (4). Analysis of SINAI coal

Ultimate Analysis (dry ash free % by weight)				
Carbon	Hydrogen	Sulphur	Nitrogen	Oxygen (by difference)
76	6.6	2.96	1.13	13.31

2.3 Test-rig and measurements

Investigations were carried out on the test-rig as shown in Fig. 1 [19and 20]. Basic elements of the test rig are: vertical reaction chamber, coal supplying sampler extinguishing system of pyrolysis products, installation of reaction chamber electric heating and gas heater, water cooling system, gas flow and temperature measuring system, system for carrying away pyrolysis products. During the operation, the reactor walls and gas heater temperature is measured with six thermocouples. The quantity of gas supplied to the reactor and the feeder and that leaving the reactor is measured by rotameters. As well, the power of heating appliances is measured. Solid and fluid pyrolysis is carried away from the reactor through the installation comprising successively: cyclone, bag filter and suction pump. All measurements probes were calibrated at various conditions in the test section.

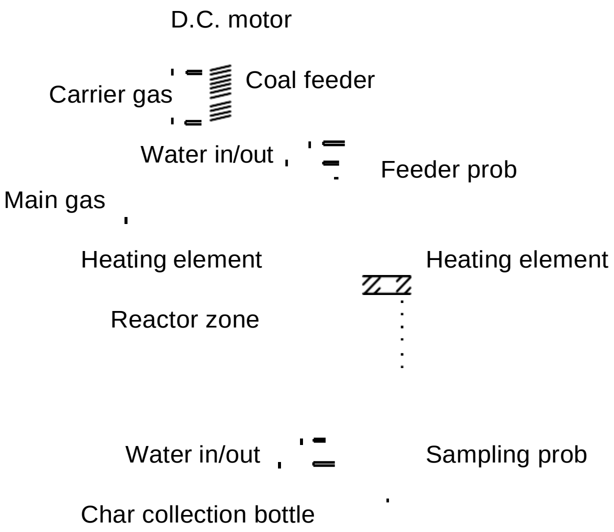

Fig. (1). The reactor system

2.4 Research range

The Experiment was based on continuous transport of pulverized coal particles by a carrier gas (Nitrogen) to the reactor filled with in active atmosphere where they are rapidly heated (10^3 deg/s-10^5 deg/s). The particles flowed through the reactor in 2s-4s. The products were sucked further to the cooling stage. The furnace temperature was controlled from 923 K to 1323 K in 100 deg intervals. The flow of carrier gas was changed from 0.0005 to 0.0023 cubic meters per second in relation to the furnace temperature. The quantity of supplied coal amounted to ca 0.00017 kg/s.

2.5. Degree of devolatilization

The degree of devolatilization of coal can be expressed by the number Q which is the ratio of the actual coal mass losses caused by rapid pyrolysis ΔM^{daf} to the change in quantity of volatile matter determined in standard conditions, i.e. ΔV^{daf} [19 and 20]

$$Q = \frac{\Delta M^{daf}}{\Delta V^{daf}} \tag{1}$$

To obtain the value of “Q” the parameters ΔM^{daf} and ΔV^{daf} have been determined as given below:

The examination of devolatilization in dust-gas stream renders it impossible to measure directly coal; mass loss caused by thermal decomposition. Coal mass loss results from the fact that not all particles reach the collector as some of then get stuck to the reactor surface. Thus, to determine the actual loss of mass requires the use of ash determined according to chemical analysis, so the actual mass loss is calculated from the equations;

$$M^{daf} = 100 - \left(\frac{100\ A^{d}}{100\ A_{d}}\right)\left(\frac{100 - A^{d}_{c}}{A^{d}_{c}}\right) \tag{2}$$

The quantity of volatile matter when left in char after coal devolatilization (V^{daf}_{c}) can be estimated from the formula;

$$V^{daf}_{c} = \frac{100\ A^{d}}{100\ - A^{d}}\ \frac{V^{daf}}{A^{d}_{c}} \tag{3}$$

The change of quantity of volatile matter which was released from coal can be determined by the following equation;

$$\Delta V^{daf} = V^{daf} - V^{daf}_{c} \tag{4}$$

The values of ΔM^{daf} and ΔV^{daf} obtained through experiments have been presented in Figs. 2 and 3. From these figures it can be said that;

- with the rise in pyrolysis temperature there is an increase in the quantity of emitted matter and the mass loss,
- for fraction of diameters 600 µm -750 µm there is a sudden increase in the values of ΔM^{daf} and ΔV^{daf} up to pyrolysis temperature of 1323 K. Beyond this temperature the increase is very slow.

The calculated values of degree of devolatilization of coal obtained are given in Table (5). From this table Q is found to vary between 1.2-1.5. Considering the small range of variation and the trend of curves in Figs. (2 and 3) it can be inferred that the particle size practically does not affect the degree of devolatilization. Devolatilization rate is reduced since a larger coal particle results in a higher inherent temperature gradient. In addition, a large coal particle size results in a higher mass transfer resistance for volatile gas. A longer path of the volatile inside a larger particle delays the time for volatile release. Smaller coal particles favor the gas and the tar yields.

Table (5). The degree of devolatilization (Q)

Temp., K	**Particle diameters, µm**				
	250-350 µ m	**350-450 µ m**	**450-550 µ m**	**550-650 µ m**	**650-750 µ m**
	Q	**Q**	**Q**	**Q**	**Q**
923 K	1.4	1.23	1.3	1.4	1.3
1023 K	1.4	1.25	1.2	1.43	1.5
1123 K	1.31	1.24	1.26	1.3	0.8
1223 K	1.3	1.20	1.3	2.2	1.3
1323 K	1.4	1.20	1.2	1.3	1.5

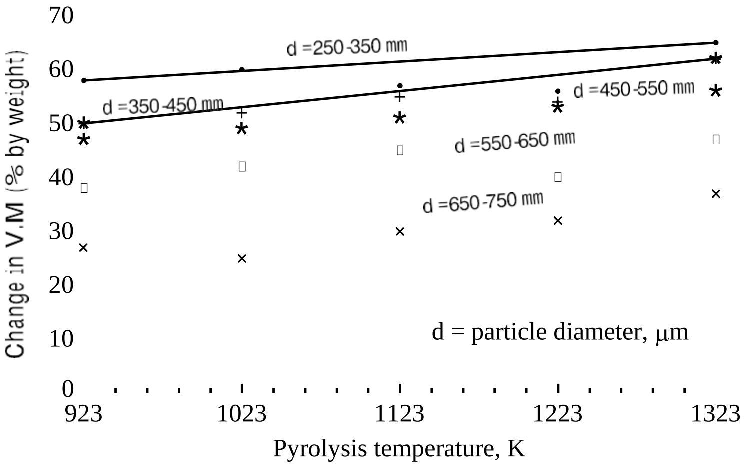

Fig. (2). Measured variation in change of volatile matter various with pyrolysis temperature.

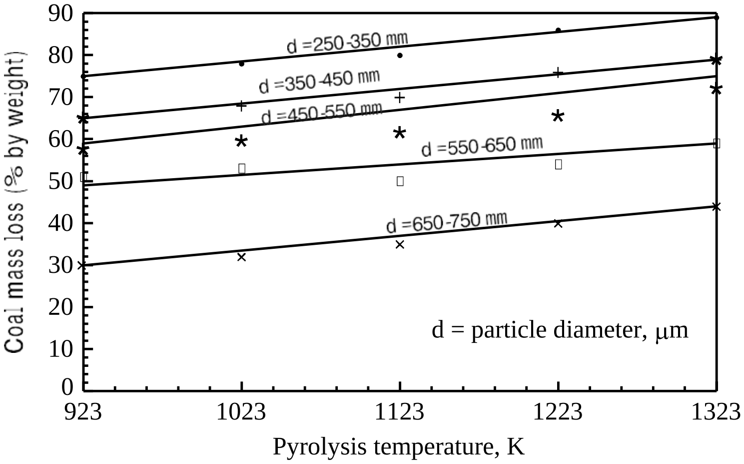

Fig. (3). Measured variation in change of coal mass loss various with pyrolysis temperature.

3. Ignition Temperature of Coal Particles

The test rig where ignition temperature and characteristic burning times were determined is illustrated in Fig. (4) [21]. A single coal particle was put on the top of a fine quartz needle and introduced into a cylindrical furnace of 0.5 m length and a diameter of 0.04 m, the air inside being static. The ignition of particle was watched through an observation port. In the absence of ignition the particle was taken out and a fresh sample was introduced after raising the furnace temperature. The experimental was repeated until the ignition occurred. (T_s) The lowest temperature, at which the ignition took place, was regarded as ignition temperature. The furnace temperature was changed by five degree centigrade at each step. At one temperature, on the average, 200 particles were tested

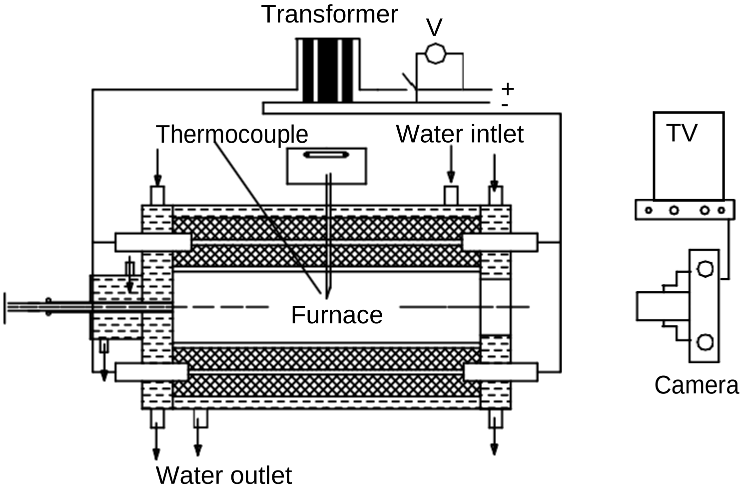

Fig. (4). View of experimental test - rig.

Figure (5) presents experimentally determined changes in ignition temperature with particle diameter for tested chars. The results are presented only for the particle diameters below 490 μm. The figure shows that the ignition temperature with particle diameter for tested chars. The results are presented only for the particle diameters below 490 μm. The figure shows that the ignition temperature increases as the particle diameter decreases. Also the ignition temperature increases with the increase in pyrolysis temperature. Thus determined ignition temperature is the basis for determining the values of kinetic parameters which, in turn form the basis for determining char reactivity.

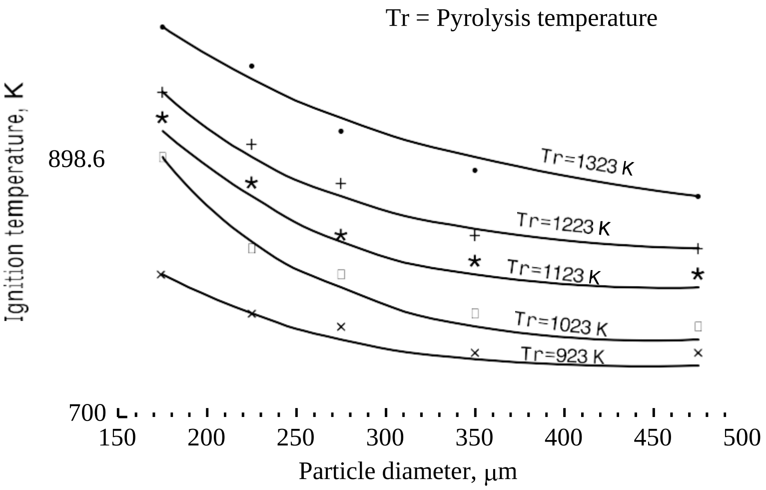

Fig. (5). Ignition temperature as a function of particle diameter for various pyrolysis Temperature.

4. Reactivity of Coal Particles

Reactivity is influenced by many chemical and physical factors characteristic for fuel, e.g.: crystalline structure, presence of mineral substance and trace elements, specific surface of pores, capacity of open pores, porosity etc. Coal reactivity changes together with its devolatilization and depends on the conditions of pyrolysis, such as: rate of heating, temperature and duration of pyrolysis, type of gas and type of coal.

Solid fuel reactivity is mathematically defined by the formula [21]:

$$q = K\ (\ C_O\ )^m \qquad [\,Kg/m^2s\,] \tag{5}$$

Where: K=the intrinsic rate constant [Kg/m^2s]; or [m/s];

C_O=local concentration of oxidizer fraction, and m= the true reaction order.

The rate constant is usually related to temperature by Arrehenius expression:

$$K = k_o \quad Exp\ (-\ \frac{E}{R_g T_s}) \tag{6}$$

Where:

k_o**= frequency factor [m/s];**	**E = activation energy [KJ/mol];**
R_g**= gas constant [KJ/mol.K] and**	T_s **= Particle temperature [K].**

The method of determining kinetic parameters on the basis of experimentally measured ignition temperatures was applied in this report. The relation between ignition temperature and kinetic parameters under the conditions of ignition was derived as given below and is presented in the following [21]:

$$Ln\left(\frac{2T_g\lambda R_g}{273*0.375e*Q*d}\right) = Ln\left(E*k_o\right) - \left(\frac{E}{R_g}*\frac{1}{T_g}\right) \qquad (7)$$

Where::

T_g = Ignition temperature K;	**d = coal particle diameter (m);**
λ = coal thermal conductivity t (KJ/m.K) and	**Q = heat of combustion (KJ/Kg.)**

From the above expression it is seen that the independent variable is given by $\left(\frac{1}{T_g}\right)$ and the dependent variable is given by: $Ln\left(\frac{2T_g\lambda R_g}{273*0.375e*Q*d}\right)$ so, the above expression can be plotted to determine kinetic parameters (E & k_o).

Figure (6) shows the plot to determine (k_o) and (E). The activation energy (E) is calculated from the slope $\left(\frac{E}{R_g}\right)$ and the reaction rate constant (k_o) is obtained from the intercept. The results also are shown in Table (6). The Table shows that the pyrolysis temperature increase to 1323K causes insignificant char reactivity decrease as compared to the reactivity of raw coal. Considerable difference in reactivity of chars and raw coal is observed for the char obtained at 923 K. Slight decrease in char reactivity together with the temperature results due to the development of porous structure and short period of particles presence in the reactor.

Table (6). Kinetic parameter values and char reactivity of Sinai coal obtained in various pyrolysis temperatures.

Sample	**Pyrolysis Temp. K**	**Activation Energy ,KJ/mol**	**Frequency Factor, m/s**	**Char, Reactivity,** $Kg / m^2 .s$
Coal	293	55.0	74	0.020
char	923	115.8	$4.4x10^5$	0.101
char	1023	61.41	$1.2x10^2$	0.020
char	1123	72.3	$6.6x10^2$	0.030
char	1223	72.7	$3.5x10^2$	0.014
char	1323	68.5	$1.3x10^2$	0.010

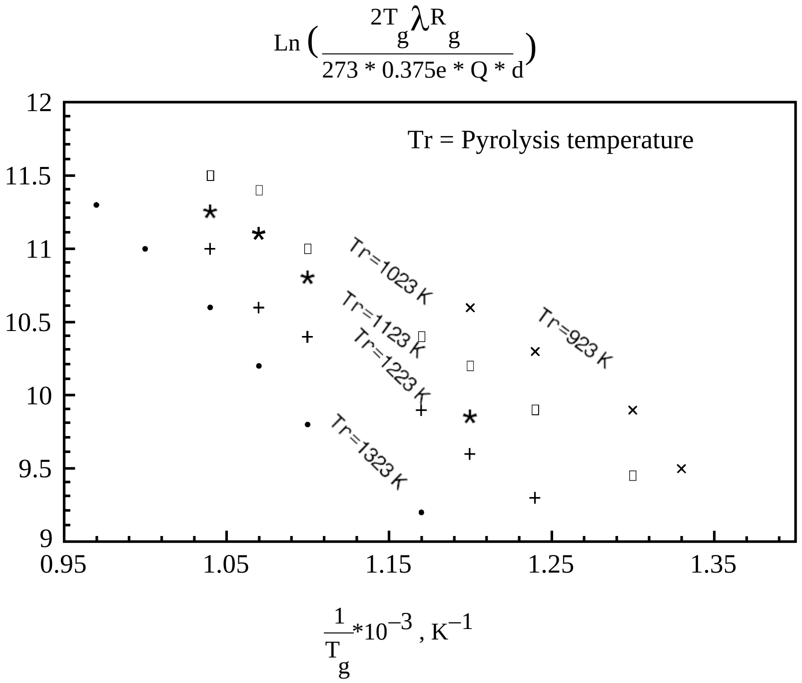

Fig. (6). Determination of kinetics' parameters for various pyrolysis temperatures.

5. Combustion Rates of Sinai Coal at Different Oxygen Concentrations

The Semenov analysis shows that the critical condition for thermal ignition requires that the values of heat generation, (Q_R) and the heat loss, (Q_L), are equal, as are the derivatives of those rates with respect to temperature [22], i.e.

$$Q_R = Q_L \tag{8}$$

$$\frac{dQ_R}{dT} = \frac{dQ_L}{dT} \tag{9}$$

The kinetics is assumed to follow the Arrehenius law, with a reaction of the apparent order, n, in oxygen. For circumstances in which the solid temperature, (T_s) differs little from the gas temperature, (T_g), i.e. (T_s -T_g) << (T_g), the Arrehenius expression can be simplified by the substitution:

$$\mathrm{Exp}\left(-\frac{E}{R_g T_s}\right) \approx \mathrm{Exp}\left(-\frac{E}{R_g T_g}\right).\ \mathrm{Exp}\left(\frac{E}{R_g T_g^2}(T_s - T_g)\right) \qquad (10)$$

The solution of equation (8), (9) and (10) for a spherical fuel particle, considered to be internally isothermal with an irreversible n the order reaction, is given in form:

$$\mathrm{Ln}\left(\frac{2\,R_g \lambda\,(T_g)^{2.75+n}}{2.718C^n \beta * Q * d * (273\rho_{O2})^n * (298)^{0.75}}\right) = \mathrm{Ln}\left(E * k_o\right) - \left(\frac{E}{R_g} * \frac{1}{T_g}\right) \qquad (11)$$

The intrinsic reactivity, which is defined as the reaction rate per unit surface area of pore surface in the absence of any mass transfer restrictions. The intrinsic kinetic parameters may be obtained directly from the experimentally determined ignition conditions, using the theory of porous particle ignition follows from the theory, is in the form of::

$$\mathrm{Ln}\left(\frac{R_g\,\lambda\left(\frac{1+m}{2}\right)^{0.5}(T_g)^{\frac{6+m}{2}}}{C^{\frac{1+m}{2}} \varepsilon * 68.3Q * d * (273\rho_{O2})^{\frac{1+m}{2}} * (298)^{0.75}}\right) = \mathrm{Ln}\left(E * (k_o)^{0.5}\right) - \left(\frac{E}{2R_g} * \frac{1}{T_g}\right) \qquad (12)$$

Using experimental data the known left hand side of equations (11) or (12) can be plotted against, ($\frac{1}{T_g}$) and hence (E) and (k_o) determined.

In the report analysis of ignition data it is assumed that (CO_2) is the product of reaction, that carbon consumption prior to ignition is negligible, that heat transfer by radiation can be neglected, that in ignition condition the Arrehenius expression can be simplified by the Frank-Kamenestkii approximation and that ignition of coal particles takes place on a solid surface.

5.1. Ignition Temperature

The influence of the oxygen concentration, (C), on the ignition temperature, (T_g), is shown in Fig. (7). The increasing oxygen concentration raises the oxidation rate and lowers the ignition temperatures of the given material.

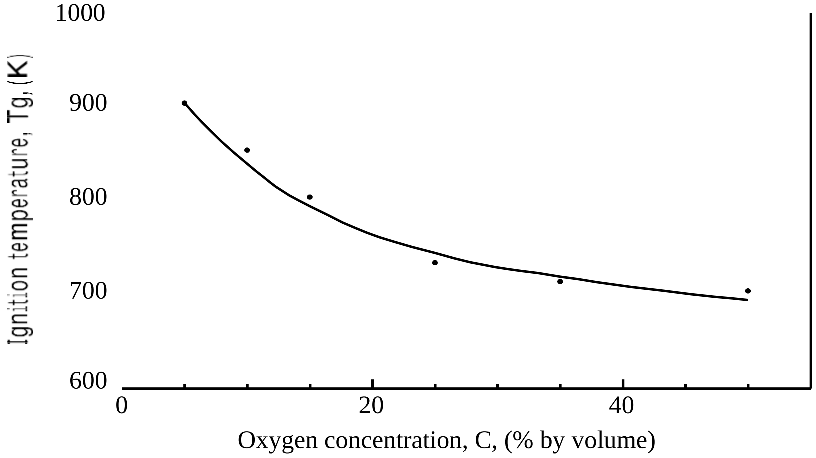

Fig. (7). Ignition temperature of Sinai coal as a function of oxygen concentration.

5.2. Observed (apparent) kinetic

The data in Fig. (7) have been used in equation (12) to give the results shown in Arrehenius form in Fig. (8), assuming n=1. The values of (E) for Sinai coal =87 kJ/mol is at the level found for the reaction of impure carbon with oxygen when pore diffusion and chemical reactions together control the burning rate.

At least squares regression analysis of the ignition data gave the rate of combustion ($\bar{m}$), (kilograms of carbon burnt per second per square meter of the external particle area) related to (T_s) and oxygen concentration (C) by:

$$\bar{m} = 1020.3\left(\frac{273C}{T_s}\right)^2 \mathrm{Exp}\left(-\frac{78}{R T_{g s}}\right) \qquad (13)$$

After conversation to a common oxygen concentration of 100 % volume the computed values of are shown in Arrehenius form in Fig. 9.

$$\mathrm{Ln}\left(\frac{(T_g)^{3.75}}{2.718C * \beta * Q * d * (273\rho_{O2}) * (298)^{0.75}}\right)$$

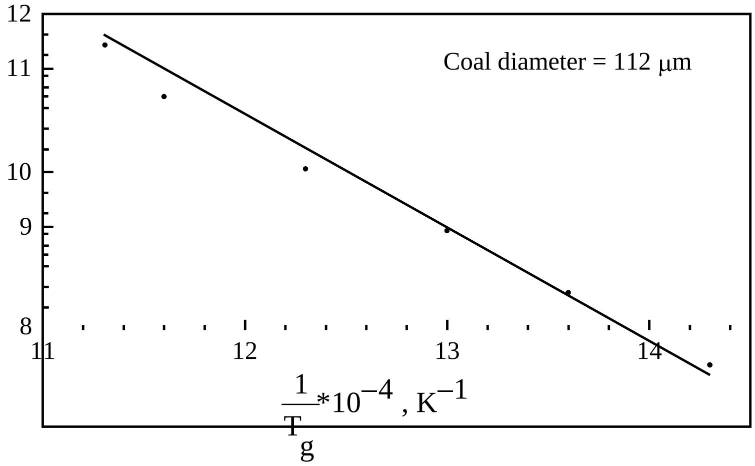

Fig. (8). Plots of observed kinetic versus ignition temperature

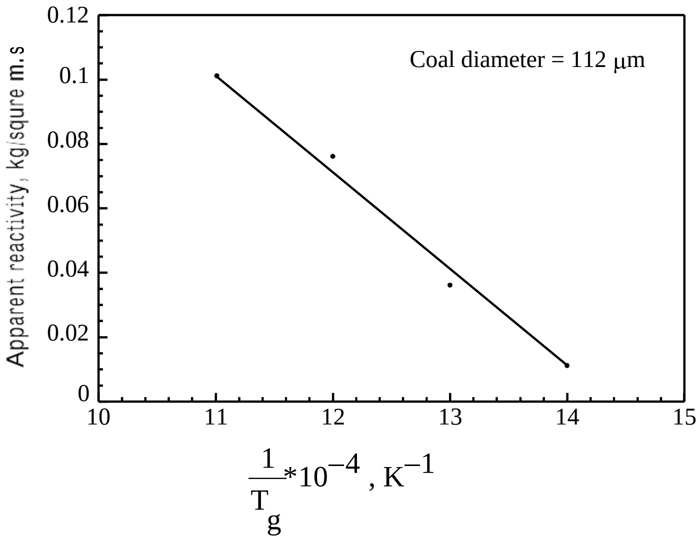

Fig. (9). Dependence of apparent reaction rate ($\bar{m}$) on temperature for Sinai coal.

5. 3. Chemical (intrinsic) reactivity

Figure (10) illustrates the Arrehenius plot for the ignition data calculated according to equation (12). The application of a least squares regression analysis to the ignition data corrected for pore diffusion yielded the following expression for the chemical rate, ($\bar{m}_t$), (kilograms of carbon burnt per second per square meter of the total surface area) related to (T_s) and oxygen concentration (C) by :

$$\bar{m}_t = 8125.2\left(\frac{273C_2}{T_s}\right)\mathrm{Exp}\left(-\frac{153.1}{R_g T_s}\right) \qquad (13)$$

The true activation energy =153.1 kJ is about twice the energy determined for the zone reaction by global model = 78 kJ/mol.

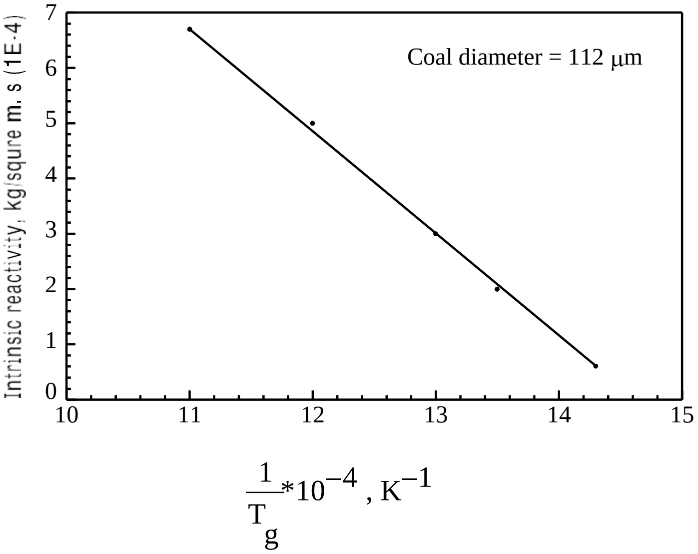

Fig. (10). Dependence of chemical reaction rate ($\bar{m}_t$) on temperature for Sinai coal.

6. Conclusions

The above reported work can be summarized in the following conclusions:

1. The degree of devolatilization of Sinai coal to temperature 1323 K is found virtually not to be affected by change in its particle diameter.
2. In the temperature range 923-1323 K reactivity of obtained chars decreased only 1.2 times in relation to the initial coal reactivity.
3. For particles diameter smaller than 500 μm, the pyrolysis temperature range

1223-1323 K, also proved very useful for char reactivity. Char reactivity in this temperature range does not differ much from the reactivity of raw coal and it is the highest compared with the chars obtained in other pyrolysis temperatures.

4. Chars leave the area of pyrolysis displaying the temperature 1123-1223 K which is much higher than the temperature of ignition.
5. The pre-exponential factor and activation energy in the Arrehenius relation for the rate of reaction of coal with oxygen have been determined using an ignition technique and taking advantage of pore structure properties. Indications are that the apparent activation energy = 78.0 kJ/mol and the true activation energy = 153.1 kJ/mol.

7. References

[1] EDinger, R. T., Friedman, L. D., and Rau, E., "Devolatilization of Coal in a Transport Reactor," *Fue1.45*, (1966), pp.245-252.

[2] Mustafa Versan .Kok., Esber Ozbasb, Ozgen Karacan. and Cahit Hicyilmaz., “Effect of particle size on coal pyrolysis”, *J. of analytical and Applied Pyrolysis*, Vol. 45, PP. 103-110, 1998.

[3] Xiaoxun Ma, Hiroshi N., Tadashi Y., Guangwen Xu and Michiaki H., “Kinetics of rapid coal devolatilization measured using a spot heater apparatus”, *Fuel processing technology*, Vol. 85, (2003), pp. 43-51.

[4] Peng Liang, Zhifeng Wang and Jicheng Bi, “Process characteristics investigation of simulated circulating fluidized bed combustion combined with coal pyrolysis”, *Fuel Processing Technology*, Vol. 88, Issue 1, (2007), pp. 23-28.

[5] Hu G.[1];Fan H.;Liu Y., “Experimental studies on pyrolysis of Datong coal with solid heat carrier in a fixed bed “, *Fuel Processing Technology*, Vol. 69, Issue 3, (2001),pp. 221-228.

[6] Badzioch S.and Hawksley P.G.W.,”Kinetics of thermal decomposition of pulverized coal particles”, *Ind. Eng. Chem., Process Des. Develop. 9*, (1970), pp. 521-530.

[7] Kobayashi H, Howard J.B., and Sarofim A.F., “Coal devolatilization at high temperature”, *Sixteenth Symposium (International), The Combustion Institute*, Pittsburgh, (1977), pp. 427-436.

[8] Ubbayakar S. K., Stickler D. B. , Von Rosenberg C.W. and Gannon R.E, ”Rapid devolatilization of pulverized coal in hot combustion gasses”, *Sixteenth Symposium (International), The Combustion Institute*, Pittsburgh, (1977), pp. 411-425.

[9] Solomon P.R., Hamblen D.G., Goetz G. J. and Nskala N.Y., ”Coal devolatilization”, *Prepr. Div. Fuel Chem, Am. Chem. Soc*., Vol. 26, No. 3, (1981), pp. 6-17.

[10] Mentser M., Donnell H. J., and Ergun S., ”*Devolatilization of coal by rapid heating*”, Advan. Chem. Series 131, 1974.

[11] Smoot L.D. and Pratt D.T., "*Pulverized coal combustion and gasification – theory and applications for continuous flow processes*", Plenum Press, New York, 1979

[12] Anthony D. B., Howard J. B. and Hottel H. C., "Rapid devolatilization of pulverized coal", *15-th Symposium (International) on Combustion*, 1975.

[13] Anthony D. B. and Howard J. B., "Coal devolatilization and hydro gasification", *AICHE J.* No. 22, (1976), pp. 625-633.

[14] Anthony D. B., "Rapid devolatilization and hydro gasification of bituminous coal", *Fuel No. 55,* (1976), pp.121-133.

[15] Nsakala N. Y., Essenhigh R. H. and Walker P. L., "Studies on coal reactivity: Kinetics of lignite pyrolysis in nitrogen at 808 ^{o}C", *Combustion Sci. Tech.*, No. 16, 1977, pp. 153-165.

[16] Nsakala N. Y., Essenhigh R. H. and Walker P. L., "Characteristics of chars produced by pyrolysis following rapid heating of pulverized coal", *Prep. Am. Chem,.* Vol. 22, (1977), pp. 102-120.

[17] Suuberg E. M., Peters W. A. and Howard J. B., "Product composition and kinetics of lignite pyrolysis", *Ind. Eng. Chem., Process Des. Develop. No. 17*, (1978), pp. 37-44.

[18] Suuberg E. M., Peters W. A. and Howard J. B., "Product composition and formation kinetics in rapid pyrolysis of pulverized coal - Implications of combustion", *17-th Symposium (International) on Combustion,* (1979).

[19] Wahhab M. A. and Morsy B. K., "Physical properties of Sinai coal and degree of devolatilization ", *Bulletin of the Faculty of Eng. and Tech.*, Minia university, Egypt, Vol. 9, part I, (1990), pp. 156-172,

[20] Morsy B.K., "Devolatilization of Sinai coal - derived chars ", *Bulletin of the Faculty of Eng. and Tech.*, Minia University, Egypt, vol. 9, part I, (1990), pp. 110 – 125.

[21] Morsy B.K., "*The small scale pyrolysis applied in a coal fired ignition burning",* Ph. D. Thesis, Technical University of Wroclaw, (1987), Poland.

[22] Morsy B. K., and Rybak W., "The combustion rates of Sinai coal", *Third Minia Conference on Energy and its applications*, (1989).

التحلل الحراري ومعدل احتراق الوقود الصلب (مقالة مرجعية)

بهجت خميس مرسى
قسم الهندسة الميكانيكية – كلية الهندسة – جامعة القصيم
bahgat52@yahoo.com

(قدم للنشر في ٠١٠٢/٢/٨٢؛ وقبل للنشر في ٠١٠٢/٦/٢)

ملخص البحث. ãe,2a ؤzדzن ŠÞ=ð,¦,õ í9> ,Qs ,و ím¸=g, i,eg,eã çi מ9zá מz,:ن 22i מ=z5ı מ2,מ,y ããe,¿ 9„QQ:و ¿IQמ ﺪ9e9מ قמ¿>מ ã¥א,د 2z> ãa,çמو ã„¥,¥eמ 5aא92מ ¿a م,”א 9záı› ,¦,mמ v,z„¥ ¿a ج,z=mSמ 9záı› ¿IQמ ﺪ9e,מ ¸ı> ¿s ã¥א,2מ ozœ. قמ¿>£מ ¿:א9í ¾ 93z=מو قמ¿>£מ قמ¿>£מ ➢,¿ 9„QQ: 2z> ã¦,و,g و õ2„áa ,g„›i 5g9=מ y ½מ ¿¦,=zמو ¿IQמ ﺪ9e9ı› جﺬ9Qzs ã„ıi,e ¿›ز,¿ ج,=íi 9œ ➢2çמ ن93¦ ,a2z> »›zsو ã2„Q=Sמ «,ã¸ðמ «מذ قמ¿>£מ ➢,¿و ã„ı́و¿ı2מ .,¦,mמ y,מ,2מ 5„ız=מ ¿a قמ¿>5›