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EVALUATION OF THE REACTIVITY OF LOW TEMPERATURE COKE

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SUBJECT:

AND CHAR, CONTAINING VOLATILE MATTER, TOWARDS CARBON

DIOXIDE. PART 1

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EVALUATION OF THE REACTIVITY OF LOW TEMPERATURE COKE AND CHAR, CONTAINING
VOLATILE MATTER, TOWARDS CARBON DIOXIDE. PART I

1. SUMMARY

In the last few years there has been a growing interest in the reactivity of low temperature coke and char towards carbon dioxide. The equation of Hedden ⁴⁾, derived for the calculation of the reactivity of metallurgical coke, containing negligible amounts of volatile matter, was modified so that it could be employed for low temperature coke and chars with high volatile matter contents.

In this present report newly-derived equations are presented for cases where the reductants contain volatile matter. For this, as well as other cases where the reductants contain little or no volatile matter, provision was made for dilution of carbon-dioxide with nitrogen.

2. INTRODUCTION

The property "reactivity" as a suitability measure of a metallurgical coke is primarily of interest in blast furnace practice and, possibly, in cupola operation. No clear definition of this desirable property has as yet been formulated. It has however, become general practice to measure "coke reactivity" in terms of the reaction rate between carbon and carbon dioxide at a suitable temperature. The standard methods usually specify a temperature of about 1000°C ^{*}, a temperature at which the equilibrium of the Boudouard reaction $C + CO_2 \rightleftharpoons 2 CO$ is shifted

* References 1 through 4 recommended 1050°C

significantly towards the formation of CO.

Also at this temperature the diffusion of carbon dioxide into the coke pores is not yet the rate controlling step. Under these conditions the conversion depends mainly on the total reaction surface, which is the sum of the external surface area and the surface area of the coke pores^{3,5,6)}. The reactivity of temperatures of up to about 1100°C may be termed "chemical reactivity". This reactivity is being considered in this paper.

Other users of solid reductants have recently also expressed their interest in the reactivity as a quality measure of their products, which generally include low temperature coke and char. In the latter cases the application of the standard reactivity method may be complicated as a result of the following:

- 2.1 Structural changes are expected to take place when, for instance, such a char is subjected to heating at 1000°C for any length of time. These changes may affect the reactivity. It is therefore recommended that when the reactivity determination is carried out the required measurements are recorded as soon as the desired reaction temperature is reached.
- 2.2 Also, chars generally contain a relatively high amount of volatile matter. Its evolution on heating to 1000°C is gradual and may persist for some time, even after reaching the desired temperature. To prevent erroneous results in this case, corrections will have to be made for i.a. the greater volume of gas leaving the reaction chamber.

At present, studies are being undertaken at the Fuel Research Institute of South Africa concerning the reactivity of chars. The main purpose of these studies is to determine the modifications required to adopt the original equation by Hedden⁴⁾ for the reactivity determination of chars.

For the work reported in this paper the assumption was made that the evolved volatile matter (regardless of its composition) will not react with either carbon, carbon dioxide or carbon monoxide and as a result, will act as a diluent which is added to the gas stream.

3. GENERAL REMARKS

The reactivity method as applied by the Fuel Research Institute, is virtually the same as that described by the International Organisation for Standards ¹⁾, the Economic Commission for Europe ²⁾ and the United Nations Publication ³⁾.

This method was originally developed by Hedden ⁴⁾ for the determination of the reactivity of metallurgical coke containing only a negligible amount of volatile matter. Hence, it seems reasonable to expect that the reliability of the method will progressively be reduced as the volatile matter content increases.

Nevertheless, the method was used by the Fuel Research Institute to determine the reactivity of chars having a volatile matter content of up to 11%. In this case the assumption was made that the volatile matter content decreased soon after the sample has reached the desired temperature, namely 1000°C. This again, is based on the fact that it takes seven minutes for the sample to reach the reaction temperature before measurements are made and it is assumed that the volatile matter content has in most cases decreased to such an extent that its effect on the ultimate results will be negligible.

The mathematical equation of Hedden ⁴⁾ can, however, be modified to allow for the reactivity determinations to be done on chars without having to assume that the volatile matter content is negligible after reaching 1000°C. Instead two assumptions are made, namely!

- 3.1 A mixture of carbon dioxide and an inert gas (nitrogen) is used.
- 3.2 The volatile matter is released from the char during the reactivity test. This mixes with the gas stream, increasing

Its flow rate through the bed of particles, resulting in a reduction of both the carbon dioxide concentration and the contact time.

In addition, it is also important to assume that during the test no additional reactions between the released volatile matter and CO_2 and/or CO take place which may result in a modification of the amount of CO_2 as introduced, or CO as generated by the Boudouard reaction.* Taking into account that the temperature during experiments is 1000°C , this assumption seems reasonable.

4. METHOD OF REACTIVITY DETERMINATION

This method is based on the conversion of CO_2 to CO according to the Boudouard reaction.

For a typical test, the material is pulverized (particle size range: $-0,853 \text{ mm} + 0,422 \text{ mm}$)** and placed in the reaction tube after which a current of CO_2 (or a mixture of CO_2 and a inert gas, e.g. nitrogen) is passed through the fuel bed at a rate of 100 mg CO_2 per minute.

A schematic representation of the reaction tube showing the supporting sintered silica plate bed is shown in figure I.

The conversion of CO_2 to CO at 1000°C *** is measured by analysing the CO_2 and CO content in the exit gas by means of infra-red gas analysis.

* A subsequent paper, dealing i.a. with the effect of adding CO_2 and CO to the gas stream through the thermal decomposition process at 1000°C , is in the process of being compiled.

** $-18 + 36$ mash B.S.S.

*** A reaction temperature of 1000°C instead of 1050°C as recommended by Hedden⁴⁾ was preferred because of the enhanced deterioration of the silica reaction tube at the latter temperature.

5. MATHEMATICAL ANALYSIS

5.1 ESTABLISHMENT AND FORMATION OF THE CONTINUITY EQUATION

For a complete list of mathematical symbols used, refer to Appendix 2.

The rate constant of the Boudouard reaction is evaluated by means of the measured conversion. Originally the reactivity constant was defined as the rate constant per unit mass of fuel. As the fuels tested contain considerable amounts of ash and volatile matter, it is expedient to express the reactivity constant per unit mass of fixed carbon as determined by proximate analysis.

It is assumed that the Boudouard reaction $\text{CO}_2 + \text{C} \rightleftharpoons 2 \text{CO}$ is of the first order^{4, 7)}. Its rate constant k_m ($\text{cm}^3/\text{g.s.}$) is defined by means of the equation of the molecular conversion of CO_2 and C with respect to the CO_2 -concentration c as follows*:

$$(1) \quad \frac{dn_{\text{CO}_2}}{dt} = \frac{dn_{\text{C}}}{dt} = k_m m c \quad (\text{mol/s})$$

where n_{CO_2} and n_{C} are the numbers of moles of CO_2 and fixed carbon, respectively t is the time in seconds and m the total mass in grams of the fixed carbon in the fuel bed. The flow of the gas mixture through the fuel bed takes place at steady state conditions. Consequently the continuity equation for the CO_2 flow can be expressed as

$$(2) \quad \text{div}(\vec{c}\vec{v}) = -k_m c \frac{dm}{d\ell}$$

where ℓ is the distance in the direction of the gas flow, or because c and v are only dependent on the x -co-ordinate

(See Figure 1)** the continuity equation can be expressed as

* See equation (1) of Hedden⁴⁾.

** c.f. equation (2) of Hedden⁴⁾

$$(2) \quad \frac{d}{dx} (c(x) v(x)) = - k_m c(x) \frac{dm}{dx}$$

where $c(x)$ is the molecular concentration of CO_2 (mol/cm^3) and $v(x)$ the total gas volume which is transported per second through the cross-section of the fuel bed (cm^3/s), both at the reaction temperature T and at the position x where x increases in the direction of the gas flow. The fuel bed extends from $x = 0$ to $x = L$, as indicated in Figure 1.

If the fuel bed has a constant cross-section and the same fixed carbon content from $x = 0$ to $x = L$, the differential quotient dm/dx is a constant viz.

$$(3) \quad \frac{dm}{dx} = \frac{m_0}{L}$$

where m_0 * is the total amount of fixed carbon (proximate analysis) in the fuel bed before the reactivity determination is started. For abbreviation

$$(4) \quad k = k_m \frac{m_0}{L}$$

is defined. Further it is of advantage to introduce the dimensionless mol fractions.

$$(5) \quad y(x) = y = \frac{c(x)}{c_0}$$

$$y(0) = y_0 = \frac{c(0)}{c_0}$$

$$y(L) = y_L = \frac{c(L)}{c_0}$$

instead of $c(x)$ where c_0 means the total mol number per cm^3 of the gas mixture of CO_2 and N_2 which enters at $x = 0$ the fuel bed.

* m_0 denotes the conditions at time $t=0$, i.e. at the start of the run. Similarly, $m(t)$ denotes the total amount of fixed carbon in the fuel bed after time t .

Considering equations (3), (4) and (5), the continuity equation (2) or (2') is transformed to

$$(6) \quad \frac{d}{dx} (y(x)v(x)) = -ky(x)$$

and taken as the basis for all following deductions.

5.2 TRANSFORMATION OF THE CONTINUITY EQUATION INCLUDING DILUTION WITH NITROGEN AND GENERATION OF INERT VOLATILE MATTER

The flow rate of nitrogen v_{N_2} with which the CO_2 is diluted before entering the fuel bed is independent of the position x because it does not undergo any reaction in the bed. The flow rates at the position x of the two gases which are evolved in the fuel bed itself, viz. CO (Boudouard reaction) and the volatile matter (thermal decomposition) are indicated by $v_{CO}(x)$ and $v_v(x)$. Thus the rate of the total gas flow is equal to the sum of the rates of the 4 gases:

$$(7) \quad v(x) = v_{CO_2}(x) + v_{N_2} + v_{CO}(x) + v_v(x)$$

Obviously it follows that

$$(8) \quad v_{CO_2}(x) = v(x) \frac{c(x)}{c_0} = v(x)y(x)$$

and

$$(9) \quad v_{N_2} = v(0) \left\{ \frac{c_0 - c(0)}{c_0} \right\} = v(0)(1 - y(0)) = \text{constant}$$

where $v(0)$ is the volumetric flow rate of the gas mixture which enters the fuel bed at its temperature of approximate $1000^\circ C$.

On the other hand the differential correlation

$$(10) \quad dv_{CO}(x) = -2dv_{CO_2}(x)$$

exists because of the Boudouard reaction for the volume rates $v_{CO}(x)$ and $v_{CO_2}(x)$ according to Avogadro. Equation (10) can be integrated to give:

$$(11) \quad v_{CO}(x) = 2 \left\{ y(0)v(0) - y(x)v(x) \right\},$$

by using equation (8) where the initial condition $v_{CO}(0) = 0$ is taken in consideration. Finally the reasonable assumption is made that the flow rate $v_v(x)$ of the volatile matter is proportional to the co-ordinate x , i.e.:

$$(12) \quad v_v(x) = Ax$$

where the constant A is expressed as:

$$(13) \quad A = \frac{v_v(L)}{L}$$

Due to the progressively increasing degasification and combustion of the fuel, the evolution rate $v_v(x)$ of the volatile matter and the reactivity constant k_m will vary. However, it can be assumed that their temporary variations are negligible during the period when the exit gas is analysed. Therefore, we may assume that the following stationary conditions exist:

$$(14) \quad \frac{\delta v_v(x)}{\delta t} = 0 \quad \text{and} \quad \frac{\delta k_m}{\delta t} = 0$$

From equations (7), (5), (8), (9) and (11) follows

$$(15) \quad v(x) = \frac{v(0)(1 + y(0)) + v_v(x)}{1 + y(x)} = \frac{B + Ax}{1 + y(x)}$$

where the constant B means

$$(16) \quad B = 2y(0)v(0) + v_{N_2} = v(0)(1 + y(0))$$

If no volatile matter is present, $v_v(x) = 0$

equation (15) simplifies to:

$$(17) \quad v(x) = \frac{v(0)(1 + y(0))}{1 + y(x)}$$

For comparing equation (17) with equation (3) of Hedden⁴⁾, the dimensionless expressions $y(x)$ and $y(0)$ are replaced by $c(x)$ and $c(0)$ by means of equation (5) yielding:

$$(18) \quad v(x) = \frac{v(0)(1 + c(0)/c_0)}{1 + c(x)/c_0}$$

Equation (18) is still not identical with equation (3) of Hedden. Only if $c(0)=c_0$, i.e. $v_M = 0$ (according to equation (9)), equation (18) will become identical to equation (3) of Hedden. Equation (18) thus applies to a more general case than that considered by Hedden, which is only valid when no dilution of CO_2 before entering the fuel bed takes place.

The fundamental differential equation is obtained by introducing $v(x)$, equation (15) into equation (6):

$$(19) \quad \frac{d}{dx} \left\{ \frac{y(x)(B + Ax)}{1 + y(x)} \right\} = -ky(x)$$

5.3 INTEGRATION OF THE FUNDAMENTAL DIFFERENTIAL EQUATION (19) FOR $y(x)$

The differentiation of equation (19) with respect to x and then solving for dy/dx yields:

$$(20) \quad \frac{dy}{dx} = - \frac{y(1 + y)(1 + hy)}{(1-h)(B/A + x)},$$

after introducing the dimensionless constant (See also equation (4) and (13))

$$(21) \quad h = \frac{k}{k + A} = \frac{k_m m_0}{k_m m_0 + v_v(L)}.$$

According to equation (21) the range of h is $0 \leq h \leq 1$. (The extreme value $h = 1$ will be discussed later on).

By separation of the variables x and y , equation (20) is transformed to

$$(22) \quad - \frac{1}{1-h} \frac{dx}{B/A + x} = \frac{dy}{y(1+y)(1+hy)},$$

and by integration at first $h < 1$ to

$$(23) \quad -\frac{1}{1-h} \ln(B/A + x) = \int \frac{dy}{y(1+y)(1+hy)}$$

By splitting the right-hand side of equation (23) into partial fractions,

$$(24) \quad \int \frac{dy}{y(1+y)(1+hy)} = \ln y - \frac{\ln(1+y)}{1-h} + \frac{h \ln(1+hy)}{1-h} + \frac{\ln D}{1-h}$$

is obtained where $(\ln D)/(1-h)$ is the integrating constant. After substituting the right hand side of equation (24) in equation (23), the integral of equation (20) can be written immediately:

$$(25) \quad D\left(\frac{B}{A} + x\right) = \frac{1+y}{y^{1-h}(1+hy)^h}$$

The integrating constant D of equation (25) can be eliminated by means of the initial conditions as given in equation (5):

$$(26) \quad y = y(0) = y_0 \text{ for } x = 0$$

which gives equation (27):

$$(27) \quad 1 + \frac{A}{B} x = \left(\frac{y_0}{y}\right)^{1-h} \left(\frac{1+hy_0}{1+hy}\right)^h \frac{1+y}{1+y_0}$$

which is the solution of the differential equation (19) and (20) respectively for $h < 1$.

To apply equation (27) to measurements, it might be noted that $\frac{B}{AL}$ can be obtained directly by means of measurements.

Equations (12), (13), (5) and (16) yield

$$(28) \quad \frac{B}{A} = L(1+y_0) \frac{v(0)}{v(L)}$$

In equation (27) $x = L$ and $y = y(L) = y_L$ are introduced respectively. y_L as well as y_0 are directly available from the experimental data.

After signifying the value which is directly measurable and independent of h with M , where

$$(29) \quad M = \frac{1 + y_o + \frac{v_v(L)}{v(0)}}{1 + y_L}$$

equation (27) can be transformed to:

$$(30) \quad M \left\{ \frac{1 + hy_L}{1 + hy_o} \right\}^h = \left\{ \frac{y_o}{y_L} \right\}^{1-h}$$

From equation (30) the value h , and therefore by means of equation (21), the reaction constant k_m can be evaluated.

Substituting formula equation (29) in equation (30) and y_o and y_L as defined in equation (5) gives:

$$(31) \quad \frac{1 + \frac{c(0)}{c_o} + \frac{v_v(L)}{v(0)}}{1 + \frac{c(L)}{c_o}} \left\{ \frac{c_o + hc(L)}{c_o + hc(0)} \right\}^h = \left\{ \frac{c(0)}{c(L)} \right\}^{1-h}$$

From equation (31) follows that all 3 gas concentrations should be known, viz. c_o , the total mol number per cm^3 of the gas mixture of CO_2 and N_2 at the entrance, dependent on pressure and temperature only, and both $c(0)$ and $c(L)$ which are the concentrations of the diluted CO_2 at the entrance and the exit of the fuel bed.

It is interesting to note that the height L of the fuel bed does not occur directly in any of the formulae (29), (30), (31) and (21). This is fortunate, because of the difficulty in accurately assessing the value of L during normal experiments.

5.4 THE SPECIAL CASE $h = 1$

In principle, the problem for $h = 1$ and thus $v_v(L) = 0$ can be solved by obtaining the mathematic limits of equation

(22) for $h \rightarrow 1$, which is presented in the appendix.
 It is, however, simpler to revert to the original differential equation (19) for the case $A = v_v(L)/L = 0$. After applying a similar technique used in the case $h < 1$, the solution

$$(32) \quad - \frac{k_m m_o}{(1 + y_o)v(0)} = \ln \left\{ \frac{y_L(1 + y_o)}{y_o(1 + y_L)} \right\} + \frac{y_o - y_L}{(1 + y_o)(1 + y_L)}$$

is obtained.

Equation (32), which permits the experimental determination of k_m for the case $v_v(L) = 0$, obviously corresponds to equation (30) for the case $h < 1$ and thus $v_v(L) > 0$.

Substituting y_o and y_L according to (5) in equation (32) leads to:

$$(33) \quad - \frac{k_m m_o}{v(0)} \frac{c_o}{c_o + c(0)} = \ln \left\{ \frac{c(L)(c_o + c(0))}{c(0)(c_o + c(L))} \right\} + \frac{c_o(c(0) - c(L))}{(c_o + c(0))(c_o + c(L))}$$

which again shows that all the three gas concentrations should be known, viz. c_o , $c(0)$ and $c(L)$.

The equations (32) and (33) are transformed to the equation of Hedden (34)

$$(34)^* \quad - \frac{k_m m_o}{v(0)} = 2 \ln \left\{ \frac{2c(L)/c(0)}{1 + c(L)/c(0)} \right\} + \frac{1 - c(L)/c(0)}{1 + c(L)/c(0)}$$

for $h = 1$ and thus $v_v(L) = 0$, but even then, only if $c(0) = c_o$ and therefore $y_o = 1$, i.e. the CO_2 introduced is undiluted.
 (Also compare equation 18 with equation (3) of K. Hedden).

* See equation (4) of Hedden ⁴⁾. The designations of this paper are used in Hedden's equation.

Equations (32) and (33) are thus of more general validity than Hedden's equation (34), as they permit the determination of k_m in cases where the CO_2 is diluted with an inert gas. Equations (30) and (31) have still wider applications, as they may be applied in the presence of diluted CO_2 and evolution of volatile matter.

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APPENDIX 1

SOLUTION OF THE PROBLEM FOR $h = 1$, $v_v(L) = 0$ BY OBTAINING THE MATHEMATIC LIMITS OF EQUATION (22) FOR $h \rightarrow 1$.

In equations (25) and (27) which were obtained from (22) by integration for $h < 1$, the limit for $h \rightarrow 1$ cannot readily be obtained.

Therefore, it is necessary to revert to the differential equation (22) which will be integrated for the extreme value $h = 1$ in another way.

The integration of the right hand side of equation (22) can be done readily for the case $h = 1$ by means of partial fractions. One thus obtains

$$(35) \int \frac{dy}{y(1+y)^2} = \ell n \frac{y}{1+y} + \frac{1}{1+y} + E$$

with E as the integration constant. Integrating the left side of (22) for $h < 1$ and thereafter obtaining the limit $h \rightarrow 1$ with due consideration of the initial conditions $y = y_0$ for $x = 0$ (See equation (26)), yields

$$(36) \lim_{h \rightarrow 1} \left\{ - \ell n \left(\frac{B}{A} + x \right)^{\frac{1}{1-h}} \right\} \rightarrow \ell n \left(\frac{y}{1+y} \right) + \frac{1}{1+y} + E$$

and for $x = 0$

$$(37) \lim_{h \rightarrow 1} \left\{ - \ell n \left(\frac{B}{A} \right)^{\frac{1}{1-h}} \right\} \rightarrow \ell n \left(\frac{y_0}{1+y_0} \right) + \frac{1}{1+y_0} + E$$

Subtracting equation (37) from equation (36) gives

$$(38) \lim_{h \rightarrow 1} \left\{ - \ell n \left(\frac{B/A + x}{B/A} \right)^{\frac{1}{1-h}} \right\} \rightarrow \ell n \left(\frac{y(1+y_0)}{y_0(1+y)} \right) + \frac{1}{1+y} - \frac{1}{1+y_0}$$

Obviously it is permissible to exchange the operation's limits $h \rightarrow 1$ and \ln (obtaining the Napierian logarithms).
For this reason

$$(39) \lim_{h \rightarrow 1} \left\{ 1 + \frac{Ax}{B} \right\}^{\frac{1}{1-h}}$$

may be treated as follows:

It must, however, be kept in mind that for $h \rightarrow 1$, $v_v(L) \rightarrow 0$ in equation (28)
 $B/A \rightarrow \infty$.

Defining $\frac{1}{1-h} = n$ and $v_v(L) = \epsilon$

then from equation (21):

$$(40) \frac{1}{n} = 1 - h = \frac{\epsilon}{k_m m_o + \epsilon}$$

and from equation (28):

$$(41) \frac{B}{A} = L(1 + y_o)v(0) \frac{n}{k_m m_o + \epsilon}$$

For $x = L$, equation (34) is converted to

$$(42) \lim_{n \rightarrow \infty} \left\{ 1 + \frac{AL}{B} \right\}^n = \lim_{n \rightarrow \infty} \left\{ 1 + \frac{k_m m_o + \epsilon}{(1 + y_o)v(0)} \cdot \frac{1}{n} \right\}^n$$

By using the formula

$$\lim_{n \rightarrow \infty} \left\{ 1 + \frac{Z}{n} \right\}^n = e^Z$$

equation (42) is transformed to

$$(43) \lim_{\substack{n \rightarrow \infty \\ (\epsilon \rightarrow 0)}} \left\{ 1 + \frac{AL}{B} \right\}^n = \exp \left\{ \frac{k_m m_o}{(1 + y_o)v(0)} \right\}$$

By applying equation (43) to equation (38) with $x = L$ and obtaining $h = 1$ for the left side, equation (44) is finally obtained:

$$(44) \quad \frac{k_m m_o}{(1 + y_o)^v(0)} = - \ln \left\{ \frac{y_L(1 + y_o)}{y_o(1 + y_L)} \right\} - \frac{y_o - y_L}{(1 + y_o)(1 + y_L)}$$

Equation (44) is identical to equation (32) which was obtained earlier in this text.

APPENDIX 2

LIST OF SYMBOLS

- A = $V_v(L) / L$ = constant of thermal decomposition
- B = $2y(0)v(0) + v_{N_2} = v(0)(1 + y(0))$
- c = molecular concentration of CO_2 (mol/cm^3)
- c(0) = molecular concentration of CO_2 (mol/cm^3) at the entrance ($x = 0$) into the fuel bed.
- c(x) = molecular concentration of CO_2 (mol/cm^3)
- c_o = total mol number per cm^3 of the gas mixture of CO_2 and N_2 which enters at $x = 0$ the fuel bed.
- D = integrating constant
- E = integrating constant
- ϵ = limit of $V_v(L)$
- h = $\frac{k}{k + A}$
- k_m ($cm^3/g.s$) rate constant of Boudouard reaction $CO_2 + C \rightleftharpoons 2CO$ assuming a first order reaction and neglecting the back (inverse) reaction.
- k = $\frac{k_m}{L}$
- L = height of the fuel bed in direction of the gas flow.
- ℓ = distance in direction of the gas flow.

$$M = \frac{1 + y_o + \frac{v(L)}{v(0)}}{1 + y_L}$$

m = total mass (g) of the fixed carbon of the fuel

m_o = total amount of fixed carbon (proximate analysis) in the fuel bed before the reactivity determination is started ($t = 0$)

$$n = \frac{1}{1 - h}$$

n_C = number of moles of C

n_{CO_2} = number of moles of CO_2

t = reaction time (s)

$v(0)$ = volumetric flow rate of the gas mixture which enters the fuel bed at its temperature of $T = (1000^\circ C)$

$v(x)$ = total gas volume, transported at reaction temperature T per second (cm^3/s) through the cross-section of the fuel bed.

$v_{CO}(x)$
 $v_{CO_2}(x)$
 v_{N_2}
 $v_v(x)$

} flow rates at the position x of CO , CO_2 , N_2 and the volatile matters (thermal decomposition)

x = co-ordinate of the fuel bed in direction of the gas flow

$y(0) = y_o = c(0)/c_o$
 $y(L) = y_L = c(L)/c_o$
 $y(x) = y = c(x)/c_o$

} dimensionless mol fractions of CO_2

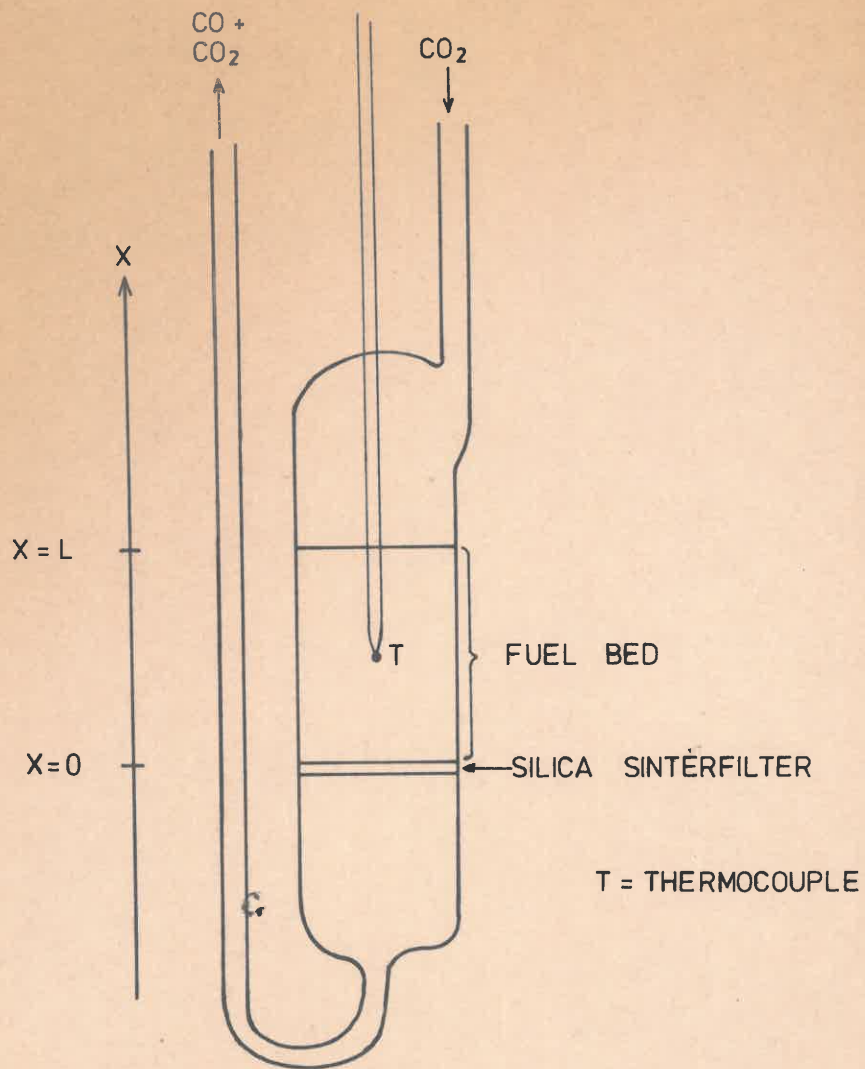


FIG. 1
SCHEMATIC REPRESENTATION OF THE REACTION TUBE
WITH SUPPORTING SINTERED SILICA PLATE.