Combustion science in aid of conversion of lignaceous solid bio-fuels to gaseous fuels

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- **Background**
  Importance for developed countries and developing countries
  What fuels, why?

- **Single particle combustion and inferences for gasification**

- **Flame propagation in particle beds**

- **Producer gas – Combustion features for engine applications**

- **Power Gasifiers and Gasifier Stoves**

Part of the inspiration for this talk –

Proceedings of the Combustion Institute, volume 28, 2000/pp 1-10.

HOTTEL LECTURE

SUPERSONIC FLIGHT AND COOKING OVER WOOD-BURNING STOVES: CHALLENGES TO THE COMBUSTION COMMUNITY

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Background

Importance for developing and developed countries

Renewable fuels need to be used sooner or later – *sooner* for the developing countries (including parts of South America) and
later for Europe and
even later for the North Americas.

Why? - Oil importing countries have large impetus to gain from the economy of biofuels

Rich countries can afford to work with expensive renewable & “fashionable” technologies (like SPV) and ignore cheaper options for a long time.

International compulsions of GHG reduction will be imposed on populated developing countries

Thus it is better for us in India to do research to help ourselves rather than wait till other countries do research and transfer technologies at high cost.

At IISc, a 300 man-year effort has gone into solid biofuel-to-gas field in a unique laboratory, on *fundamental research*, technology development, field testing and improvements in design over the last 20 years.

What fuels and why?

Agro-fuels

Rice husk and Rice straw – for India, China, S-E Asia
Other straws, Sugarcane trash (& Bagasse), Peanut shells,

--------------- These are light (~100 kg/m^3), fine sized (a few mm), high ash (5 to 20 %), highly alkaline ash – Potassium from the fertilizer application, Moisture problem not serious (because of thin walls)

--------------- Coconut shells, Cotton stalk, mustard stalk, weeds like Ipomia, Parthenium (properties like woody fuels)

Aim

Convert these into gaseous fuels through thermo-chemical conversion process – gasification process – and enable them to be used for electricity generation through reciprocating engines/gas turbines or heat applications – cooking, industrial drying or melting all with highest possible efficiency and little emissions, keeping cost as low as is possible.

Just what is this technology?

Get all biomass into solid form -

Biomass

Coconut Shells

Coffee Husk

Dry Grass

Marigold Pellets

Paper Trash

Pine Needles

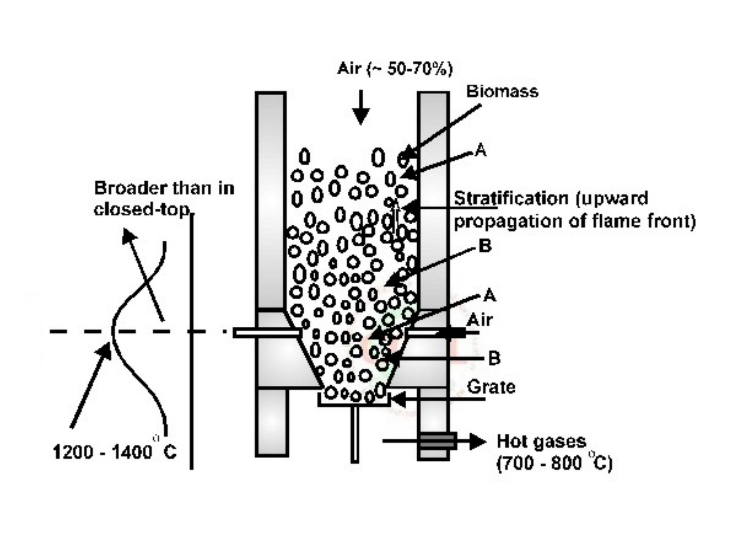
Rice Husk

Saw Dust

Sugar Cane Thrash

Wood

Use them in a vertical cylindrical reactor Introduce air at appropriate places to create the correct thermal profile for the conversion of lingo-cellulosic material to char and reactive gases that react further with red hot char to result in “producer gas” which when cleaned and cooled is equivalent of any combustible gas like natural gas.



Biomass + Air $\xrightarrow[\textit{Heat}]{}$ **Products (Partial) + Char,** N_2 **+ Heat**

(Upward propagation of flame front) $\longrightarrow$ **A**

Char + Air $\xrightarrow{\textit{Heat}}$ CO_2, H_2O **+ Char,** N_2 **– Heat**

Char + CO_2, H_2O, N_2 $\rightarrow$ **CO,** H_2, CH_4, N_2 $\longrightarrow$ **B**

Schematic of Wood Gasifier for Power Generation application

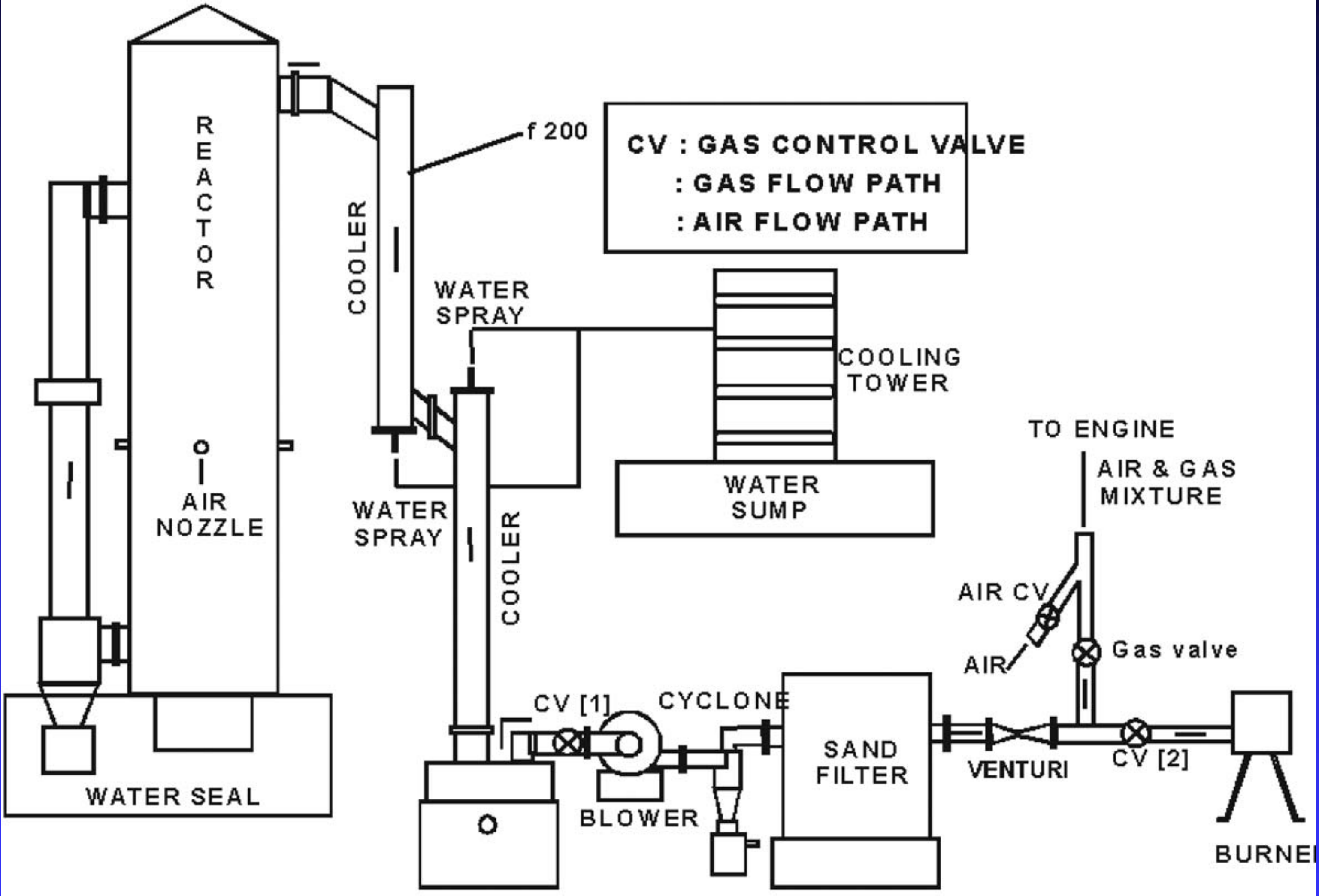


Fig. 2 SCHEMATIC OF WOOD GASIFIER FOR POWER GENERATION APPLICATION

Summary of the results on the tests of the gasifier

IISc Gasifier System at Chatel-St-Denis Switzerland.

IISc Gasifier based power generation system deployed in Chile

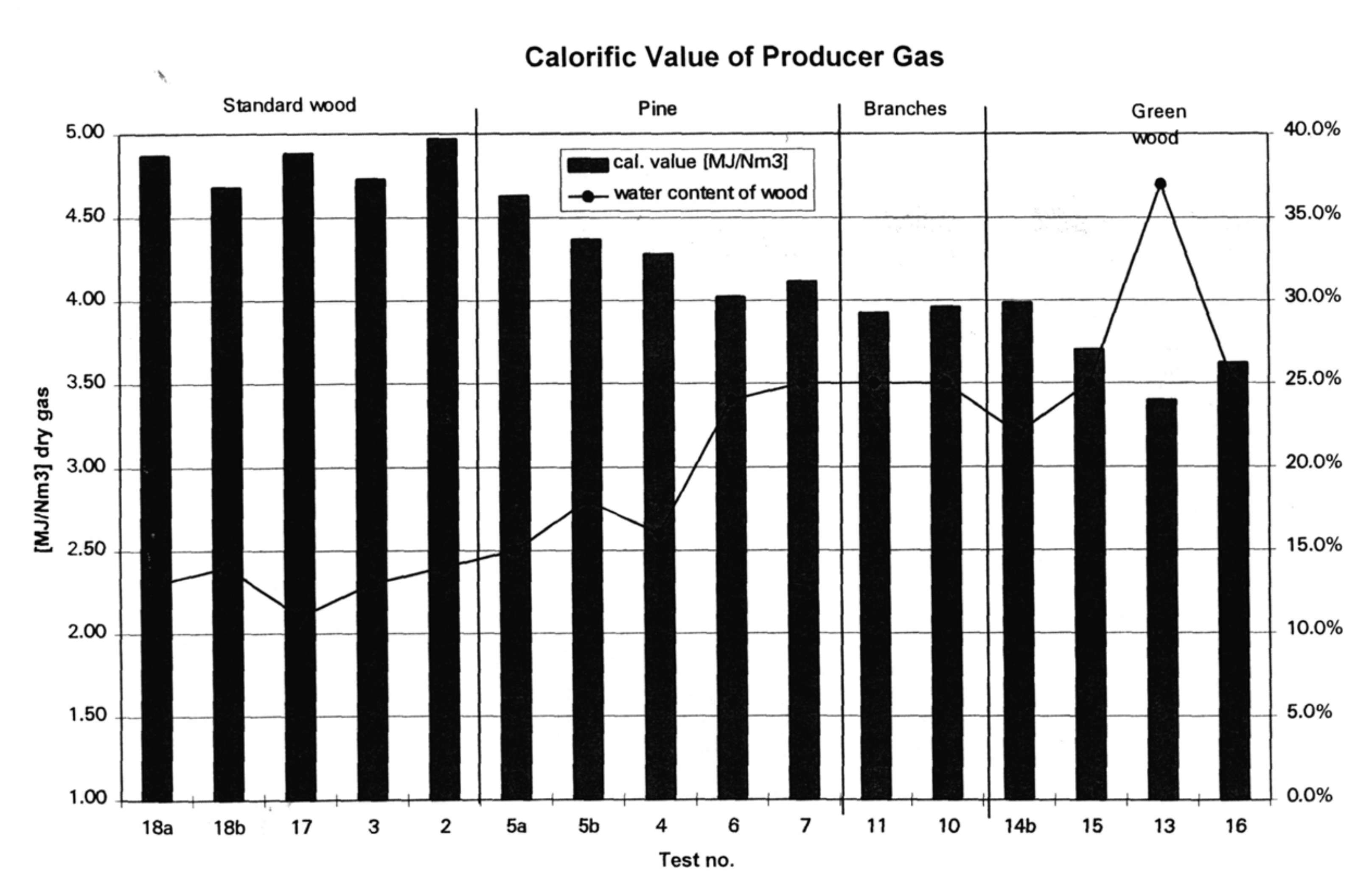
Quality of the gas demanded of the gasifier

For woody biomass:
Cold gasification efficiency ~ 80 % +
Composition (%) – CO~20, H_2 ~ 18, CH_4 ~1.5, CO2 ~ 12, rest N_2 (Calorific value – 4.5 to 5 MJ/n.m^3)

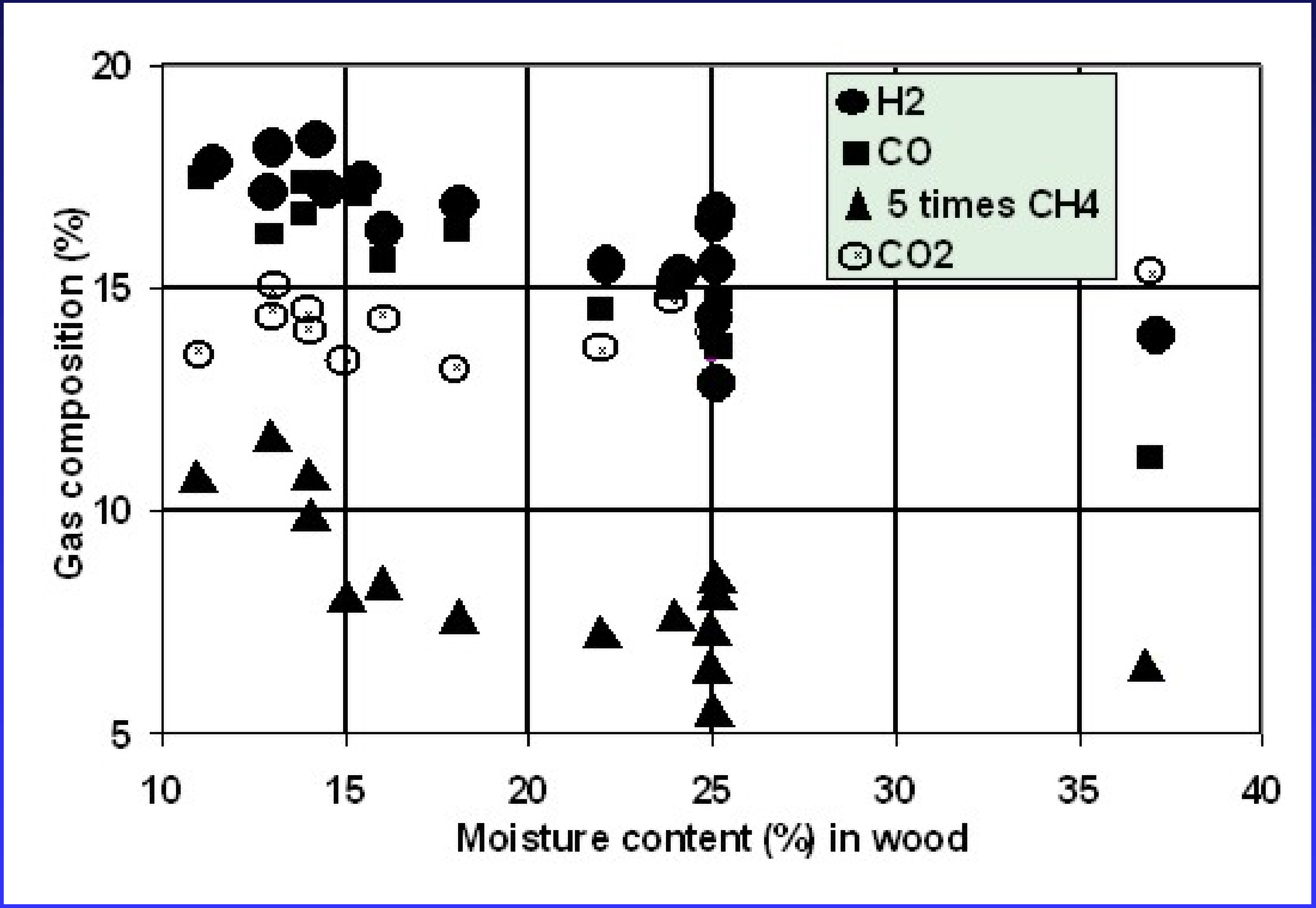
Particulates and Tar ~ as low as possible – 50 mg/m^3 or less,
Liquid effluents must be treatable with moderate cost.

Enable use of the same gasifier for all solid biomass since agro-residues are seasonal

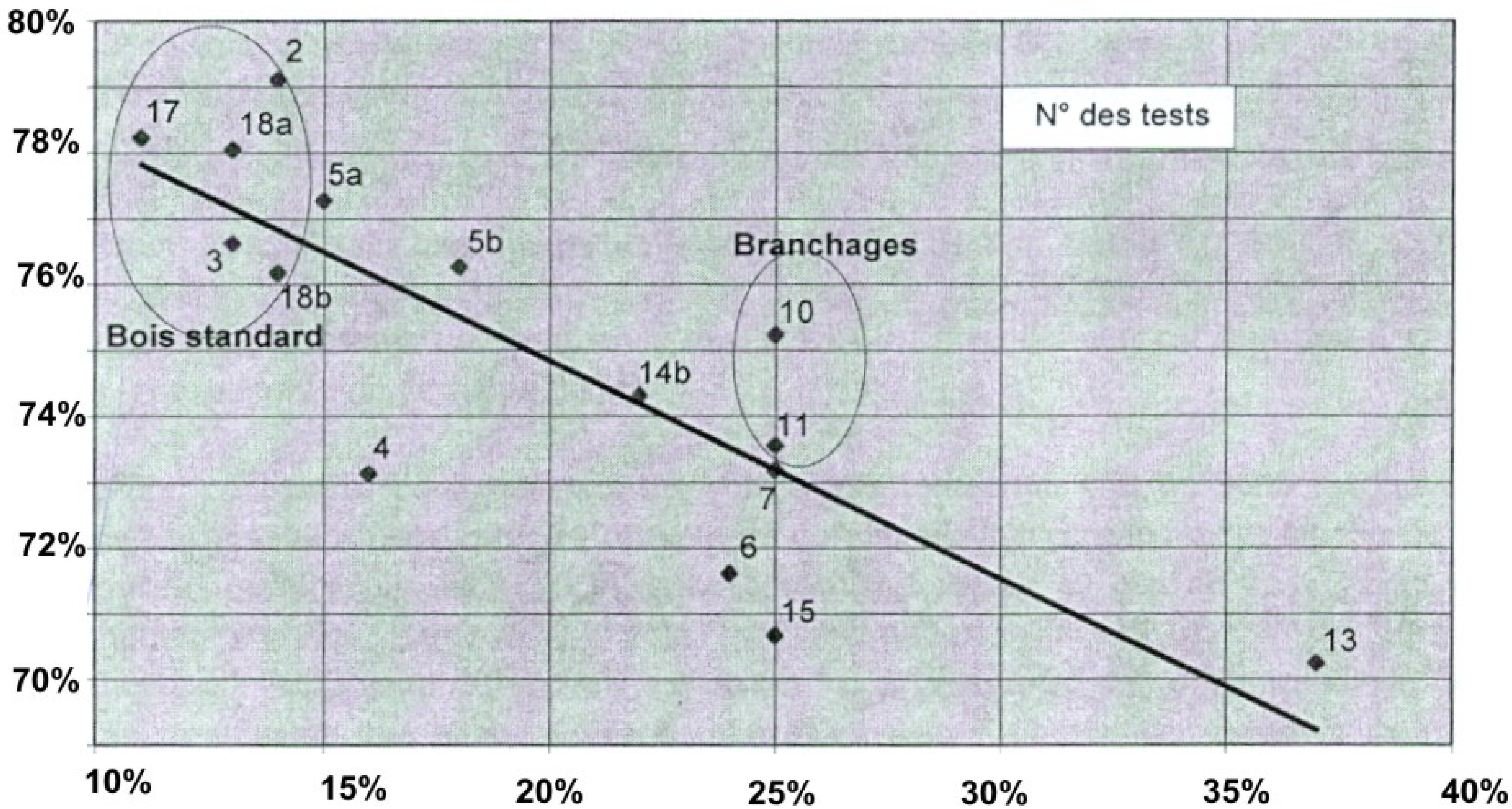
Calorific Value (gas) vs Wood Species



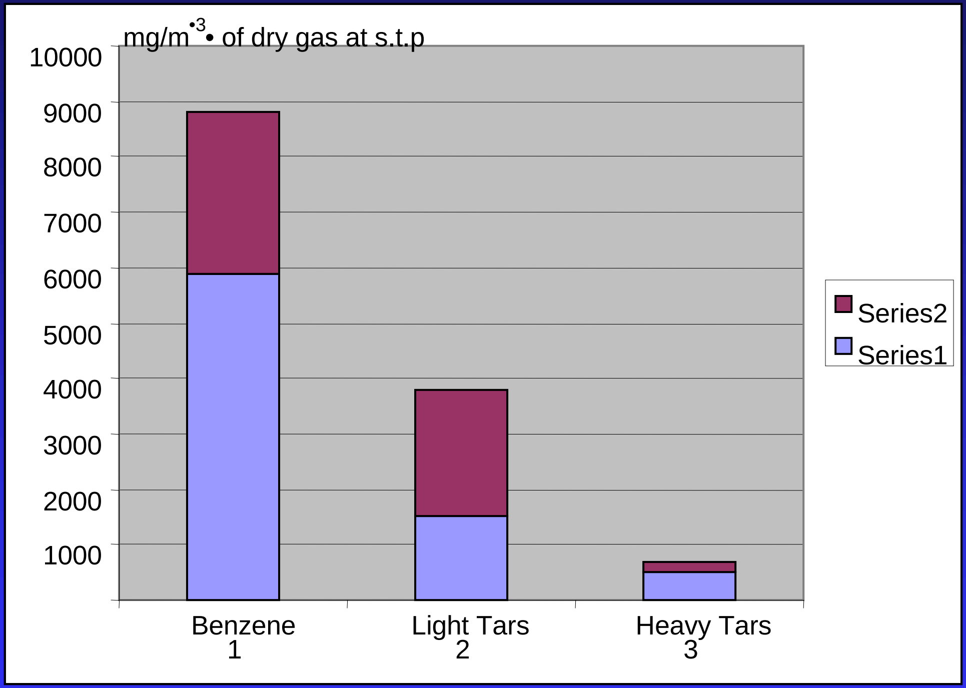
Composition vs Moisture in wood

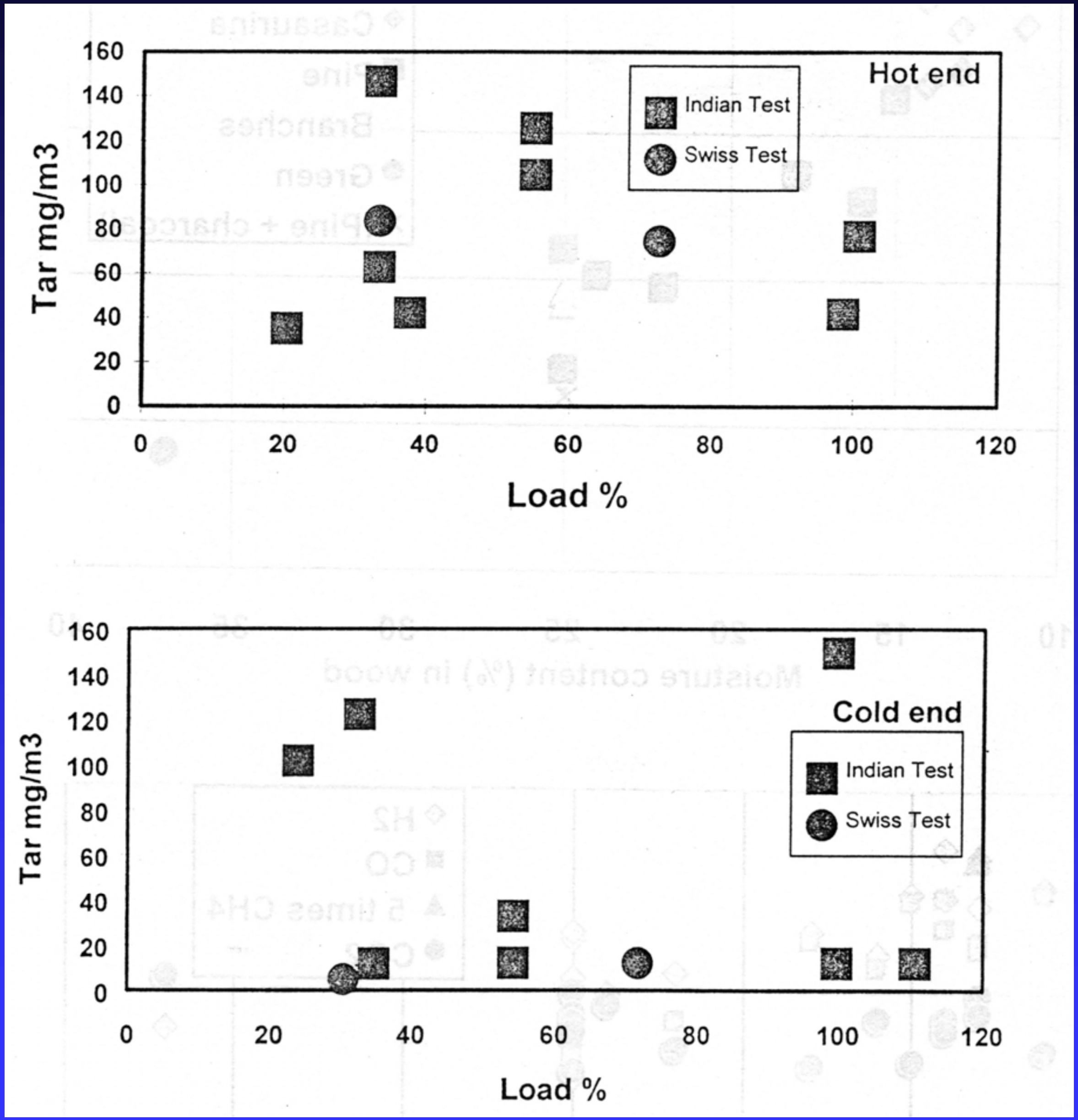


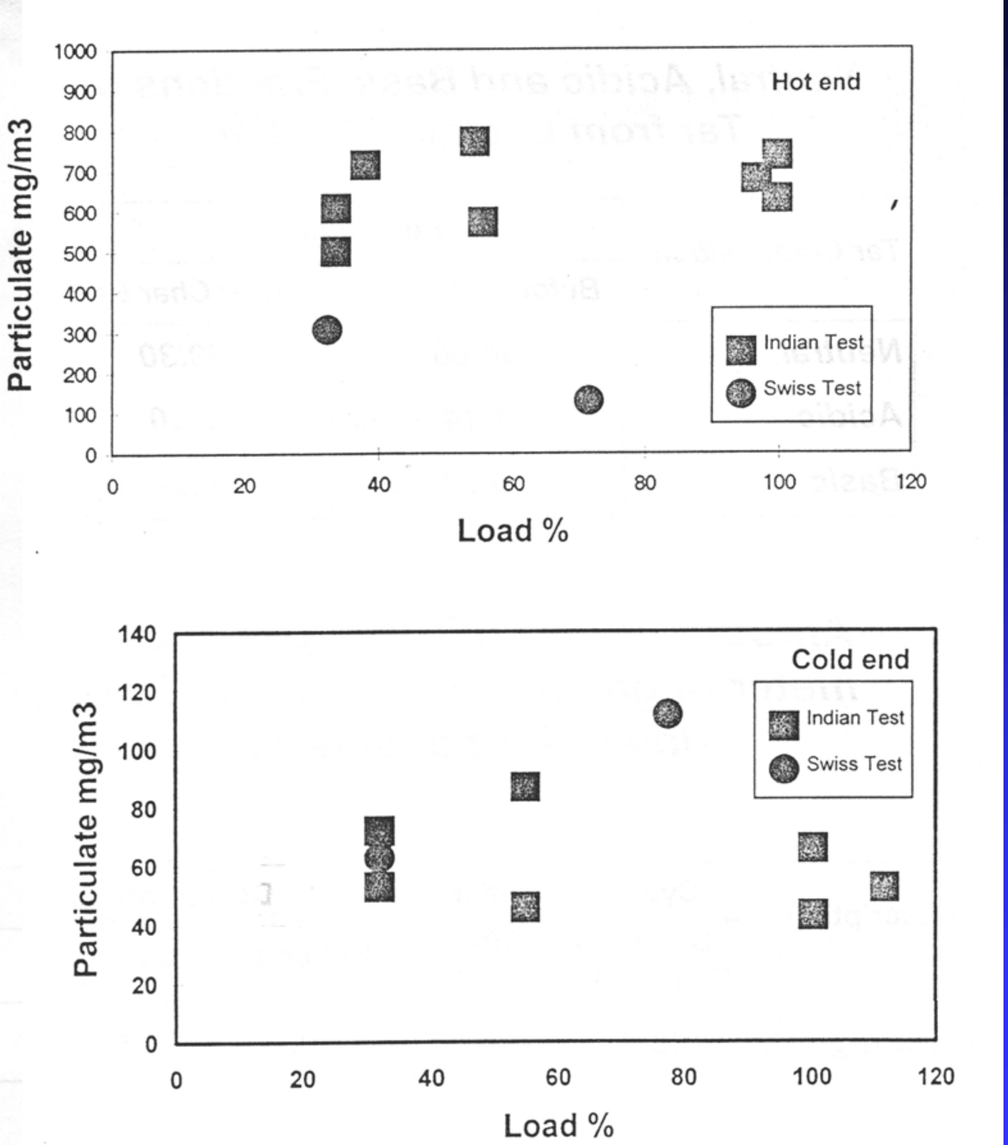
Gasification Efficiency vs Moisture in Wood



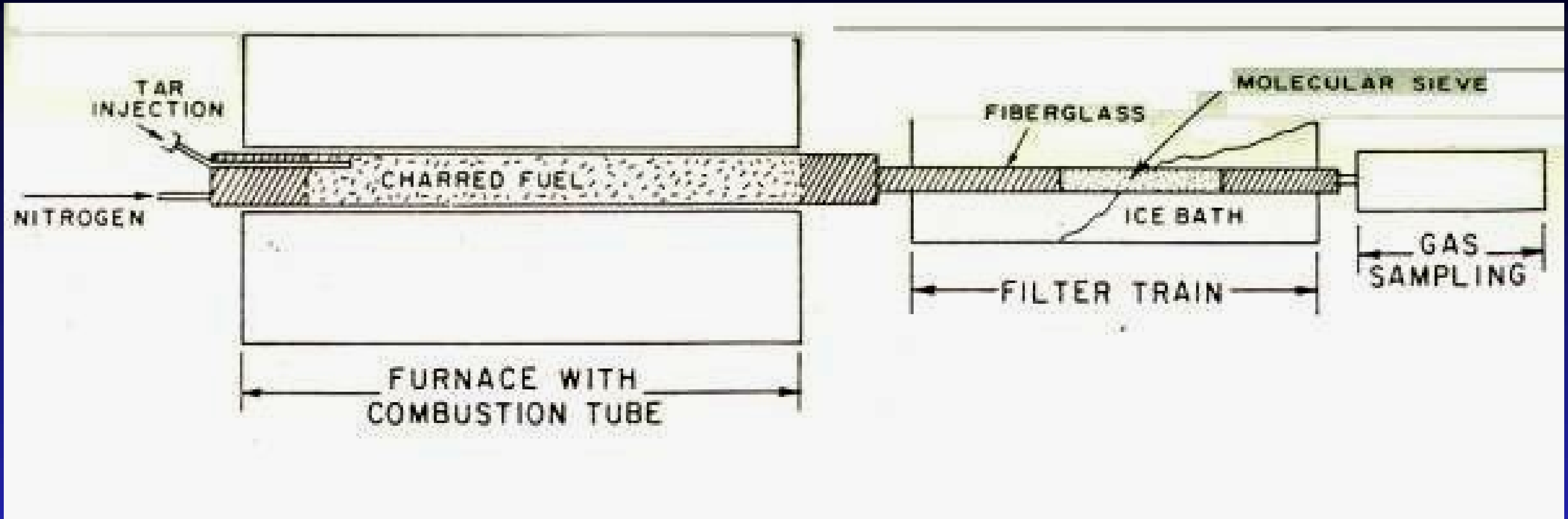
Tar Composition for the High Pressure Gasifier (CFBG) of Vernamo, Sweden

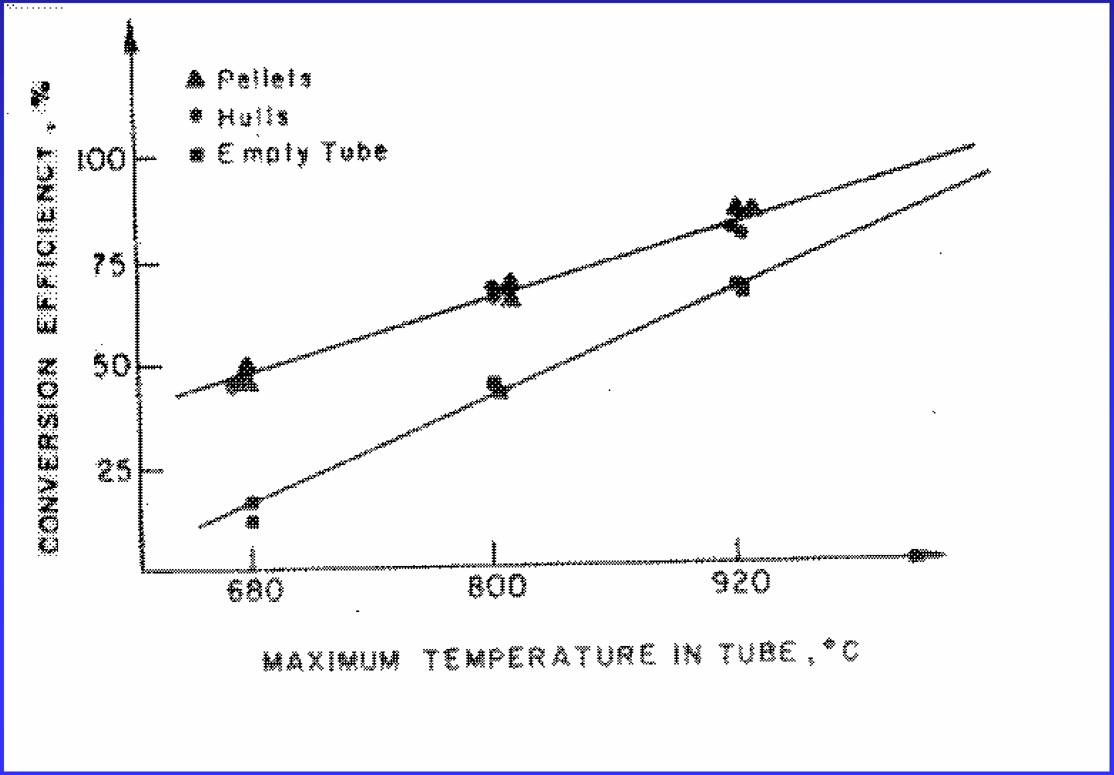



Hot end
Indian Test
Swiss Test
Tar mg/m3
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Load %
Cold end
Indian Test
Swiss Test
Tar mg/m3
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Load %

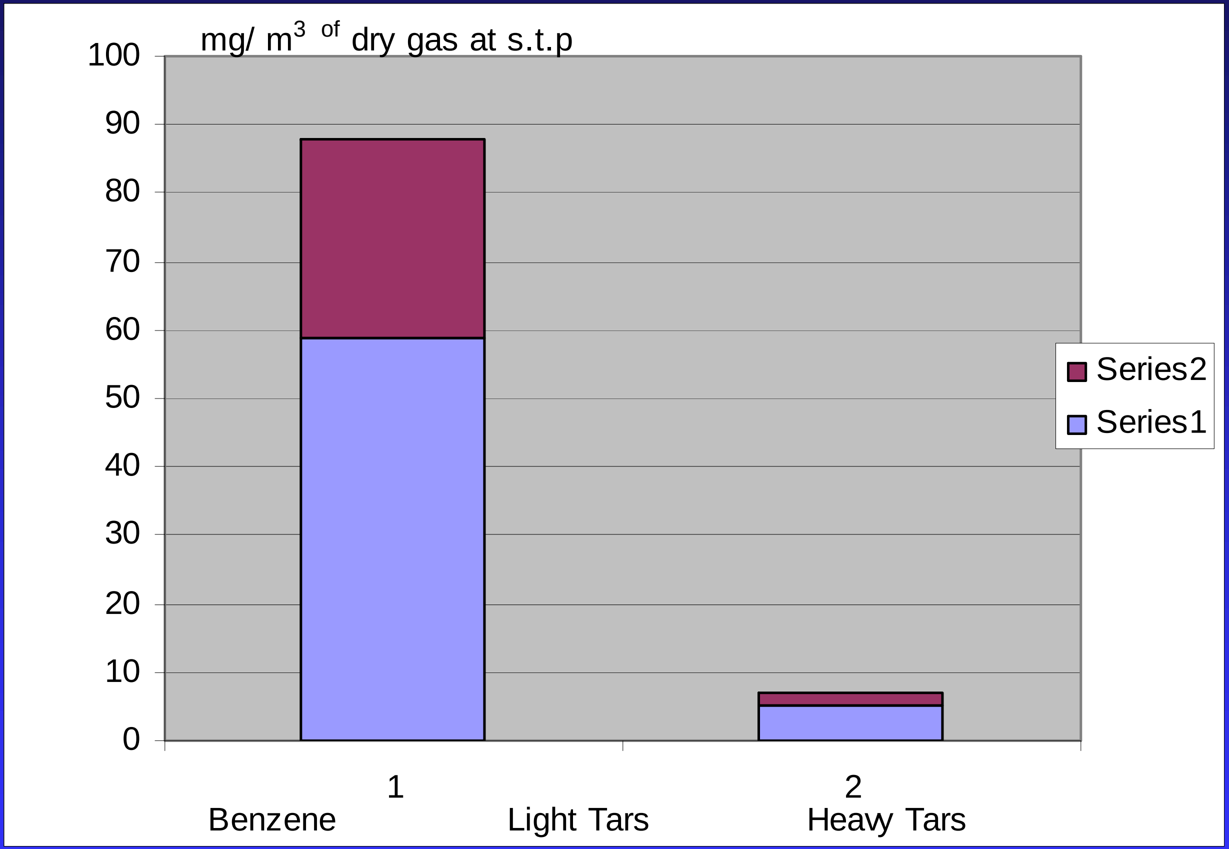


Particulate content in the gas at hot and cold ends as a function of load


TAR INJECTION
NITROGEN
CHARRED FUEL
FURNACE WITH COMBUSTION TUBE
FIBERGLASS
MOLECULAR SIEVE
ICE BATH
FILTER TRAIN
GAS SAMPLING


Pellets
Hulls
Empty Tube
CONVERSION EFFICIENCY, %
100
75
50
25
680
800
920
MAXIMUM TEMPERATURE IN TUBE, °C

Tar Composition for the ambient pressure Gasifier of IISc design



Nox Emissions from Gasifier Based Furnace and US Emission Standard

Size	NO, g/MJ	**Particulates**
Large > 250 X 10^6 kJ/h	0.09	0.014
Small < 250 X 10^6 kJ/h	-	0.068
Furnace in lab	0.07	-

SSingle particle combustion and inferences for gasification

The fuel used is usually cylindrical of dimensions between 5 to 50 mm, dia and length comparable.

A series of studies were initiated (1984 to 1998) on

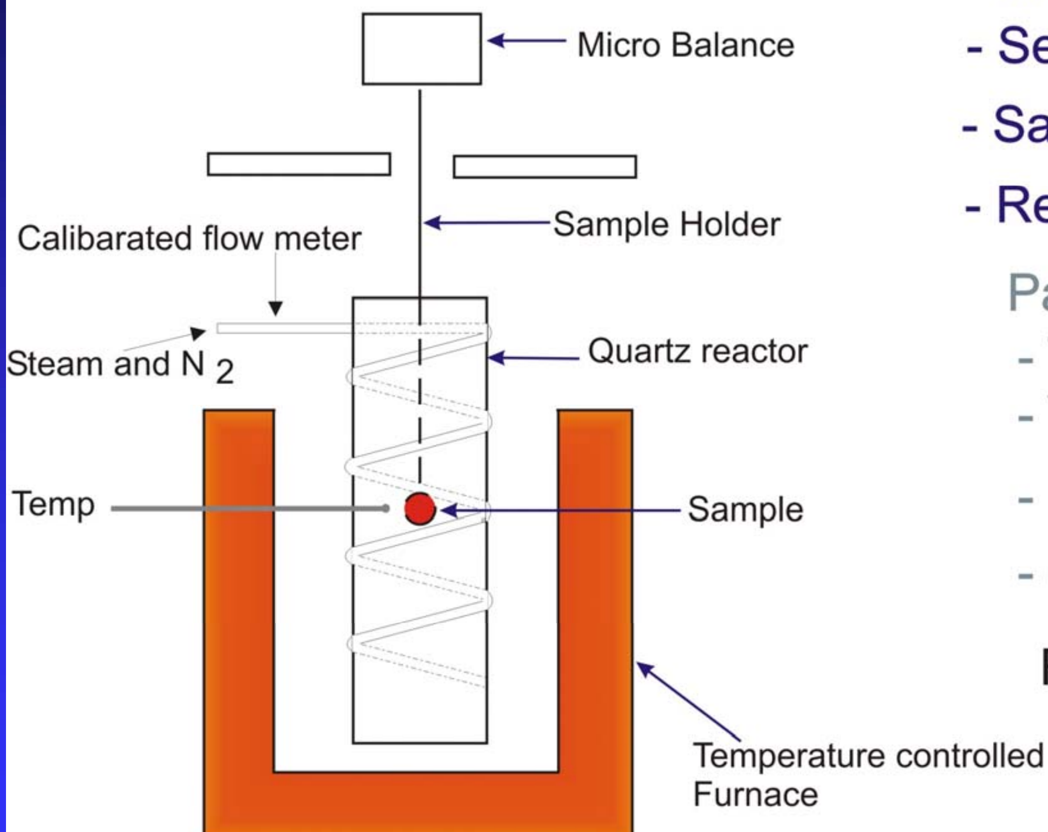
Biomass sphere flaming combustion

b. Biomass char glowing combustion in O_2 – N_2 environment

c. Char sphere conversion with mixtures of CO_2, H_2O, O_2 and N_2. Aim: Spherical geometry is clean; mathematics will be simpler.

Measuring Conversion time / wt loss time, etc..

Experimental setup

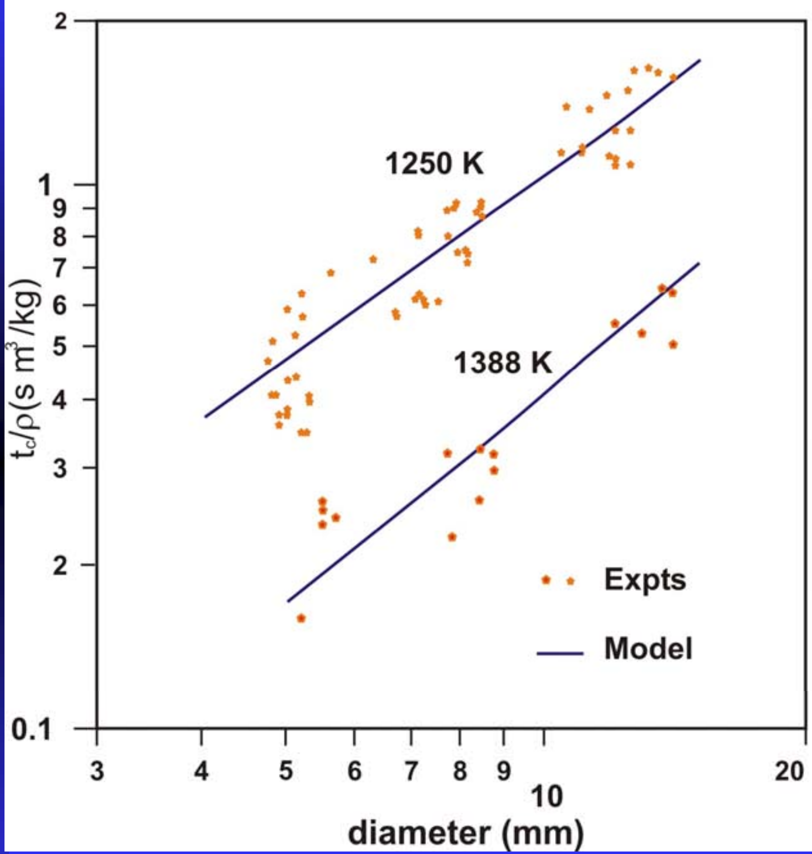


Procedure :
- Set the temp & Y_{H_2O} in the ambient
- Set flow rate
- Sample is ignited & inserted
- Record the weight with time

Parameters :
- Temperature
- Y_{H_2O}
- Flow rate
- diameter

Result weight loss vs time

Conversion time vs Diameter



Reactant - Steam

$t_c \sim d_0^{1.2}$ at 1280 K

$t_c \sim d_0^{1.33}$ at 1388 K

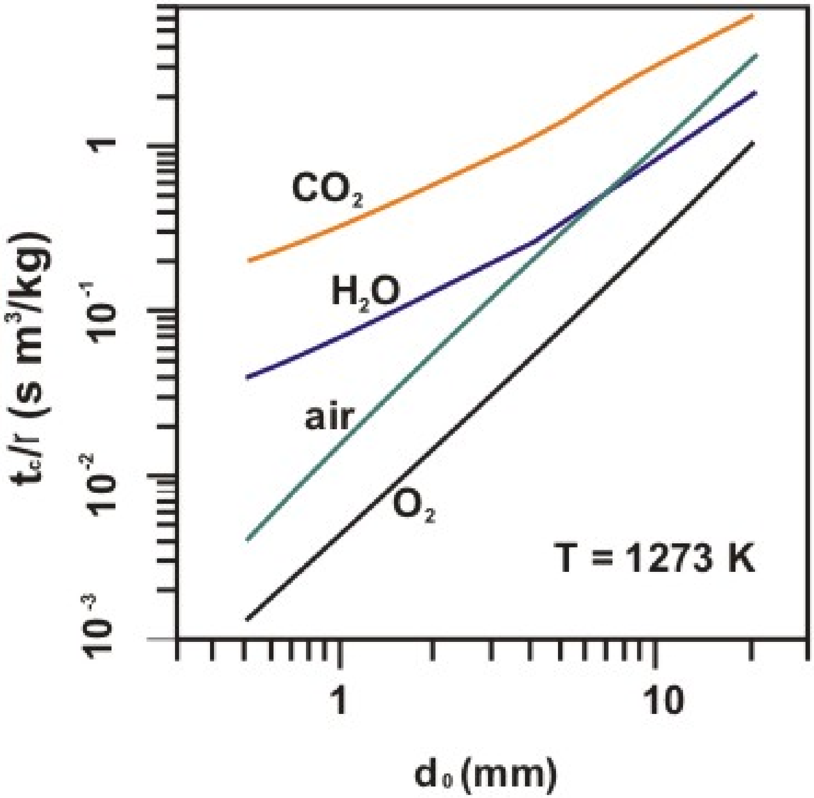
$t_c/\rho = d^{T/1080} \exp[-3.26 + 15470 (1/T - 1/1270)]$

Behaviour differs from that of C - O_2 and C - CO_2 reaction

- departs from d^2 law.
- Increase in exponent at high temperature is an indication of higher reactivity and shift towards diffusion controlled.

Comparison of Conversion time with diameter

Reactants : (a) CO_2 (b) H_2O (c) air (d) O_2



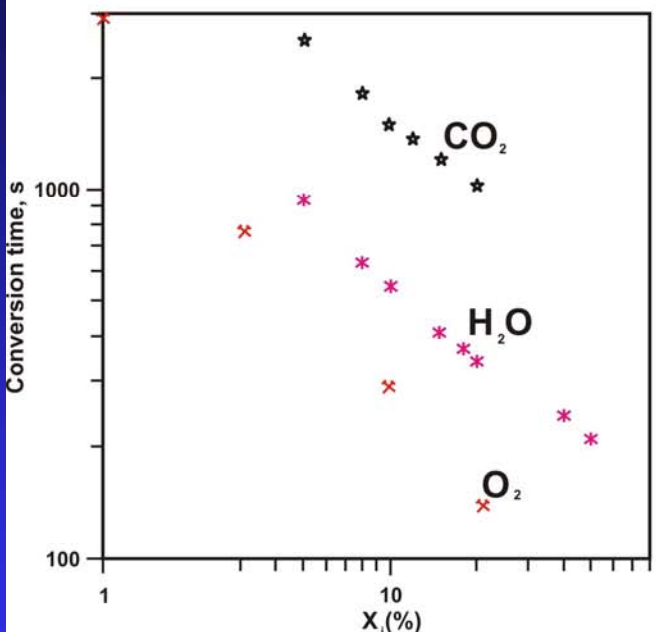
$t_b \sim d_0^{1.03}$	CO_2	Kinetic and diffusion dependence
$t_b \sim d_0^{1.2\text{-}1.3}$	H_2O	Kinetic and diffusion dependence
$t_b \sim d_0^{1.9}$	air	diffusion limited
$t_b \sim d_0^{2}$	O_2	diffusion limited

Conversion time for char reaction with

1. **CO_2 is 3-4 times that of H_2O**

2. **H_2O is comparable to air at d_p > 8 mm**

Char conversion time vs ambient reactant mole fraction



Reactants :

O_2, CO_2 and H_2O with N_2 as the dilutant

$$\left(\frac{t_c}{\rho}\right)_{CO_2} = a_0^{1.05} \exp\left[-1.715 + 35300\left(\frac{1}{T} - \frac{1}{1273}\right)\right] X_{CO_2}^{-0.65}$$

$$\left(\frac{t_c}{\rho}\right)_{H_2O} = a_0^{T/1050} \exp\left[-3.26 + 15470\left(\frac{1}{T} - \frac{1}{1273}\right)\right] X_{H_2O}^{-0.70}$$

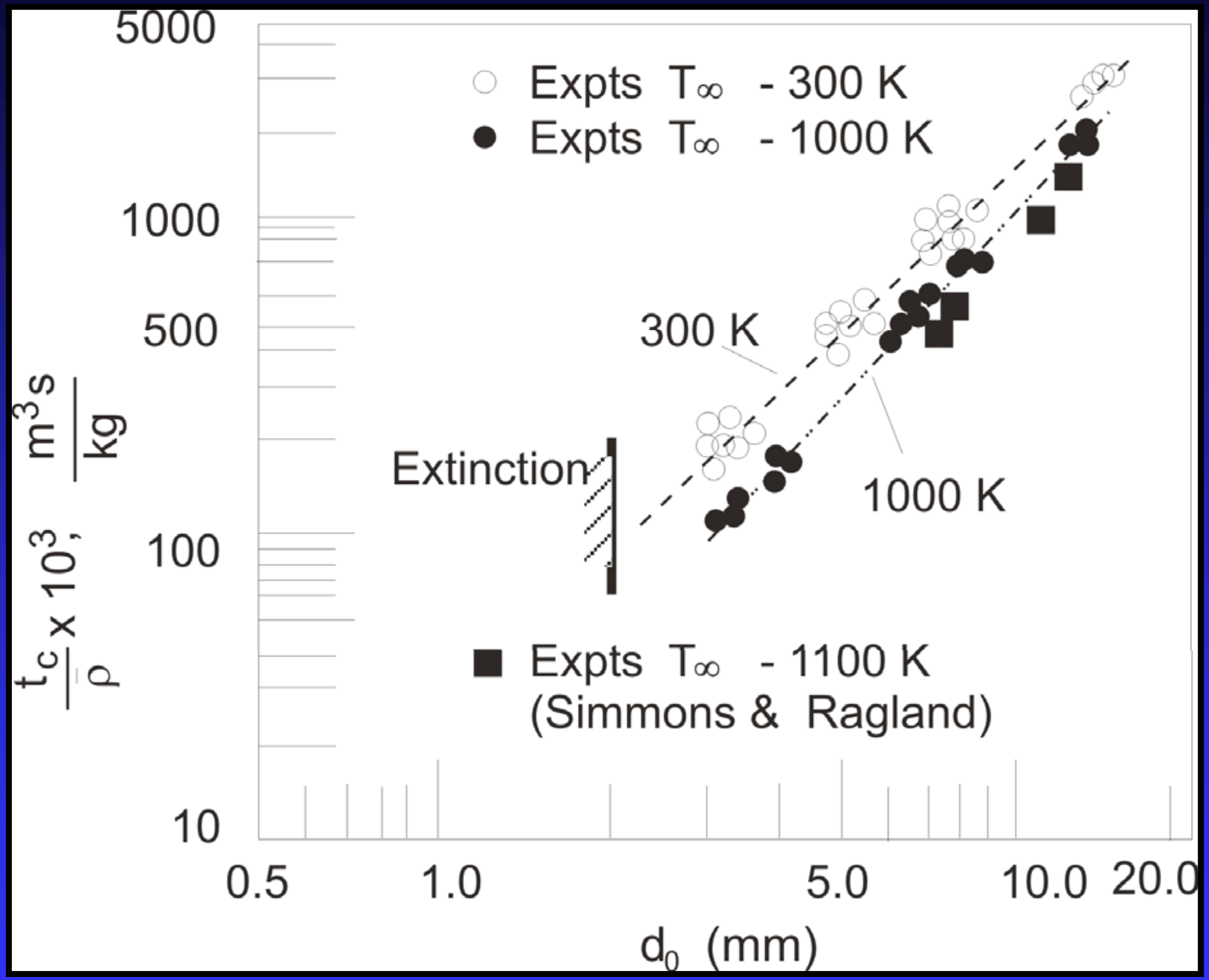
$$\left(\frac{t_c}{\rho}\right)_{O_2} = 0.0022\, a_0^{2}\, X_{O_2}^{-1.0}$$

X_i is the mole fraction of the reactant in the ambient

Validity : $d_0 > 4$ mm, T = 1000 to 1400 K

Accuracy $\pm$10%

Single Particle Conversion – Experiments and Results



Burn time for different particle diameters in air at 300 & 100K and the experi-

-mental data of Simmons and Ragland(1986) (Dashed lines indicates trends)

A simple Analysis of Extension

Heat release rate at the surface = Heat taken away by connection + Heat loss by radiation

$$A_s \delta_f e^{-E/RT_s} F \bar{Y}_{ox} = \dot{m} c_p (T_s - T_o) + A_s \varepsilon \tau (T_s^4 - T_0^4)$$

$$\bar{Y}_{ox} = (T_s - T_o)/(T_{ad} - T_o)$$

$$\delta_f \left[(T_s - T_o)/(T_{ad} - T_o) \right] e^{-E/RT_s} F =$$

$$\dot{m}'' c_p (T_s - T_o) + \varepsilon \tau (T_s^4 - T_0^4)$$

Radiation is a small fraction of the heat transfer.

$$\dot{m} = K r_s ;$$

$\dot{m} = K r_s ;$

$$\dot{m}'' \approx \frac{x_{o\infty}}{4400} \frac{1}{r_s}$$

r_s, mm	$T_{s,\ cr,nt}$ $T_s > T_{s,\ crit}$
4	803
3	825
2	843
1	900

r_s

$$r_s < \frac{1}{-dT_s / dr_s} \cdot \frac{1}{(E_s / RT_s^2)}$$

For < 1 mm Extinction occurs.

Combustion Experiments with

a) Rice Husk

b) Sawdust with 20% Silica

c) Pulverised Rice Husk

d) Sawdust

e) Spheres- Wood and Rice Husk Briquette

Rice Husk

Sample being Ignited

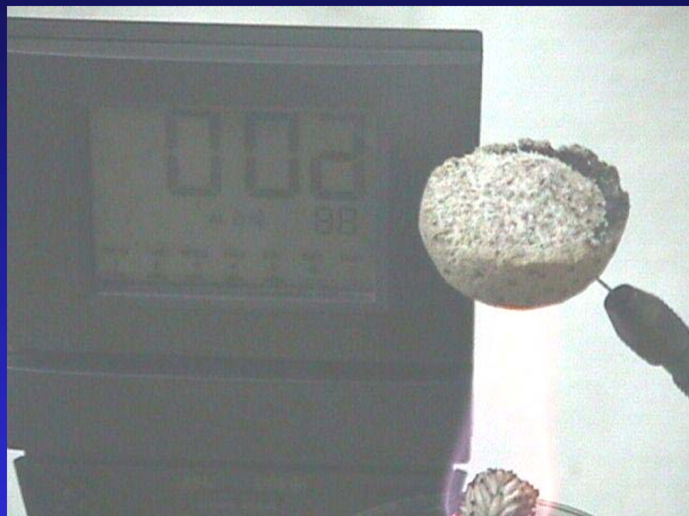
Sample with the Flame

Ultimate Product

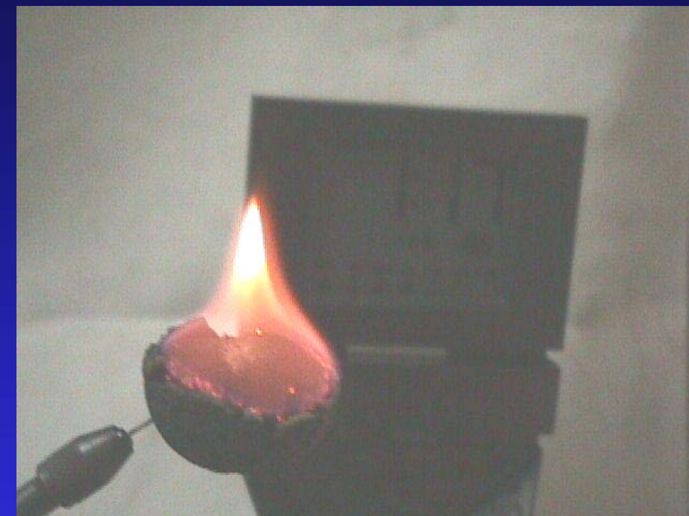
Percentage Residue=31.3

Sawdust with 20% Silica

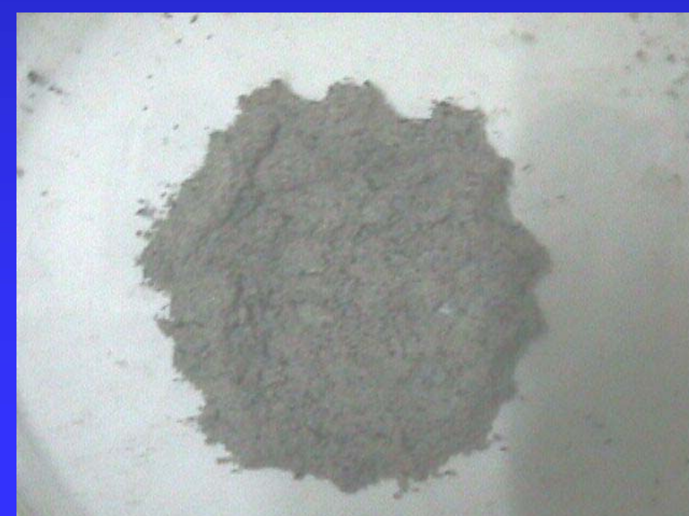
Sample being Ignited



Sample with the Flame



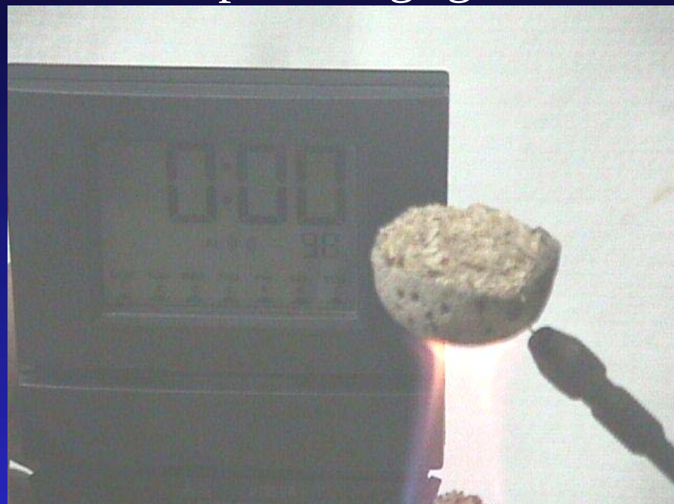
Ultimate Product Formed →



Percentage Residue= 18.3

Pulverised Rice Husk

Sample being Ignited



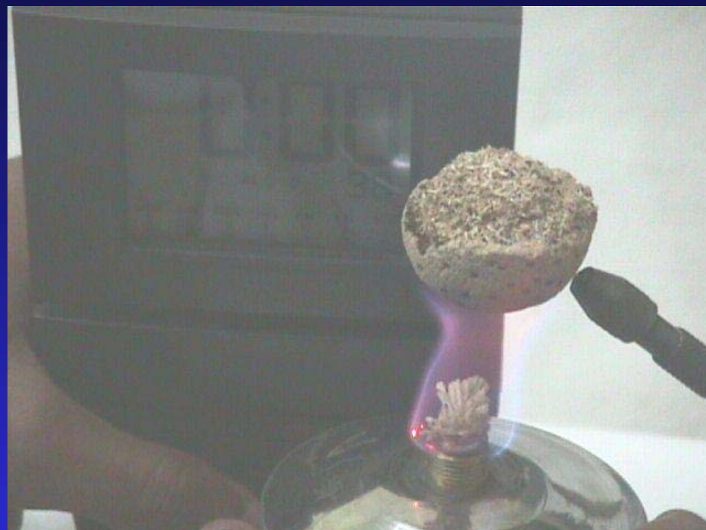
Sample with the Flame

Ultimate Product Formed →

Percentage Residue= 31.3

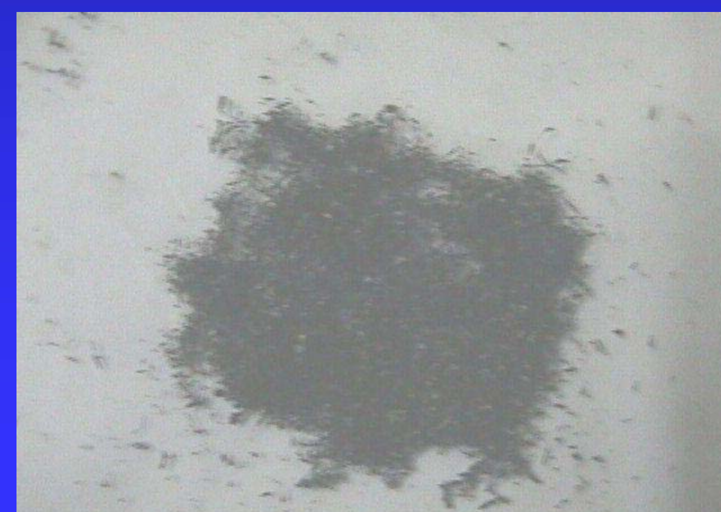
Saw Dust

Sample being Ignited



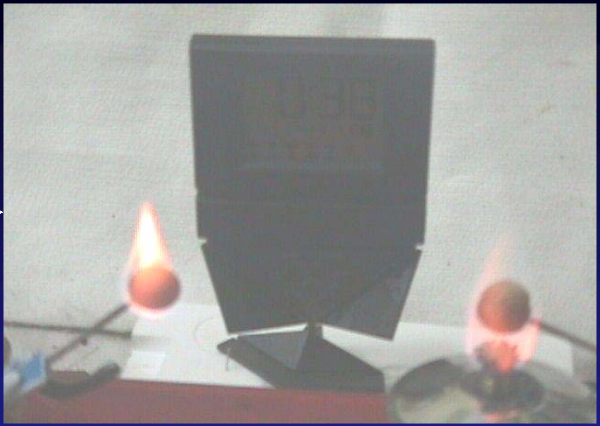
Sample with the Flame

Ultimate Product Formed →



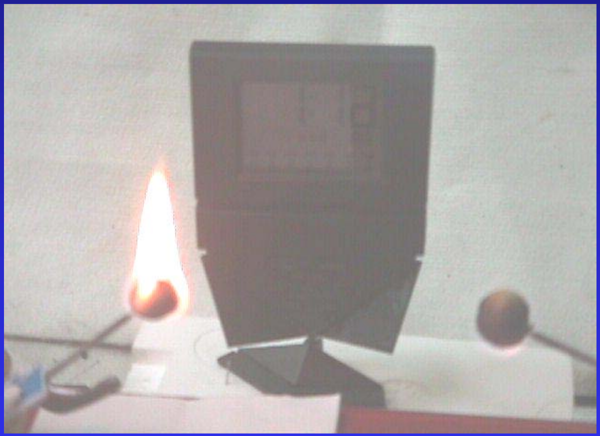
Percentage Residue= 6.9

Wood sphere catching the flame and briquette sphere being ignited



Percentage Residue =1.7

Wood sphere burning and the briquette starting to burn.



Percentage Residue = 21.0

Glowing wood sphere and the flame dying away in case of briquette.

Ash formed from wood sphere

Percentage Residue= 1.69

Process Time : Ignition = 36 s
(In Seconds)
Flame = 108 s
Glow = 604 s

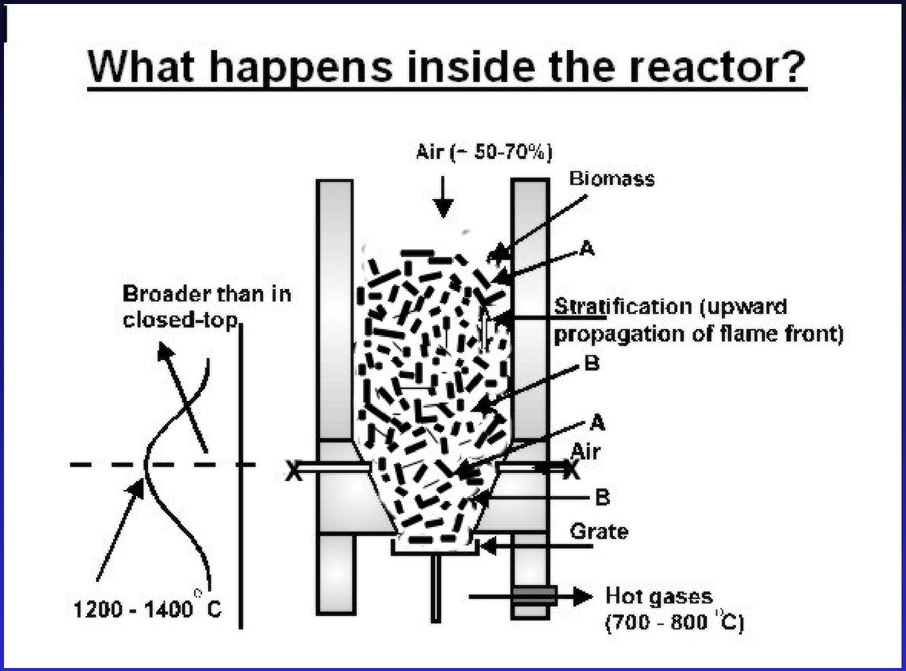
Ash formed from Rice husk briquette Sphere

Percentage Residue= 21.0

Process Time : Ignition = 68 s
(In Seconds)
Flame = 195 s
Glow = 1332 s

Relevance to Rice Husk gasifiers

- The conversion of rice husk char is slower than of wood char.
- It occurs only at very slow heating rates and at temperatures below 800^{0}C.
- Rice husk char is structurally more complex than wood char. It has 40 to 50 % inert. The Silica (~95 % inert – ash) is molecularly interspersed with carbon making carbon more inaccessible to conversion by O_2 and for sure, CO_2 and H_2O as these are less reactive with endothermicity.
- One can therefore expect that rice husk gasifiers using as-received rice husk to work virtually as pyrolisers with limited cracking at high temperatures.
- One can therefore expect more tarry gas.

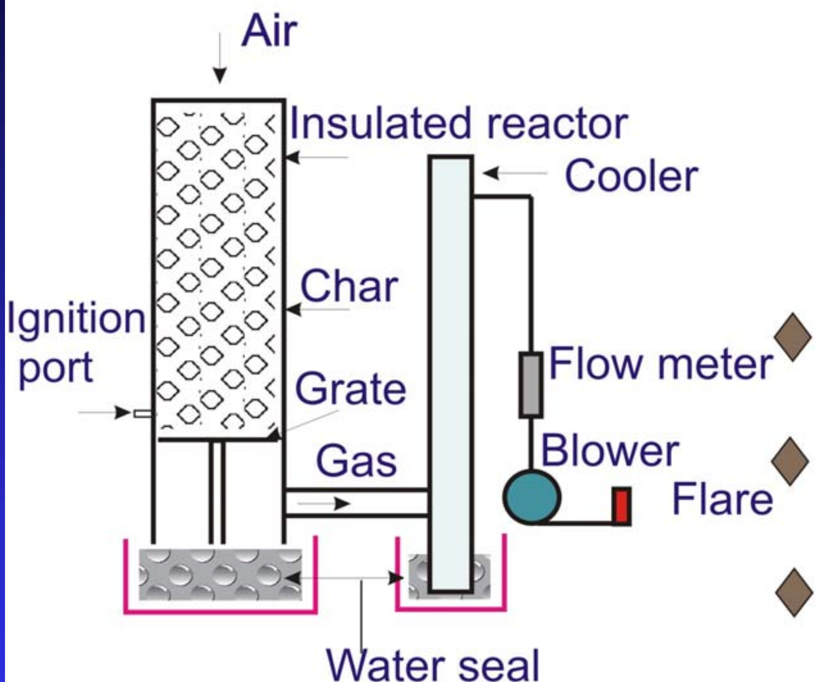


- Also fluid mechanical effects tunneling of air through the bed of rice husk.

- This leads to varying quality of the gas over the operating period.

- Use of briquettes whose mechanical Integrity is good leads to uniform flow of air and gases through the porous bed.Conversion can be expected to be higher inferred from single particle studies. Performance of the reactor will be more robust and reliable.

Experimental setup for the packed bed



One-fortieth scale version of wood gasifier of 275 kWth

Procedure

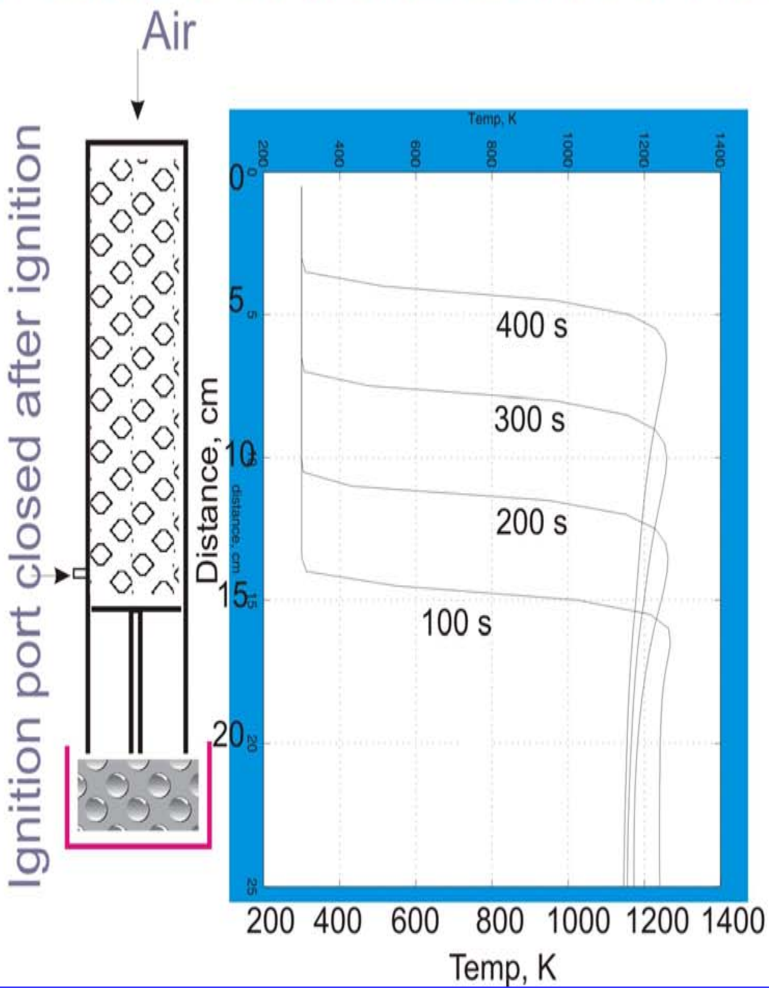
- Charcoal pieces of approximately 8 mm dia was used
- Initial light-up through ignition port and close it later
- At a fixed flow rate, flame front movement upwards was measured

Observation

- Glowing zone was approximately 25 - 30 mm (3-4 particle depth)
- Peak bed temperature measured in the range of 1000 - 1200 K depending upon the mass flux

Typical temperature profile in the packed bed (model prediction)

Coordinate system is fixed to the solid phase; coordinate system moves with respect to the gasifier hardware at a velocity equal to the particle velocity



Procedure

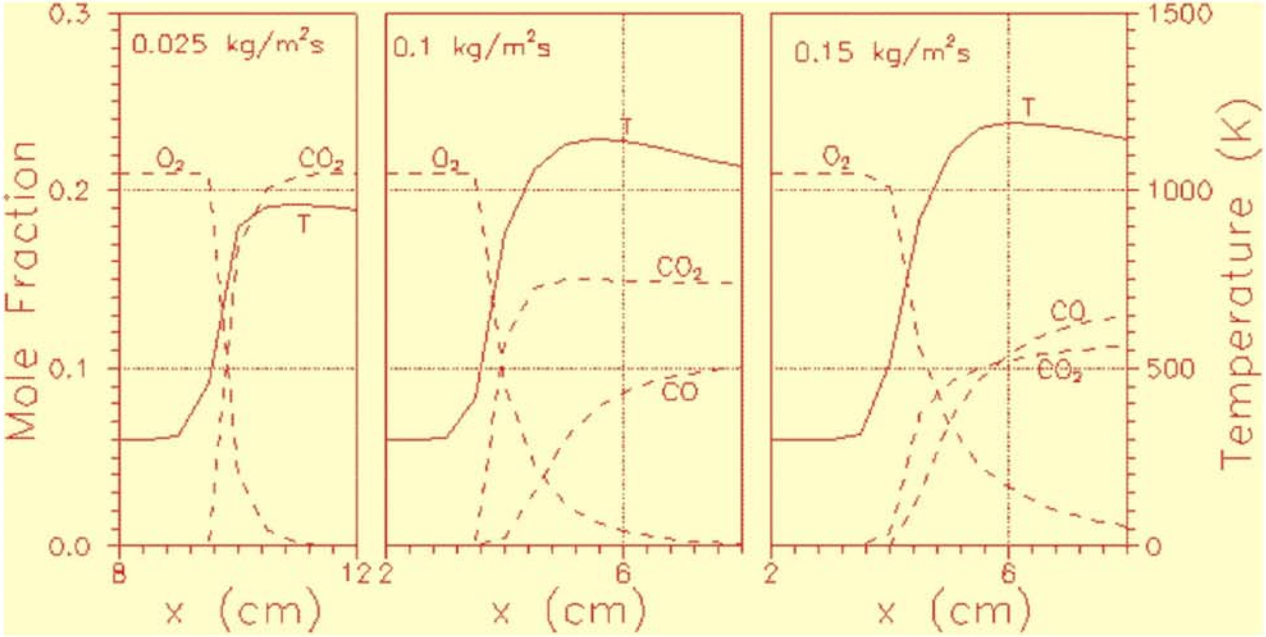
Set the initial conditions same through out the bed, except below certain height assign higher temperature for ignition

Solve for the individual particle and then for the packed bed

Axial distance, local particle velocity, temperature and the species fraction are obtained

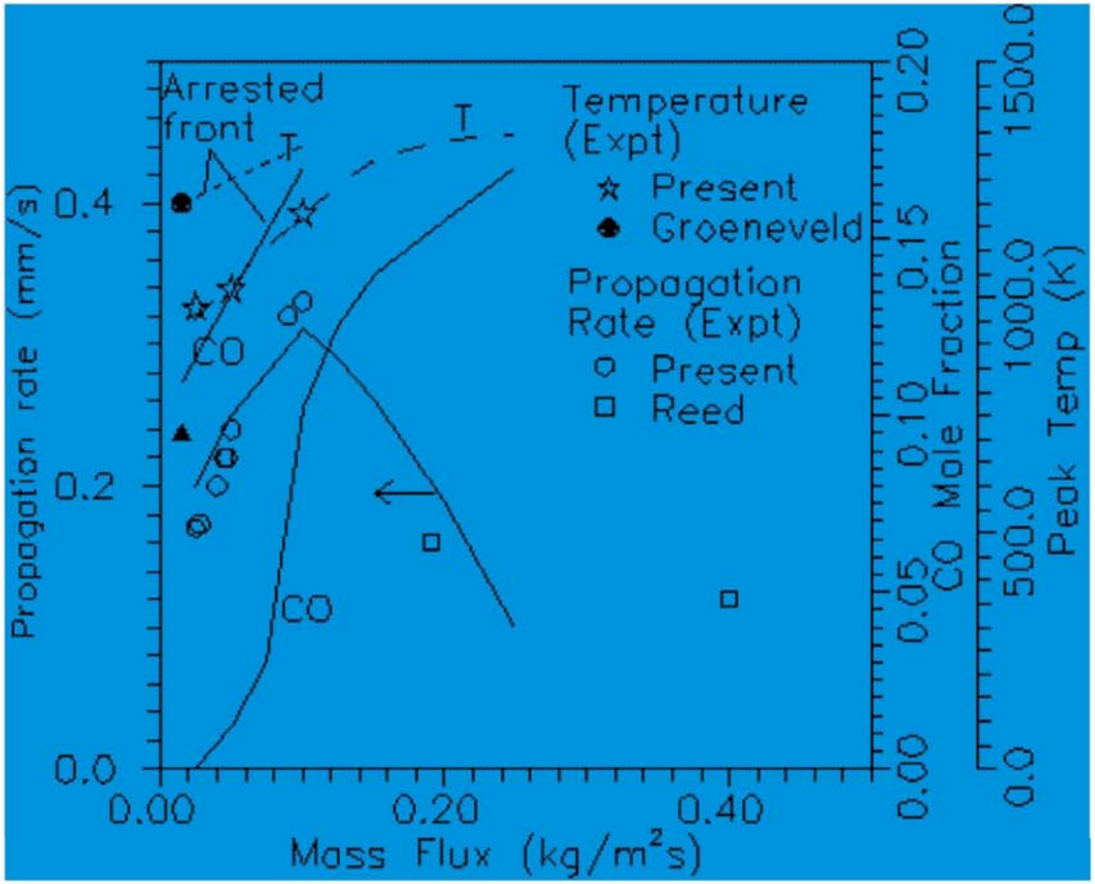
Temperature and reactant profile in the bed near the reaction zone for different air mass flux

- Profile chosen when the rate of propagation of the reaction front through the bed is constant



- Peak temperature increases as the air mass flux increases
- Thickness of the propagation front increases with air flux; consistent with the qualitative observation during the present experiments and earlier references[5]
- At low air flux CO concentration is low and increases with air flux

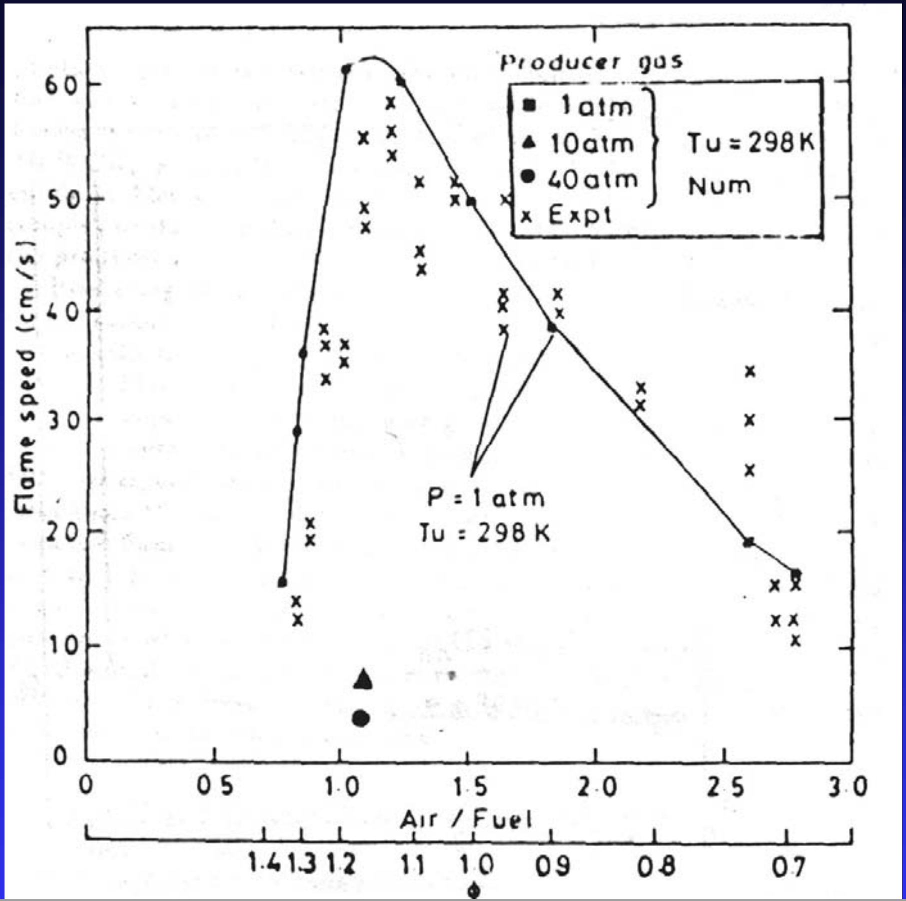
Propagation rate vs mass flux in a packed bed char reactor with peak bed temperature and CO concentration



- With increase in mass flux the front velocity initially increases and then reduces
- With increase in mass flux the CO concentration in the exit gas increases

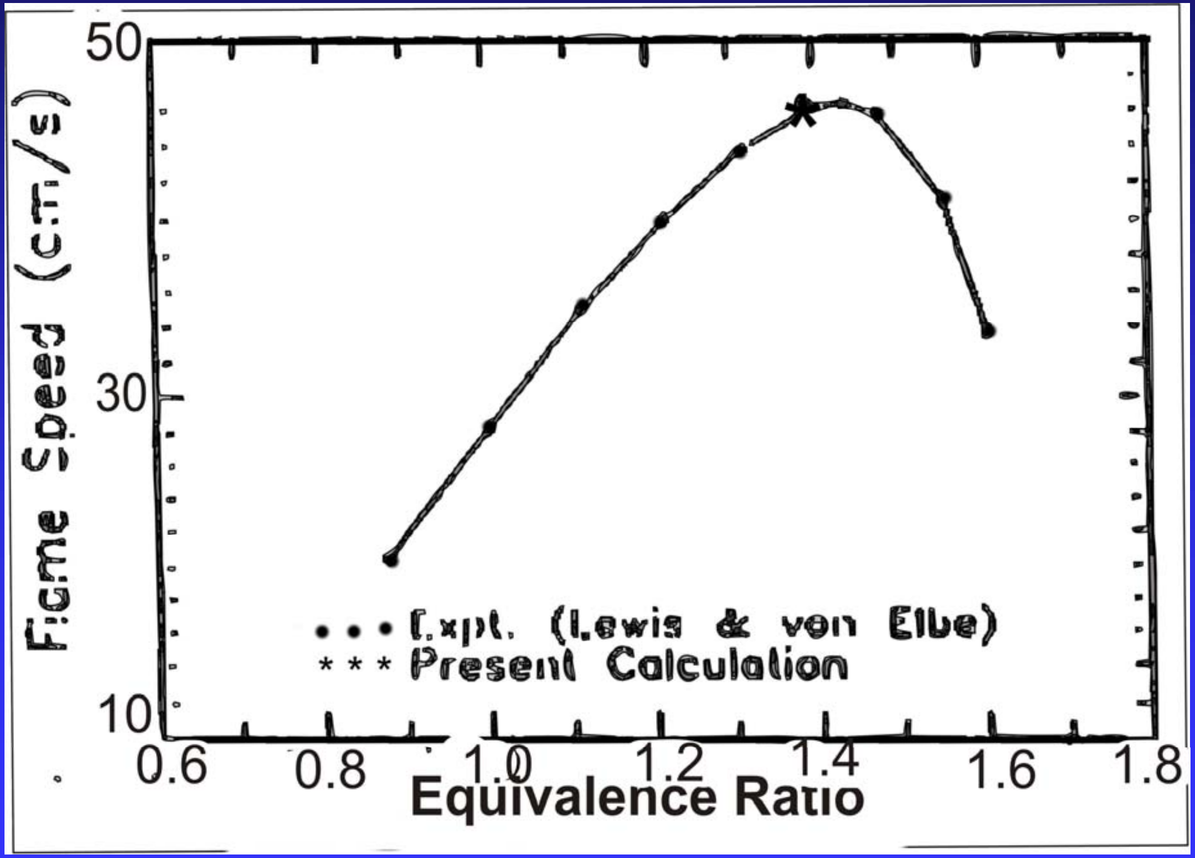
Producer gas
Combustion features for engine applications

Plot of the flame speed vs air-to-fuel ratio

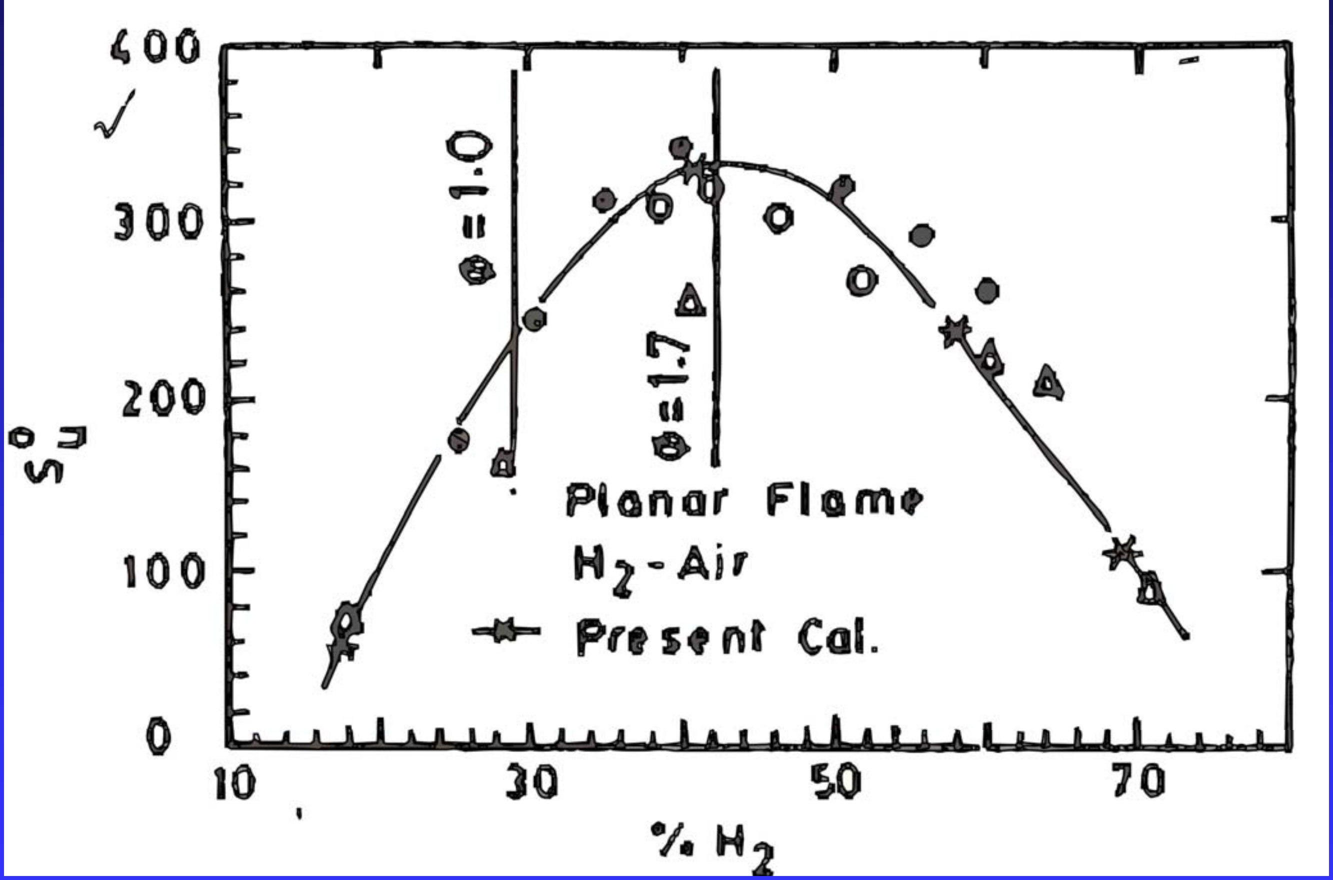


Computed for nominal compositions			Experimental		
	A/F	Flame Speeds (cm/s)		A/F	Flame Speeds (cm/s)
Rich	0.689 ± 0.028	6.0 ± 0.2	Rich	0.83 ± 0.03	13.0
Lean	3.1149	5.82	Lean	2.8 ± 0.05	10.3

Flame speed vs equivalence ratio for the CO-air mixture

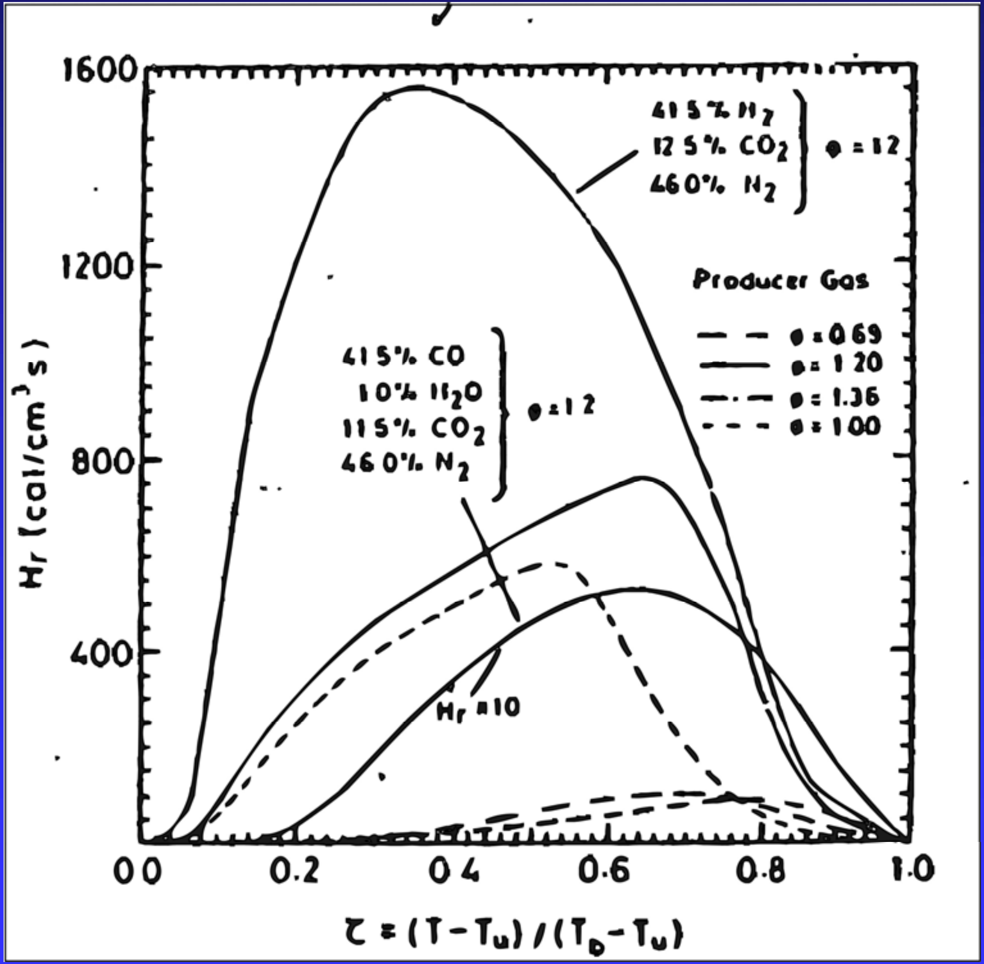


Plot of Flame speed vs % H_2 for H_2-air mixture



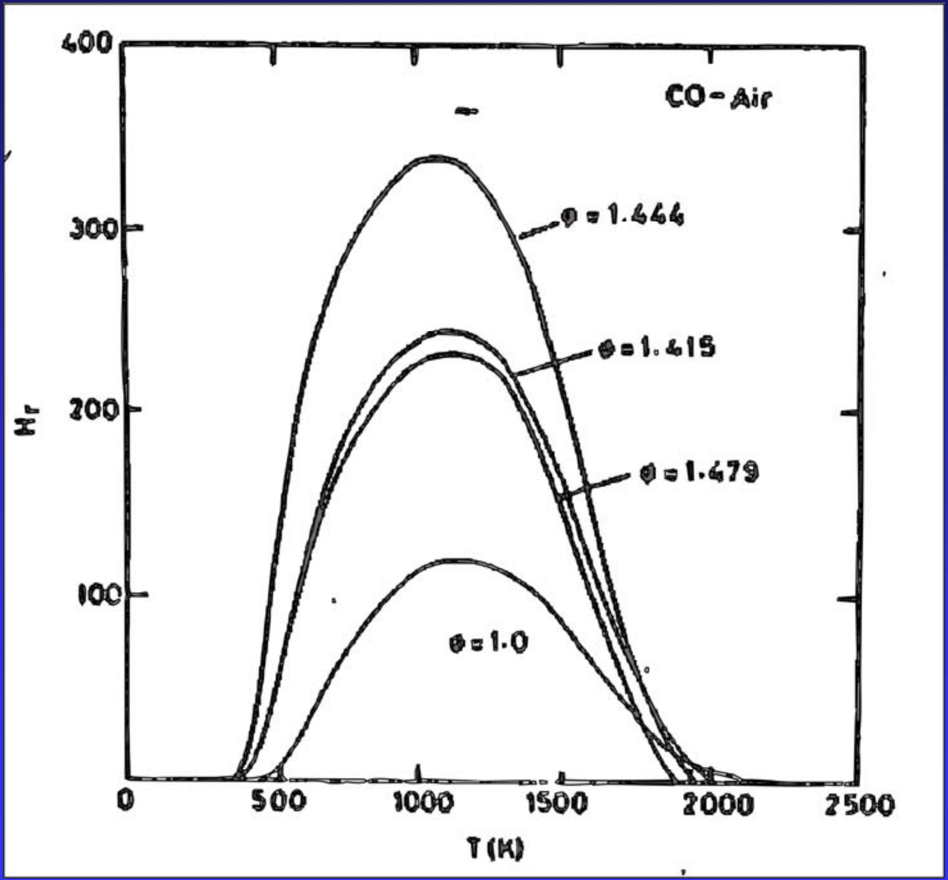
The heat release rates v/s $\tau = (T-T_u)(T_{ad} - T_u)$ for the producer gas,

H_2-CO_2-N_2-air(ϕ=1.2) and CO-CO_2- N_2-(H_2O)-air (ϕ=1.2)

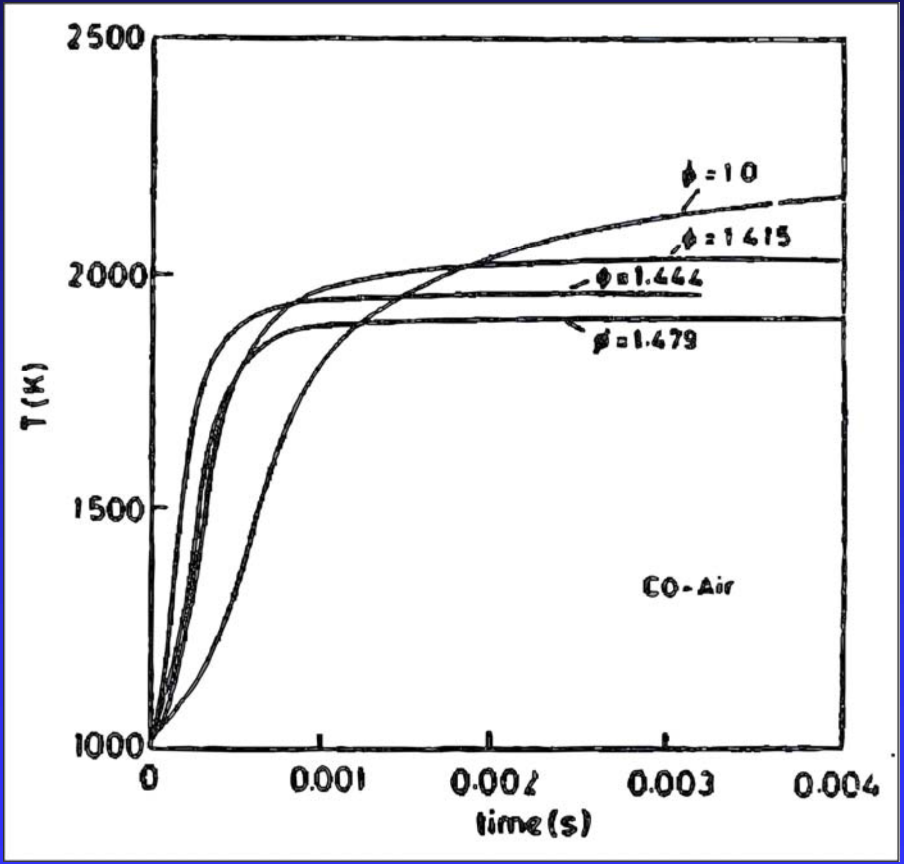


Heat release rates vs Temperature

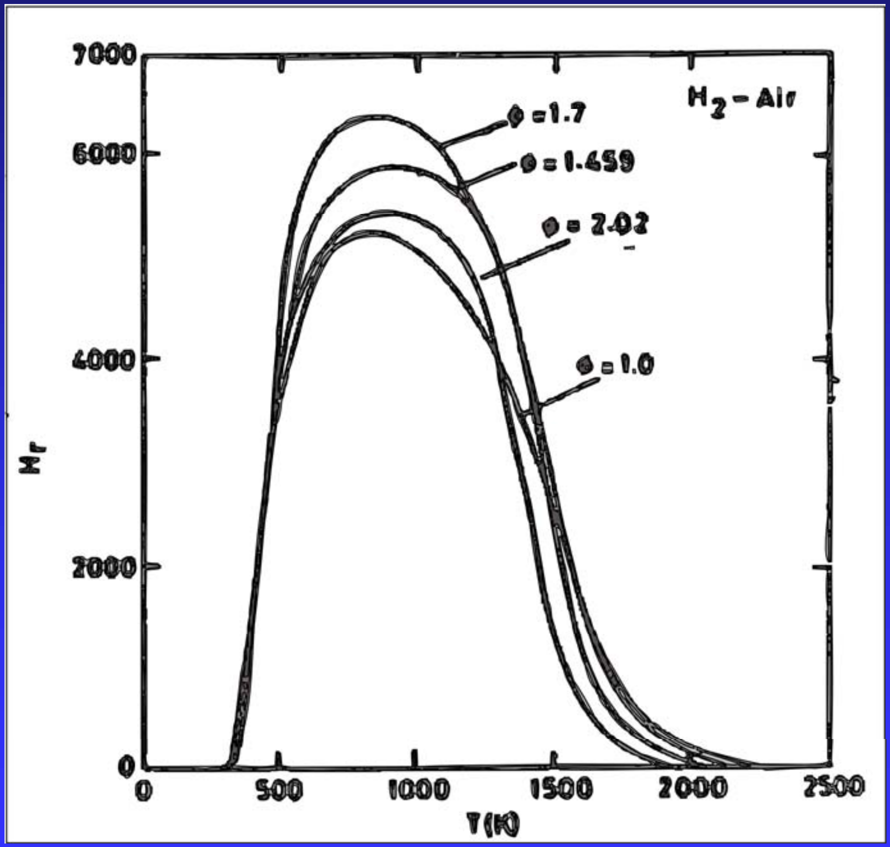
for ϕ=1.0,1.415,1.444,1.48 for CO-air



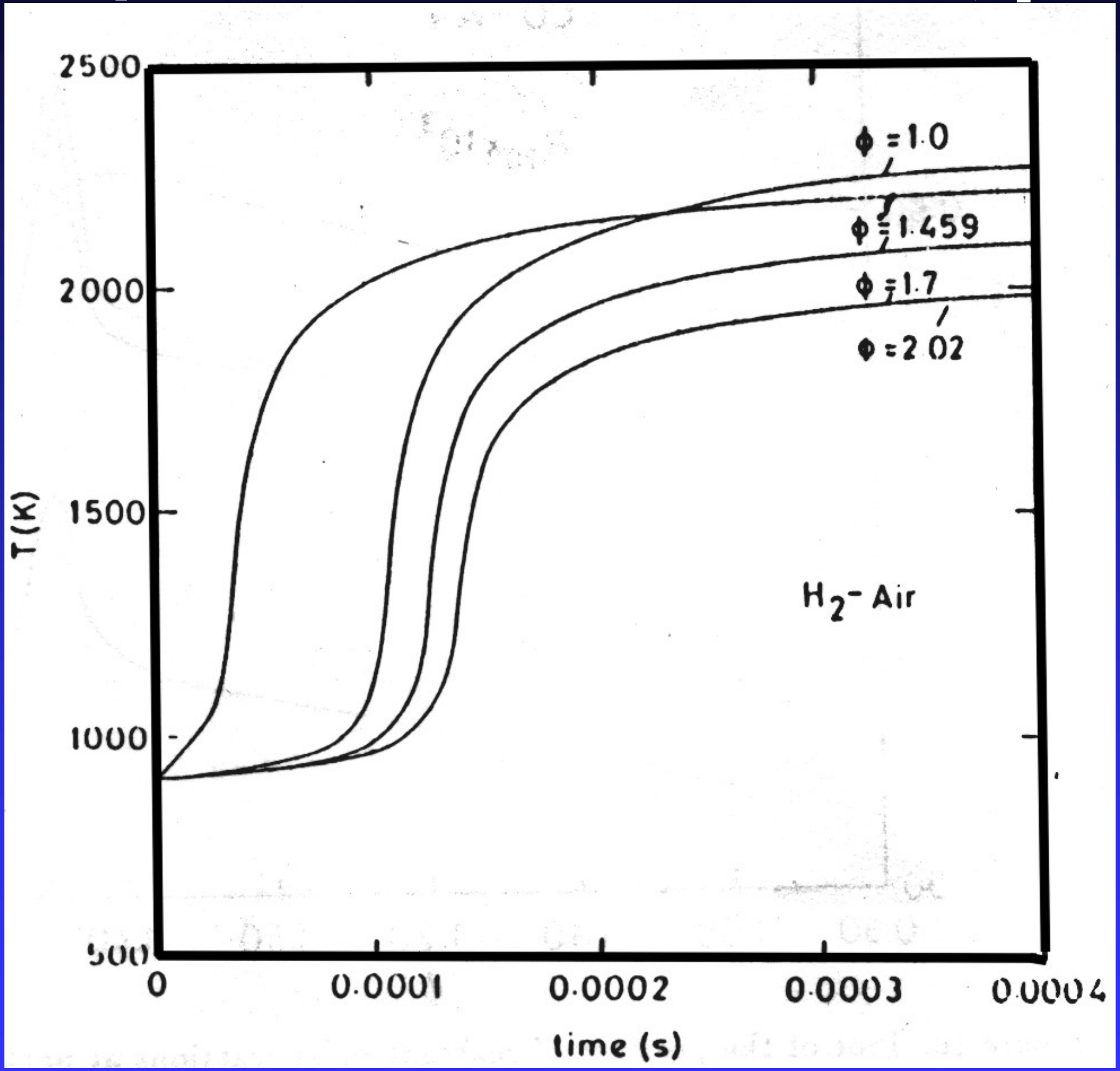
Plot of temperature vs time for an adiabatic reactor (CO –air)



Heat release rates vs Temparature for ϕ = 1.0,1.459,1.7 and 2.02 for H_2- air



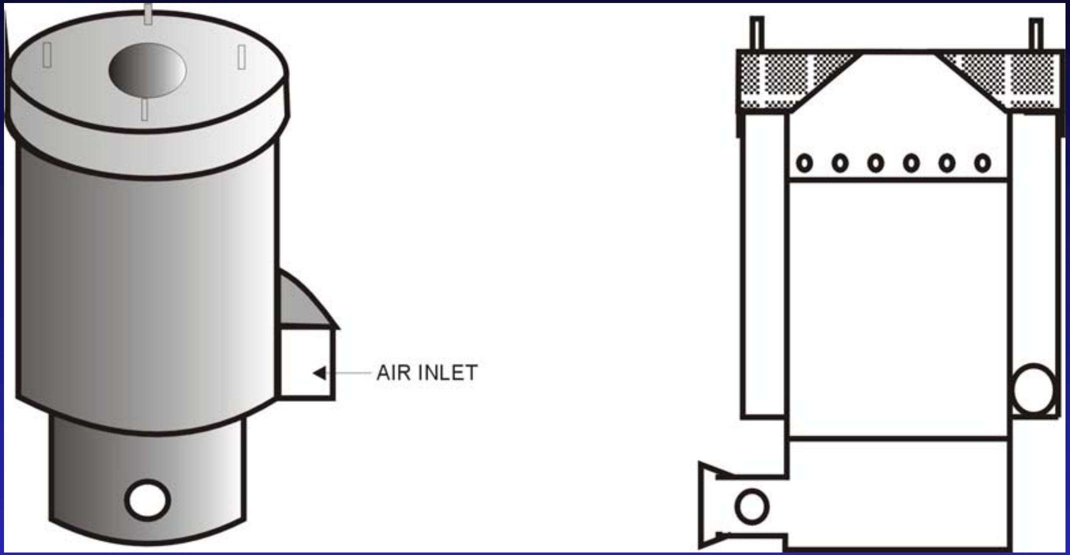
Plot of temperature vs time for an adiabatic reactor (H_2 –air)

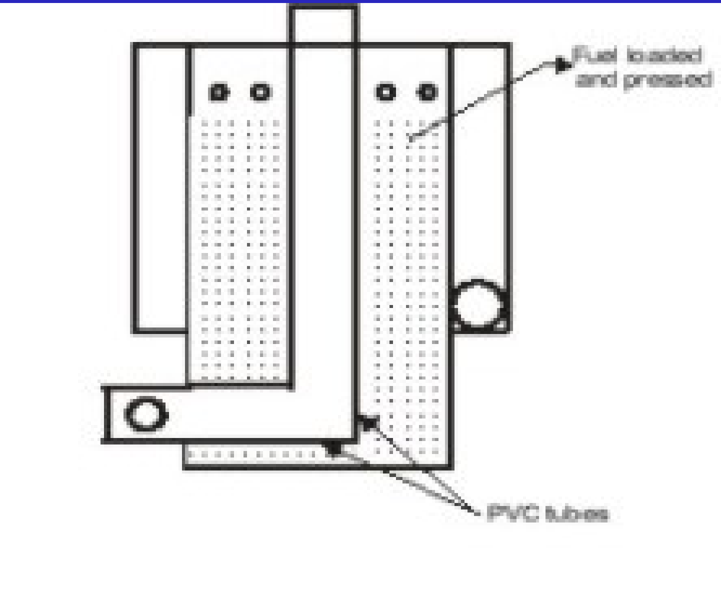


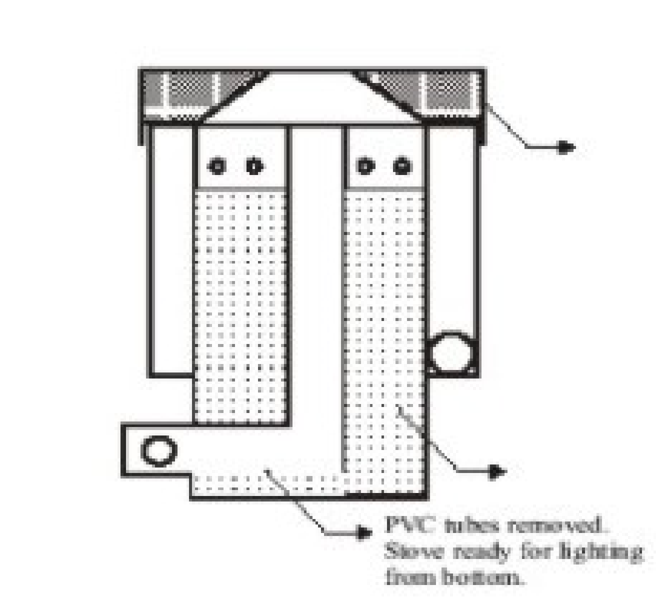
Power Gasifiers

M/s Senapathy Whiteley Pvt Ltd, Ramanagaram, Bangalore Rural district.

Gasifier Stoves







In this presentation, we have seen:

- **Background on biofuels and their importance**
- **Single particle combustion and inferences for gasification**
- **Flame propagation in particle beds**
- **Producer gas – Combustion features for engine applications**
- **Power Gasifiers and Gasifier Stoves**

THANK YOU