Incense sticks, Stoves and Rockets

Similarities and Scale differences in combustion

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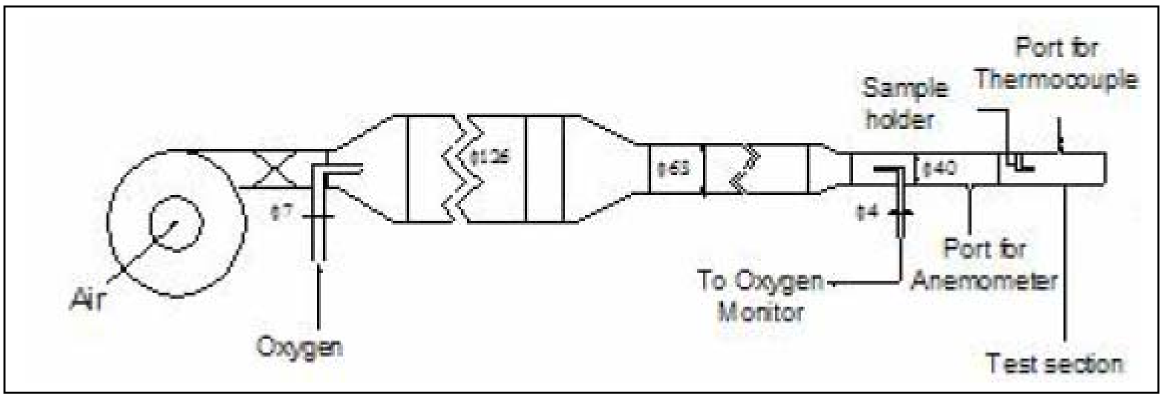
- Incense sticks –oxidative pyrolisis or ablation
- Stoves and hybrid rockets
- Last word in science – possible at all in engineering? Formula by a name?

Incense sticks

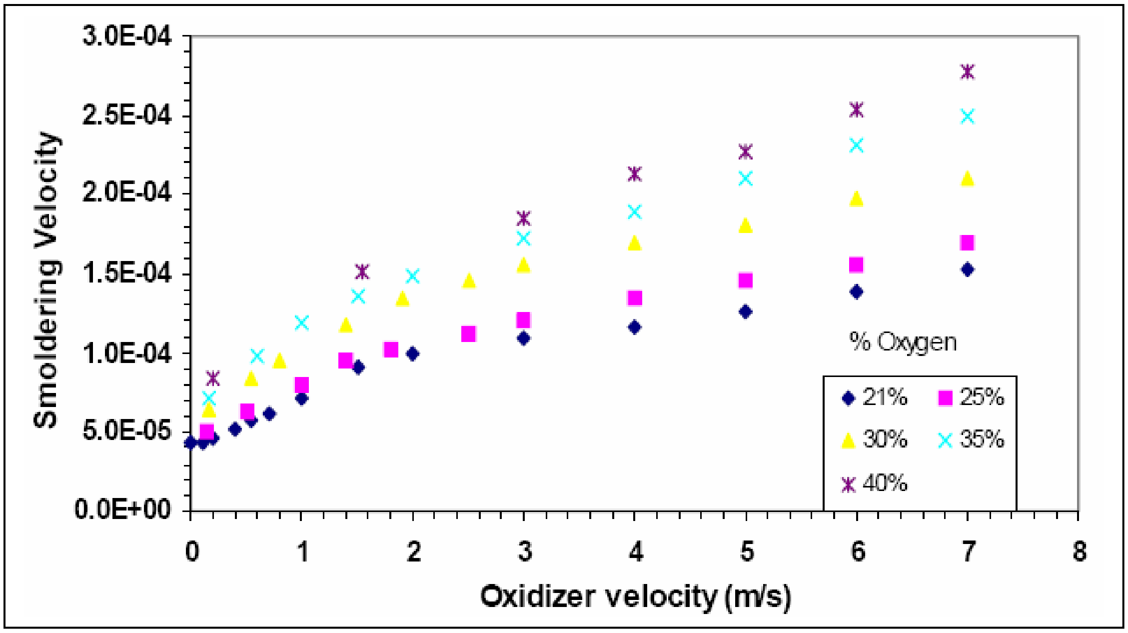
Composition –

Sawdust (30 %, charcoal (30 %) and cow dung (38 – 39.5%) + incense chemical (< 1.5 %)

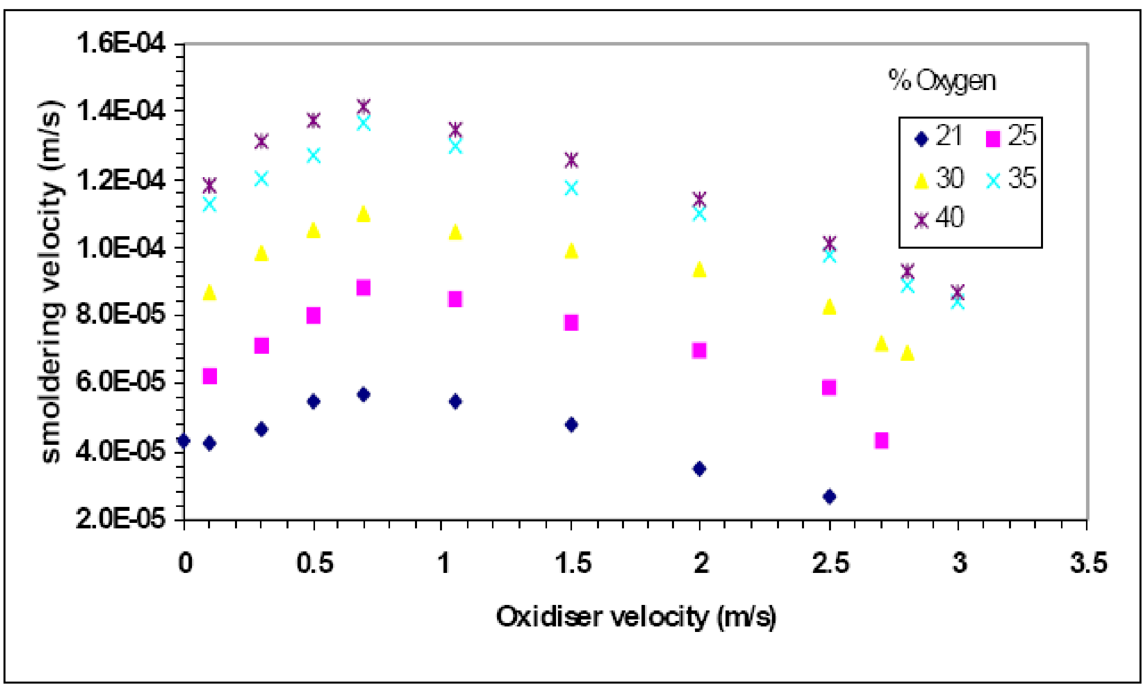
Composition matters weakly around these values



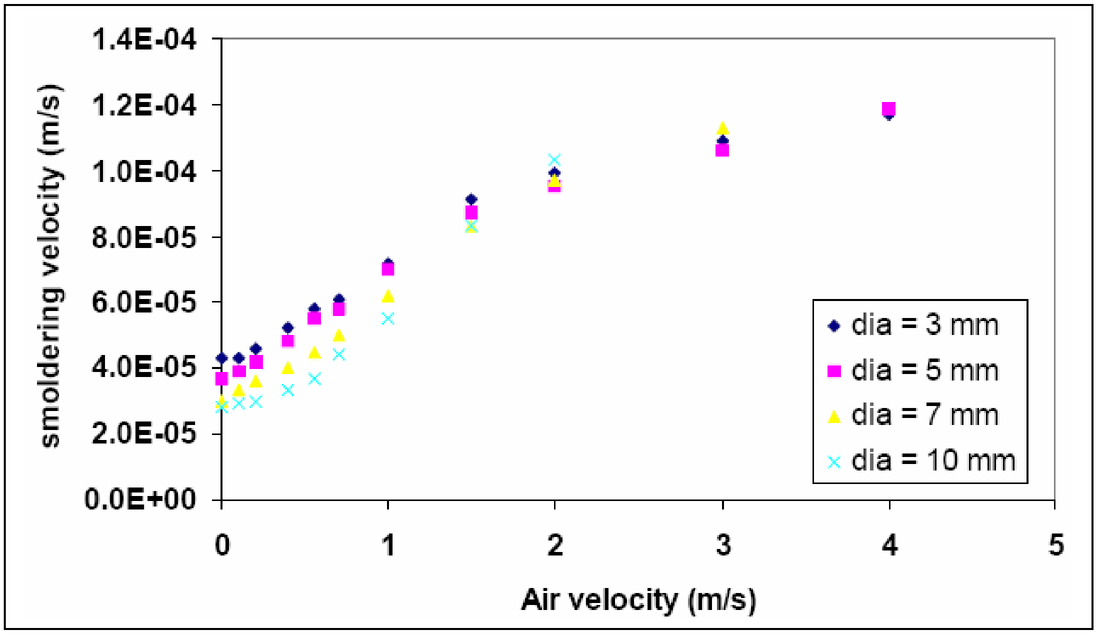
Experiments with incense sticks for *forward* and *reverse* smol



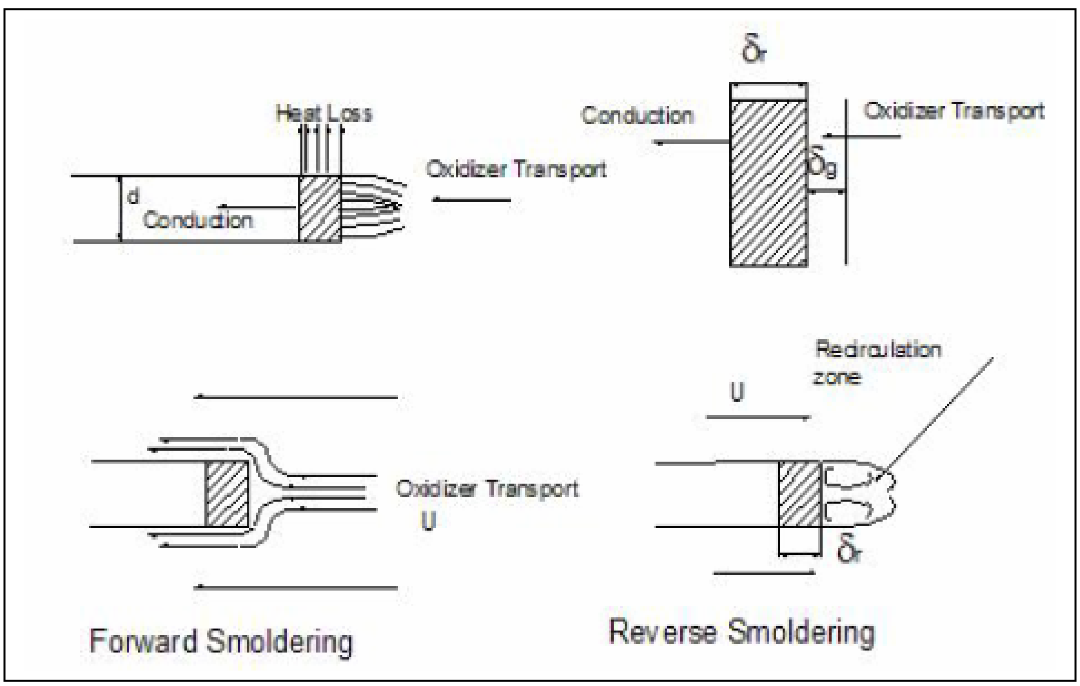
The *forward smolder* velocity vs. velocity of enriched air (smolder velocity ~ 180 – 600 mm/hr)



Reverse smolder velocity with stream velocity – at large speeds, the smolder velocity decreases and extinction results.



Diameter effect on forward smolder velocity – Increase in diameter decreases the smolder rate at low stream speeds. As speeds increase, the diameter effect disappears



Forward smolder – forward stagnation point transfer of oxygen from air to surface and then surface reaction – oxidative pyrolisis – generates aromatic components

Reverse smolder – A recirculation zone like backward facing step and the associated transfer of oxygen to surface

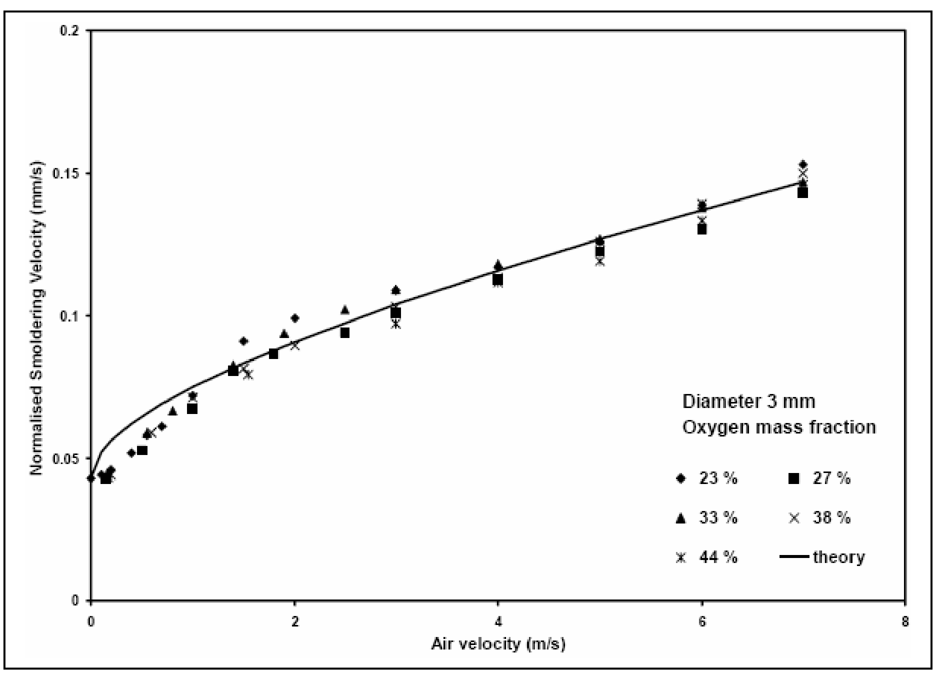
The heat balance at the surface:

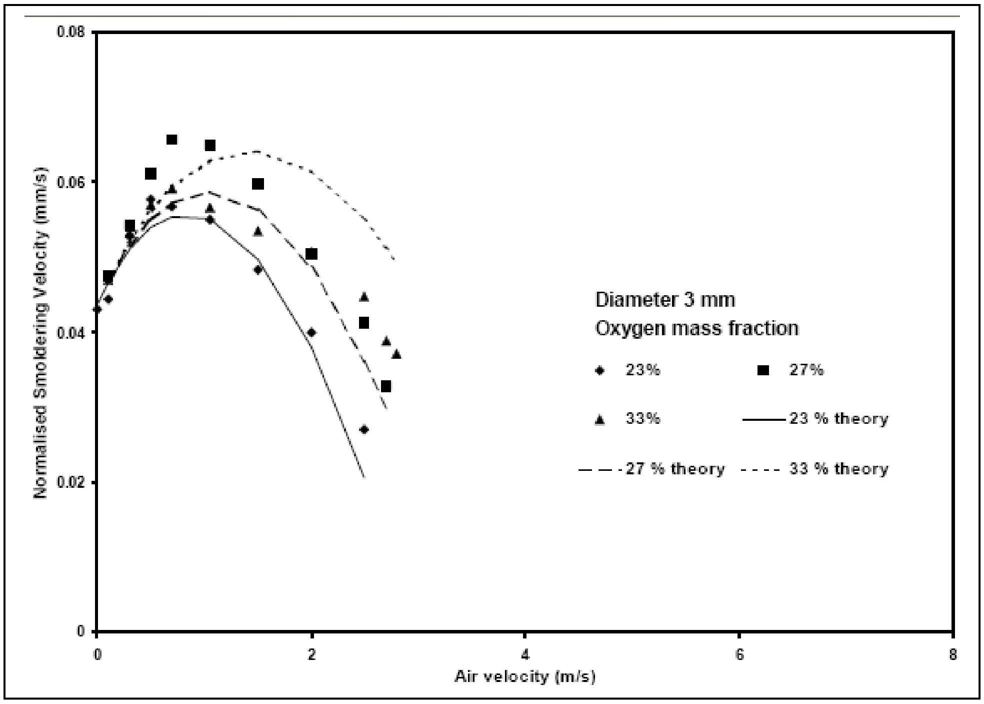
Heat released by reaction = Heat conduction into the solid + Heat loss to the ambient

$$\dot{\omega}'''\delta_r = D\rho \frac{\partial Y_0 / s}{\partial y} = D\rho \frac{Y_{0\infty}}{s\delta_g} \qquad \frac{1}{\delta_g} = \frac{1}{\delta_{g,forced}} + \frac{1}{\delta_{g,free}}$$

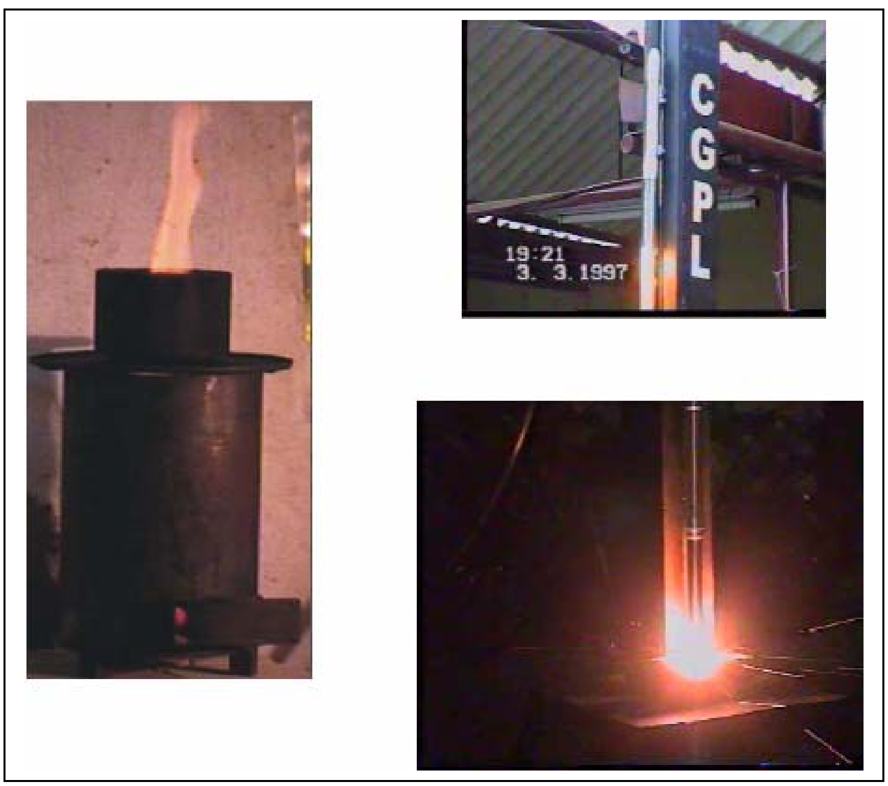
$$\bar{\dot{r}} = \frac{0.232\dot{r}}{Y_{0,\infty}} = \left[A_0 d^{(3m-1)} + B_1\sqrt{\frac{U}{d_0}} + C_0 U \right]$$

$$\bar{\dot{r}} = \frac{0.232\dot{r}}{Y_{0,\infty}} = \left[A_1 d^{(3m-1)} + B_1\sqrt{\frac{U}{d_0}} + C_1 U \right] - D_1 \frac{0.232}{Y_{0,\infty}} U^n d_0^{(n-1)}$$

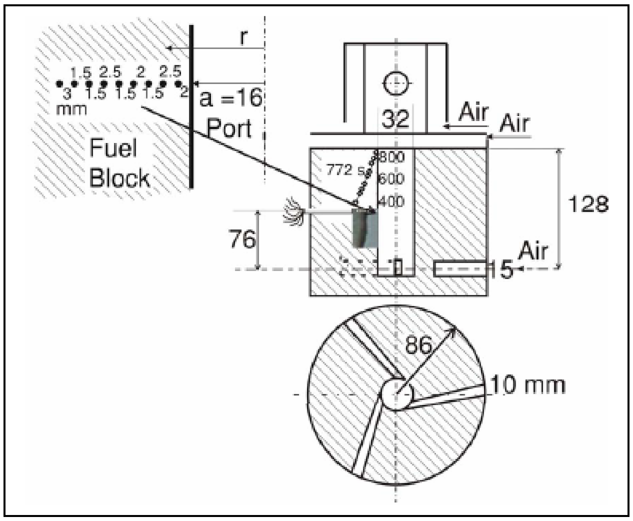


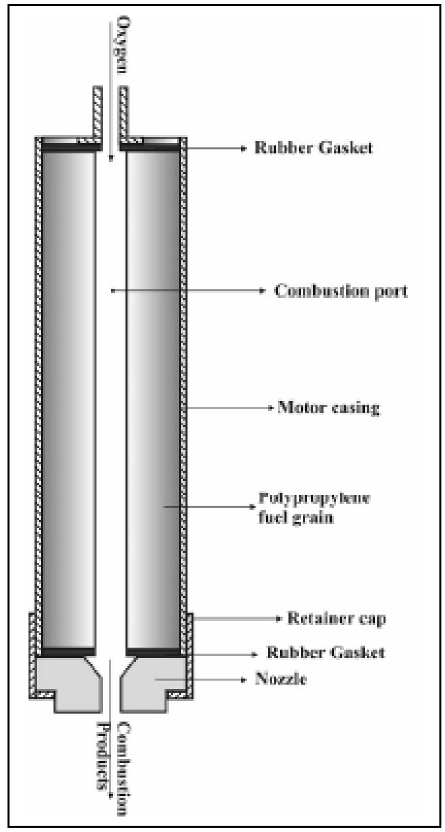


Stoves and Hybrid Rockets



Stove depends on buoyancy for air; Rocket engine needs injection of oxidizer the constraints on a stove are more – more challenging scientific problem than a rocket engine!

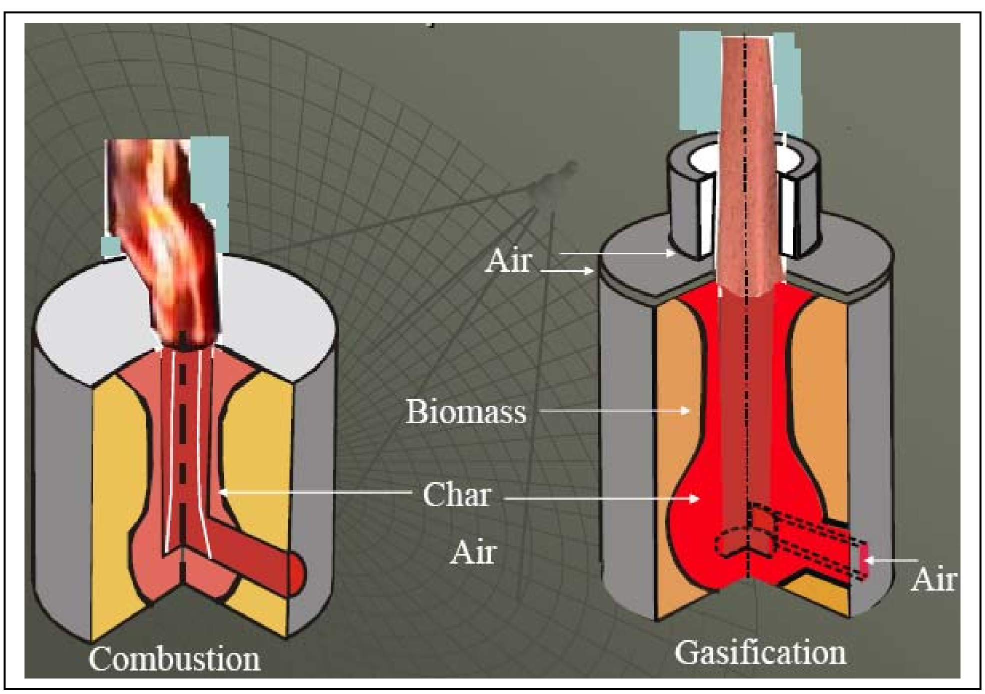


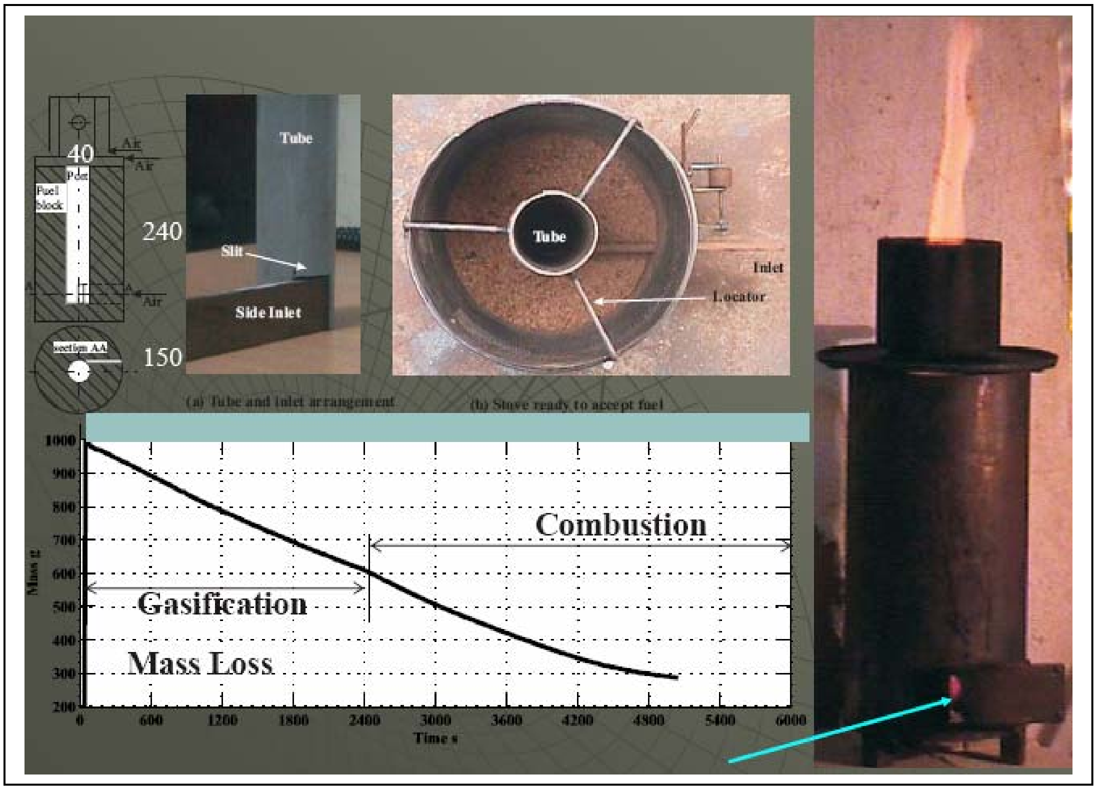


The biomass stove
Specs: Air management by free
Convection; low emissions
Pyrolisis rate: 60 mm/hr (0.02 mm/s)

The hybrid rocket
Regression rate ~
0.2 mm/s (with O_2)

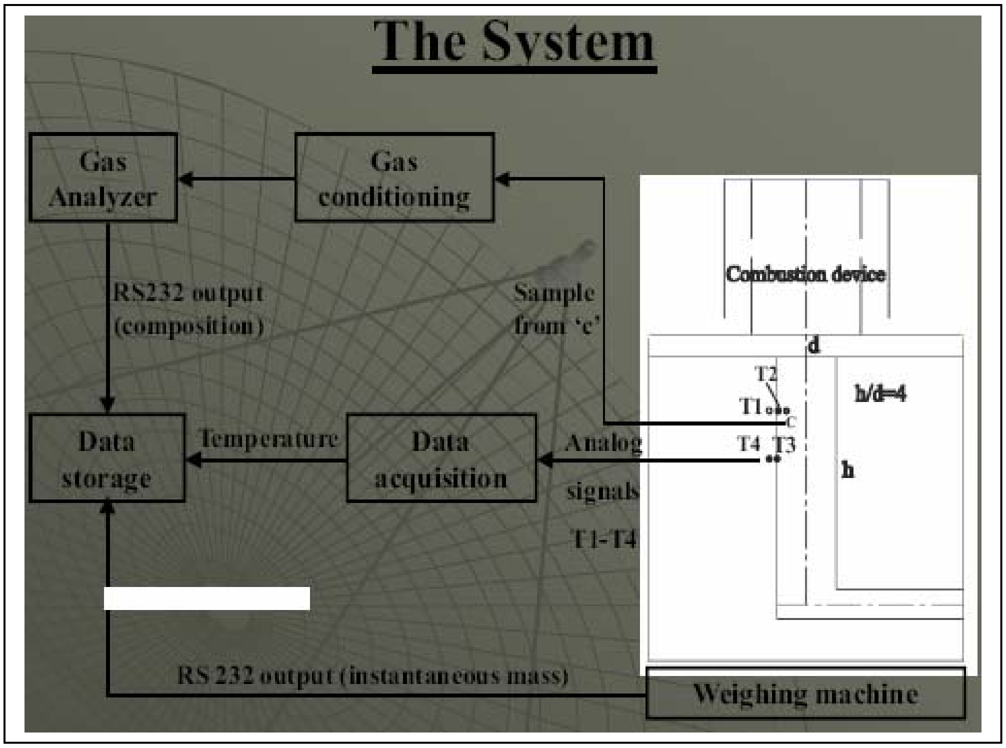
Modes of operation of stoves



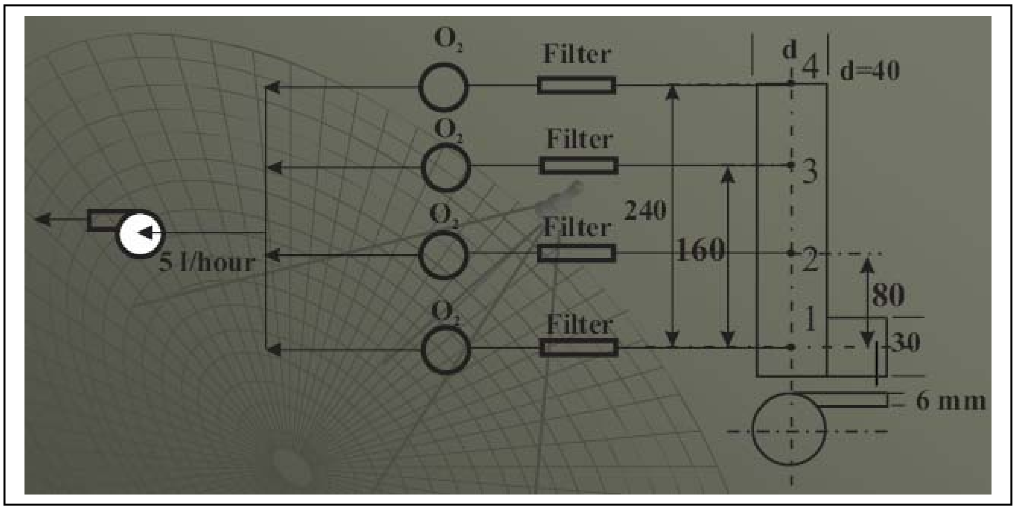


Measurements made

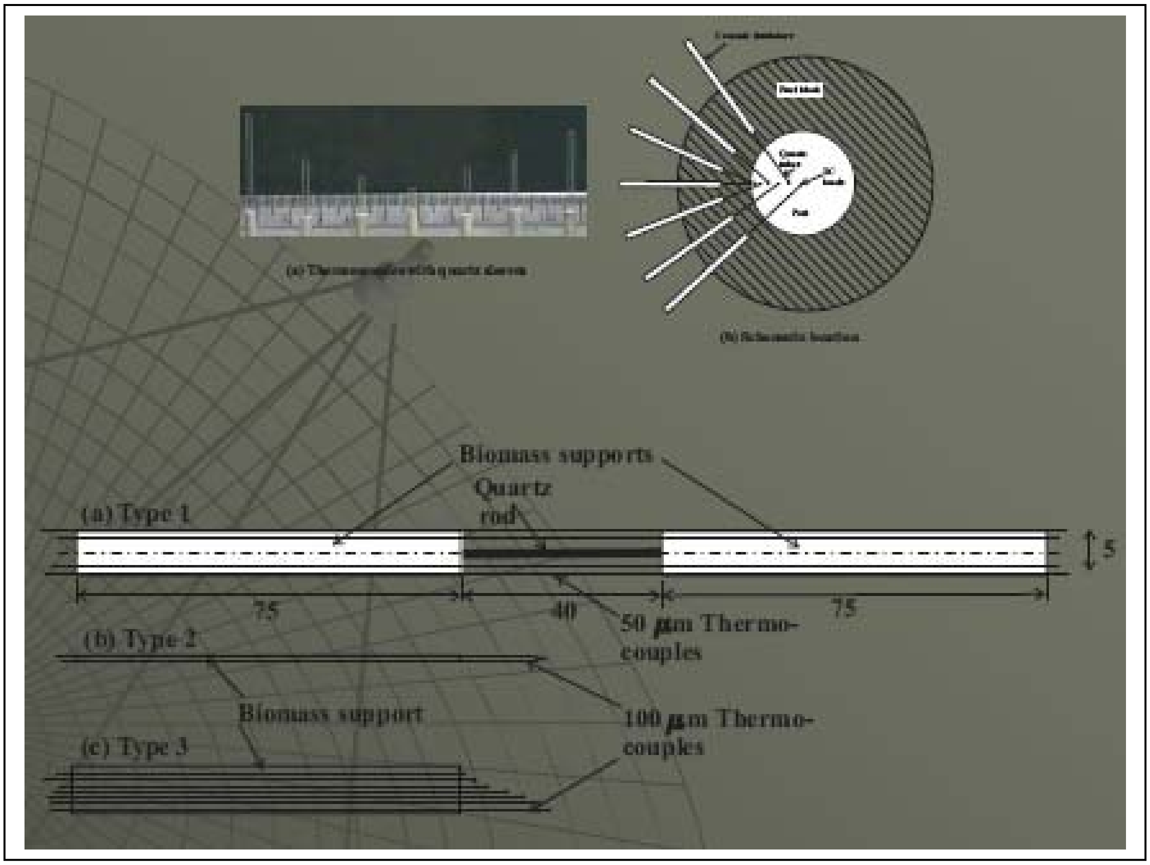
- Weight loss v/s time - Power
- C-phase temperature distribution - c-phase pyrolysis front propagation rate
- G-phase temperature and distribution
- G-phase composition
- Efficiency and Emission measurements



The measurement system



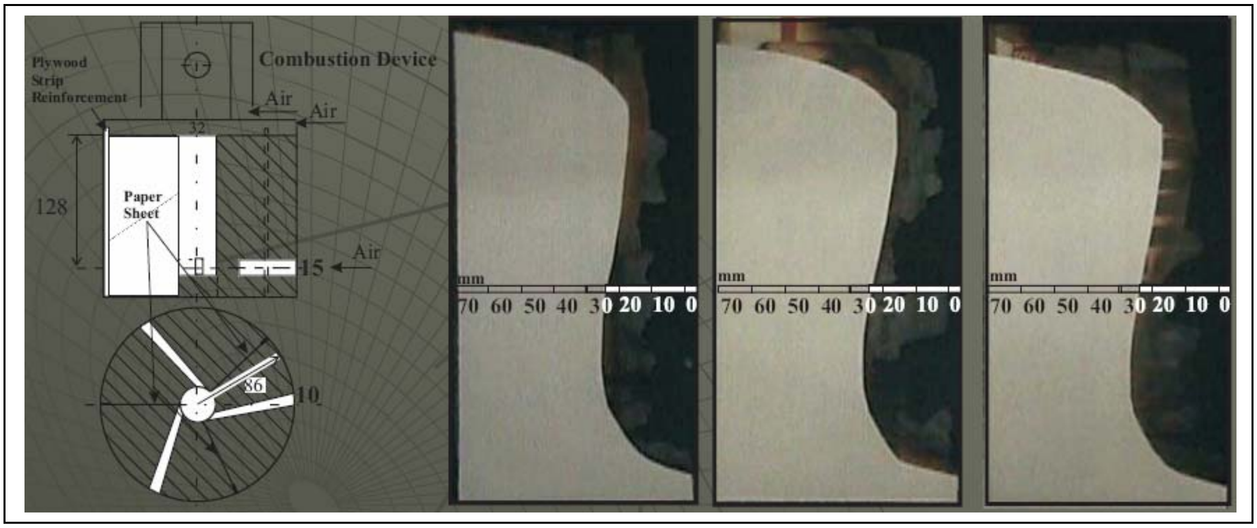
Oxygen and temperature: Apparatus schematic



C- & G-phase Temp. Measurement schemes

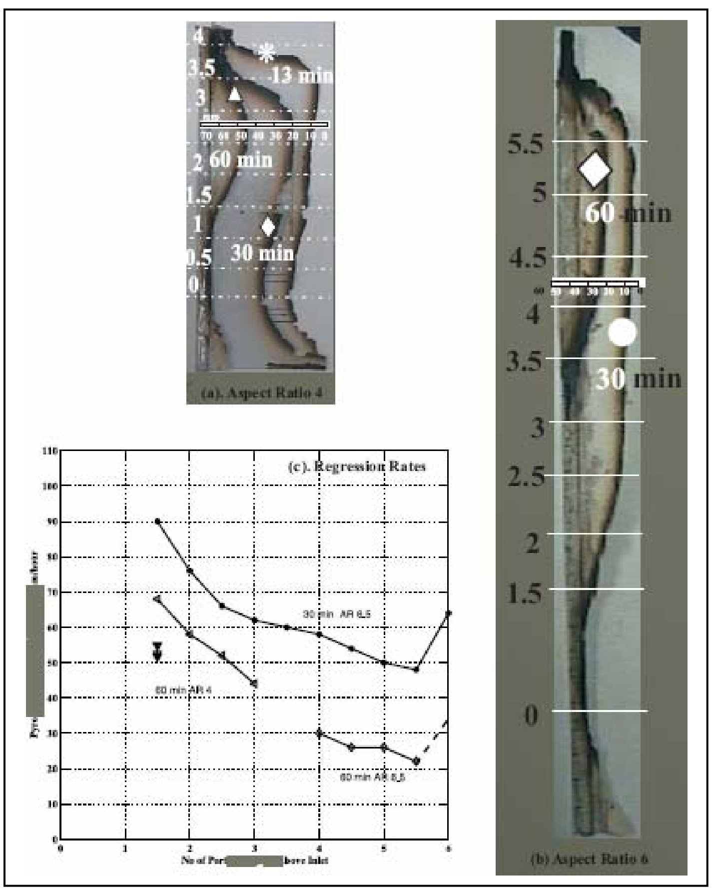
- C-phase and g-phase temperatures were measured with thermocouples Supported on thin biomass sticks
- Pyrolysis front position during stove operation was tracked using paper sheets

Paper sheet study for assessing pyrolisis front progress



Pyrolysis front propagates into c-phase symmetrically as can be seen by char profiles extracted simultaneously at the end of 30 minutes of stove operation.

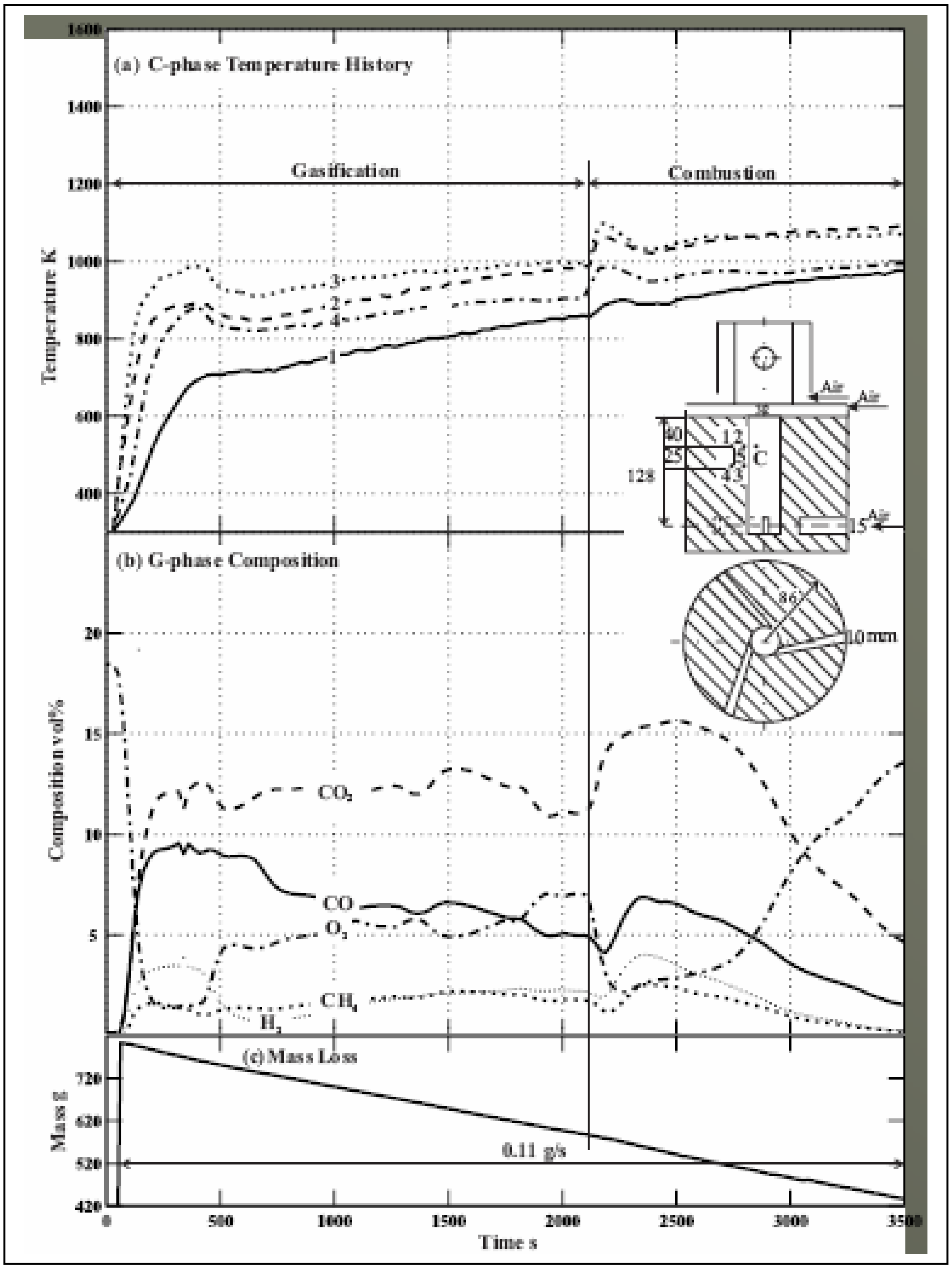
C-phase: Pyrolisis front movement rate



Front motion was obtained using three techniques -
(a) Paper sheets
(b)Radial Temperature profile
(c)Measurement of vertical wall temperatures

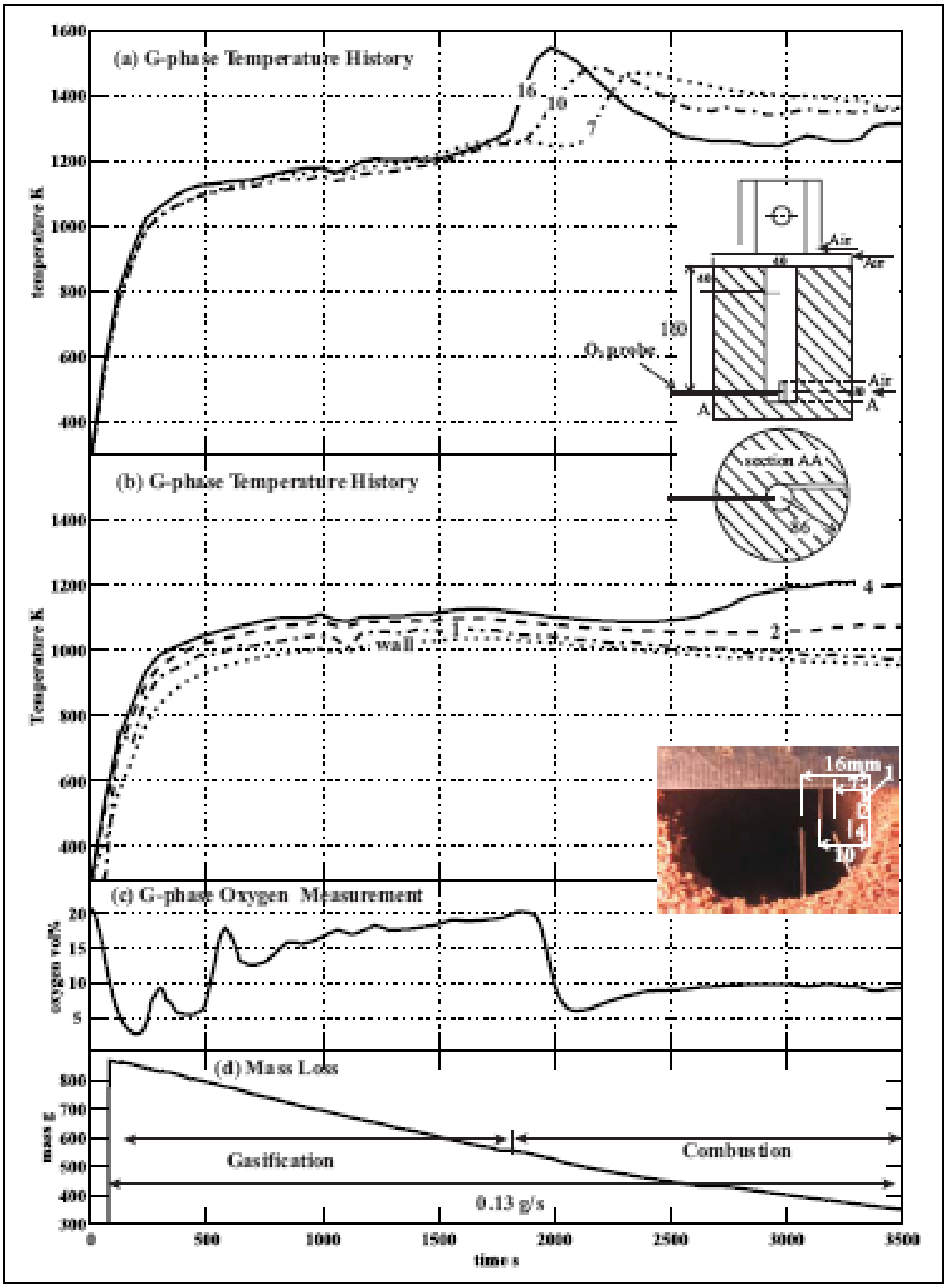
Spatial and temporal variation of regression rate of 25 – 90 mm/hour was observed.

G-phase composition & surface temp. measurement

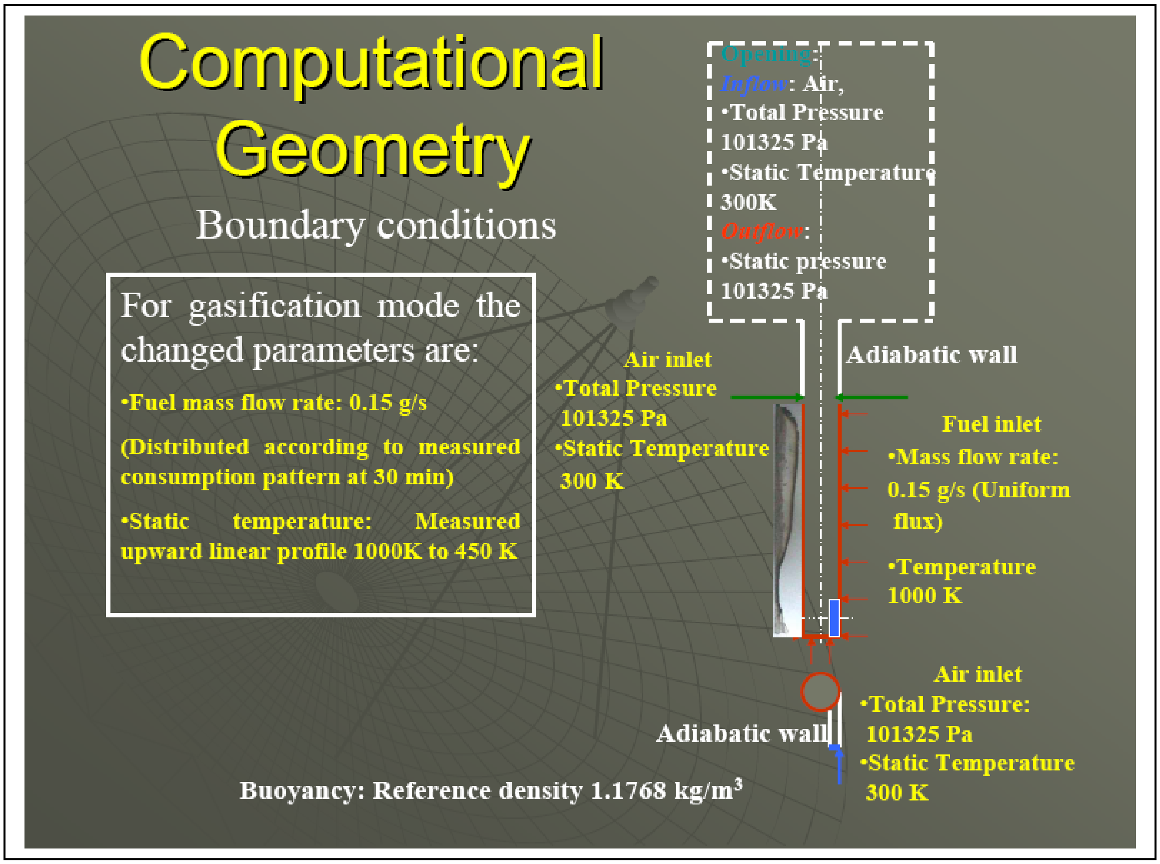


Measurements indicate that limiting the size of the air inlet has led to partial gasification mode operation

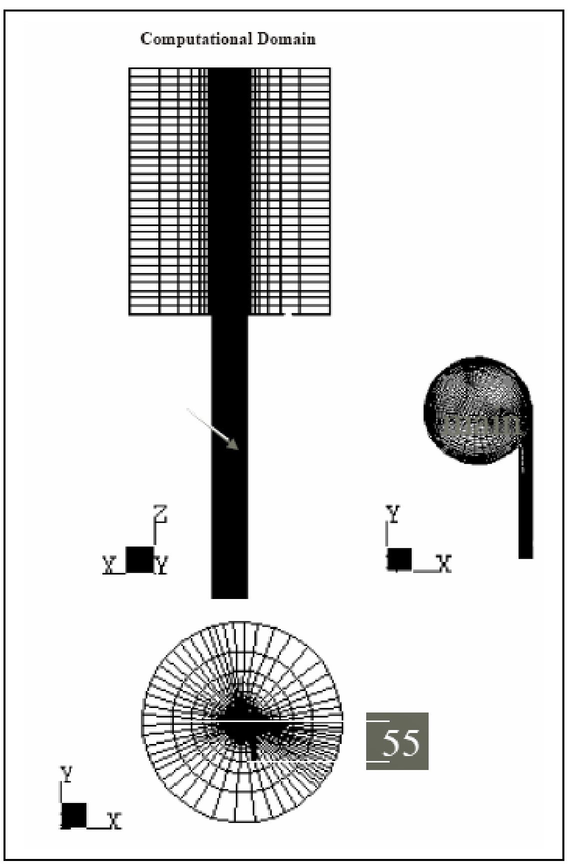
G-phase port radial temperature distribution (AR – 4)



Measurements give temperature profile data for comparison



Computational Domain

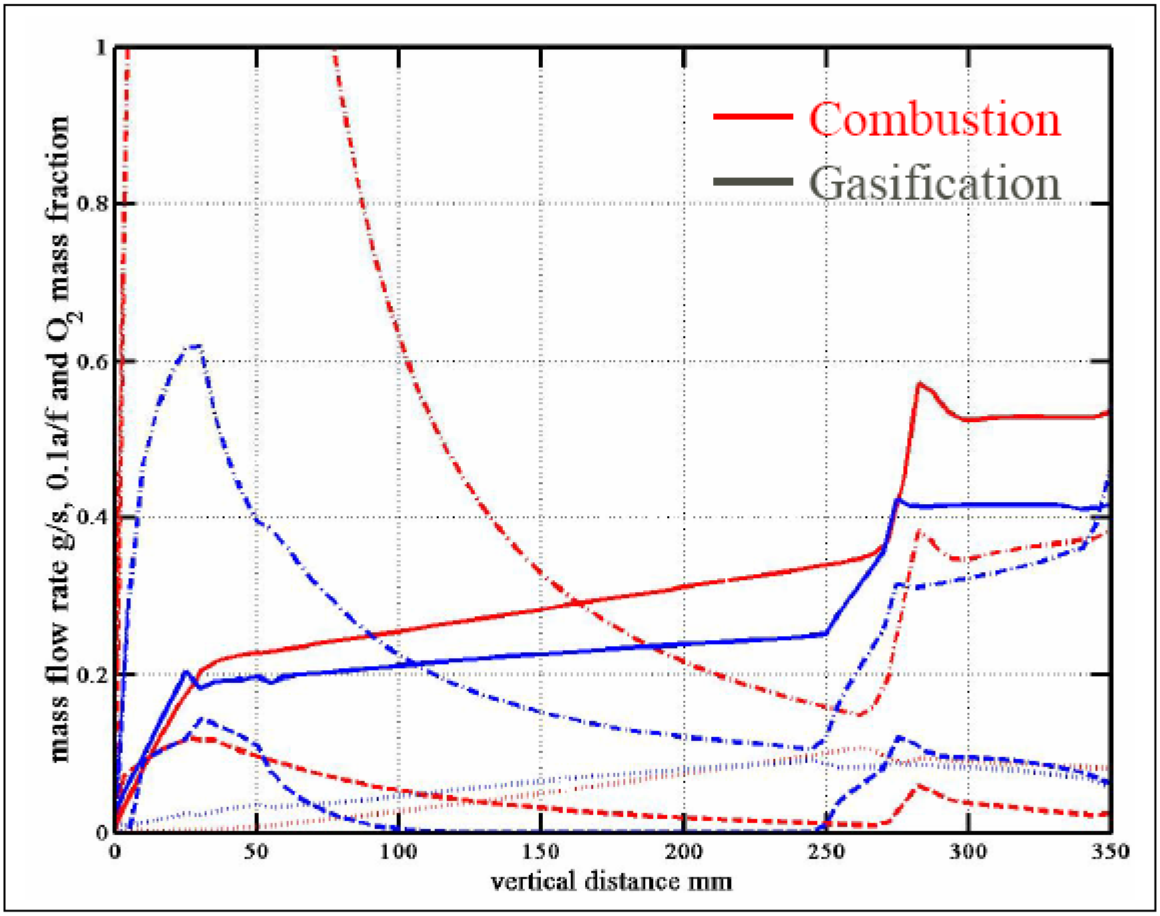


Multi block

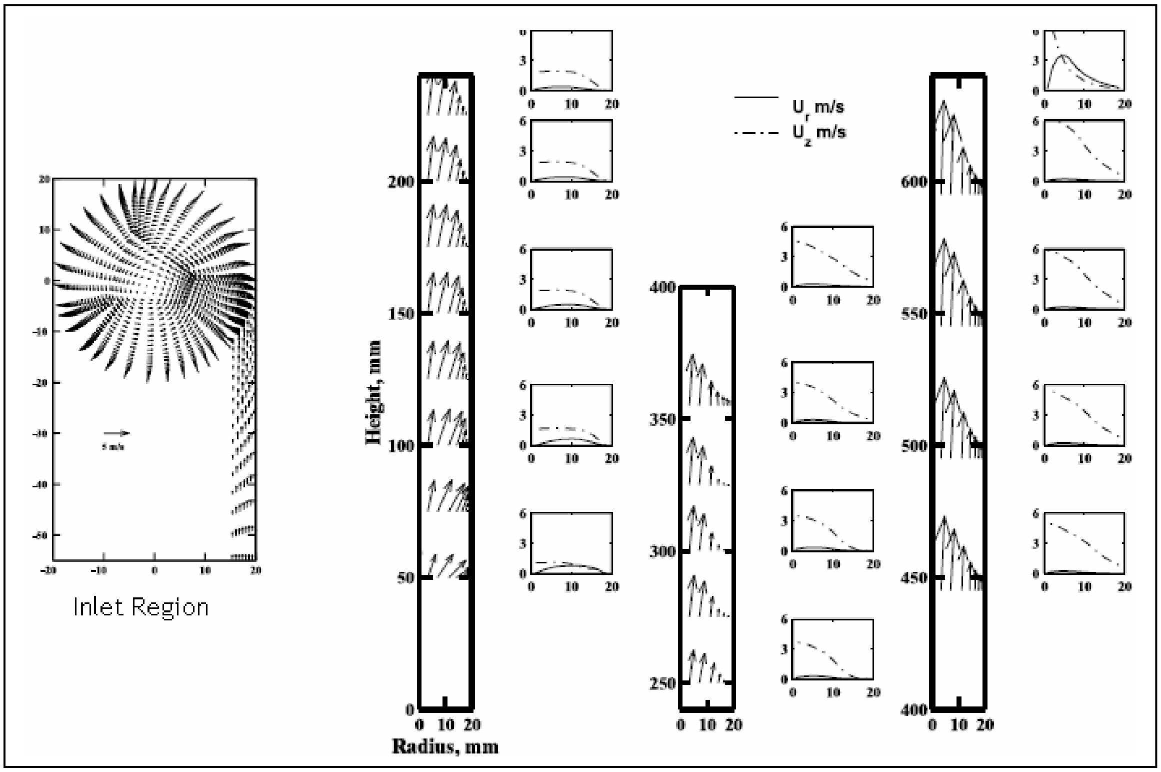
grid	i	j	k
main 16	16	81	7
geo2 26	26	100	16
geo3 26	26	100	16
geo4 66	66	94	16
geo5	31	61	13

216119 nodes

Flow Rate & Air to Fuel ratio

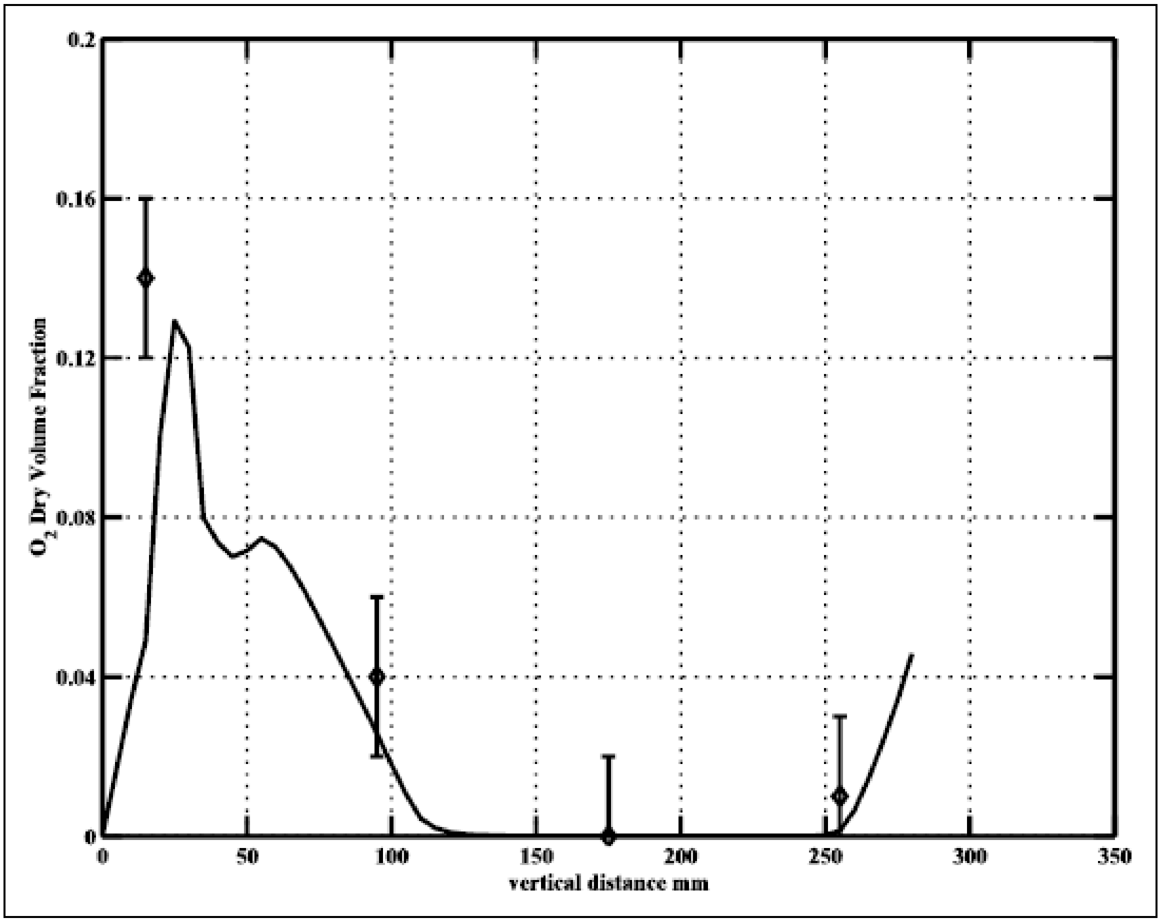


Computational results: Vector Plots



Vectors are indicative of entrance region flow (Flow is not developed) within the fuel port

Vertical Oxygen Profile



Computed Oxygen fraction drops to zero beyond 120 mm

Reactivity of systems

Incense sticks in free convection – 0.04 to 0.06 mm/s

Regression rate limited by the oxygen transport to the surface with surface reaction rates at surface temperatures of 800 to 1000 K.

Pyrolisis gets initiated at 575 – 650 K

Stoves – with air - 0.02 mm/s

G-phase exothermic reaction – peak temperatures of 1500 K, diffusive/premixed mode depending on the design of the process.

C-phase heat transfer in low conductivity sawdust/other pulverized biomass limits the power.

- Hybrid rockets – with O2 - 0.2 – 0.4 mm/s G – phase diffusion controlled heat transfer at g-phase temperatures of 3000 K, Re ~ 2 million
- Solid rocket propellants 2 – 20 mm/s g-phase reaction controlled heat transfer at g-phase temperatures of 3300 K, Re ~ 30 million

Reactivity of systems – a comparison

	Incense sticks	**Stoves**	**Hybrid Rockets**	**Solid Rockets**
Regression Rate, mm/s, pressure	0.04 – 0.06 1 atm	0.02 – 0.04 1 atm	0.2 – 0.4 20 – 40 atm	2 – 20 40 – 60 atm
Regression Rate Control	Oxygen transport to surface	C- phase heat transfer (char presence)	G-phase diffusion controlled heat transfer	G-phase reaction controlled heat transfer
Flow rates	0.3 – 0.4 mg/s	0.1 – 0.3 g/s	3 (f) kg/s 7 (Ox) kg/s	1600 kg/s
Re	~ 50	5000	2 million	30 million
Cal Value	0.5 MJ/kg	16 MJ/kg	12 MJ/kg	5 MJ/kg
Thrust	-	-	25 kN	4000 kN
Power	0.15 – 0.2 W	1.5 – 5.0 kW	120 MW	8000 MW

These have provided an interesting scale range for study

Last word in a field!

- Erosive burning in a solid propellant in highly loaded solid rockets is studied by a large number of international groups.
- It is the dependence of the burn rate of a propellant on the lateral flow.
- A subject of special interest to propulsion designers and very few others.
- An opportunity arose to say the last word and it was said – a correlation for erosive burning.

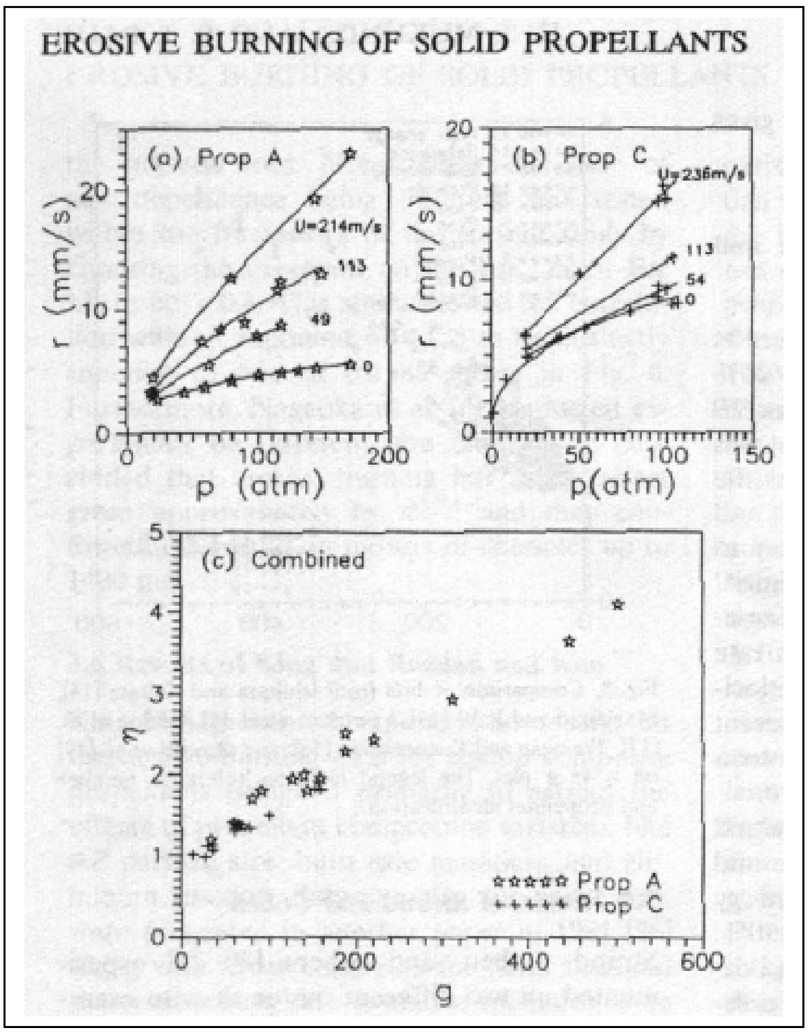
The classical Lenoir and Robillard relation

$$r = ap^n + \frac{\alpha G^{0.8}}{L^{0.2}} \exp(-\beta \rho_c r / G)$$

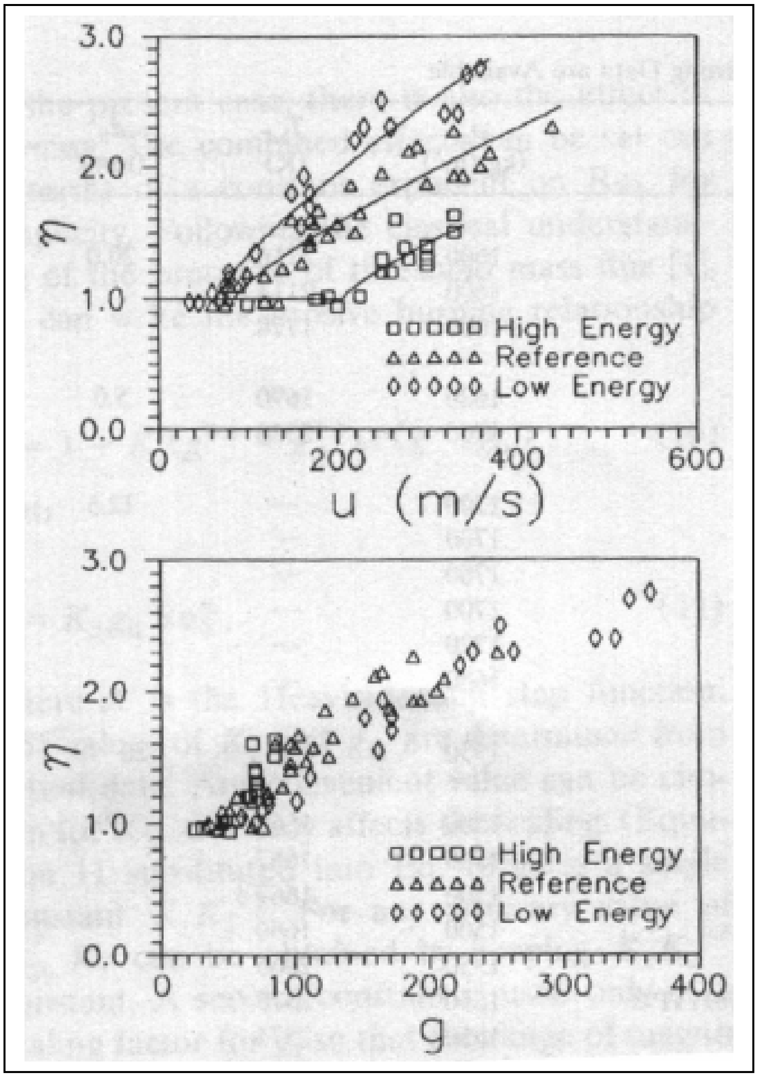
$$\eta = r/r_0,\ g_0 = G/\rho_c r_0$$

The present expectation of all the dependence: η = F (g0)

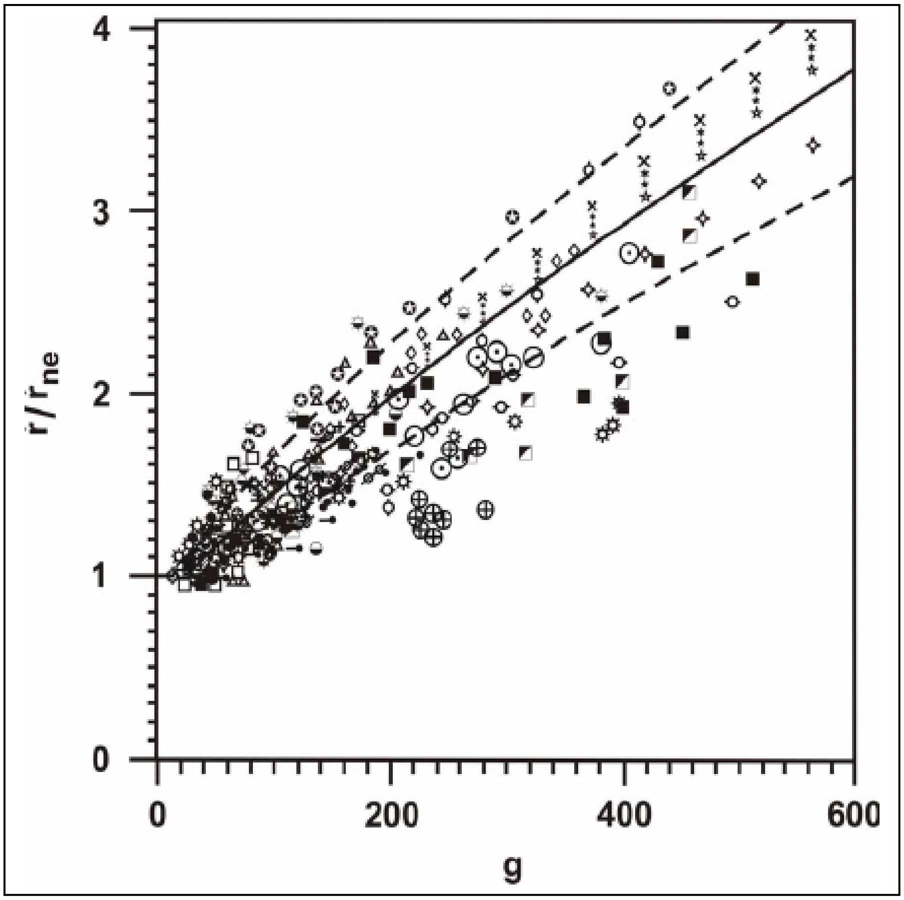
$$\eta = 1 + K_1 (g^{0.8} - g_*^{0.8}) \mathcal{H}(g - g_*)$$



The original data on erosive burning from Marklund and Lake, 1960 and the present coordinate system



The original erosive burning data from three double base propellants by Ishihara and Kubota, 1986 and in the present coordinates



Recognition of a *dimensionless relationship arising out of a fluid dynamical heattransfer* is all that has been used to put together the data from twenty international sources with different facilities, in two cases the same propellant. *There is no way of improving the quality of data given the fact that in building these data many techniques were used carefully.*

Final Remarks

There are a number of problems of combustion – to improve the efficiency of combustion and reduce the emissions that need fine inputs from advanced analytical and experimental tools

A few of them are depicted above.

A few others – gasifier stove for wood sticks whose quality of combustion can be improved with the addition of air by forced convection – using a blower whose electric power is about 0.2 % of the thermal power are needed

Gasifiers for electricity generation using solid fuels is another area that has developed but needs more inputs

All these await attention of scientists and engineers