Combustion S&T in Aerospace & Industry and India

- The actors and aims
- Being followers – even good ones at that or can we be leaders at all?
- Combustion Science and Technology – a few examples
- Possibilities of being leaders? - two examples

The actors and aims

- VSSC, LPSC, DRDL, HEMRL – Rocket propulsion systems
- GTRE, HAL, NAL – Air breathing Engines
- BHEL, IICT, CFRI, CMPDI – Coal energy
- ARA, IIP, Cummins, Greaves, Kirloskers, etc – Reciprocating engines
- BHEL – Industrial gas turbines
- IITs, IISc & other academic institutions – All and sundry R & D

Being followers – even good ones at that or can we be leaders at all?

- 1

VSSC, LPSC

Let us remember we were late to start R & D in space segment

- Solid rocket development for launch vehicles has reached maturity. ‘technology strength’ is commendable
- Scientific strength is respected. New tools like RCFD are accepted without resistance.
- Liquid rocket engine development has had a strange track record. Despite the problems with cryo systems, all related to management issues, the intellectual strength is distinctly present.

Being followers – even good ones at that or can we be leaders at all? - 2

DRDL, HEMRL

- Vigorous focused R & D started only in the eighties.
- Learning from existing systems is a good strategy; this aspect should neither be discarded nor overemphasized.
- W.r.t. propellant system development, there have been some strides; issues are more complex for meeting defense needs compared to space requirements.
- Foundations of managing propellant development not very sound.
- Interface aspects are still poorly handled. ‘S & T’ strength has still to grow substantially.

Being followers – even good ones at that or can we be leaders at all? – 3

GTRE, HAL (NAL)

- Gas turbine engine development – admittedly more complex than rocket engine development.
- HAL’s accomplishments seem to outshine the better profiled GTRE
- Has failed to capitalize on the available resources – academic and otherwise.

Being followers – even good ones at that or can we be leaders at all? – 4

GTRE, HAL (NAL)

- Has been an extraordinary effort to insist that new tools of design – CFD be used – success is still limited.
- Has depended too deeply on expensive, inadequate external inputs through consultancies.
- No attempt to internalize such inputs by involving other institutions.
- On this score, we are perhaps poor followers of known models of technical management in India, let alone other countries

Being followers – even good ones at that or can we be leaders at all? – 4

R/C Engines, Furnaces, etc

- Most designs of R/C engines are imported.
- Very little *mechanistic* work in the country – in academic or industrial institutions; it is largely semi-empirical
- Liberalization has allowed industries to produce more elegant products in automotive sector; concomitant innovation in engine R & D is still insignificant

Acad. Research – Fundamental? Relevant? Both or neither?

- Till mid-eighties had little of major Aeronautical development
- Space technology provided promise of development and involvement even in the late sixties.
- In any case, academics would need to be involved in fundamental work, relevant or otherwise for survival and international respectability; relevance would be valuable but inessential
- It is possible to keep piling up papers, neither truly fundamental nor relevant. Judgements are more fuzzy

Combustion Science – a few examples

- Role of variable properties in diffusion dominated combustion
- Role of chemical kinetics in combustion
  - Flammability limits – Is chemical kinetics alone responsible?
  - Can chemical kinetics cause chaos?
  - Reduced kinetics – is it meaningful?

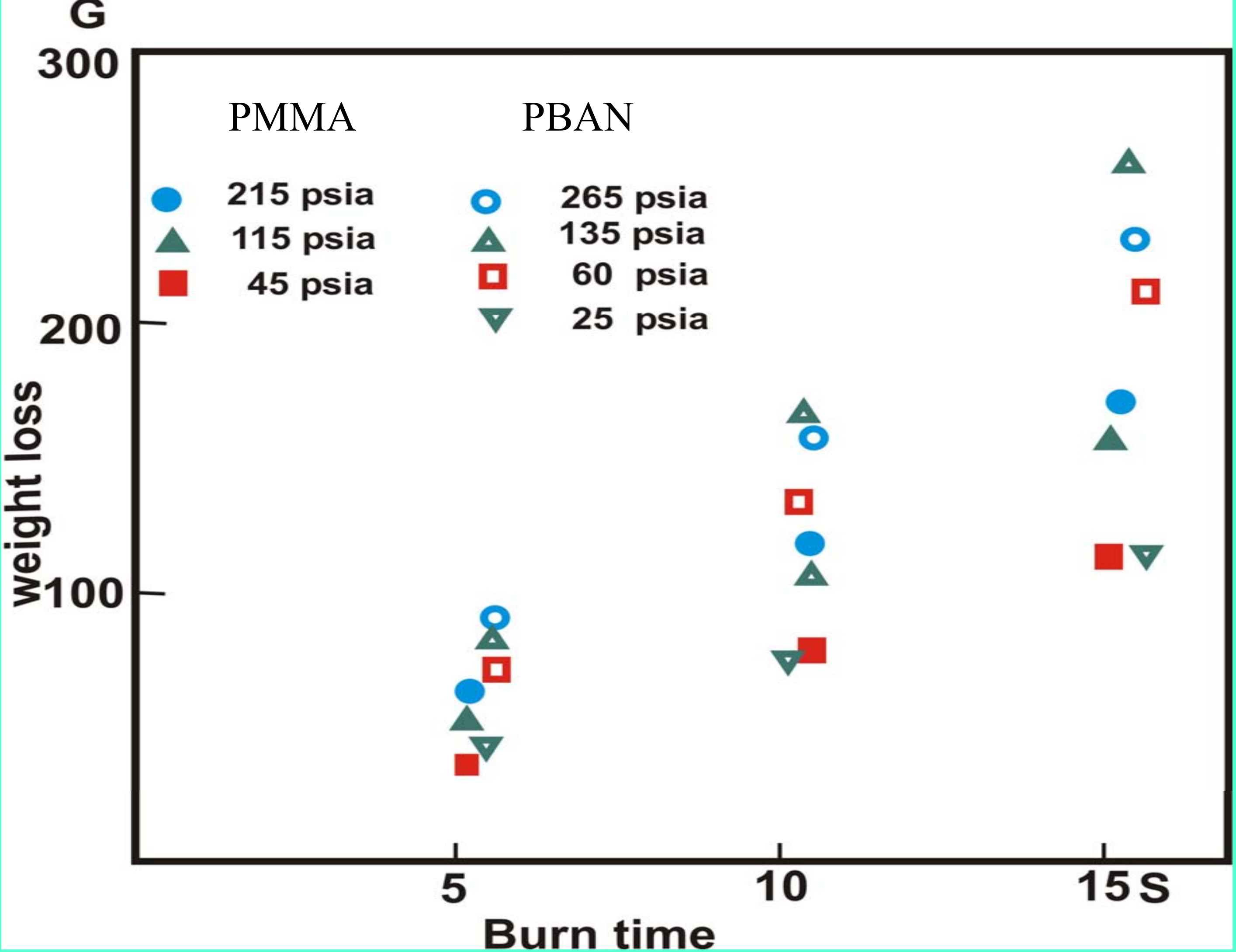
Effect of property variations on diffusive combustion behavior -1

- Turbulent boundary layer combustion over polymeric surfaces
- Free convective combustion over vertical polymeric surfaces
- Liquid droplet combustion process

are all influenced by variable property effects.

Turbulent Combustion over polymeric surfaces

- Limited experiments and a simple constant-property theory showed little dependence of the fuel regression rate in a boundary layer combustion and this led to a ***major conclusion*** that fuel properties do not matter.
- Specifically designed experiments showed that the above result was incorrect.
- The theory was shown to be incorrect since property variations were not properly accounted.



Experimental data for two different polymers and different pressures show substantial differences In regression rate

The regression rate of a fuel block dominated by boundary layer under conditions of fuel injection from wall with variable density – due to temperature and Molecular weight of gases – as high as 400 to 600 near the wall and obtain -

$$\rho_{\rho}\dot{r} = 0.03G^{0.8}B^{0.23}$$

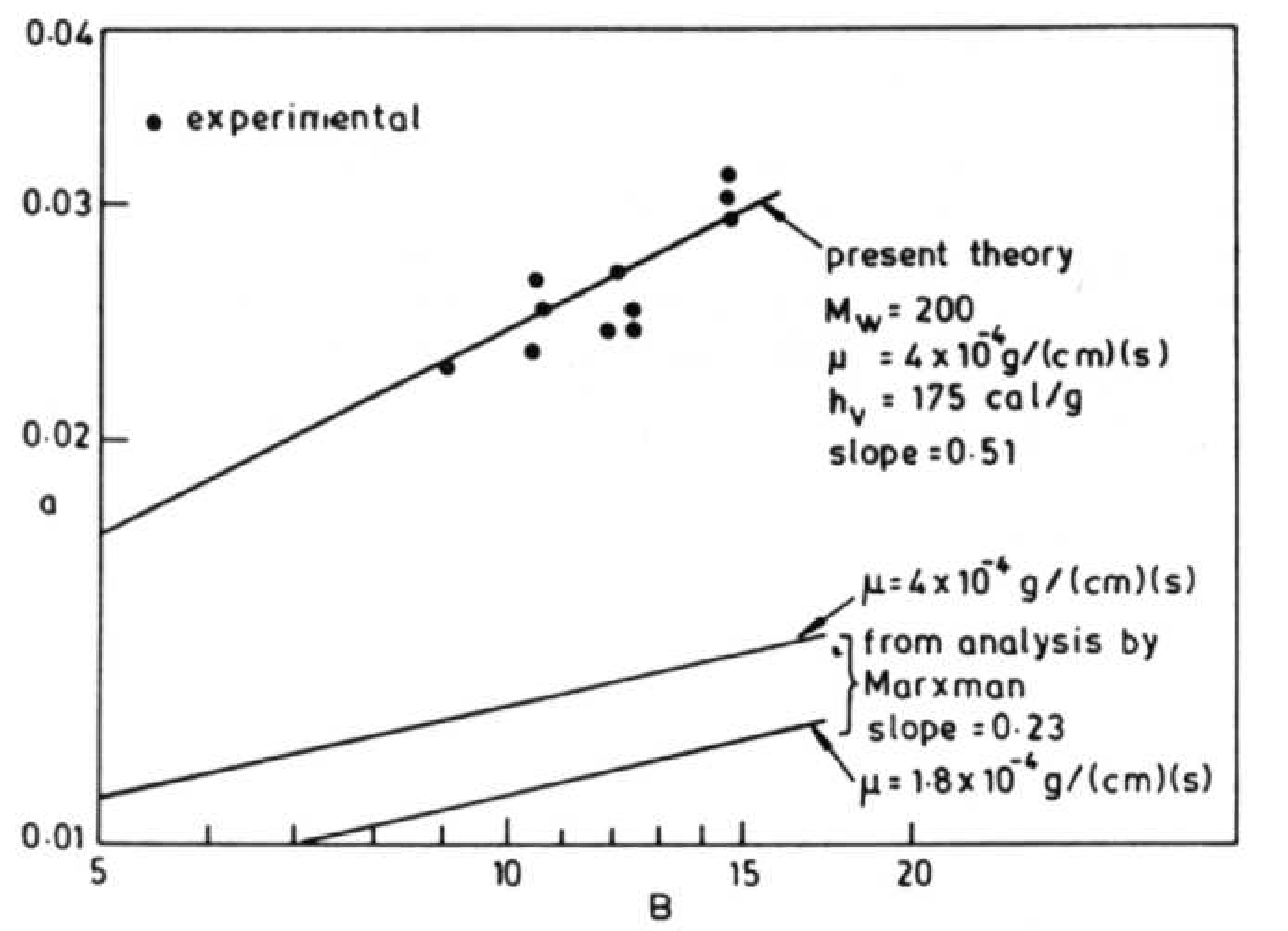
$$\rho_{\rho}\dot{r} = 0.056G^{0.8}(x/\mu)^{-0.2}(\rho_{f}/\rho_{\infty})^{0.71}(\rho_{w}/\rho_{\infty})^{0.14} \times B(1+B)^{-[0.73-0.002(\rho_{w}/\rho_{\infty})]}.$$

Where ρ is the density with suffixes – p – c-phase, w – fuel vapor at wall, G, the mass flux across the fuel block, B = Transfer number

“Blocking” effects due to high Molecular weight segments affecting the local gas density, variation of thermal conductivity and specific heat are all responsible for the observed effects.

Weight loss data of Woodridge et al (1969) and theory

Fuel	**B**	**G_{ox} kg/m^{2}s**	**Exptl fuel weight loss, g**	**Fuel Wt. loss Marxman's theory, g**	**Molecular weight of gases near wall**	**Weight loss by present theory**
PMMA	9.3	70.3	160	130	90-100	180-190
PBAN	8.0	77.3	260	132	250-350	260-280
PU	8.0	77.3	220	132	150-250	220-250



Notice the different slopes – **use of variable properties leads to altered physics**, not just accuracy of prediction

Paul, Mukunda and Jain, 19th Symp (Int) on Combustion, 1982

Free convective laminar combustion over vertical surfaces (including polymers)

- Constant property similarity solutions based predictions were considered qualitatively “good”
- Quantitative comparisons were poor.
- Variable property theory improved the comparisons for a dozen fuels of interest including polymeric fuels.

Comparison of results with experiments

Fuel	B	Constant Properties		Variable Properties		Experiment	% Error
		$y_f/x^{1/4}$ $(\times 10^3)$	$\dot{m}''_{av}$ $(\times 10^3)$	$y^f/x^{1/4}$ $(\times 10^3)$	$\dot{m}''_{av}$ $(\times 10^3)$	$\dot{m}''_{av}$ $(\times 10^3)$	Theory experiment /experiment $(\times 100)$
Methanol	2.57	14.4	13.1	12.0	13.0	15.0	-13.3
Ethanol	2.73	16.9	15.3	12.1	13.0	15.0	-9.3
Acetone	4.61	18.7	20.2	12.8	15.6	15.9	-2.0
Benzene	5.58	21.4	24.4	13.9	16.7	16.5	1.2
Toluene	5.38	21.6	24.5	13.4	16.4	15.7	4.5
Xylene	5.10	21.7	23.5	13.6	15.4	14.3	7.7
Kerosine	3.15	21.2	20.1	11.6	14.1	16.5	-14.5
Cellulose	1.08	13.5	9.4	8.2	8.0	7.5	6.6
PMMA	1.69	15.6	12.1	10..2	11.2	10.4	7.9
PMMA-O_2	7.79	20.1	29.0	10.3	23.1	24	3.8

Hegde, Paul and Mukunda, 21st Symp. (Int) on Combustion, 1986

Units for $y^f/x^{1/4}, m^{3/4}, m''_{av}$ are $kg/m^2 s$. Oxidant in all cases is air (except the last one).

Liquid droplet combustion

- Liquid drop combustion under zero-g conditions has been extensively studied experimentally (Japanese scientists)
- Under steady conditions, the flame-to-drop diameter ratio (d_f / d_0) is known to be around 12 to 15 for many hydrocarbons like n-heptane.
- Simple constant property theory predicts a value of 32 for d_f / d_0. Predictions of mass burn rate are "fixed" by the choice of parameters.
- These issues are to be resolved using a variable property theory – that can be very accurately formulated and results obtained.

The Formalism involves coordinate transformations as below

$$1/r = (4\pi)/\dot{m}J(\eta), \quad J(\eta) = \int_{\eta}^{1} (k/c_p)(d\eta/\eta),$$

was used to obtain (d_f/d_s) as

$$(d_f/d_s) = J(\eta_s)/J(\eta_f), \quad K_c = (\delta/\rho_c)J(\eta_s),$$

$$T_f = [T_\infty/I_2(1) + T_s/I_1(\eta_f)\exp P(\eta_s,\eta_f) + (a_1 h_{1f} + a_2 h_{2f} + a_3 h_{3f})/(\eta_f a_1)] \div$$

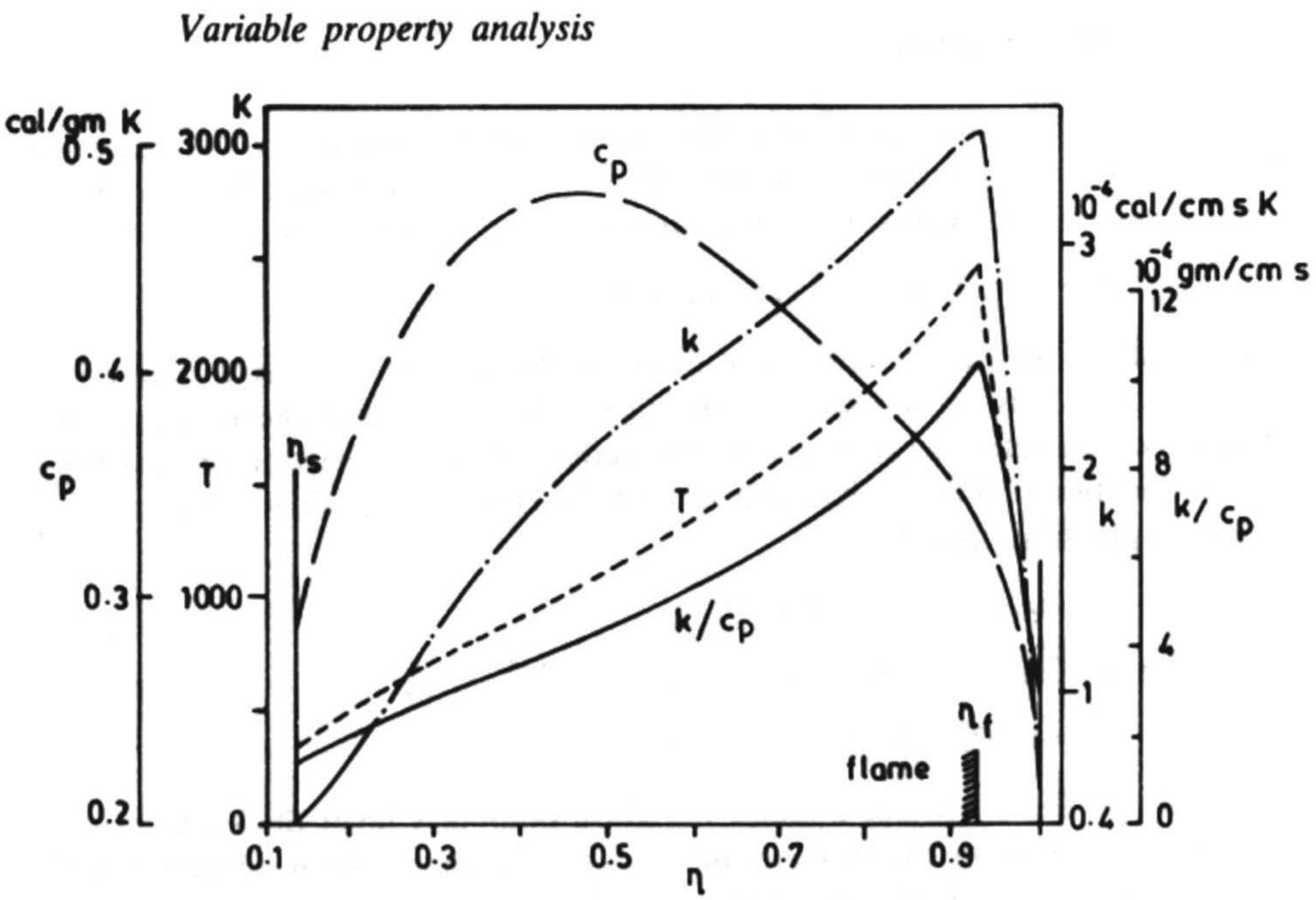
$$\{1/I_2(1) + [1/I_1(\eta_f)]\exp P(\eta_s,\eta_f)\},$$

where ,

$$I_1(\eta) = \int_{\eta_s}^{\eta} \{(1/c_p \exp[P(\eta_s,\eta)]\} d\eta, \quad I_2(\eta) = \int_{\eta_f}^{\eta} \{(1/c_p \exp[P(\eta_f,\eta)]\} d\eta$$

$$P(\eta_1,\eta_2) = -\int_{\eta_2}^{\eta_2} \sum_{1}^{4} \{(1/c_{pi}/c_p)Le_i(dY_i/d\eta).$$

Raghunandan and Mukunda, Combustion and Flame, 1977



Use of variable property analysis reproduces d_f/d_0 quite accurately, and improves the mass burn rate prediction

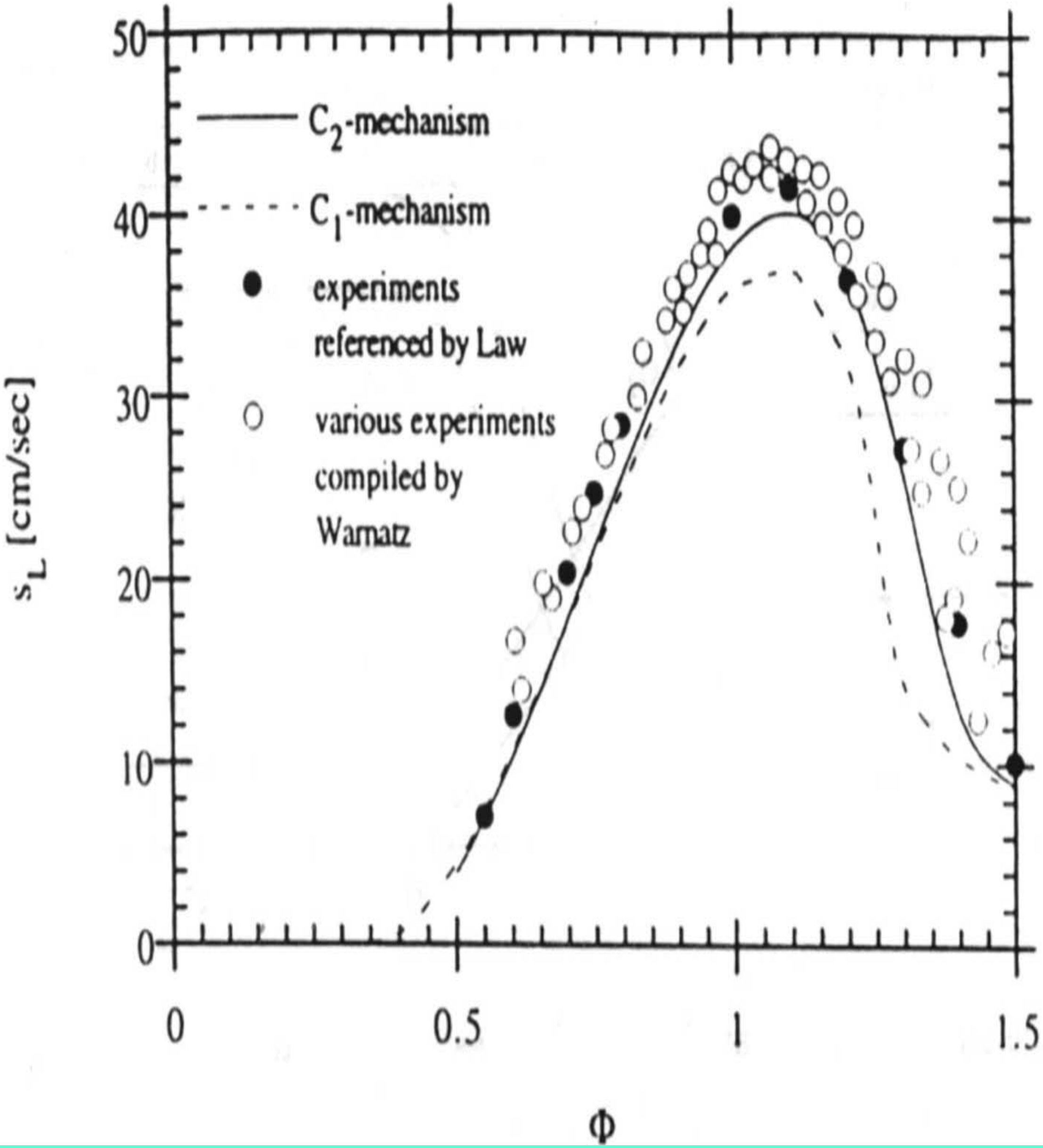
Raghunandan and Mukunda, Combustion and Flame, 1977

Role of chemical kinetics in combustion - 1

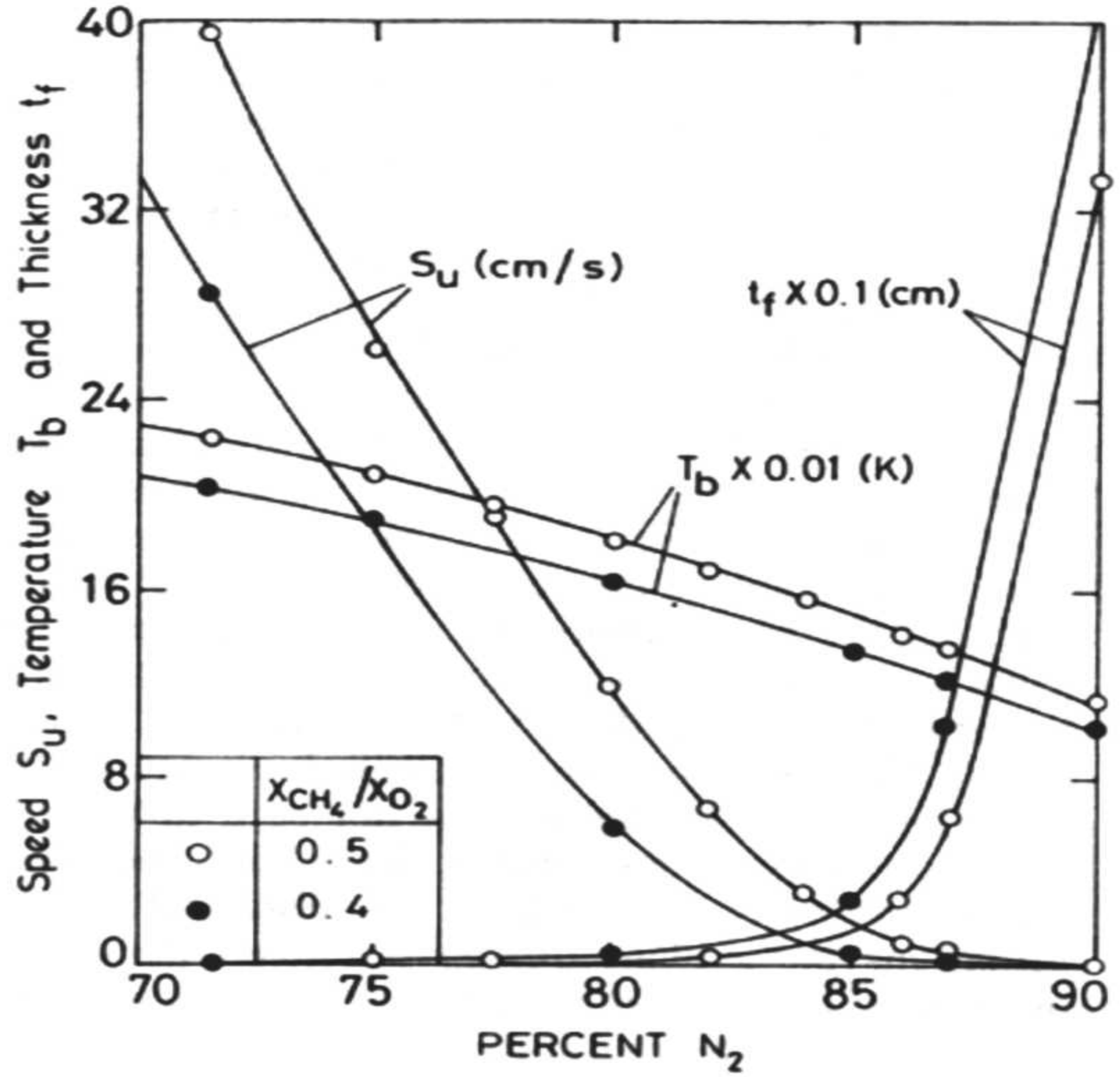
- In the early seventies, single step chemistry and asymptotics were the fashion.
- The key parameter activation energy, E in $\exp\{-E/RT\}$ was taken large; rather $\theta = E/RT_{ad} \rightarrow$ infinity
- This led to some understanding of the processes
- For instance, ignition delay, rate of premixed flame propagation, thickness of a diffusion flame all were varying like $\exp\{-\theta\}$, a result that is definitely elegantly deduced, but can be obtained nevertheless by less elegant means.

Role of chemical kinetics in combustion - 2

- Development of chemical kinetic models, faster computational tools – algorithms and computers have all allowed detailed exploration of combustion processes.
- Yet some scientists have asserted the value of asymptotics for the next 20 years!
- One problem that needed full chemistry to resolve a fundamental combustion problem was “flammability”
- Flammability limits – is chemical kinetics alone responsible?

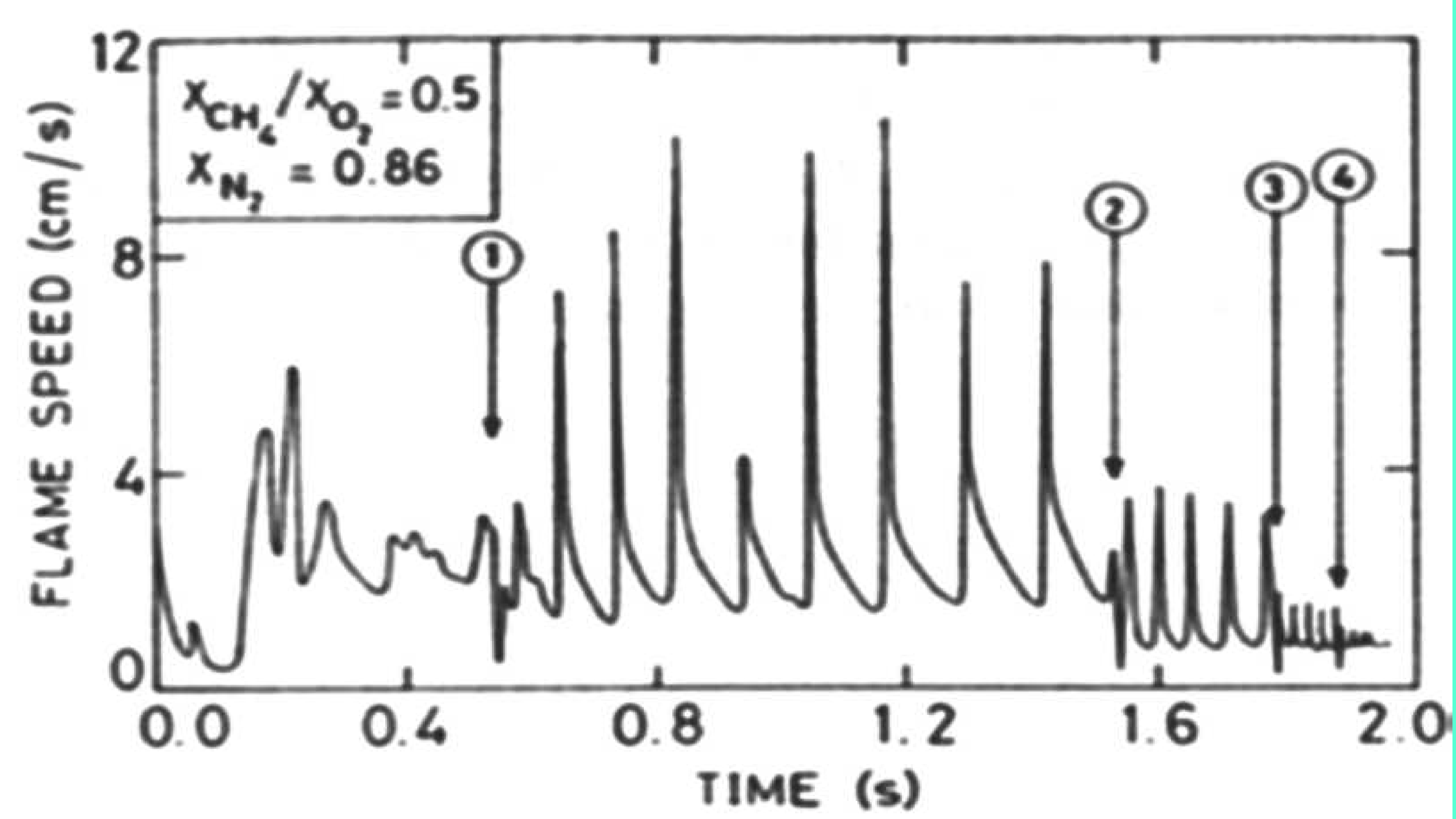


The flame propagates in the equivalence ratio between Φ = 0.5 (lean) to 1.5 (rich). The values of Φ = 0.5 and 1.5 are the lean and rich limits



Computational results for $CH_4 - O_2 - N_2$ mixtures; Experimentally observed limit = 85 % N_2 ; Full chemistry calculations – 14 species and 29 reversible steps

Lakshmish, Paul and Mukunda, 22nd Symp (Int) on Combustion, 1988

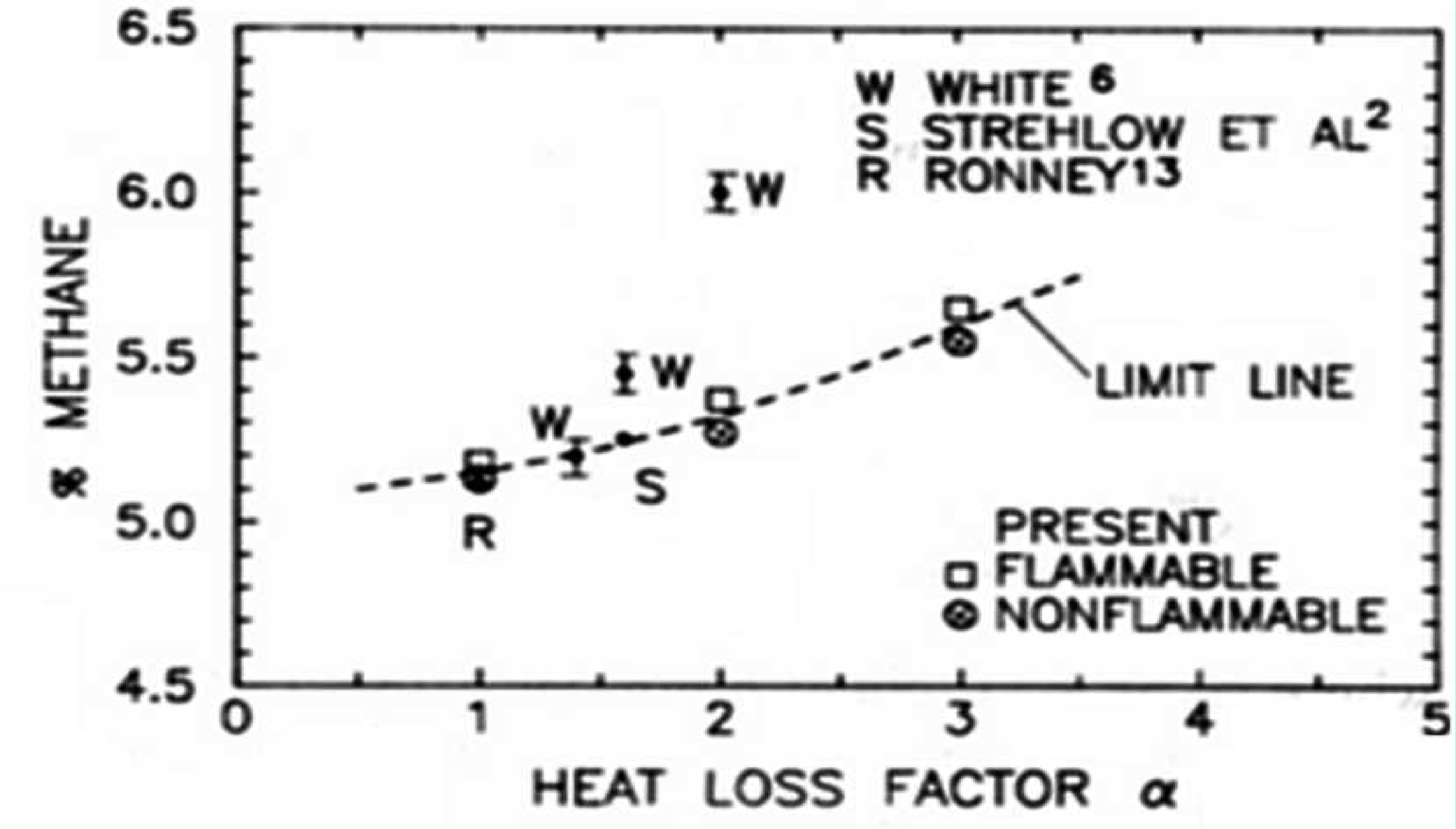


The numerical calculation with a time dependent one-dimensional code developed at the laboratory showed steady state after many grid refinements a clear steady state. The oscillations are not real.

Lakshmish, Paul and Mukunda , 22nd symp (Int) Combustion, 1988

The message -

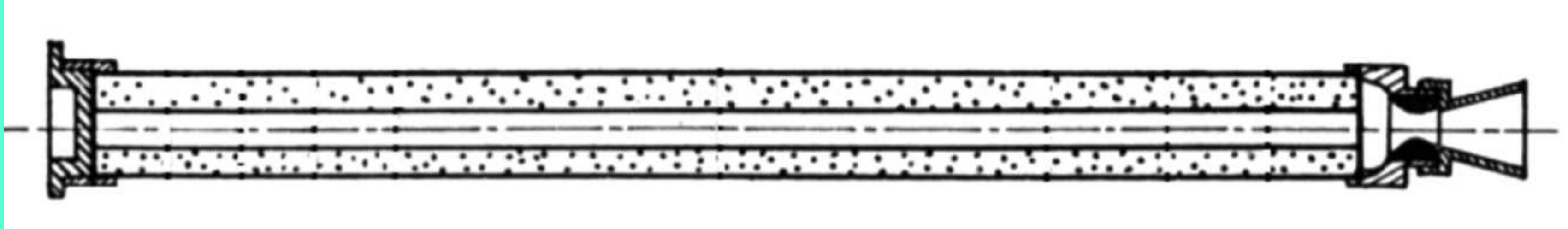
- Adiabatic flame does not have a flammability limit.
- If observed limit has to be explained or predicted, one needs to use a irreducible minimum heat loss by radiation/convection in the procedure.



Calculations made with a model for heat loss for propagation in tubes showed that experimentally observed limits could be Predicted. Not only that – that a larger heat loss factor alters the Limit only slightly.

Lakshmish, Paul and Mukunda, 23rd Symp (Int) on Combustion, 1990

Erosive burning in solid propellants



- Burn rate dependence on lateral flow of gases.
- Argued as due to enhanced convective transfer.
- There is large amount of experimental data for various dependences (composition & pressure)
- There is simple theory – Lenoir and Robillard understood and interpreted variously.
- There are some fifty papers with at least four review articles over the last forty years – with 26 different correlations – the perception of the problem becoming more and more complex with time!

L & R Theory

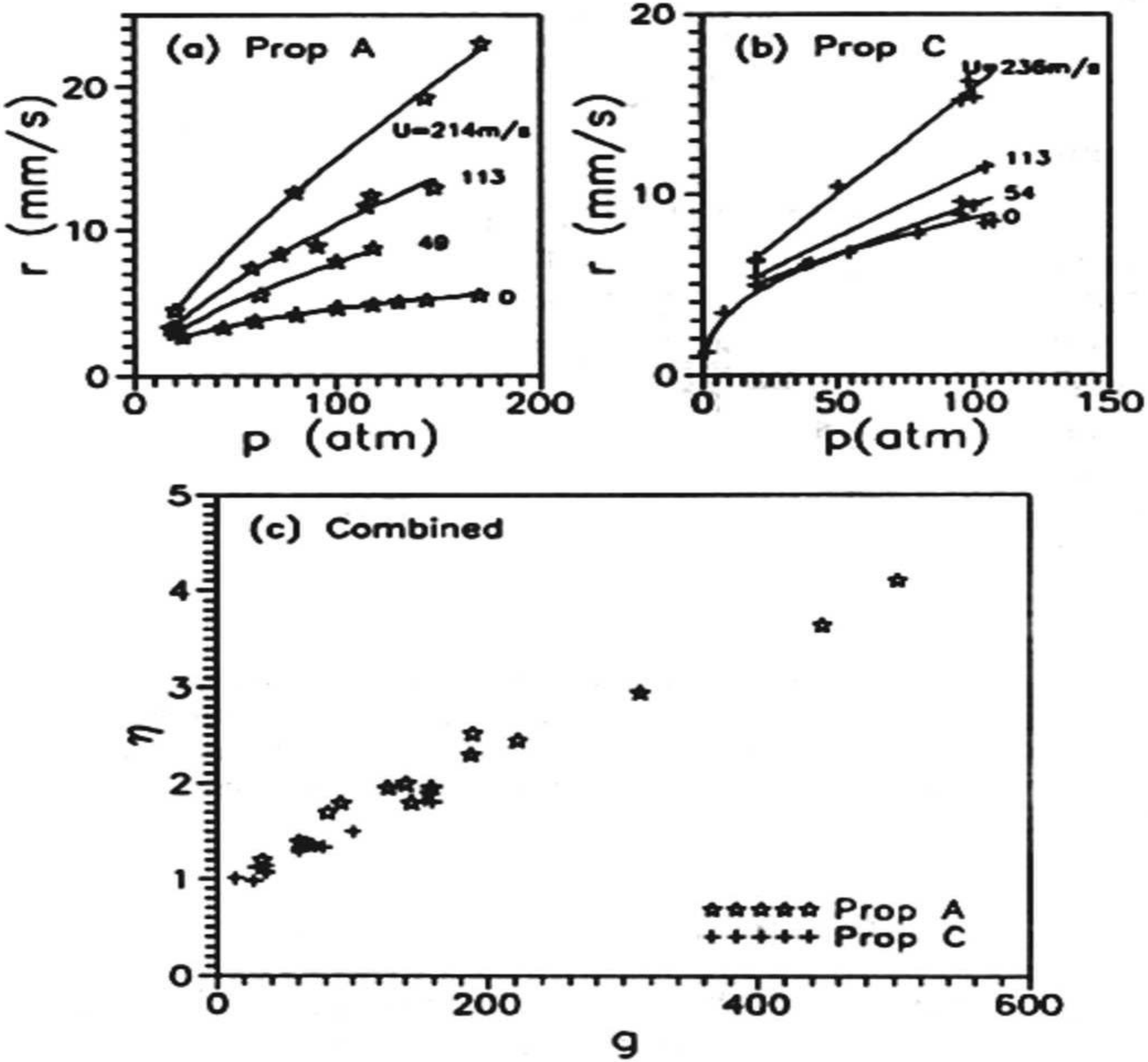
$$r = ap^n + \frac{\alpha G^{0.8}}{L^{0.2}} \exp\left(\frac{-\beta \rho_p r}{G}\right),$$

The present Non-dimensional expression

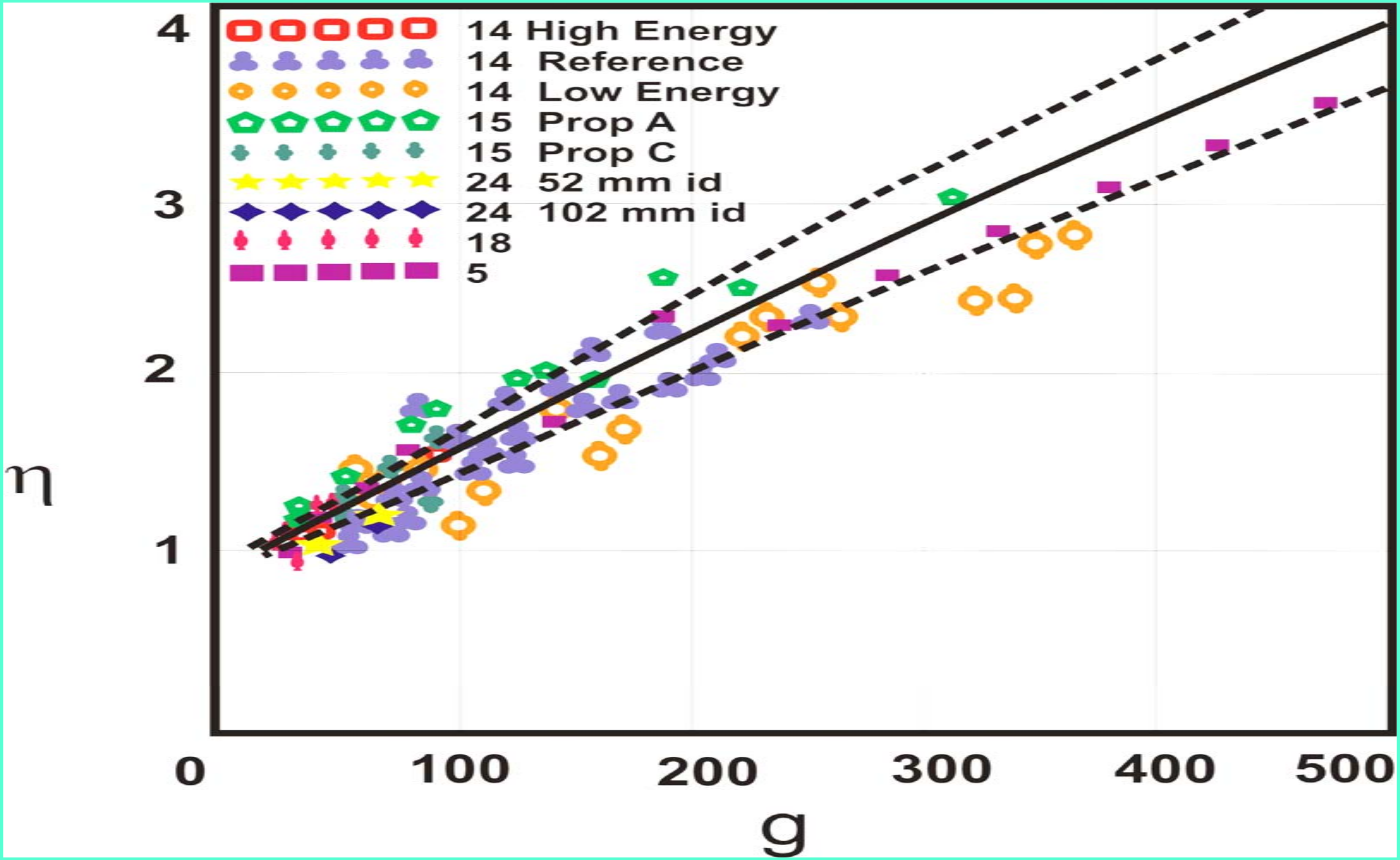
$$\eta = 1 + K_1 (g^{0.8} - g_{th}{}^{0.8}) \mathscr{H} (g - g_{th})$$

with

$$g = K_2 g_0 \operatorname{Re}_0^m, \;\; \eta = r / ap^n$$

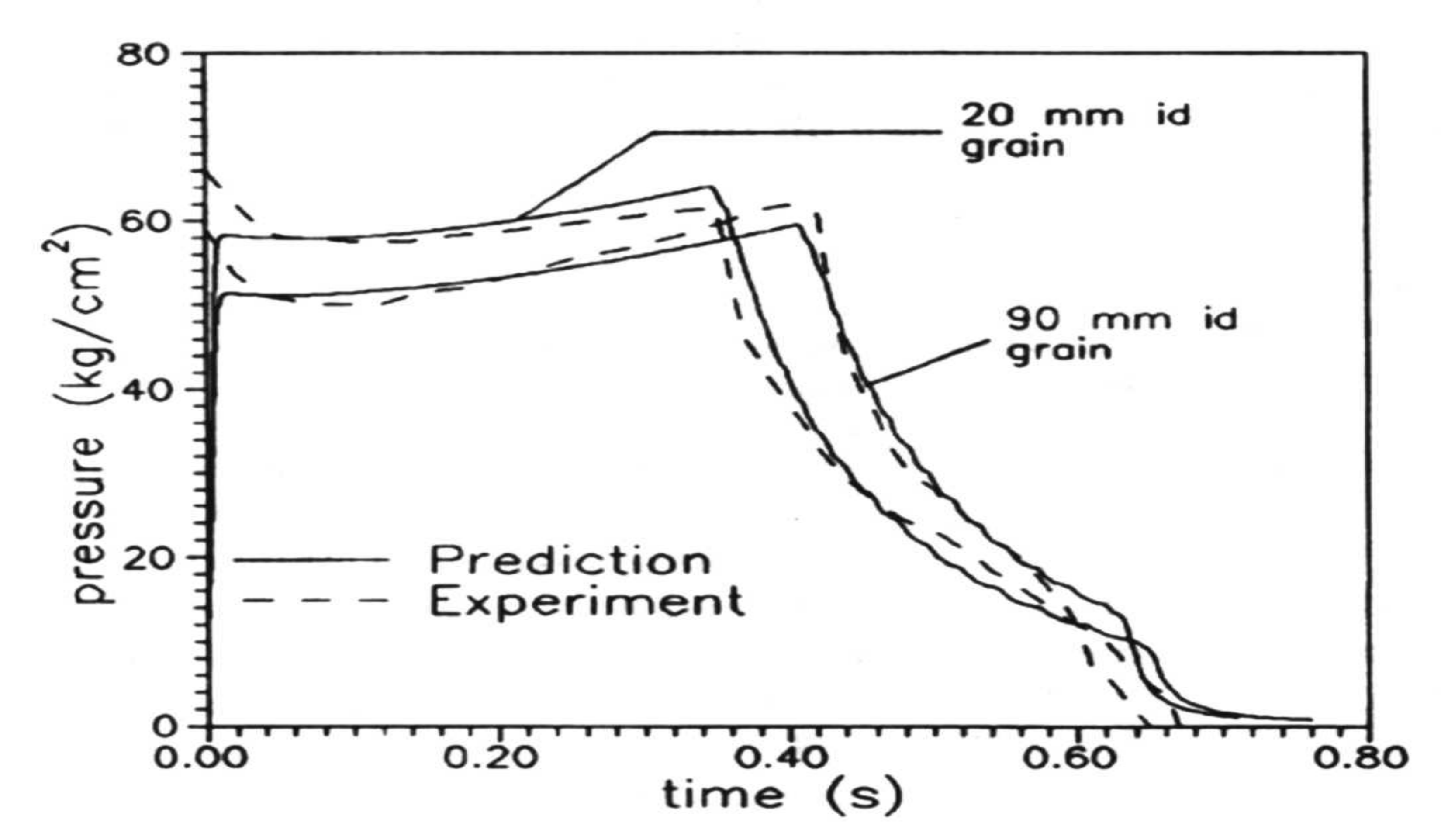


Mukunda and Paul, Combustion and Flame, 1997



With experimental data from over twenty investigators over 6 countries and over thirty years on a dozen different propellants all the data fitting into, the curve is universal.

Mukunda and Paul, Combustion and Flame, 1997



Predictions of pressure time curve of a highly loaded (implying significant erosive burning) solid motor and experimental data from a Japanese work.

Mukunda and Paul, Combustion and Flame, 1997

Conversion of solid fuels to clean gaseous fuels and use for heat and electricity

- Literature – scientific or engineering/technology showed that issues of the clean use of solid fuels have been addressed much less than gaseous or liquid fuels.

- This position has not changed much even today.

- This provided opportunity to do frontier work in the science and technology and due to concerted action and support has led to world leadership in the area – science and more importantly technology.

- 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 320 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.

Consequently ….

- There are 20 published papers in refereed journals.
- Technology development of gasification systems for converting any bioresidue including USW into clean gas for heat or electricity.
- The only well tested scientific data on gasification systems published in journals and on the web.
- Technology transfer to four industries in India, one in Switzerland and one to Japan (in fact fourteen countries through this company).
- Two international training programs for scientists from South America, South east Asian countries, and Europe

[web page: http://cgpl.iisc.ernet.in]

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

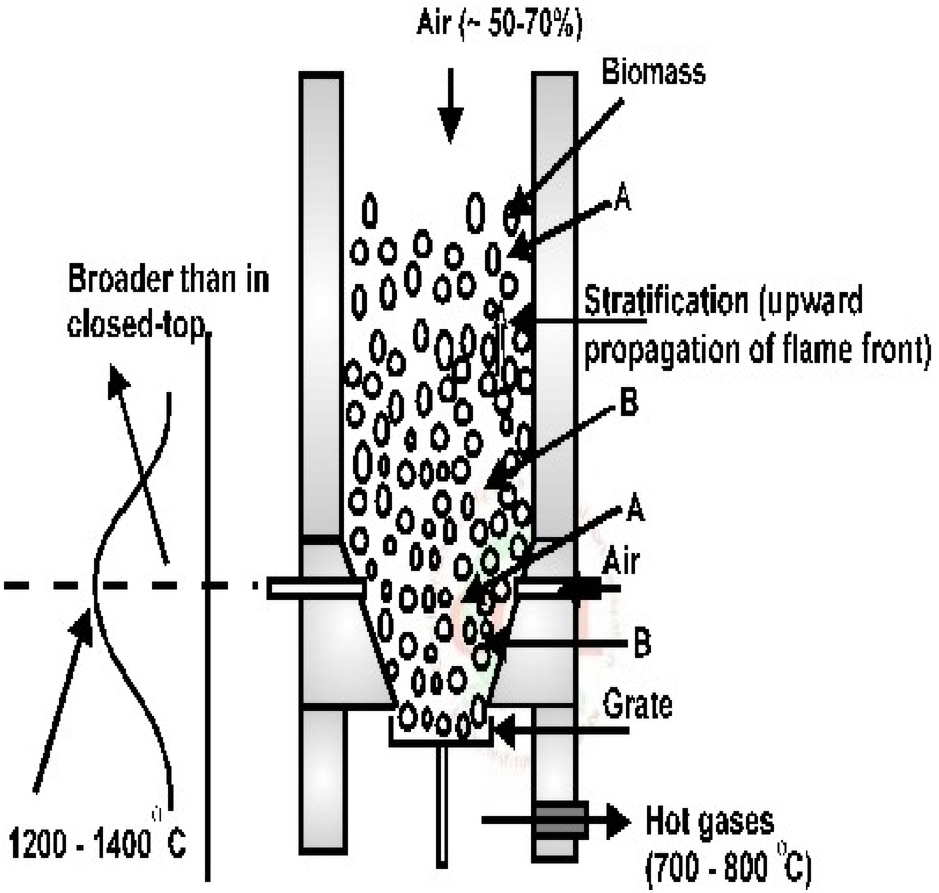
Pine Needles

Rice Husk

Saw Dust

Sugar Cane Thrash

Wood



Use them in a vertical reactor. Introduce air at appropriate places to create the 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.

$$\textbf{Biomass + Air} \xrightarrow{Heat} \textbf{Products (Partial) + Char, } N_2 \textbf{ + Heat}$$

$$\textbf{(Upward propagation of flame front)} \rightarrow \textbf{A}$$

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

$$\textbf{Char + } CO_2, H_2O, N_2 \rightarrow CO, H_2, CH_4, N_2 \rightarrow \textbf{B}$$

Schematic of Wood Gasifier for Power Generation application

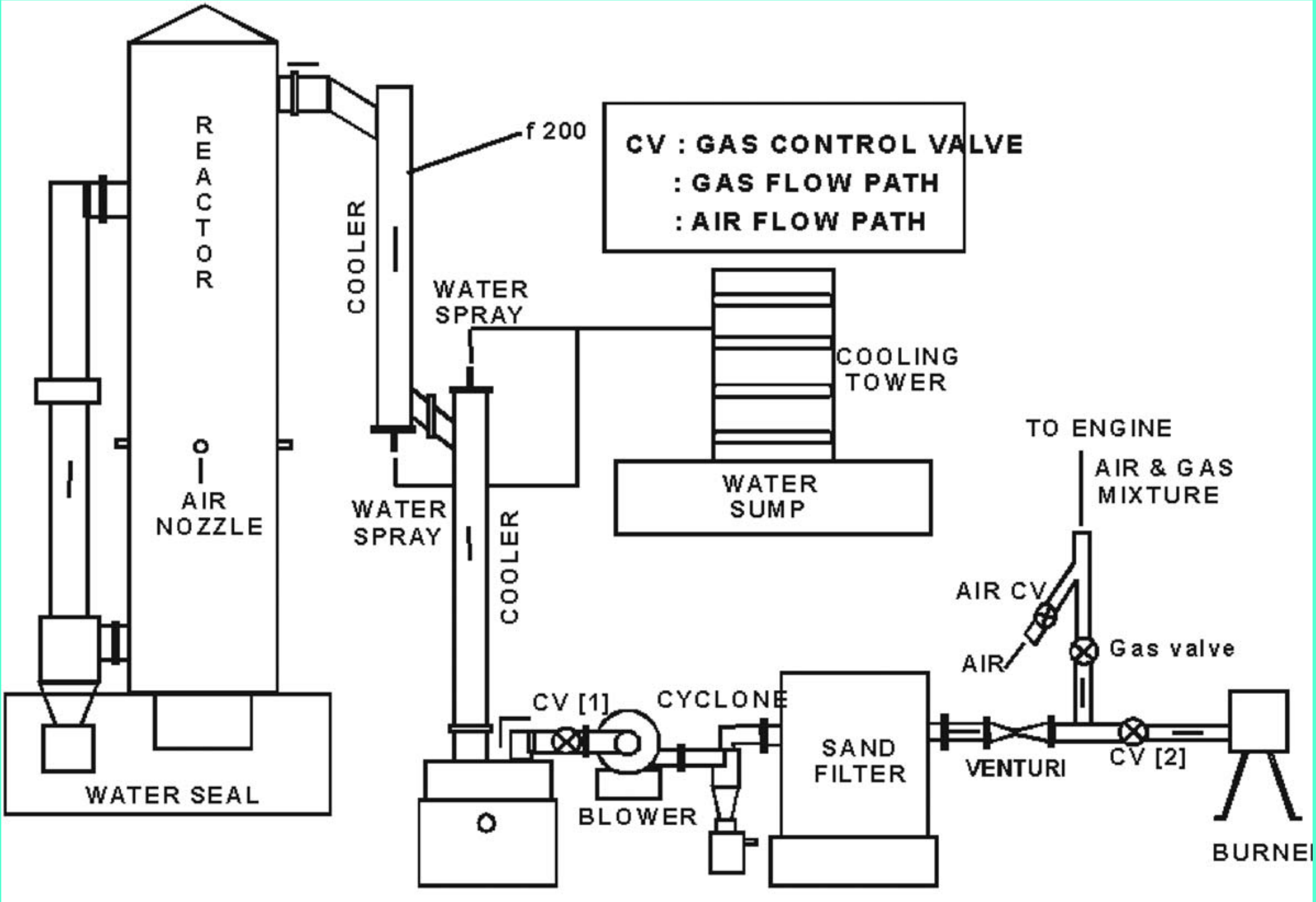


Fig. 2 SCHEMATIC OF WOOD GASIFIER FOR POWER GENERATION APPLICATION

Installations

- Four industrial thermal applications – heat treatment, drying tea, marigold flowers – all where the cost of energy in the product is high (30 to 40 %) – 300 to 500 kg/hr
- Six Electricity generation – 20, 100, 300, 1000 kWe – village electrification, industrial needs
- Research and Development – for trying out new biomass or non-biodegradable organics from USW.
- A dozen other industrial projects in India (including USW for Bangalore) and abroad are getting formulated (Brazil, Thailand and Cuba)

Power Gasifiers

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

Trigeneration to improve economics of operations

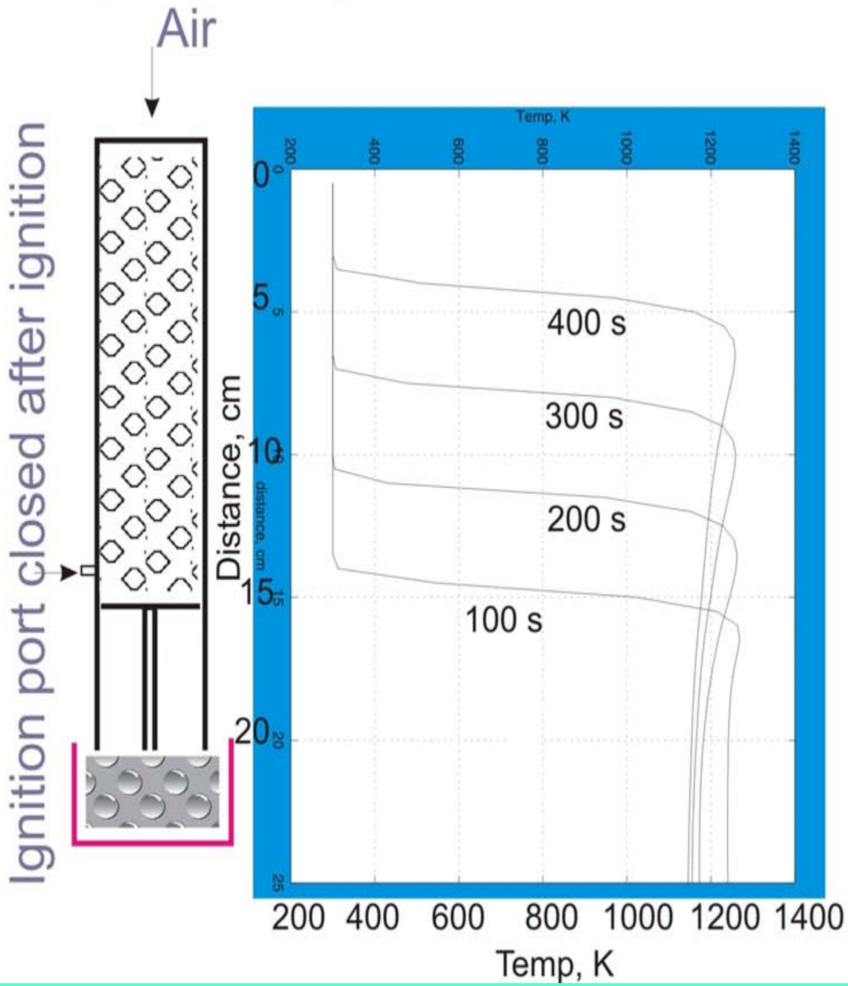
- Generate electricity, heat and value added products simultaneously.
- Coconut shell or hard wood can give electricity, heat and activated carbon of industrial quality directly. With slight up-gradation, one gets pharmaceutical quality product.
- Rice husk can give electricity, precipitated silica and activated carbon.
- 1 MWe power plant near Coimbatore generates electricity and activated carbon (Iodine number 550 to 600)

Useful scientific studies on biomass conversion

- Flame propagation rate in the reactor and ash fusion processes – important for several agro-residues like coconut coir pith, sugarcane tops and leaves, all of which have high inorganic low melting compounds – Potassium based (from fertilizer use)
- Calibrated predictive procedure for the above – needing rates of conversion of char with mixtures of air, CO_2 , H_2O and N_2.
- Characterization of Producer gas as a fuel in external and internal combustion engines.
- Modeling of producer gas based SI engines.

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

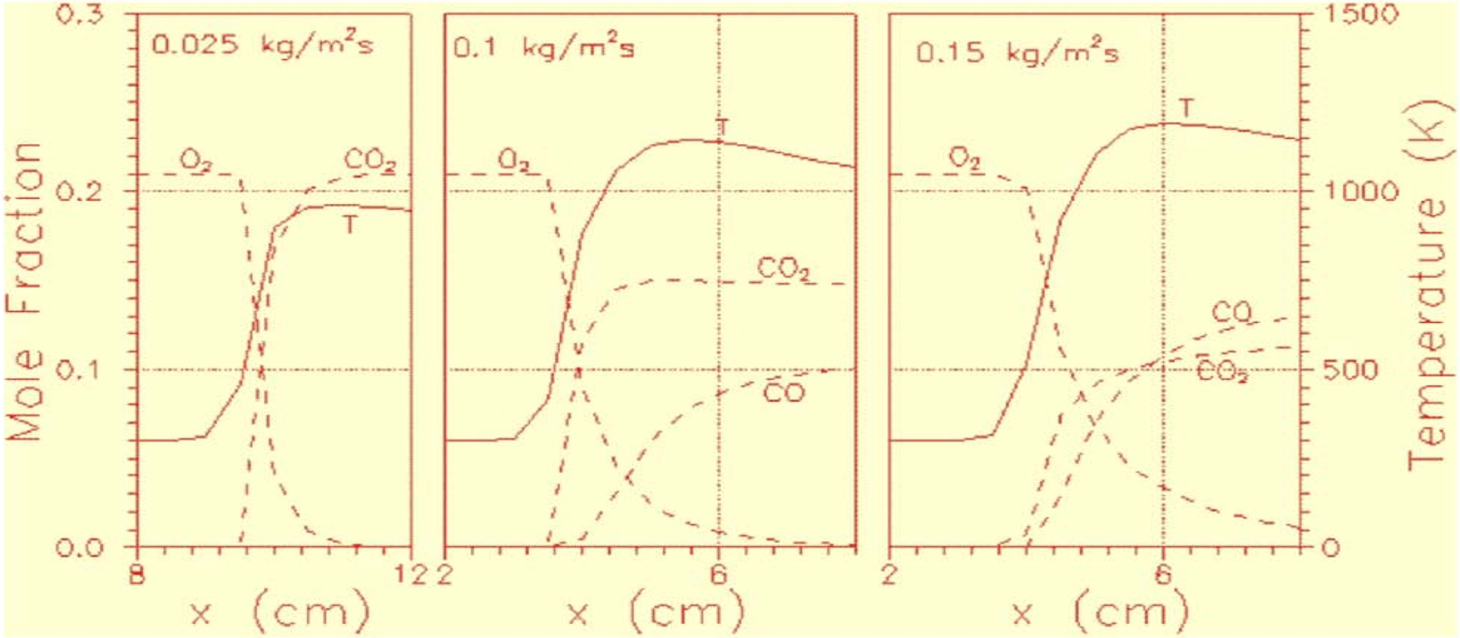
Solve for the individual particle and then for the packed bed

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

Dasappa, Paul and Mukunda, and Srinivasa, 27th Symp. (Int) on Combustion, 1998

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

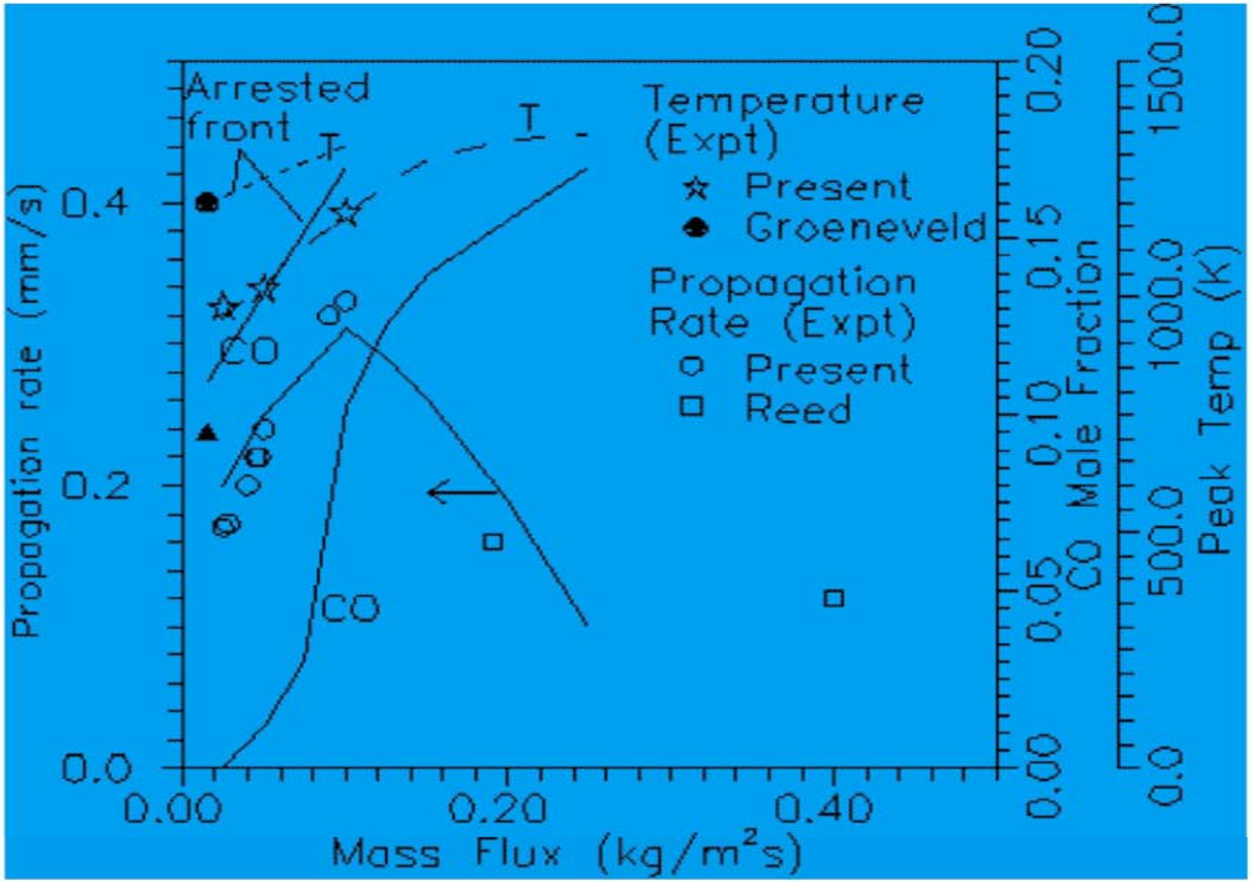
- Profile chosen when the rate of propagation of the reaction front through the bed is constant



- 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

Dasappa, Paul and Mukunda, and Srinivasa, 27th Symp. (Int) on Combustion, 1998

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



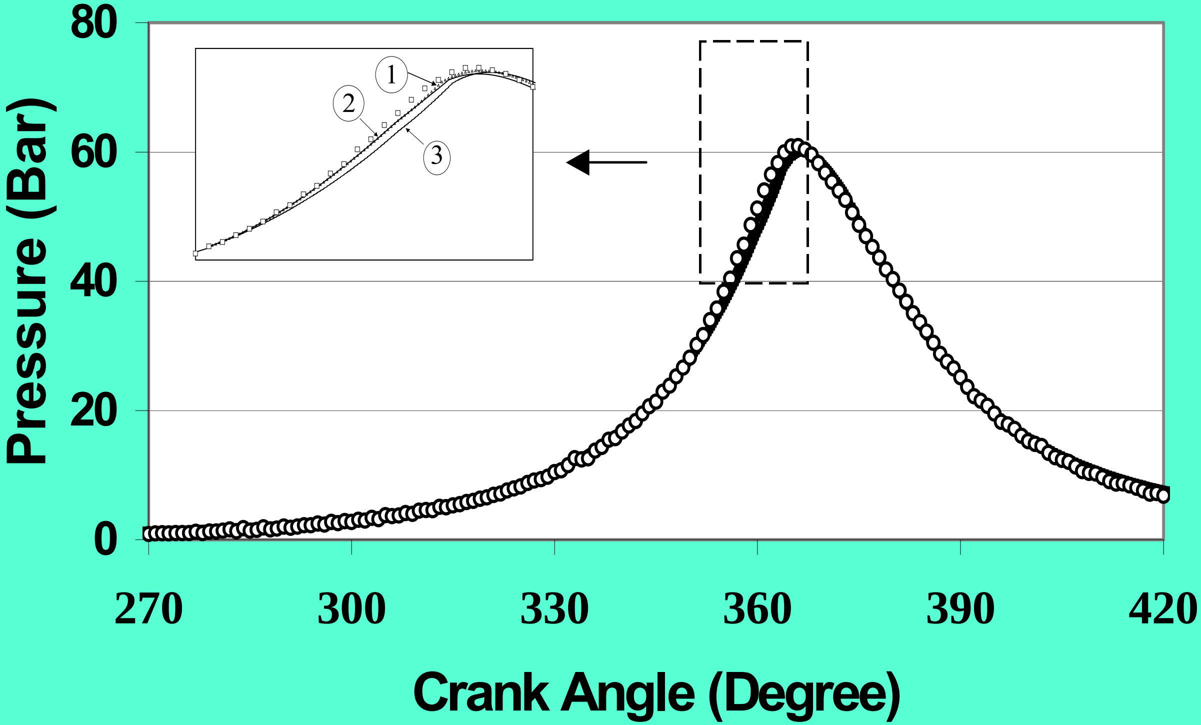
- With increase in mass flux the front velocity initially increases and then reduces
- With increase in mass flux the CO concentration in the exit gas increases

Dasappa, Paul and Mukunda, and Srinivasa, 27th Symp. (Int) on Combustion, 1998

Engine modeling

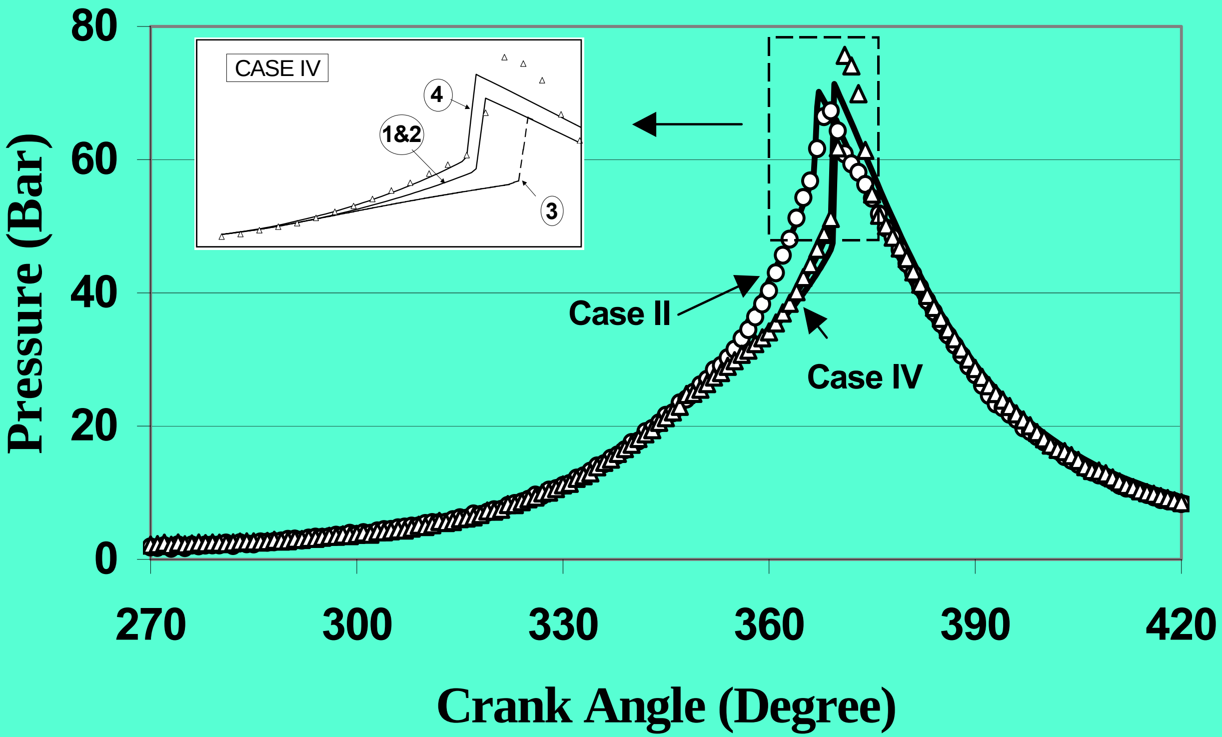
- Producer gas based spark ignited engines have been experimentally characterized and modeled using 0 – D model and some CFD simulations to understand the internal flow dynamics.

O-D predictions



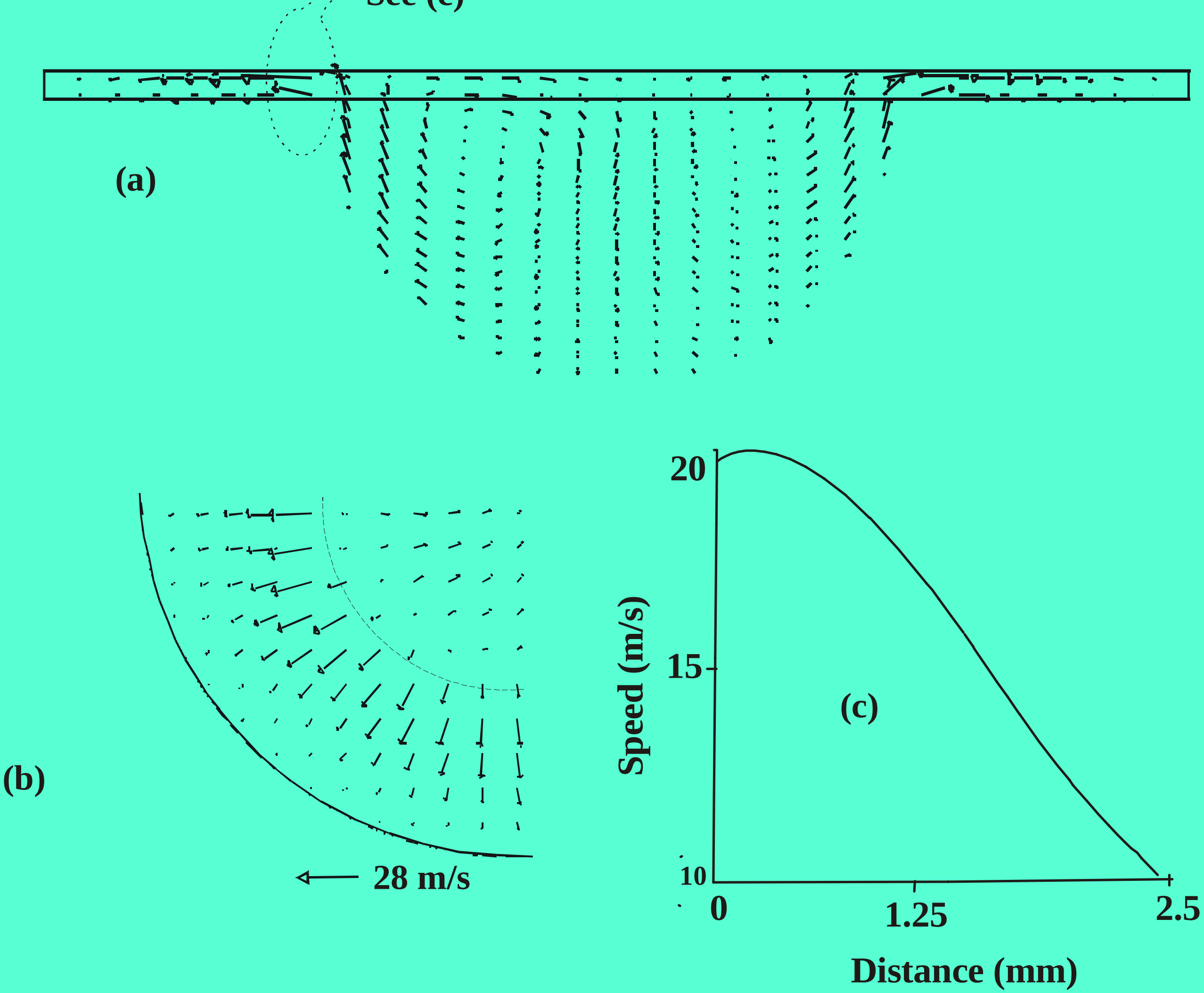
Comparison with experimental p-θ results for CR =17 at an ignition advance of 26° before TC. Circle indicates experimental values (ensemble averaged over 30 consecutive cycles). Solid lines indicate 0-D predictions. Inset shows predictions with the following trends for turbulent intensity (1) CFD result in pre-TC period and [18] trend in post-TC (2) CFD results in pre-TC and post-TC period. (3) trend in pre-TC and post-TC period using [18].

O-D predictions



Comparison with experimental results at CR =17. Circle and Triangle indicate experimental values (ensemble averaged over 30 consecutive cycles) at 17° and 12° CA ignition advance respectively. Solid lines indicate 0-D predictions. Inset shows predictions (at 12° CA ignition advance) with the following trends for (1) CFD result in pre-TC period and [18] trend in post-TC (2) trend in pre-TC and post-TC period using [18] (3) CFD results in pre-TC and post-TC period

CFD Results



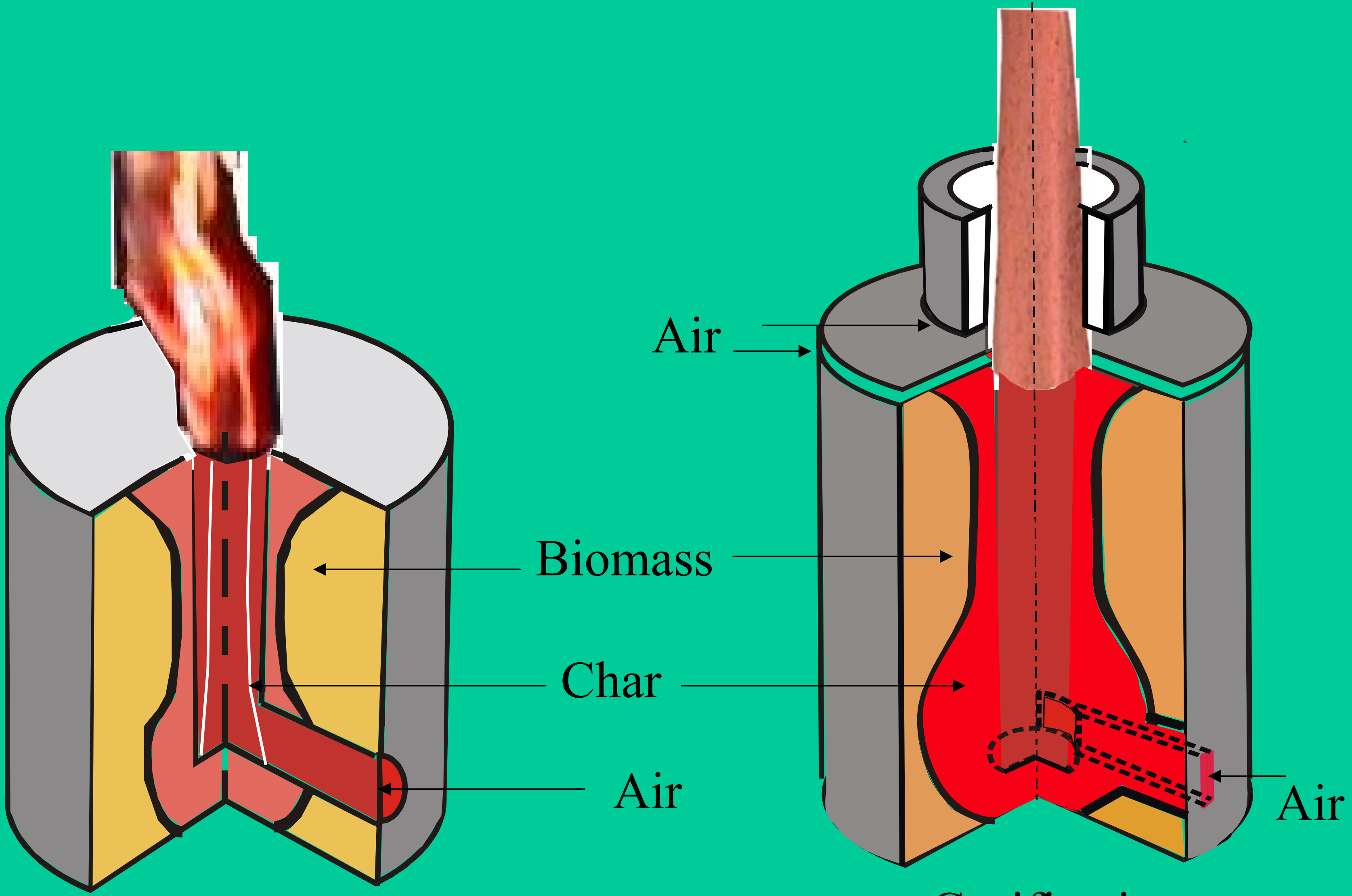
Velocity vectors during reverse squish at 10° CA after TC (a) vertical plane through centre of the geometry – notice the flow vectors pointed outwards. (b) One quarter image in the horizontal plane at a distance of 1mm below the cylinder head. Dotted line indicates the outer periphery of the bowl – notice higher gas velocities in the flat region (c) gas speed measuring from cylinder head towards piston top – close to the outer periphery of the bowl

A very difficult S & T problem on domestic solid fuel based stove

- High “embedded” efficiency.
- Very little **smoke** (lean combustion related issue) and **soot** (rich combustion issue).
- Management without electric power devices.
- Should be able to use pulverized fuels more than “fire wood”; should allow multi-fuel option.
- As long a life a stove life as possible

Difficulty in design and realization comparable to the design of a gas turbine combustion system

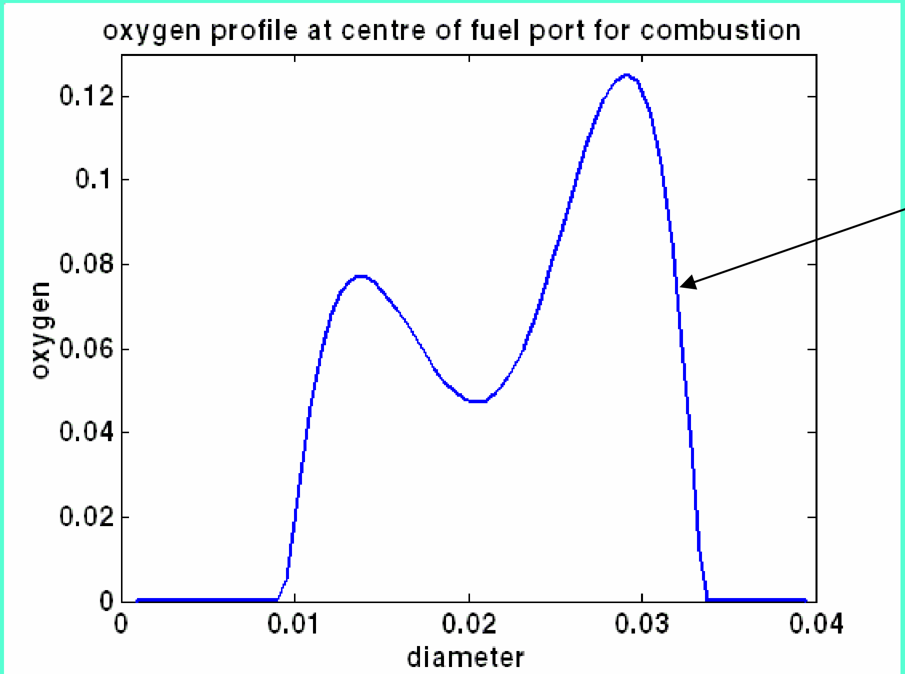
Modes of operation



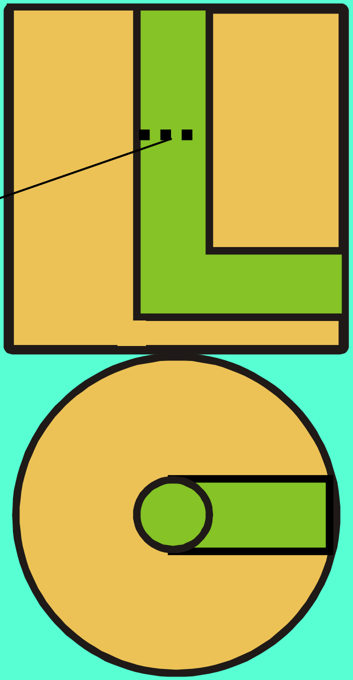
Combustion

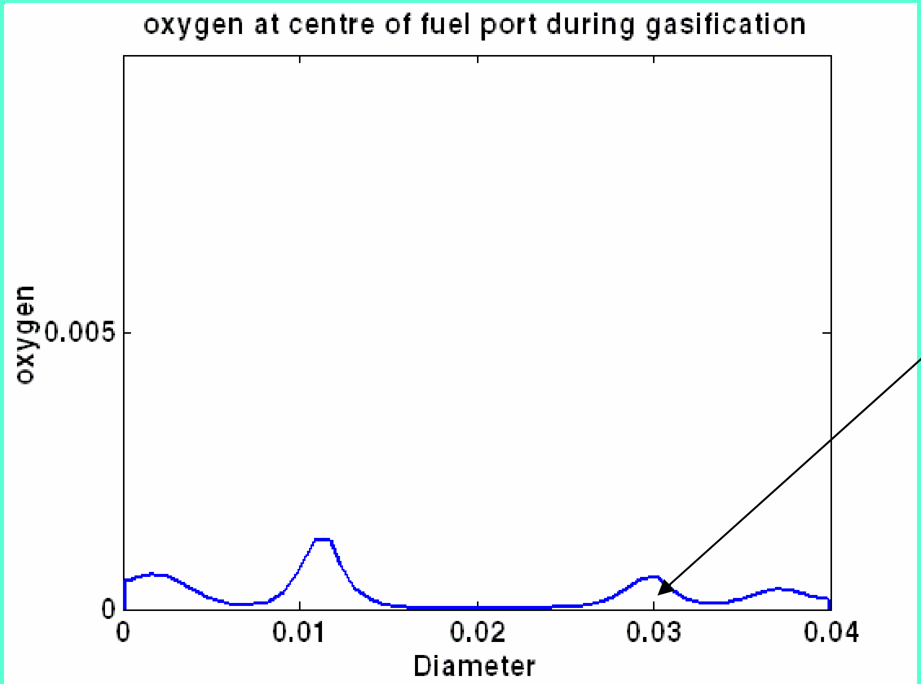
Gasification

Dixit, Paul and Mukunda, 29th Symp (Int) on combustion, 2002

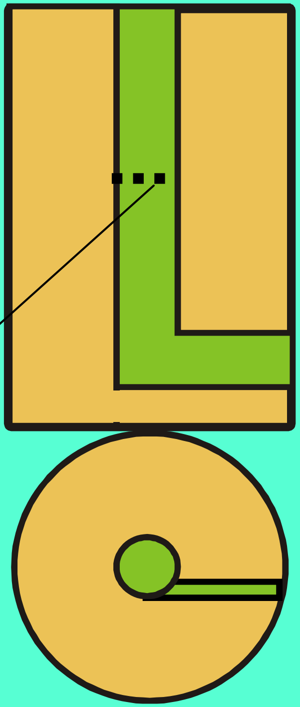


oxygen profile at centre of fuel port for combustion





oxygen at centre of fuel port during gasification



Performance of the stove

- Power levels studied are 2.5 to 3 kWth
- Limited power control.
- Constant power for 1 hour. Power drops to about 25 % in the next half hour.
- Sawdust, other agro-waste + leaf droppings pulverized have been tested.
- Emissions of SPM < 10 mg/m^3, No sooting in gasification mode, about 0.4 g/m^3 in Combustion mode.

New horizons in Aerospace

- Low cost access to space. There is work going on, but without much focus in ISRO.
- DRDL has a very dynamic program of hypersonic vehicle demonstrator development currently in the formative stage.
- Hopefully, this will become the catalyst for new research and development in several places including NAL that is putting forth a major effort in this area.

Summary

- A few highlights of combustion science and science relevant to technology are set out.
- Many other R & D activities, not necessarily of a frontier nature, but of value to the organizations are going on in several places.
- Providing world leadership in some areas of S & T requires (a) careful choice of problems that touches the society around, (b) that they need fundamental S & T inputs and (c) **are not already addressed by the advanced world**.