Aspects of recent progress in combustion science and technology

- Background
- Combustion instability in solid and liquid rockets
- Clean combustion of solid fuels – biomass
- Final remarks

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Background

- There has been substantial progress in understanding of the combustion processes in gaseous, liquid and solid fuels, both passive and reactive over the last six decades.
- - Very much greater attention has been provided to gaseous and liquid fuels than solid fuels, far more in controlled clean combustion processes.

- Solid fuels can be passive or reactive. Reactive fuels like solid rocket propellants have been pursued because of greater interest in missiles and space launch vehicles.
- Solid fuels like biomass are "poor man's" fuel and hence have not had as much attention from organized science. It has been relegated to enthusiast's arena.
- Biomass stoves developed over the last fifty years offer a humungous variety in terms of looks but little in terms of distinguishable performance.
- It has taken a very long time to realize the basic problems and seeking solutions for them even though nearly half the World depends on it!

Background - contd

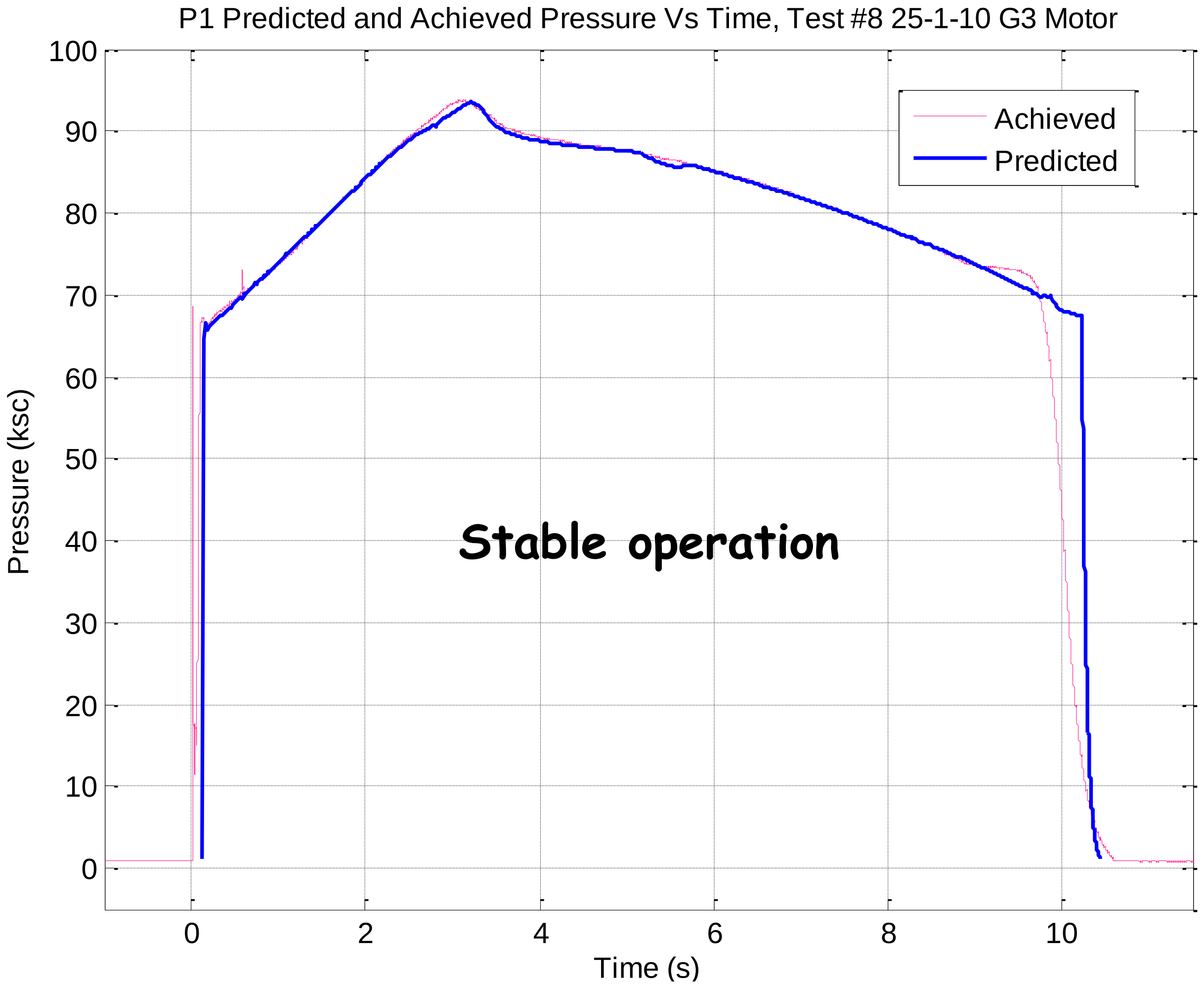
- Seeking challenging unsolved problems or questions of relevance in combustion science is indeed a tough exercise.

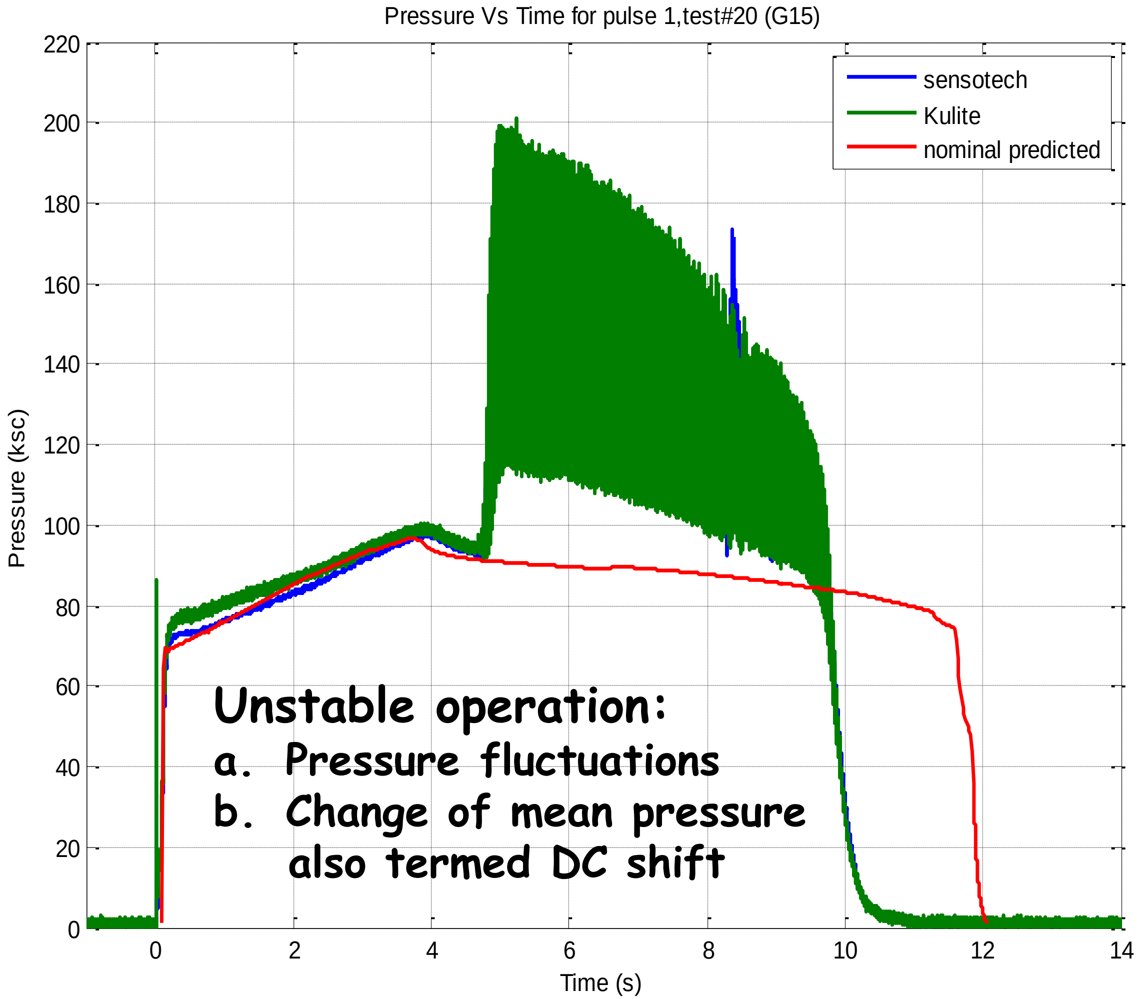
- While study of literature may provide unresolved aspects to be addressed, but joy is always higher when you need to address questions that affect developments around.

- I shall describe two major aspects here –
  a. Instability in rocket engines at one end of high technology spectrum and
  b. Finding solutions for clean combustion of biomass and charcoal

Instability in solid rocket engines

A composite solid propellant rocket – 2 m long, 68 mm ID, 200 mm OD



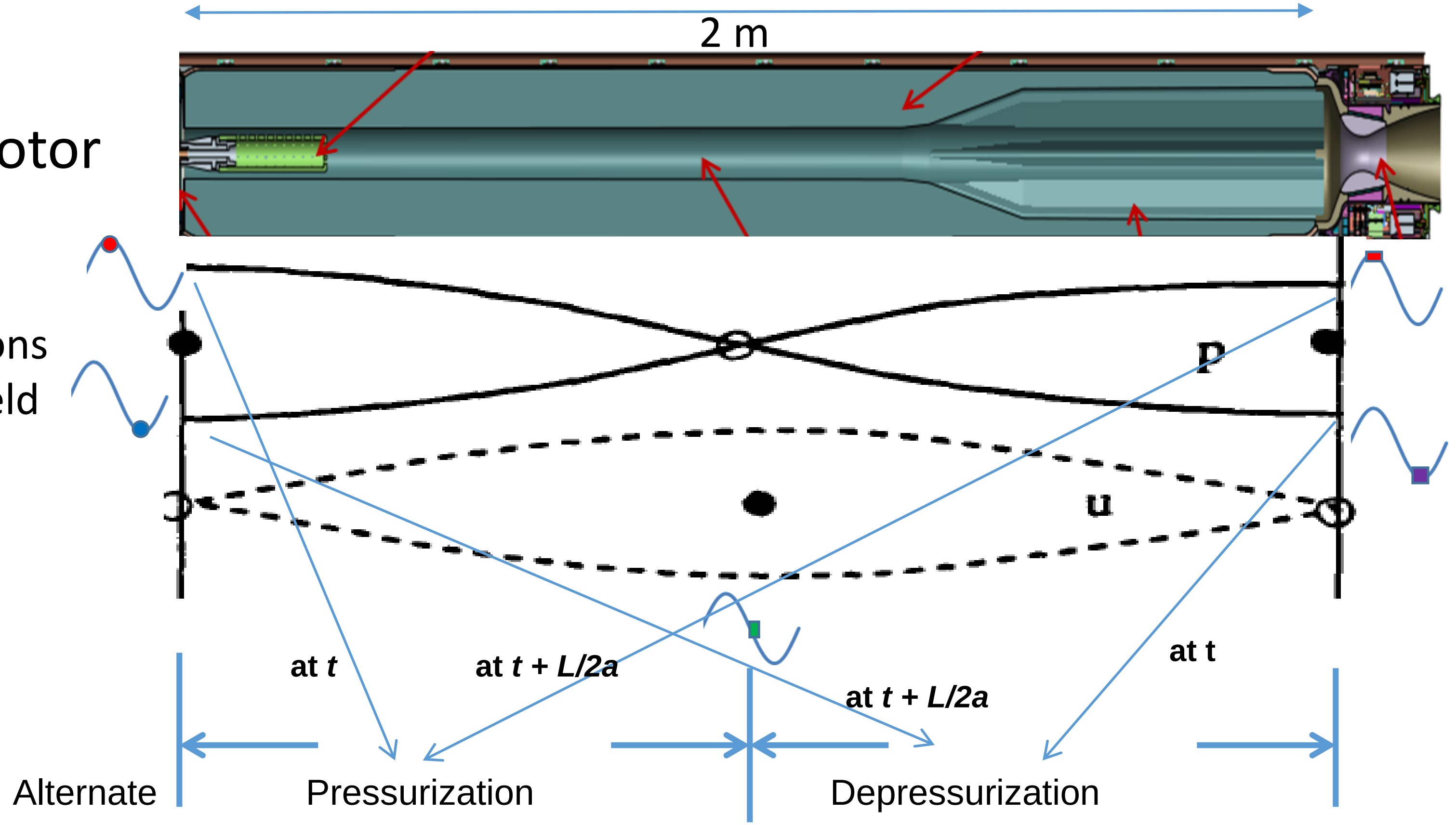


Why does instability occur – Mechanisms? and how to overcome…..

Why does instability occur – longitudinal mode here?

The rocket motor

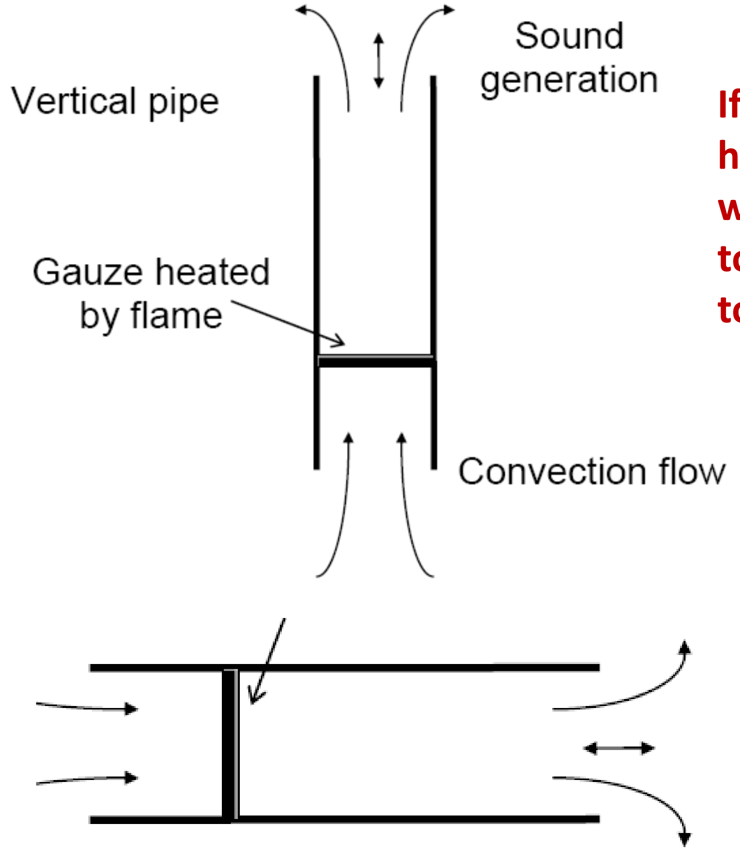
Pressure oscillations
Inside the flow field



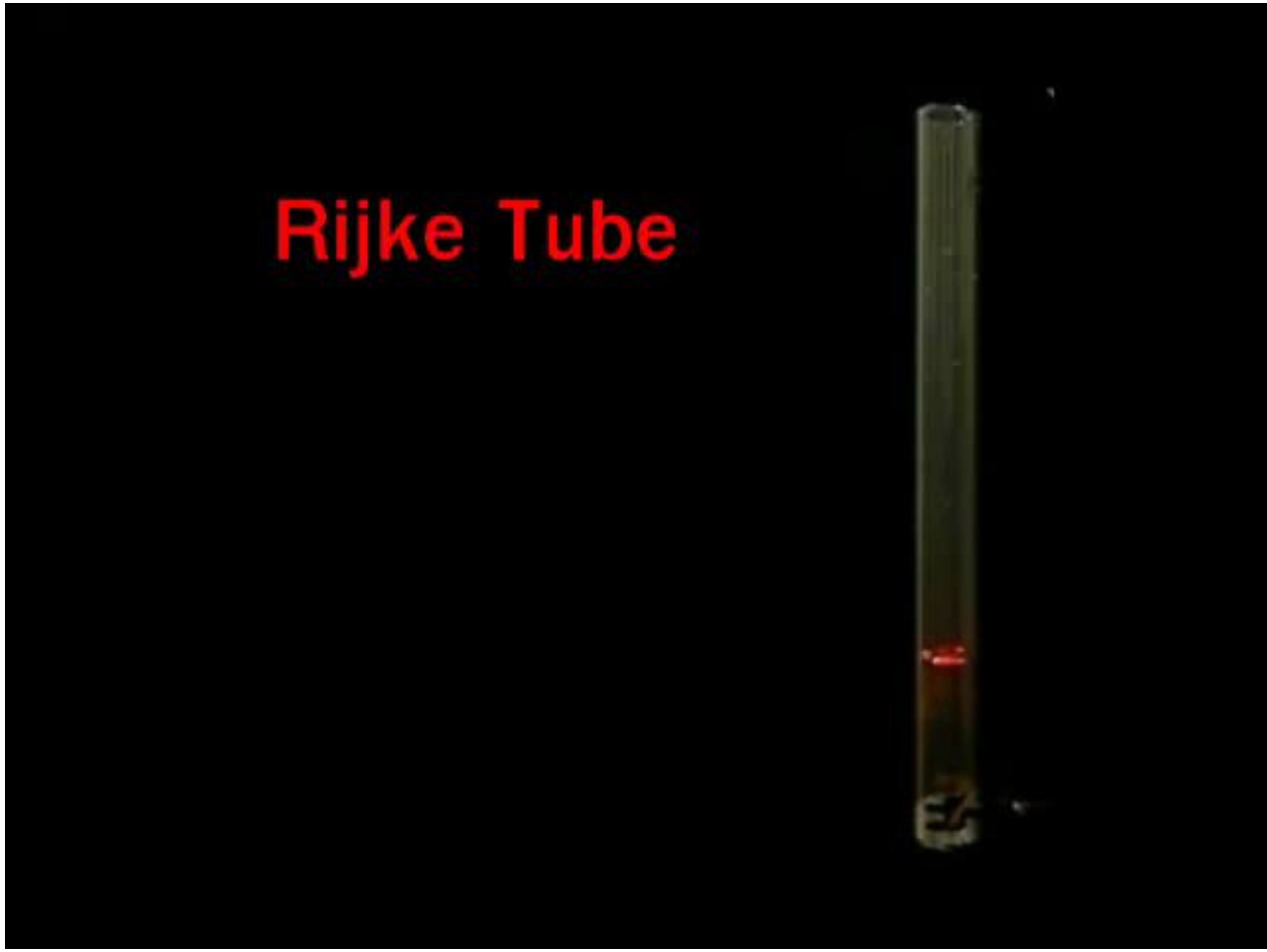
Reminds of

- There are always acoustic oscillations in any flow field - same as pressure oscillations shown.
- The pressure variations affect the gas phase flux and control the burn rate of the propellant.
- If the fluctuations in burn rate are in phase with pressure fluctuations, then burn rate fluctuations increase. (following Rayleigh's criterion)
- This means that the response function $\{ (\dot{r}'/\dot{r})/(p'/p) \} > 1$. This kicks of a linearly increasing fluctuation.
- Later, instability grows and the sharp pressurization and depressurization aspects cause larger burn rate changes.

A model – Rijke tube (1859)



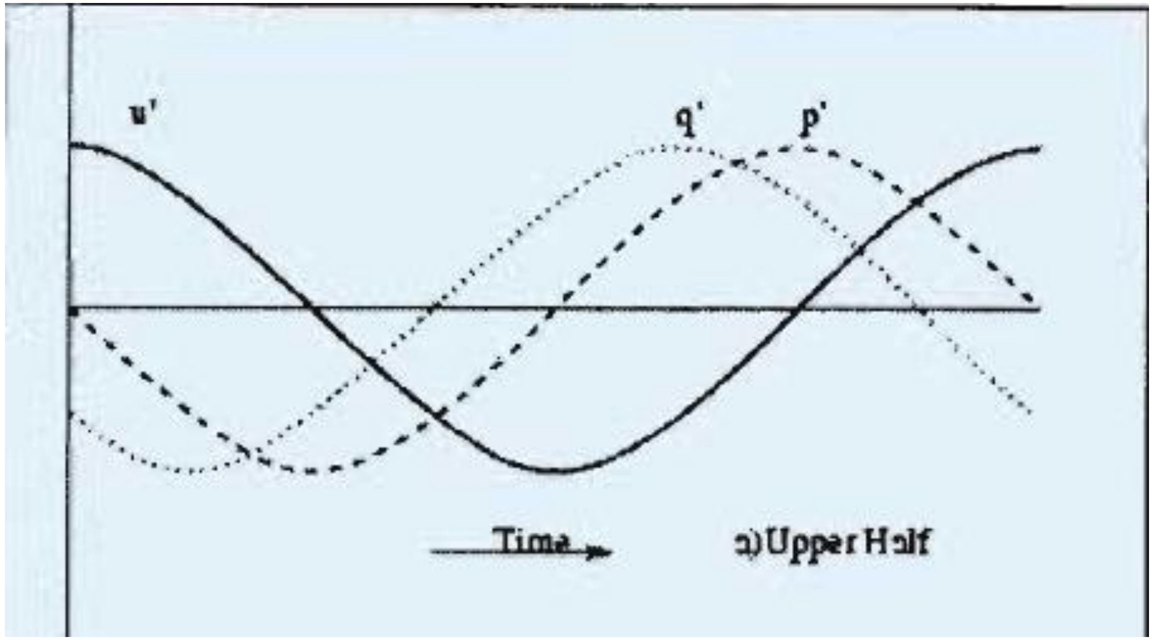
If around quarter length, heat is released, it interacts with the acoustic field to amplify the acoustics to larger levels

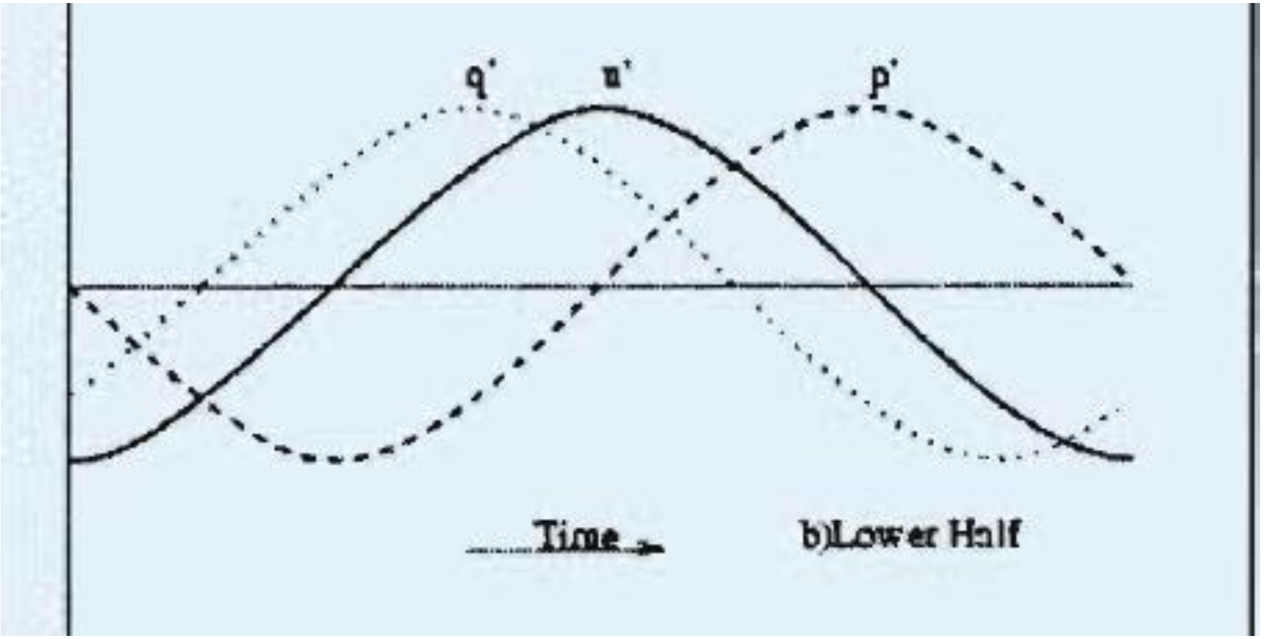


Configuration can be Vertical or Horizontal.

In the vertical case, mean flow is established by free convection.

If it is horizontal, flow has to be established - by using a blower, for instance





$q = \bar{q} + q'$; $I = \frac{1}{T}\oint p'q'\,\mathrm{d}t$, $q'(t) \propto v'(t-\tau)$;

$\bar{q}$ $\bar{v}$ = mean heat release and velocity values;

If $I<0$, then acoustic oscillations will damp out.
If $I>0$, then acoustic oscillations will grow.

p', v', q' = Pressure, velocity and heat release fluctuations

Therefore, the approximate analysis is:

- Heat release by due to electrical heating or combustion needs a time lag for transfer of energy into the stream (τ).

- In solid rockets, propellant amplifies the fluctuation when the times of lag roughly match with time of acoustic oscillations

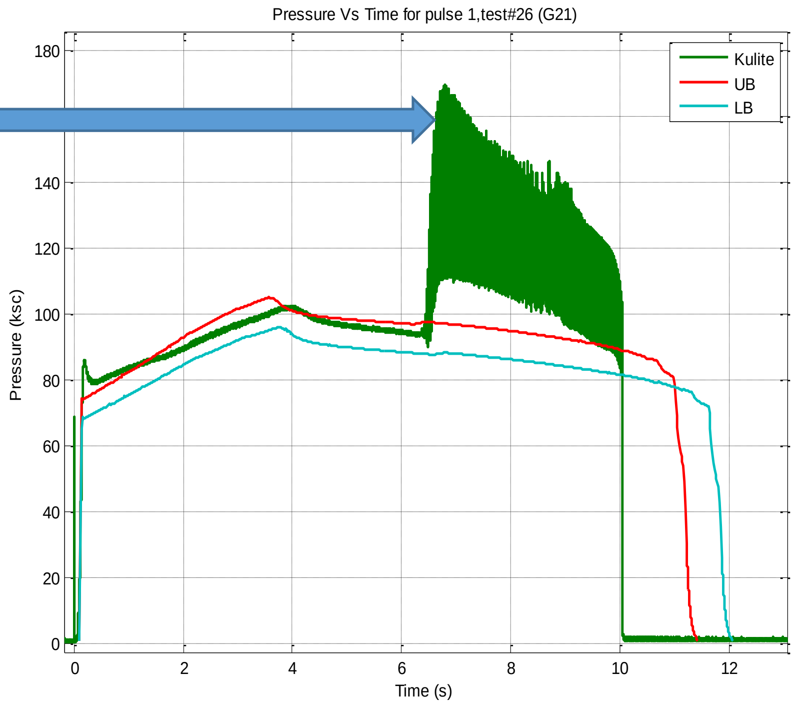
- With solid rocket, the condensed phase heat transfer processes create a time lag, $\tau = \alpha/\dot{r}^2$; $\alpha \sim 0.12$ mm^2/s, $\dot{r} \sim 6.5$ mm/s; $\tau = 0.09/(7^2) = 2.8$ **ms**

- Acoustic frequency, $f = a/2L$; a ~ 1100 m/s, $L = 2$ m gives f = 275 Hz; This means $\tau_{acoustics} \sim 3.6$ **ms**; This matches roughly with τ and with suitable phase lag will cause instability.

- If $L \sim 12$ ***or*** 20 m as in launch vehicle rockets ***(PSLV/GSLV)***, $\tau_{acoustics} \sim 24$ ***to*** 40 ***ms***, so large that there is no coupling – the acoustics is too slow to couple to c-phase dynamics.

- In rockets, there are amplifying and damping elements as well. They need to be accounted. One way of overcoming instability is by increasing $\dot{r}$. If it is 7.5 mm/s, $\tau = 2.1$ **ms** allowing more separation from acoustics; This is one way of overcoming the instability. There are other ways……

On DC shift



- Oscillations of small amplitude (~ 1 atm) are present right from the beginning
- This is followed by an increase in the amplitude of the oscillation

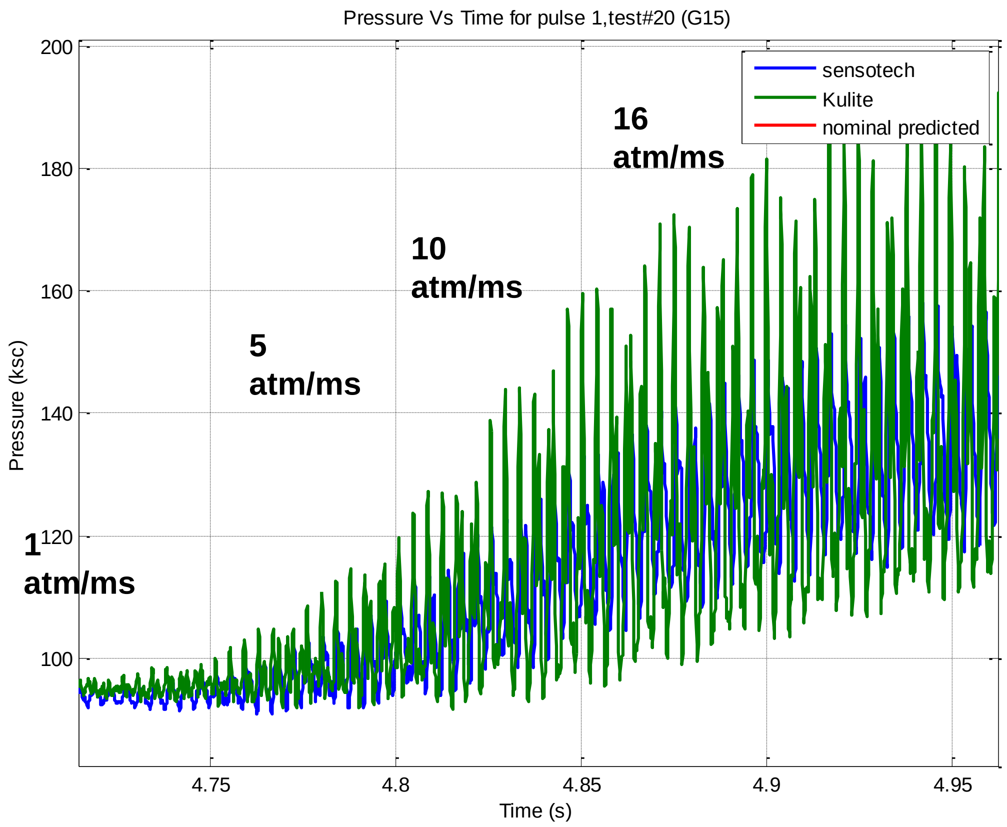
  Then there is a fast shift in the mean pressure (DC shift) from about 120 atm to 200 atm

- Pressurisation-depressurisation rates can be as high as 100 atm/ms leading to extinction of the propellants
- Burn rate as high as 100 mm/s is required of the propellant to maintain this levels of pressurisation rates.
- Earlier studies suggest the possibility of pressurisation following extinction, because of the acoustics, can lead to very high regression rates for very short durations (~ 50 μs)

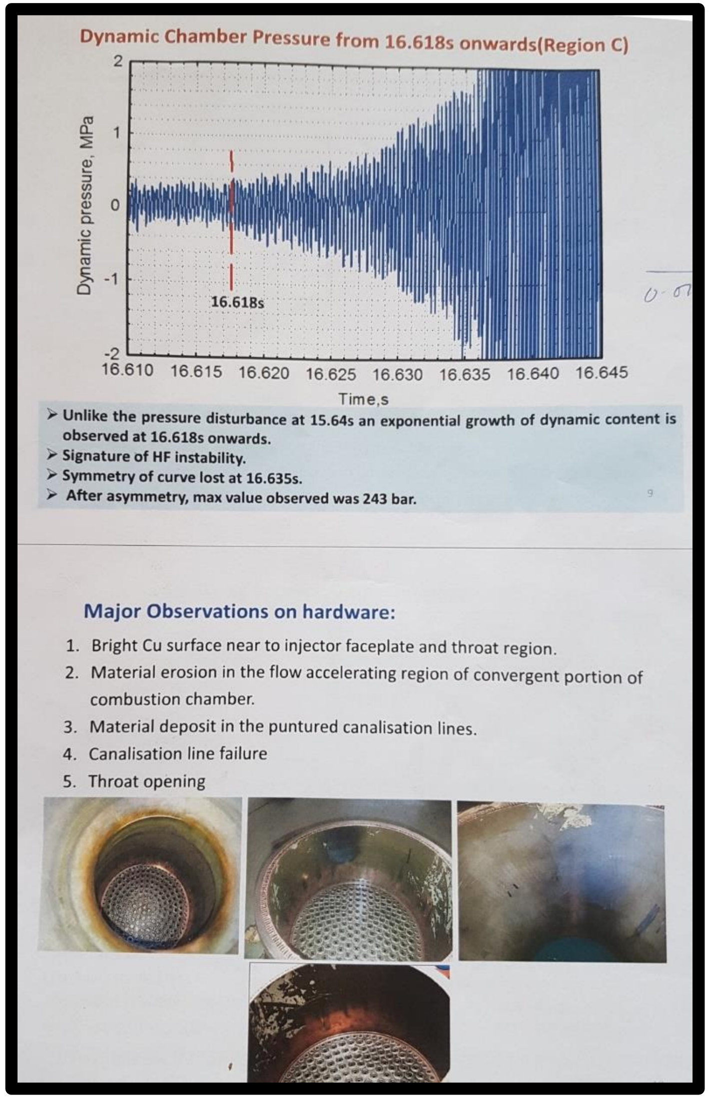
- Computing the critical de-pressurisation rates has led to values of time scales of depressurization of less than 2.5 ms and these values lead to cause extinction of the propellant since c-phase time scales are about these values.

Comparison between solid rocket longitudinal instability and liquid rocket tangential instability

SOLID ROCKET



LIQUID ROCKET



Acoustically triggered Linear Instability both In solid and liquid rockets

DC shift is seen only in longitudinal mode and not tangential mode. The asymmetry in the burn rates between the head end and the aft end is primarily Responsible for the DC shift

Liquid rockets generally suffer **1st**, 2nd **Tangential mode** and in addition 1st radial mode instabilities.

Data on instabilities of earlier rockets show

Hypergolic propellants in unlike impingement mode experience most instability

Propellants injected in unlike impingement mode must experience larger instability (F1)

Propellants injected in like-on-like impinging mode are stable next

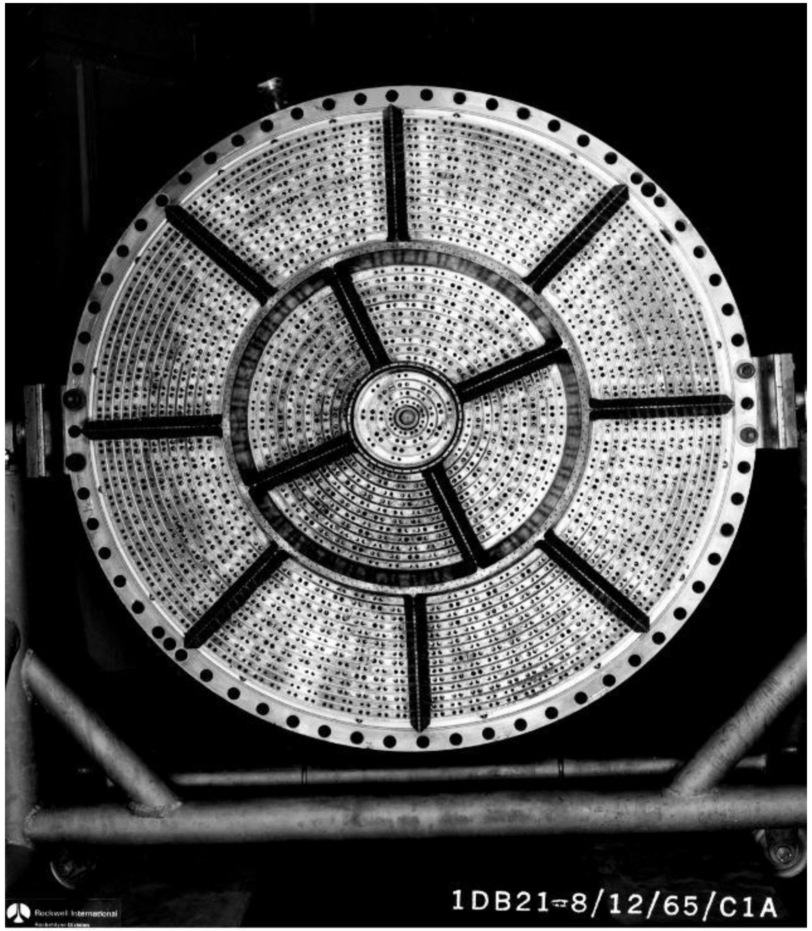
Propellants injected through closely spaced coaxial injectors must be very stable

Propellants injected coaxially with one propellant as a gas must be most stable

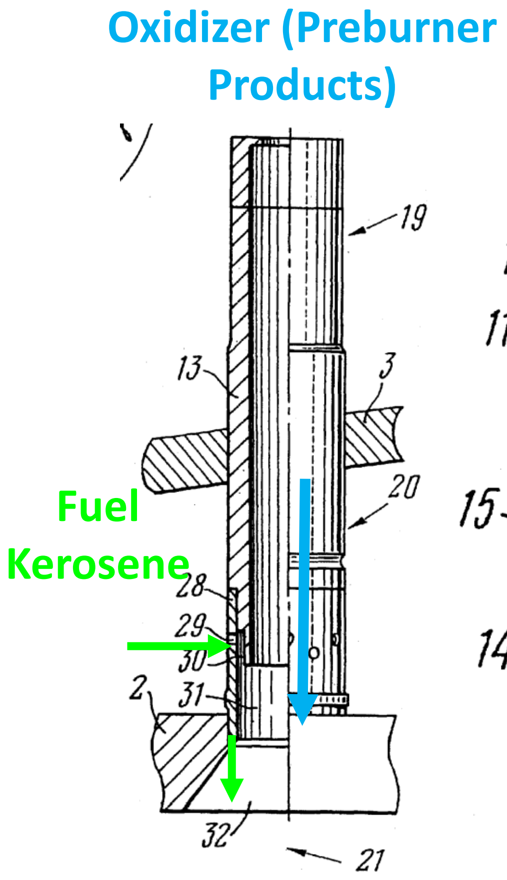
Given an injection framework – injector diameter, pressure drop, there is a pressure boundary that below which combustion process is stable. Given a pressure, one can alter the injection framework – normally coarser injection that provides for stability

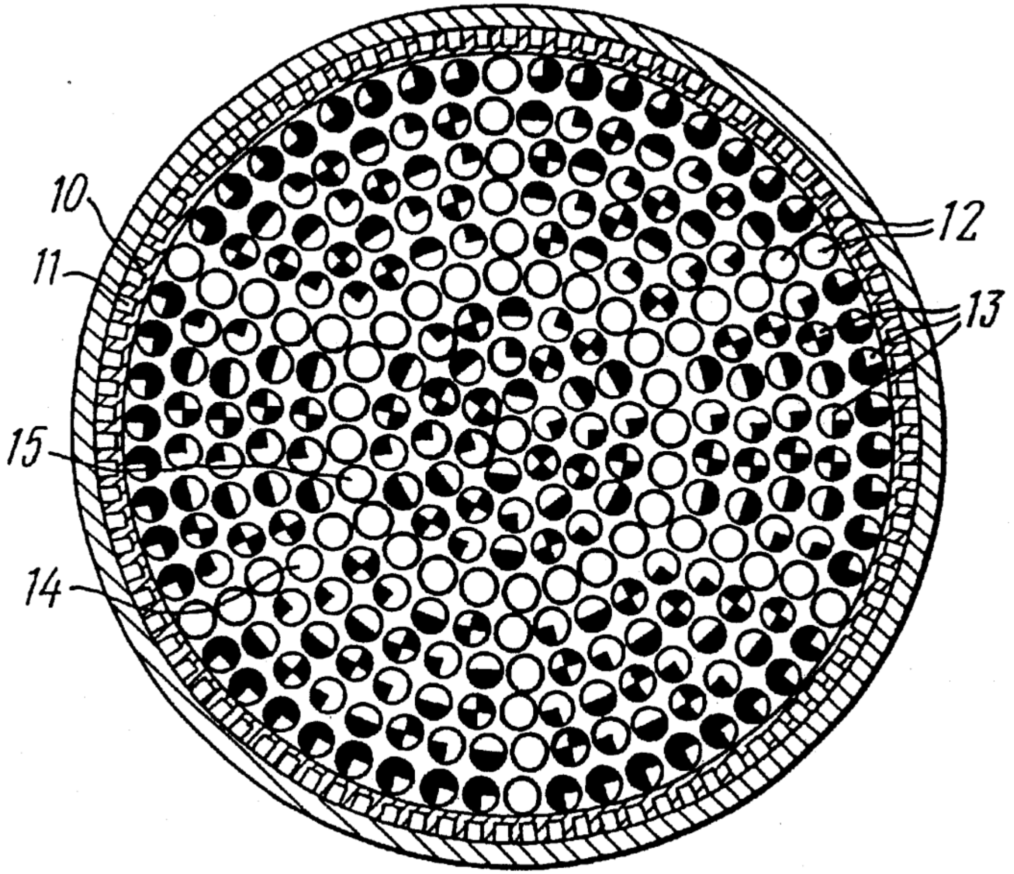
Finally, creating a uniform homogeneous heat release profile in the combustion chamber leads to most stable operation. If this is difficult, minimizing the deviations from uniformity to possible extent helps a great deal

F1 injector (USA) and RD180 injector, USSR (LOX – Kerosene as propellants)



F-1 Engine / Injector - 1965





2800+ injector holes, doublet injection

271 coaxial elements, d = 12.7 mm

The unlike injection system of F-1 engine

- F-1 engine that powered the Apollo mission underwent development from late 50's to 60's.
- 207 tests with 11 injectors, 422 tests with 46 injectors and 703 tests with 51 injectors

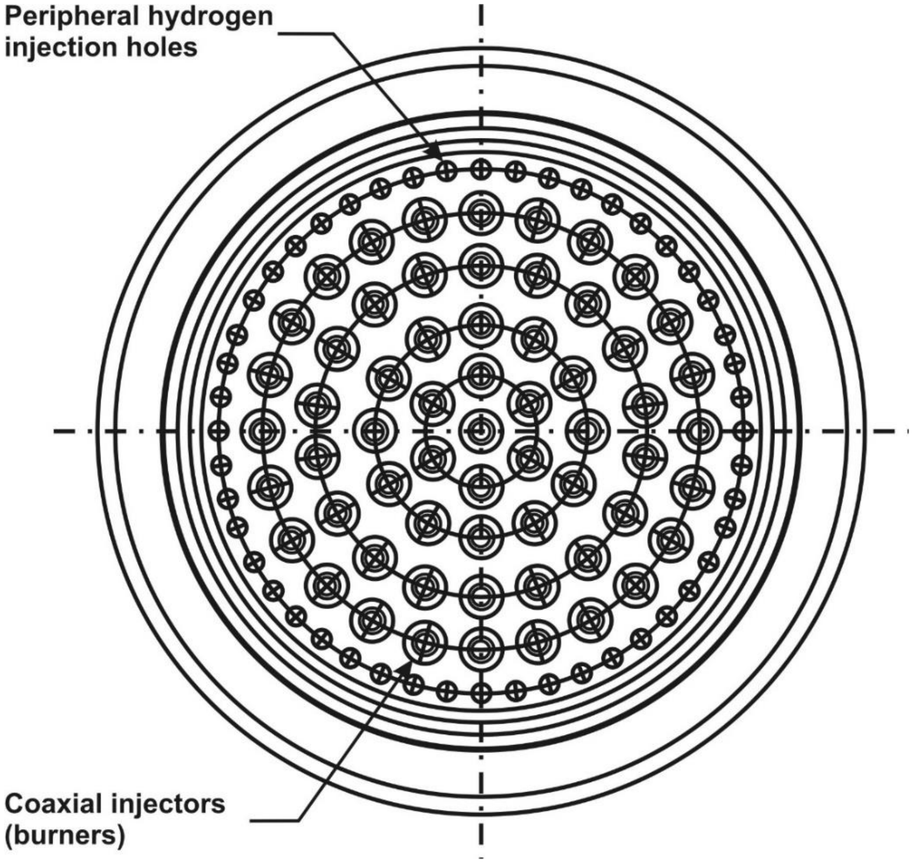
- Observations (Oefelien and Yang, 1993) on the cause for instability in F-1 engine:
- "***The mixture ratio gradients produced by this condition promote mixture ratio oscillations in the vicinity of vaporizing droplets, inducing burning rate oscillations which could couple with the acoustic field***"

- The final configuration has increased orifice sizes – for oxidizer in doublets, 6.15 mm with half-impingement angle of 20° and for fuel elements doublets at 15 ° with 7.14 mm orifice size with element spacing of 10.9 and 10.6 mm.
- Viewed from the principle of the present document, the small impingement angles imply a much lesser lateral velocity contribution and lesser lateral disturbance.

- "***Sensitivity toward instability was always observed if major combustion zone was relatively close to the injector face where oxidizer vapor existed in a sufficient degree of angular non-uniformity.***
- ***If the combustion zone was moved to a region downstream where oxidizer vapor concentration was essentially uniform, displacement effects decayed to a level incapable of supporting instability***"

LOX-LH_2 Cryo engines

always use coaxial injection USA or USSR because LH_2 is injected as gas.
In all likelihood, these are special development of Russians even though they did learn a whole lot from German V2 technology which appears to be more complex than the Russian injector strategy



Further,

- Further, even smaller liquid engines based on storable propellant combinations like RFNA and Aniline-Xylidiene combination used in the early Prithvi engine or later RFNA-UDMH combination used coaxial injection but with swirl.

- Admittedly, use of swirl creates lateral velocities, but the hope is that they will get cancelled in the mean because there are ever so many small injectors on the injection face.
- No instabilities were encountered in this engine and this is partly due to the engine being small (3 tonne thrust)…only partly because this engine had an inner dia of 200 mm.

- However, other US engines - RS 14 of 81 mm chamber dia had HFI at 9.5 kHz,
  LMA engine at 198 mm dia had a HFI at 3.5 kHz
  Titan St 2 engine at 368 mm dia had a HFI at 1.8 kHz.

- The difference lies in the fact that all American designs are with impinging jet injectors, unlike-doublet (F-on-Ox) in the case of RS 14, triplet in case of LMA and unlike-doublet for Titan S II engine. These engines used hypergolic fluids and so heat release is near instantaneous and leads to significant mean lateral velocities.

Further,

- Culick (2002) from Cal Tech, USA describes aspects of high frequency instability in liquid rockets.
- On Russian RD -0110 engine, he states:
- "***Coaxial swirl injection elements were used, with emphasis on injector dynamics; Combustion instability was rare in the final design, did occur 'randomly' during ignition transient – observed during qualification tests***".

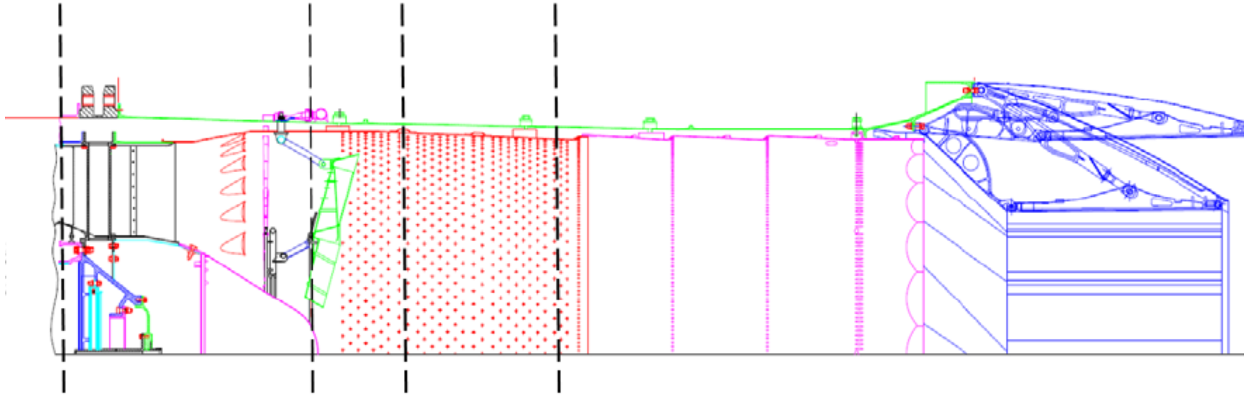
- The extent of preoccupation of most studies in America including those influenced by Prof. Culick seem to have bypassed the eminent features of coaxial injection
- They seem to have accepted the benefits of coaxial injection grudgingly for semi-cryo engines.

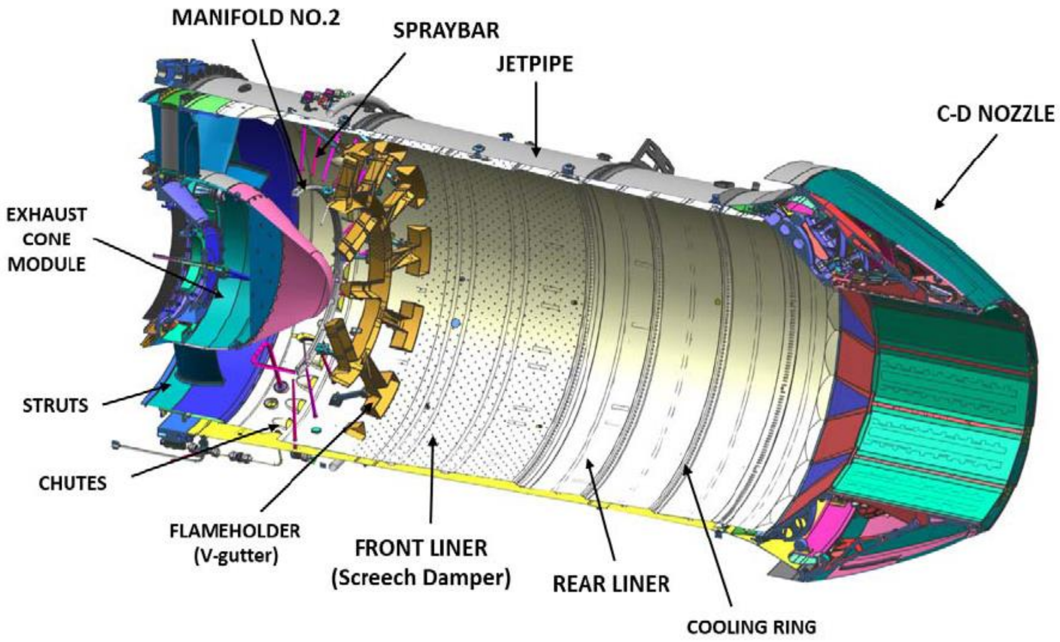
- Though there are always tell-tale observations in the writings leading to the importance of coaxial injection, they have not been set into a principle to follow by which the design is created.

- Perhaps, the fact that American research holds much greater sway on Indian research is partly responsible for not recognizing the true benefits of coaxial injection.
- This is despite the fact that the semi-cryo engine being designed at LPSC, ISRO has its origins in the Russian RD 0180 design.

- Elon Musk seems to be a very smart person who has benefited from Russian tech. - RAPTOR engine

Screech (instability) in Gas turbine afterburners





- Screech is a serious problem in the afterburner of GT engines – 1st T mode, f ~ 2 kHz
- Afterburner operating conditions are: p ~ 3 - 5 atm, T ~ 2000 K.
- Heat release rates are much lower than in rocket engines where p ~ 100 atm, T ~ 3300 K.
- In rocket engines, instability is catastrophic to the hardware.
- In afterburners, it is unacceptable due to vibrations because the operation is man-rated
- The instability occurs despite acoustic damping provided by perforated liners
- The inference is that heat release (combustion) in the flow is phase-coupled with acoustics.

From: Italian work (1998)

6.2. Turbine Exhaust Diffuser

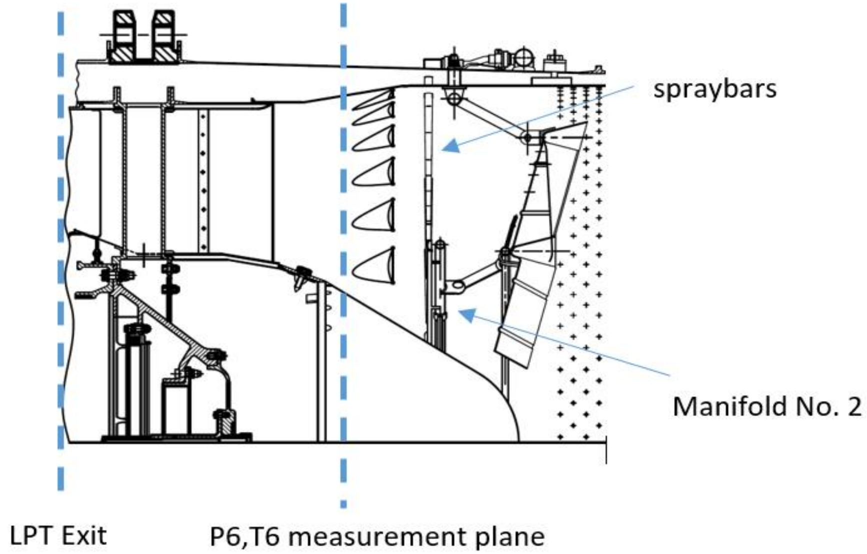
This component, placed downstream of Low Pressure Turbine (LPT) exit, has different purposes :

- to recover the residual flow swirl at the turbine exit, in order to ideally feed the afterburner "core" section with a no-swirl flow,
- to reduce flow velocity at R/H entry, in order to make combustion in the core stream stable,
- to straighten the flow in order to obtain a flow ideally parallel to engine centreline, maximising engine thrust.

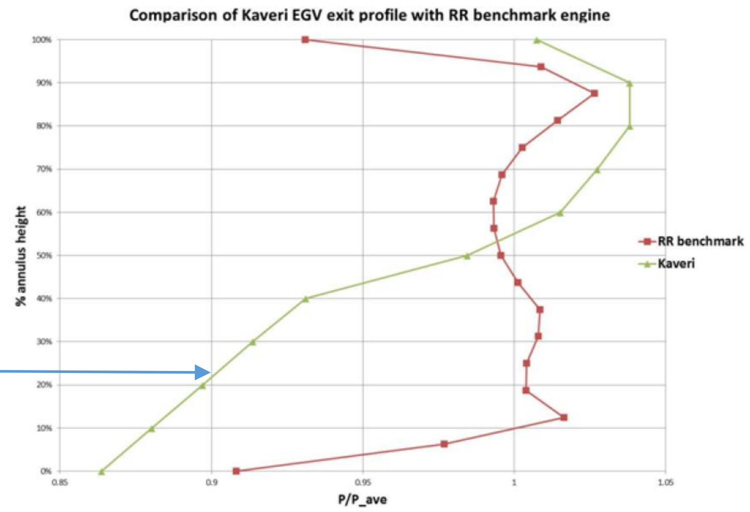
The first of these functions is obtained with a row of vanes located upstream of the conical diffuser and giving a "counter-swirl" angle to the flow.

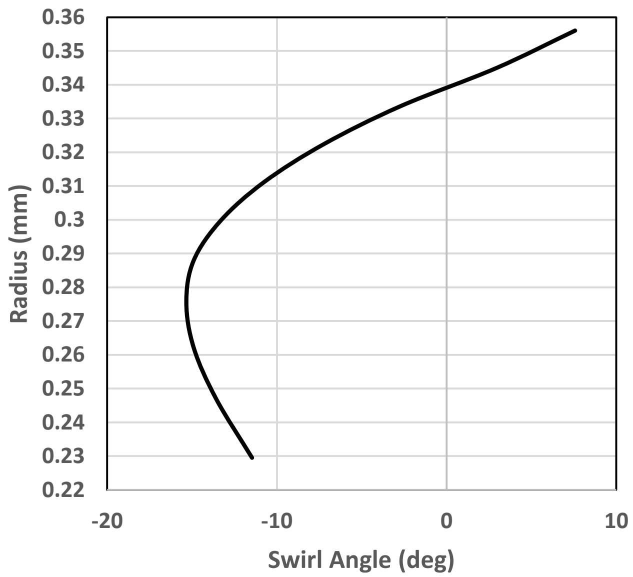
Troveti, A., Turreni, F., and Vinci, C., Afterburner design and development, Paper at RTO AVT symposium on Design principles for Aircraft gas turbines, Toulouse, 1998

The actual situation in the afterburner



More prone to instability





A stand alone test with uniform inlet conditions showed no instability

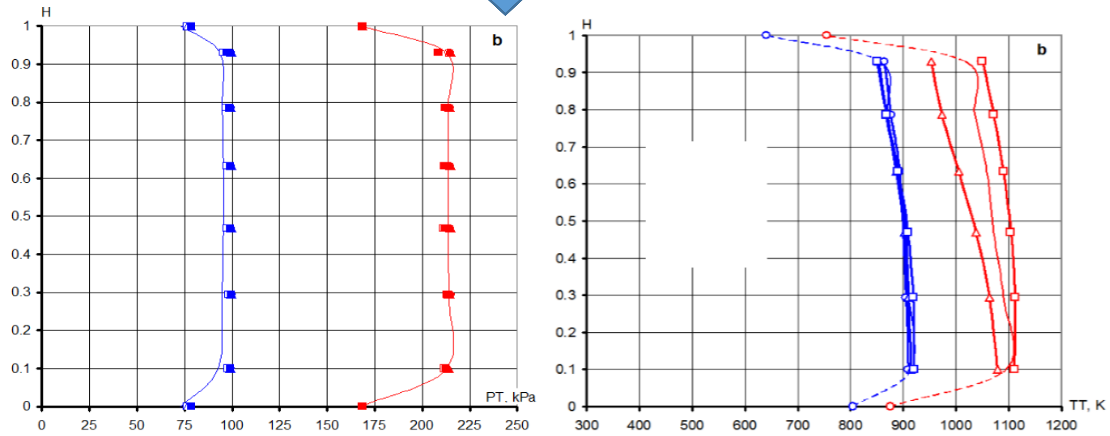


Figure 2 – Total Pressure (PT) and Total Temperature Profile (TT) for core flow at instrumentation plane 2-2 for 0.9 km/0 Mach (red) and 9 km/0.5 Mach (blue) condition

Therefore, summing up

- For solid rockets, one must choose a suitable composition to reduce instability. If we remove linear instability, there will be no DC shift.

- For liquid rockets with storable, semi-cryo or cryo- propellants, it is correct to choose coaxial injection strategy with reduced swirl to minimize lateral mean flow.

- Reduced lateral flow reduces coupling to acoustics and so, incidence of instability.

- For GT afterburners, one should create a near uniform flow from turbine exit to the afterburner.

- Also, fuel injection system should help create uniform heat release across the section of the afterburner.

Message: So much of literature on instability can cause loss of direction if not carefully contemplated upon.

Moving on to clean combustion of solid fuel – biomass

How is biomass different from solid propellant?

	Biomass	Solid propellant
Material:	Biomass	Solid propellant
Composition:	~ $CH_{1.6}O_{0.7}N_{0.003}$	~0.7 (w)NH_4ClO_4 + 0.17 (w) Al + 0.13 (w) $CH_{1.5...}$ OH
Density kg/m^3:	50 to 1000	1700 – 1800
Shape:	Odd	Designed geometry
Size:	fine (1 mm) to large (100 mm)	Designed – particles mixed with binder
Moisture:	10 to 30 %	-
Oxidizer for comb:	Air (~ 7 $\dot{m}_f$)/ O_2-steam (2 – 3 $\dot{m}_f$)	- (self burning, slightly fuel rich)
Burn rate in a packed bed:	0.1 kg/m^2s	10 to 30 kg/m^2s

Inferences:

Biomass is very non-reactive compared to solid propellant.

Both have size issues. Particle size does affect the burn rate of the propellant. Larger size firewood when split into parts burns at higher rate. Industry expectation is to use a variety of solid bio-fuels.

Moisture is a serious issue with biomass not adequately recognized by the society.

Therefore, Design of clean combustion system is more complex for a biomass than for a solid rocket!

Clean burning biomass stoves

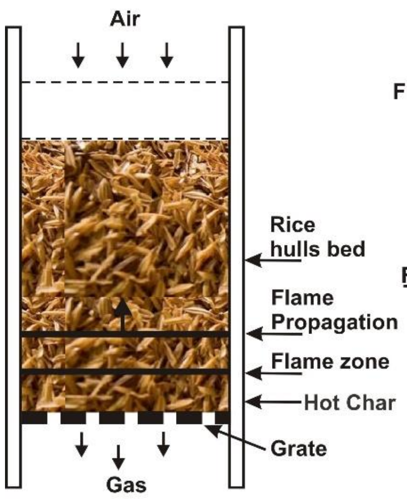
Principle: Gasification

1. Batch process, fixed biomass amount

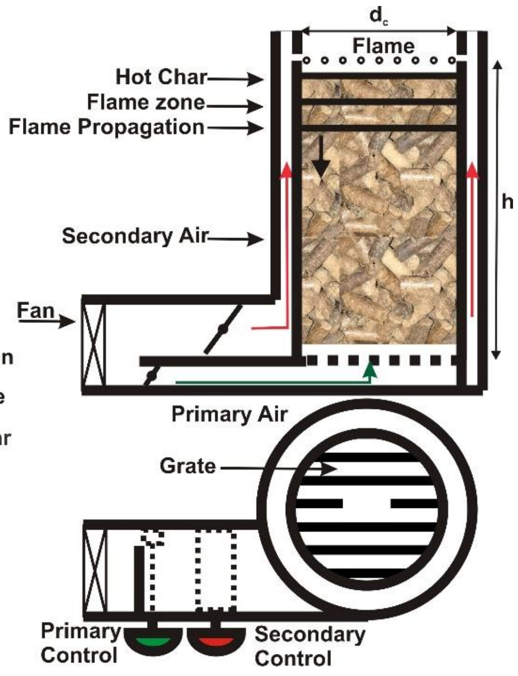
Principle: Partial gasification

2. Horizontal Continuous Clean Combustion Device(HC^3D)

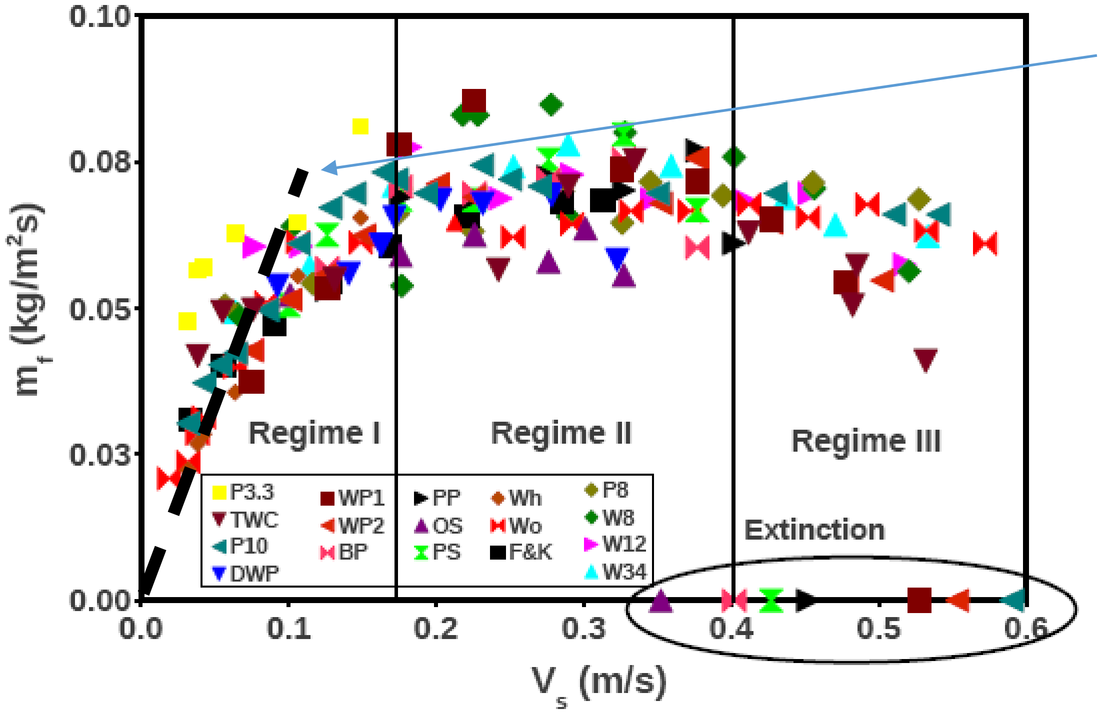
3. Vertical Ejector based combustion device (VEBCOD)



Down-draft Gasifier

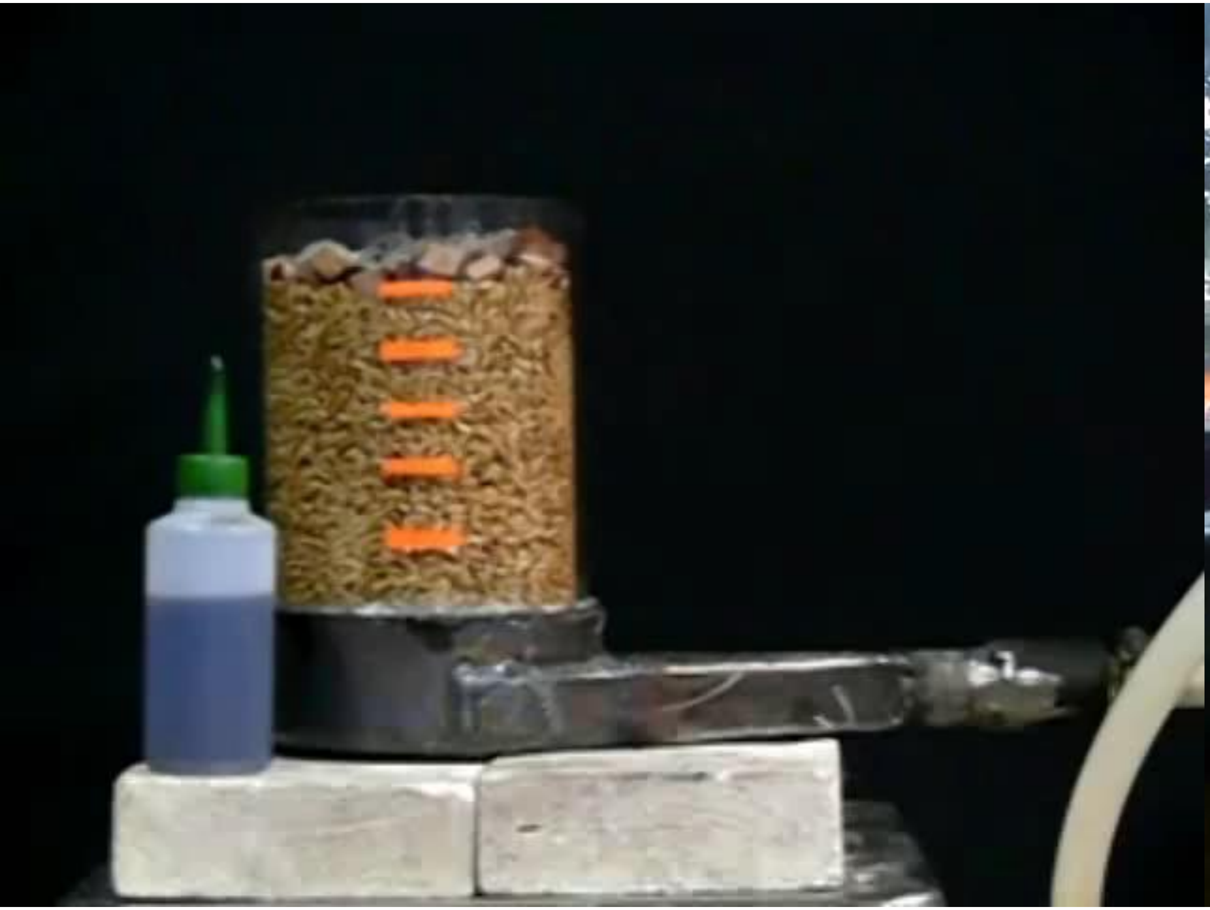


Reverse down-draft Gasifier;
Gasifier stove



Power ~ $\dot{m}_{\text{bottom air}}$

The commercial system working on pellets of agri-wastes



Fixed fuel magnitude – fixed burn time, clean combusting, High efficiency combustion, minimum most emissions

1 kg/h, waste wheat (or biomass pieces)
only primary air – controls the burn
rate. Product – combustible gases

6 kg/h biomass pellets
Commercial hardware
Has both primary and combustion air


Pellets, 700 kg/m^3


Cut tree fallings, 400 kg/m^3

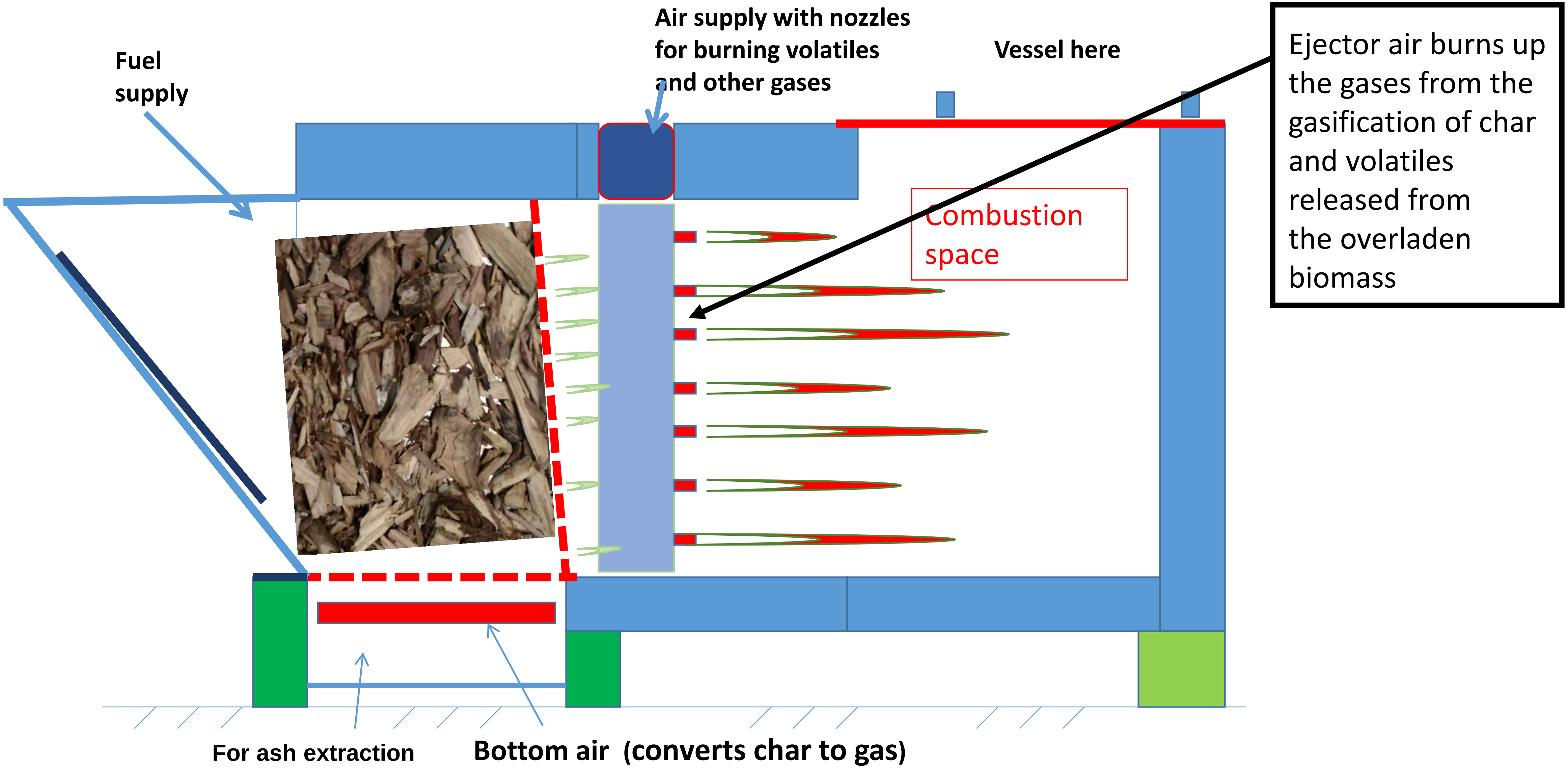

Corn cobs, 150 kg/m^3


Waste Cashew shells, 200 kg/m^3


Cowdung + sawdust, 100 kg/m^3

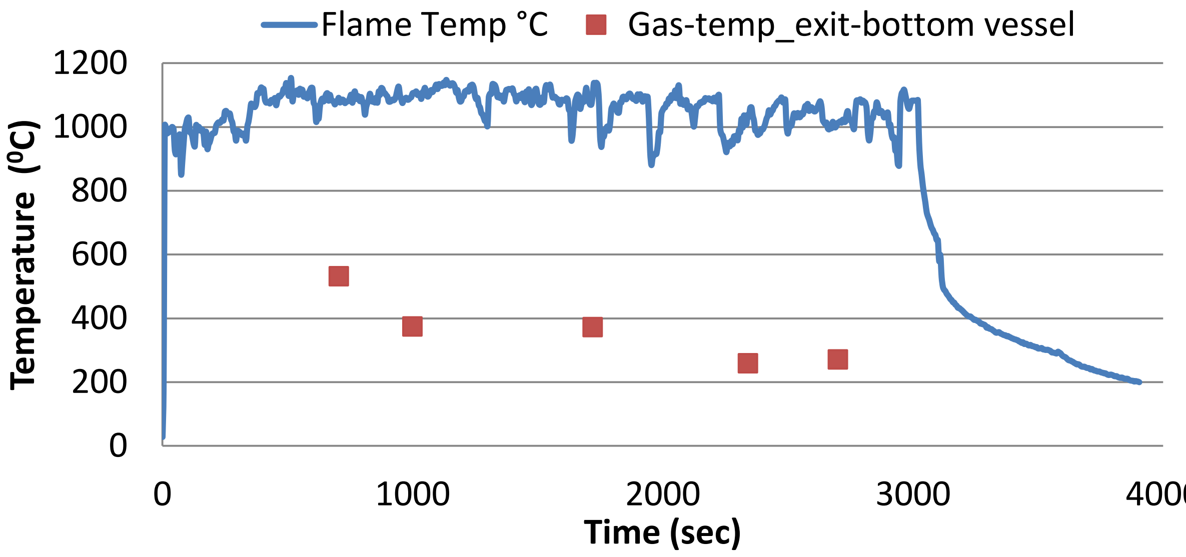

Wood wastes, 150 kg/m^3

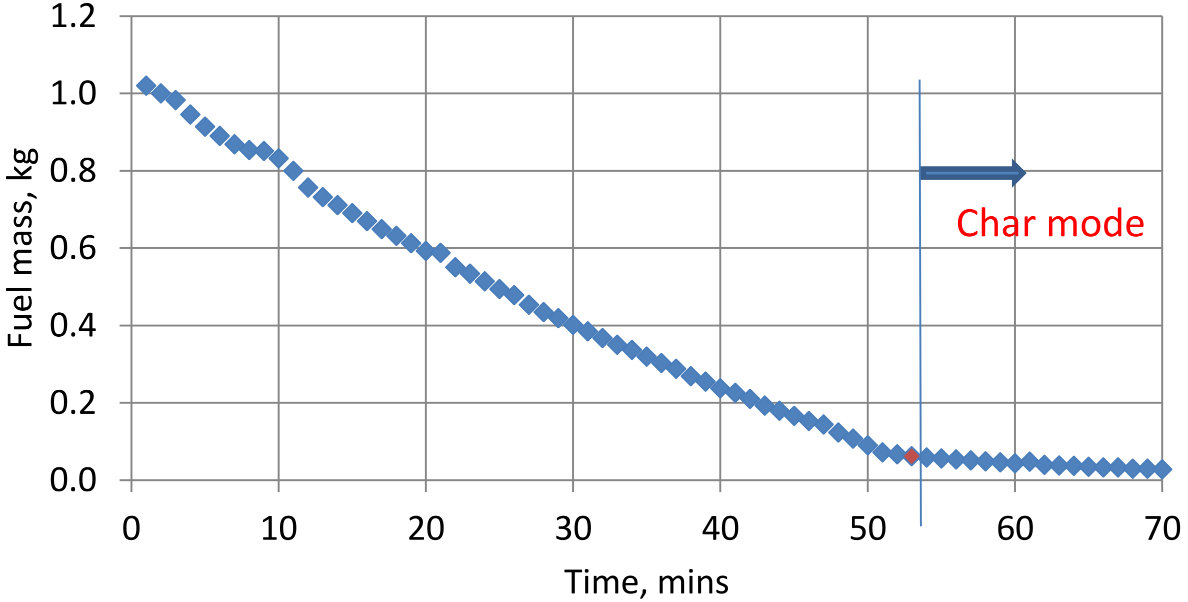
The partial gasification based combustion process

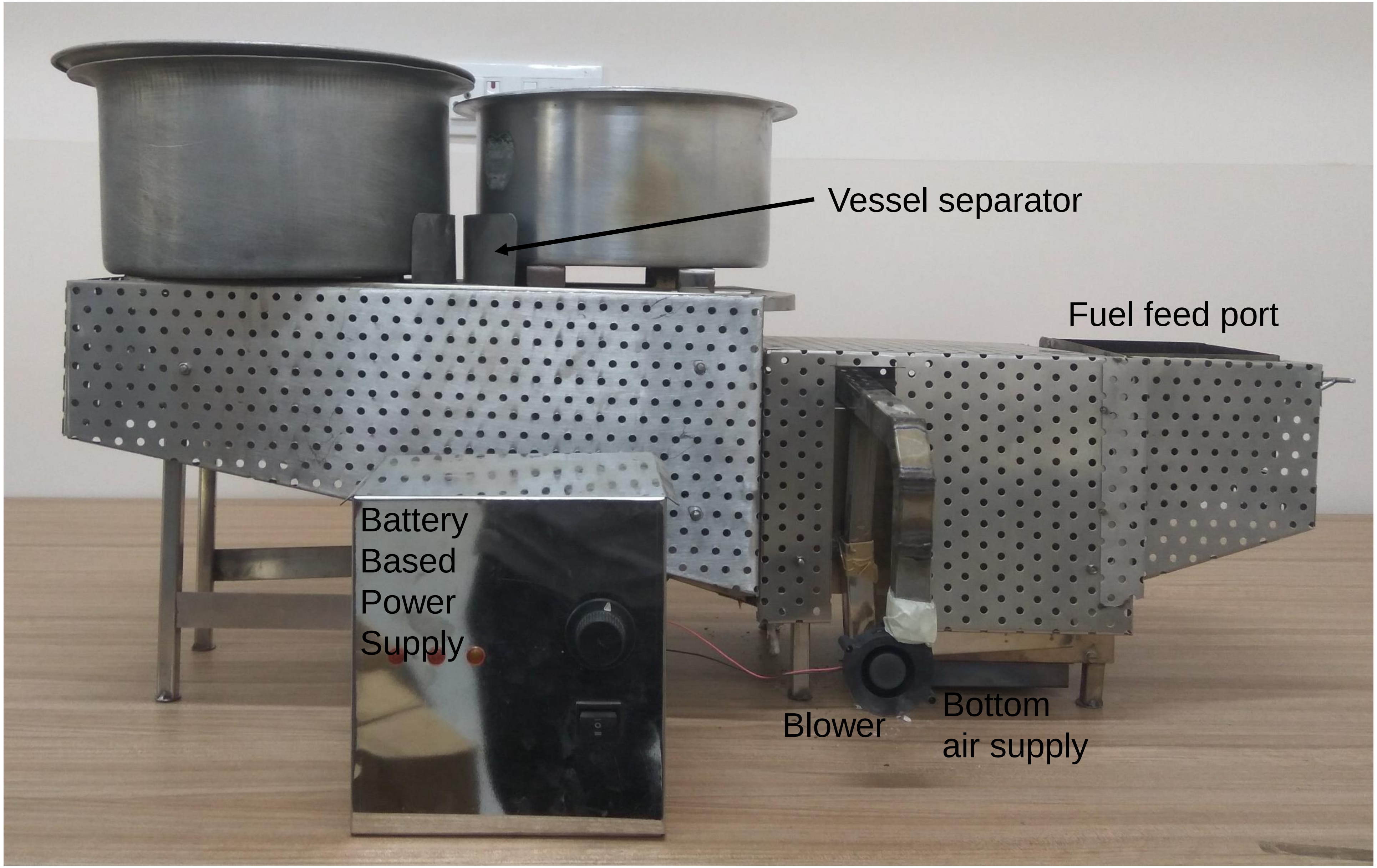


AGNI – SAKHI on a emission-efficiency test

Performance







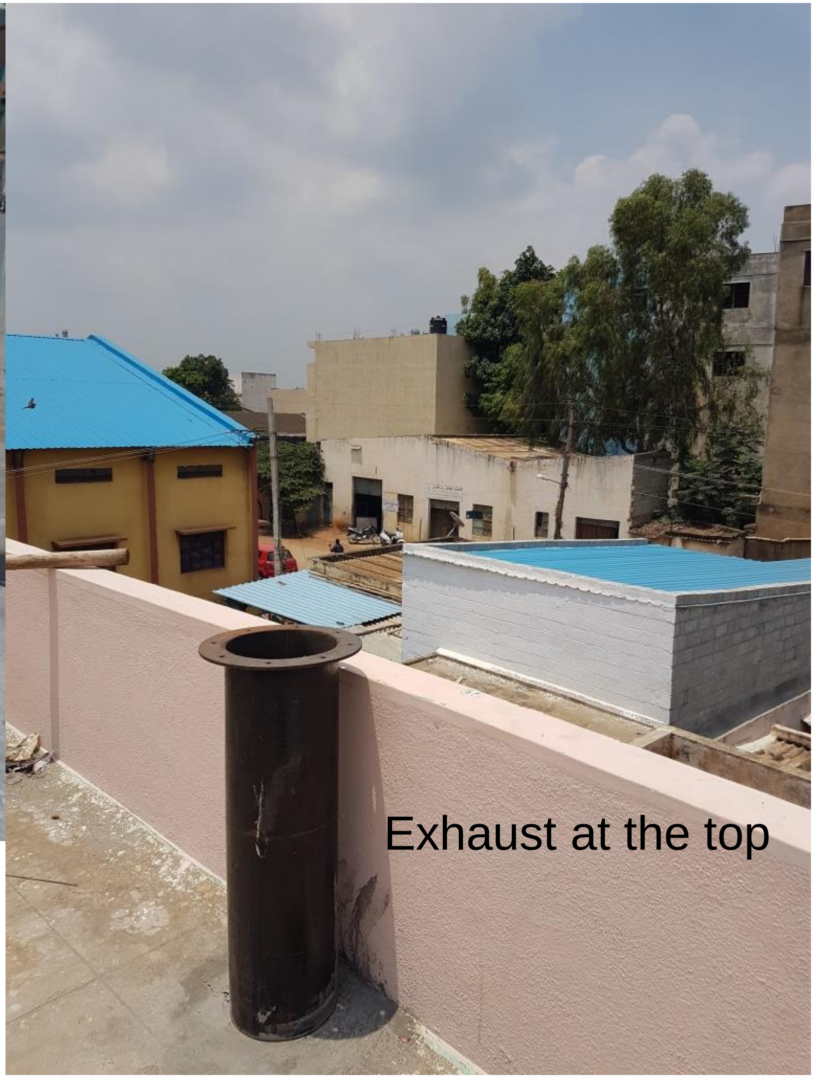
Vessel separator
Fuel feed port
Battery Based Power Supply
Blower
Bottom air supply

3 kg/h system (AGNI-MITRA)

System in laboratory test

System at Mother Theresa's care home for distressed

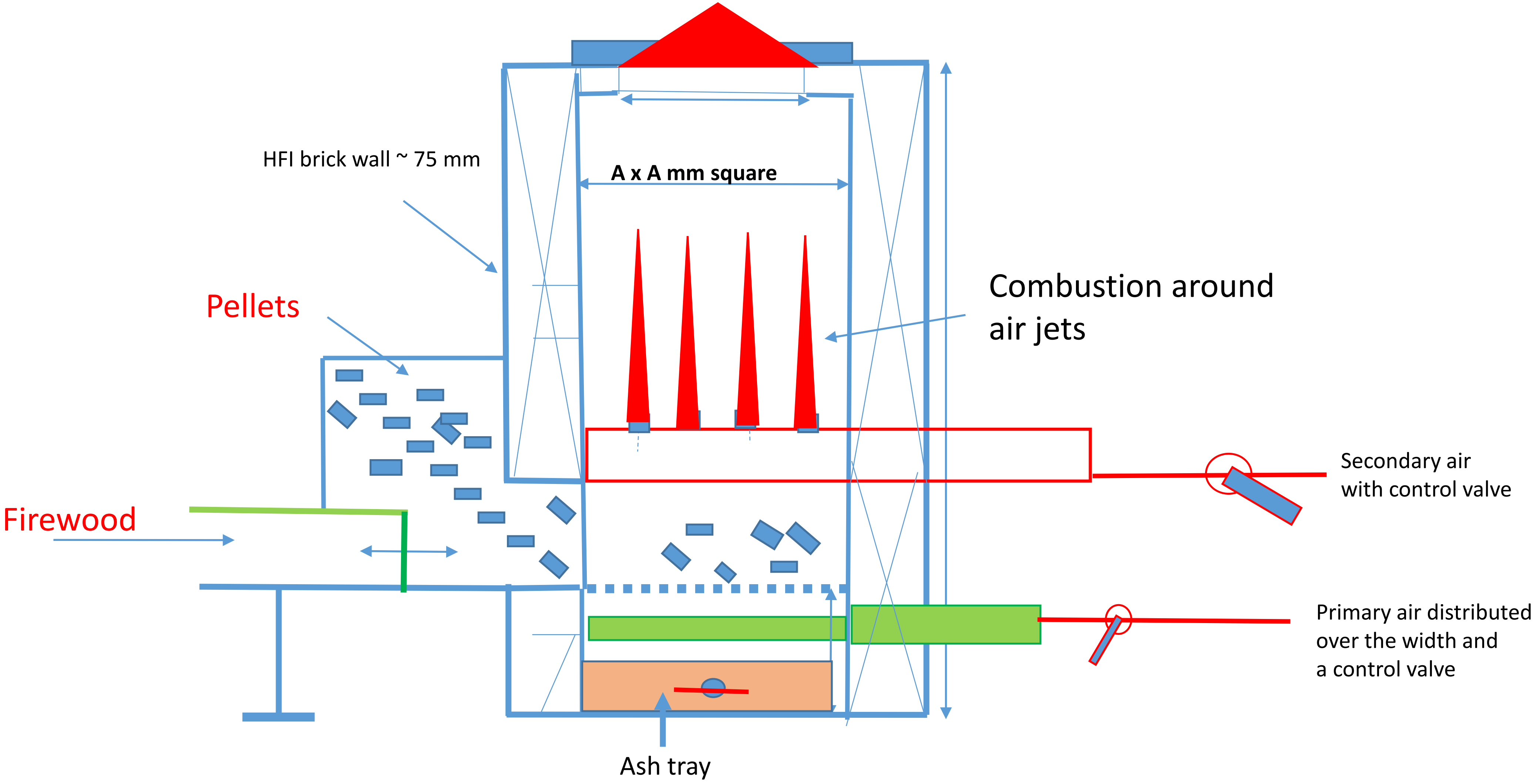
50 kg/h installation at (Peenya, Bangalore) for a blackening process industry



The 50 kg/h system being operated daily using waste wood bought at Rs. 6/kg for 4 to 16 hours daily using a blower of 3 kW capacity.

The exhaust is taken out in a pipe at the top (right side picture) and particulate matter out of the exhaust is negligible

VEBCOD –
Vertical Ejector Based COmbustion Device



Industrial Combustion systems

Potato frying, Blower – 5 hp Centrifugal

HC³D = Horizontal continuous clean combustion device

Final Remarks

- Finding challenging problems of significance in not easy to come by is what I said initially.
- Chose two problems for discussion – Instability in aero-space engines and clean combustion of biomass.
- Instability in solid, liquid rockets and GT afterburner are "old" problems awaiting clean solution strategy.
- Solid rockets require "simpler" propellant combinations.
- Serendipity allowed a simple strategy to be adopted for liquid rockets and gas turbines – Make the injection and reactive flow geometry as uniform across the section as possible
- It should be stated that these strategies are embedded in literature and had to be picked out like diamonds in a mine!
- Clean combustion of biomass provides challenges because of the density- shape-size-moisture complex.
- Several solution strategies – Batch mode and continuous mode with different arrangements as needed in the field have been developed using the associated science.
- There may be more challenging problems awaiting resolution and wish you all the best in hunting them

……………………………………………………………………………………………………Thank you.