6th Prof. P J Paul Memorial Combustion Researchers Meet

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Some intriguing aspects of pan fires and an approach to modelling the behaviour

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Continuing from the past…

- At the last PJP memorial meet at Hyderabad in 2018, Prof. H S Mukunda presented "Quantitative minimalism and scaling laws"

- The example of pan fires the experiments we had conducted and an approach to steady modeling were brought out.

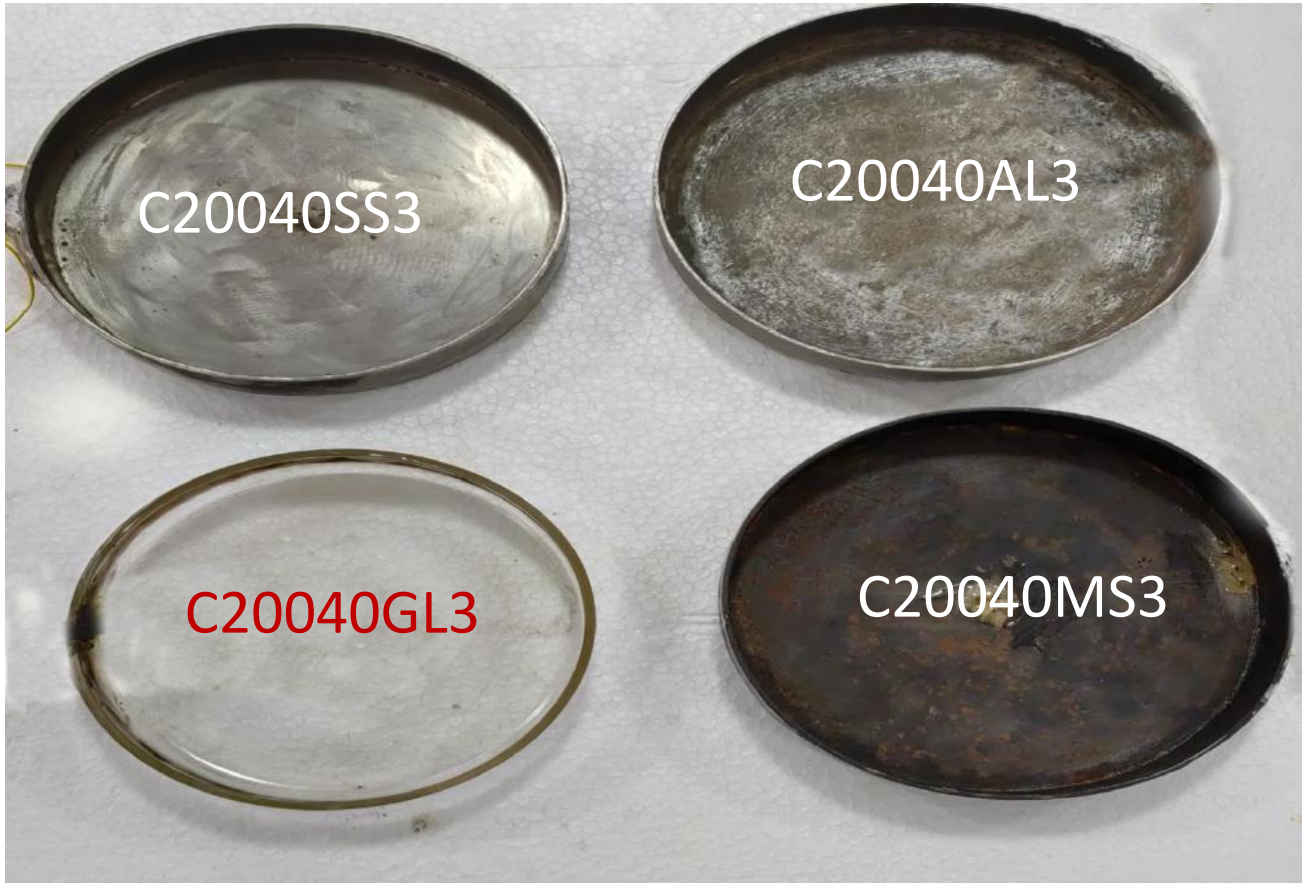
- The need for an unsteady approach to the predictive procedure as being more appropriate was suggested.

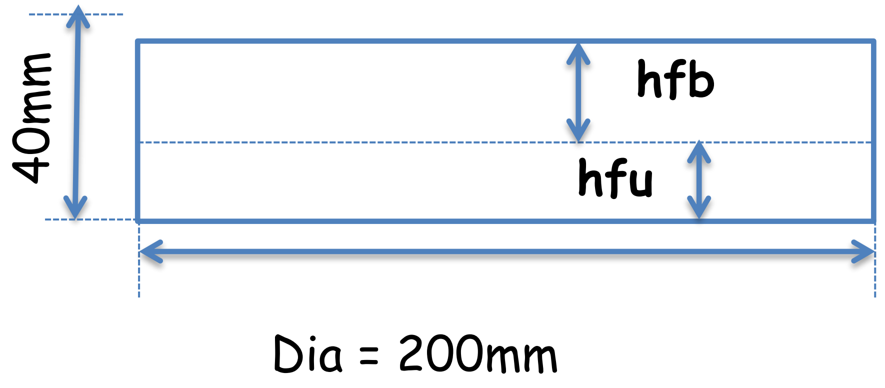
- The present effort is along these lines. It was thought appropriate to elucidate wall conduction effects through specifically conceived experiments

- Additional experiments with several T_{wall}, T_{liquid}, m vs time data along have obtained on 200 mm dia pans of 40 mm depth with different materials – Glass (GL), Stainless steel (SS), Mild steel (MS) and Aluminum alloy (AL) with a wide range of thermal conductivities and different n-heptane fuel thicknesses (10, 13 and 20 mm).

- Many intriguing aspects of the burn behavior have been explored through analysis of data with the aim to help the unsteady modeling using scaling laws.

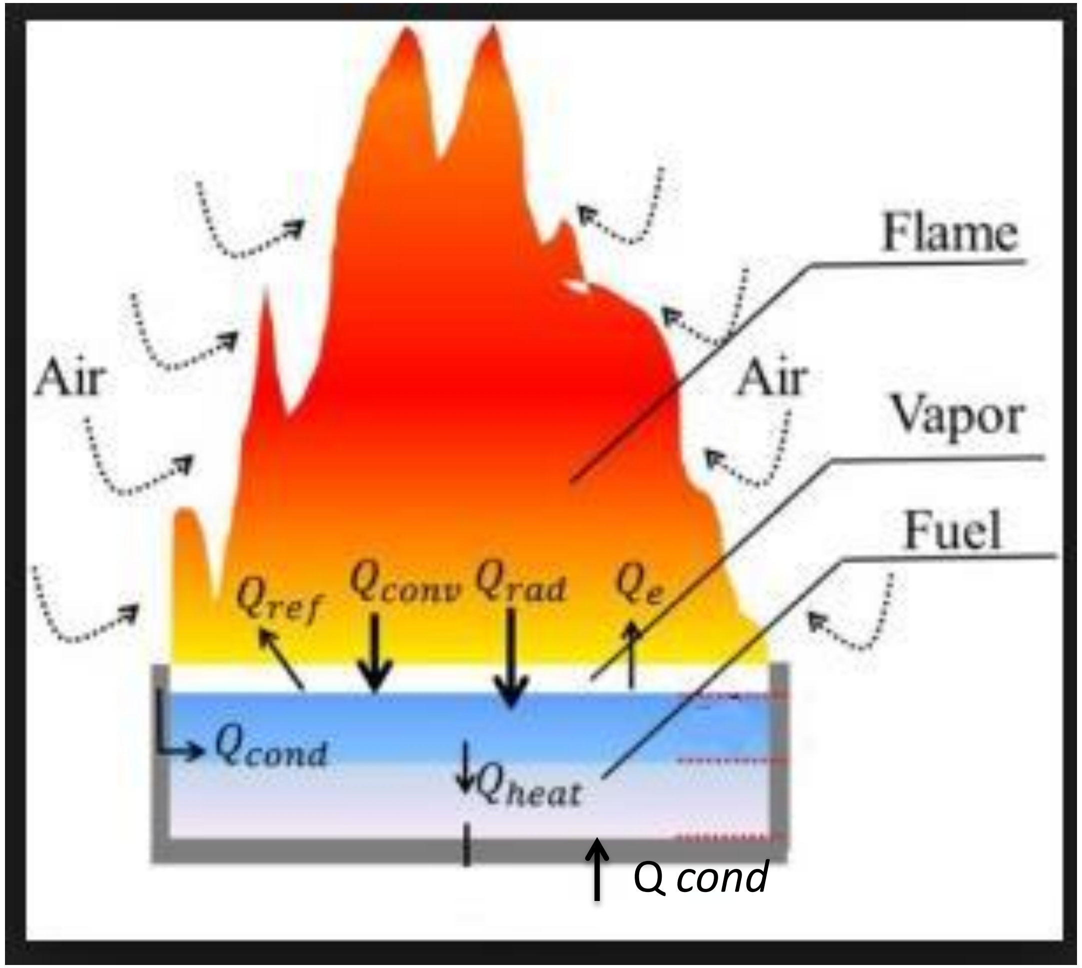
Pans used for experiments

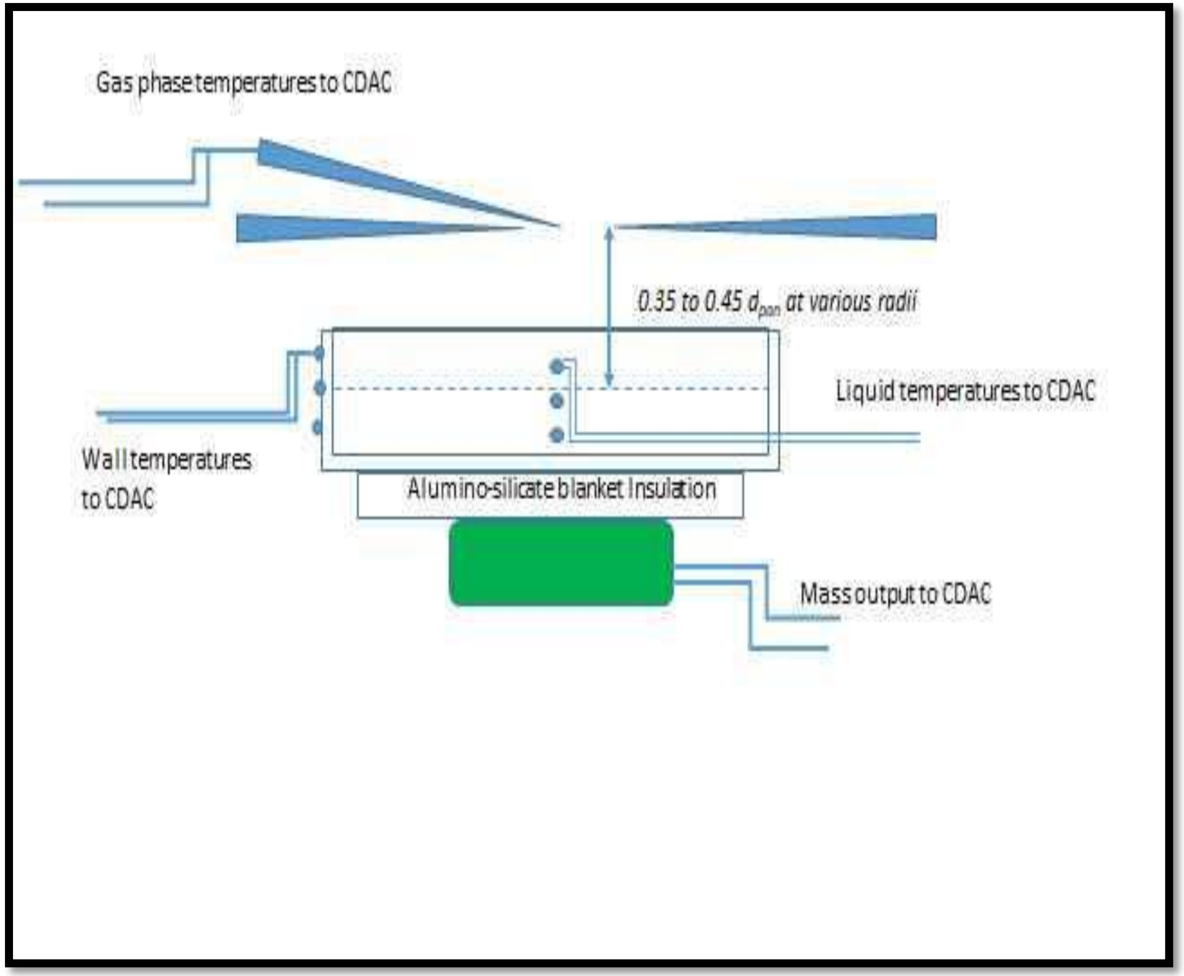




C20040MS3 → Circular pan of 200 mm dia,40 mm deep and 3 mm thick MS

The burn process and measurements in Pool fires





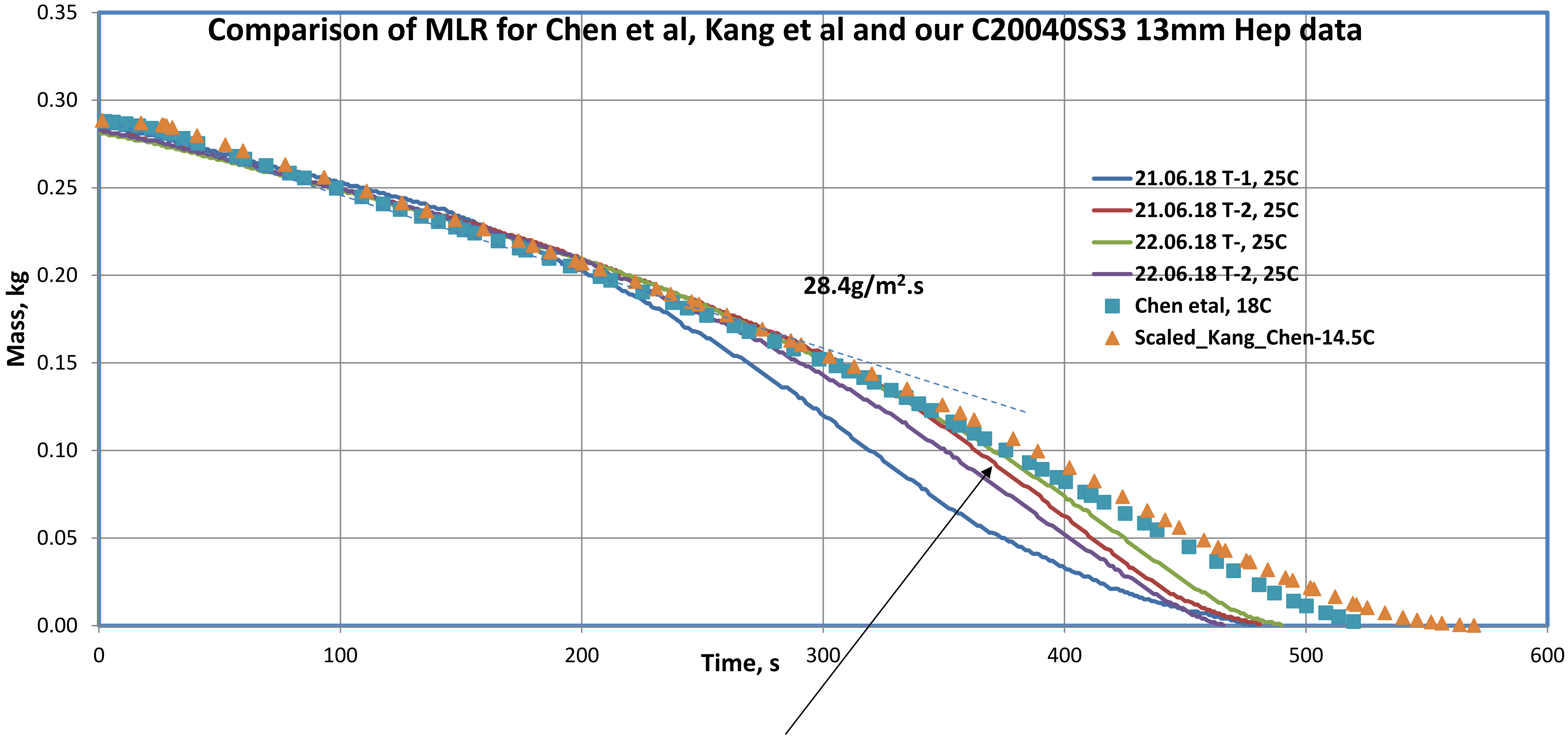
$$\rho . r_p = \frac{(\ddot{Q}_{cond} + \ddot{Q}_{conv} + \ddot{Q}_{Rad})}{(L + Cp(T_s - T_0))}$$

Flame picks up in a few seconds, Convective and Radiative fluxes also become effective at this time. Conduction along the walls takes time

The experiments….

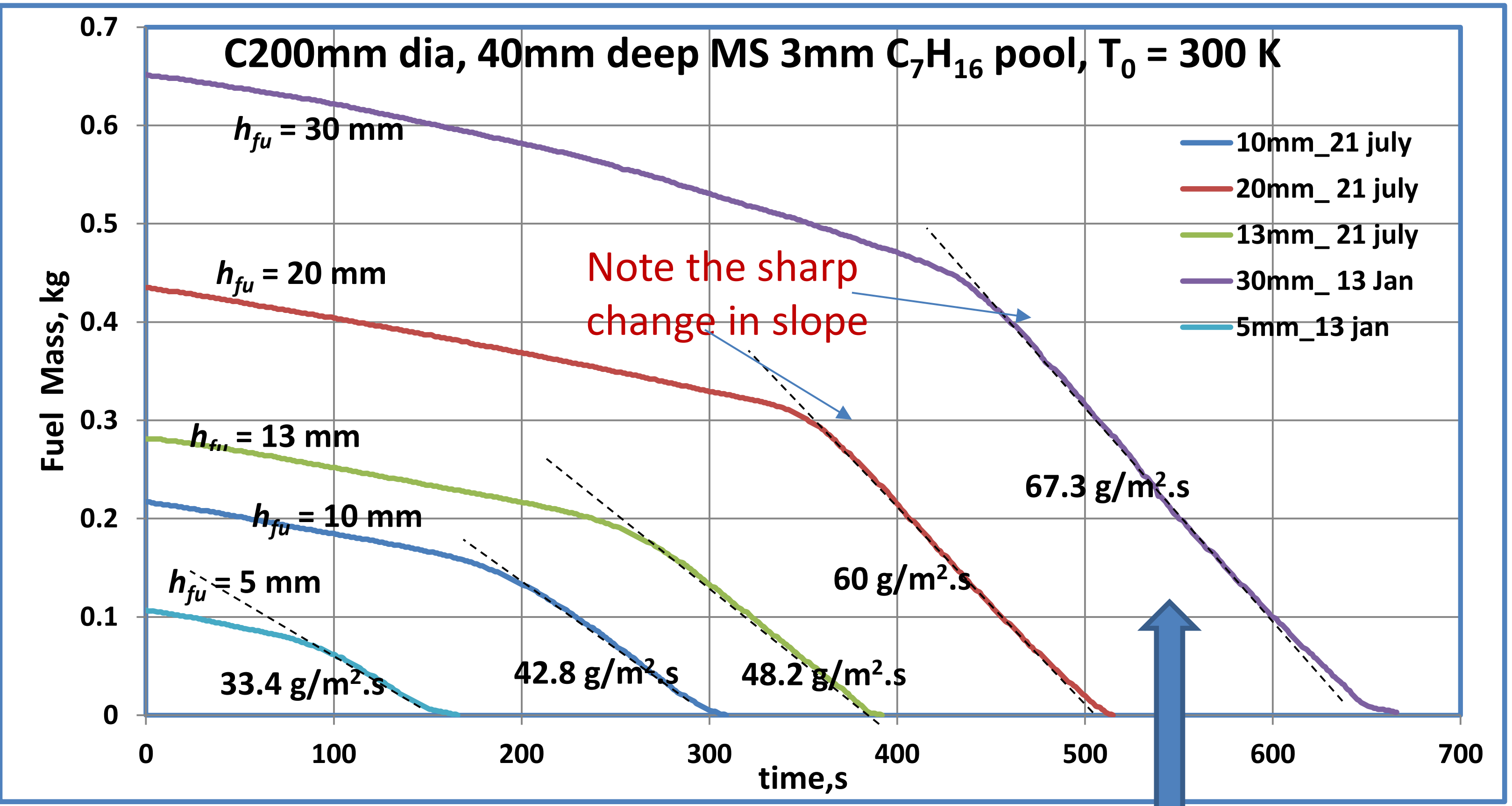
- All the experiments were conducted at FCRC fire lab largely on n-Heptane.
- Measurements have included fuel mass, centre line in-depth liquid temperature, wall temperatures at various heights on the pan wall, bottom wall temperatures, some in which temperatures across the wall, gas phase temperatures vs burn time in several experiments.
- Fuel depths tried were 10 mm, 13mm and 20 mm. The choice of 13 mm was because of earlier studies by Chen et al and Kang et al (from China) for 200 mm SS pan. They have been the only studies of significance attempting to elucidate the unsteady burning behavior in pans.
- More than 180 different experiments have been conducted – with four different pans and different depths and repeats to check on accuracies.
- Significantly new results have emerged……

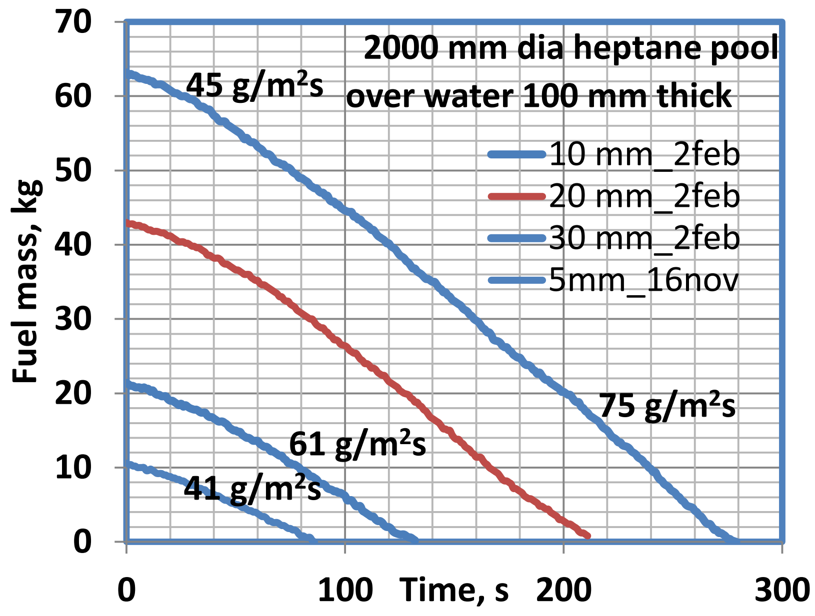
Comparison of Chen, Kang et al & our 200mm pan data



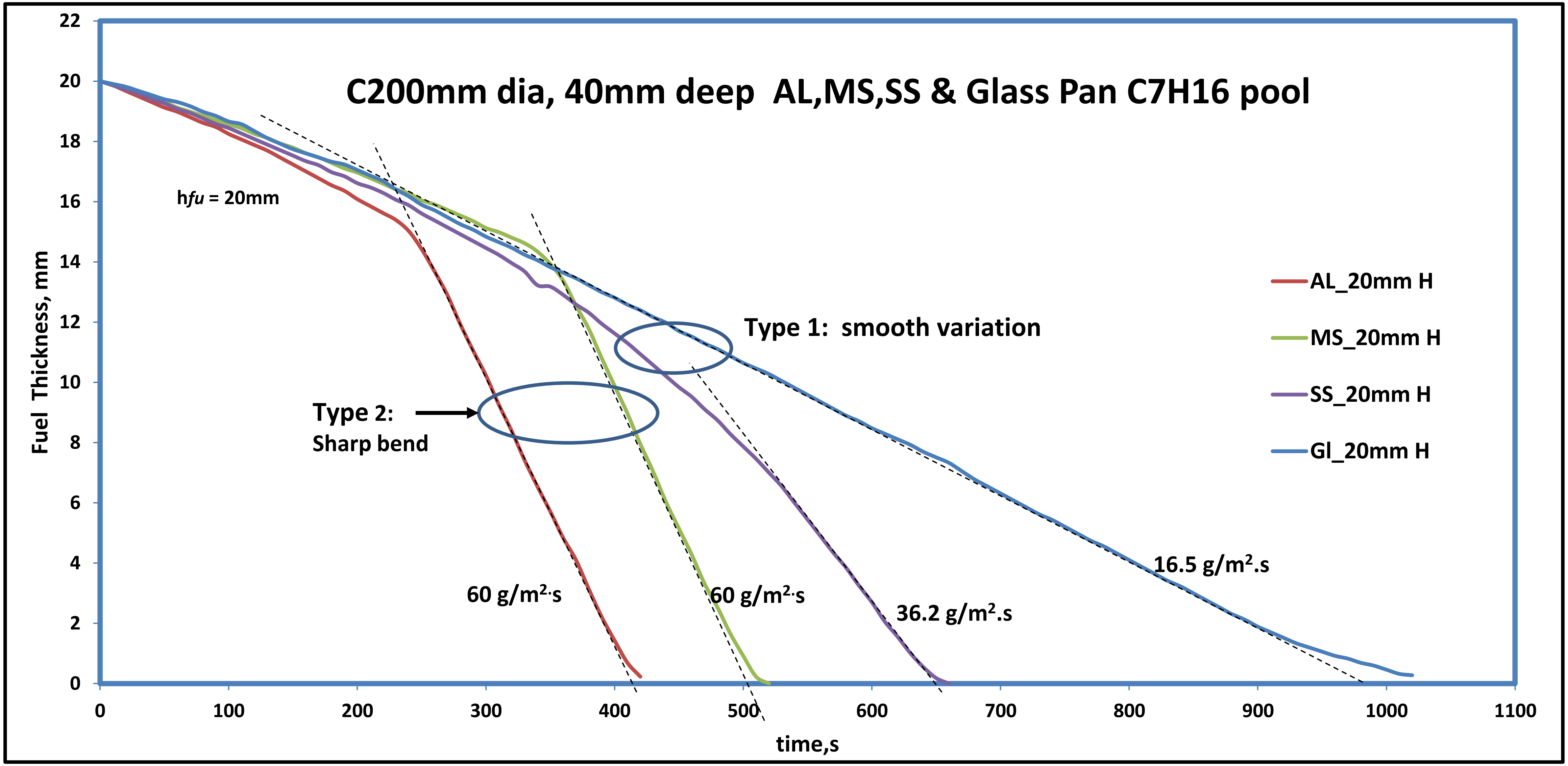
The comparison is considered “good”. The higher slopes are due to enhanced initial temperature at FCRC.

Fuel depth Effect on the mean and Peak Flux

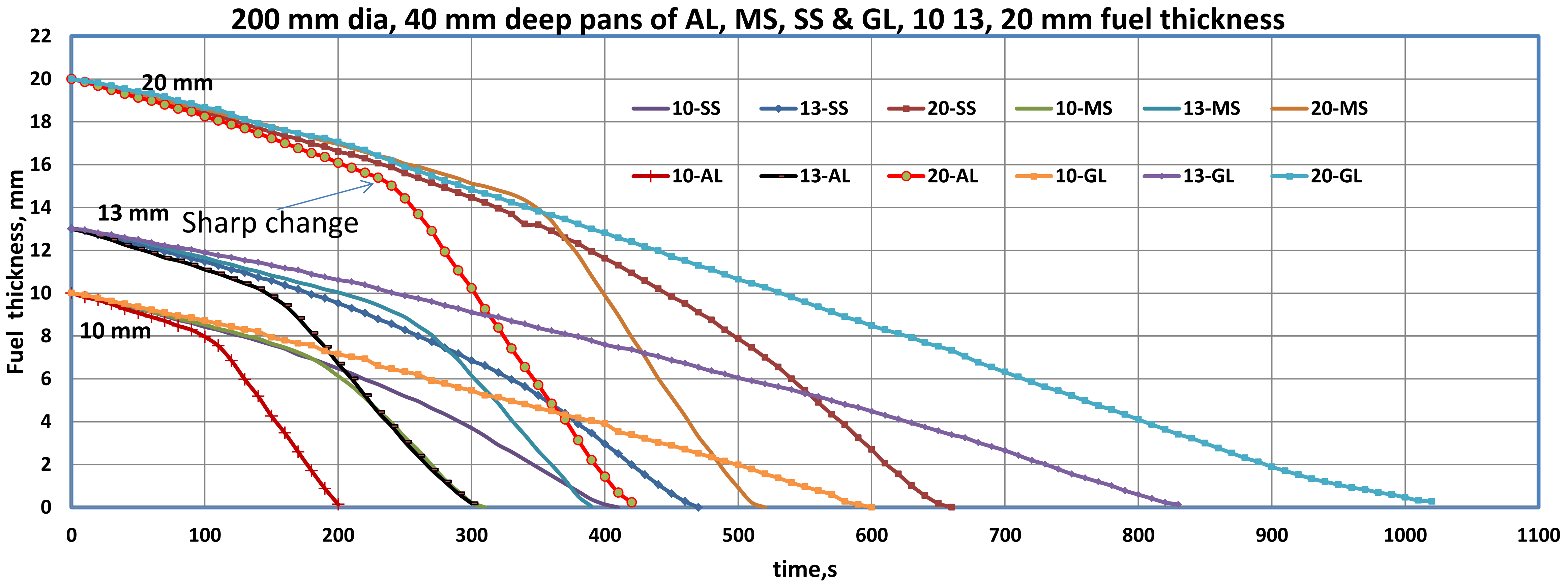




At this small pan dia, the peak flux is 67 g/m².s at fuel depth > 20 mm, a flux found only in large pans because of large radiation flux



Aluminium with thermal conductivity of 60 W/m K shows faster burn rate compared to Glass with a thermal conductivity of1.14W/m K. Thermal conductivity of the wall material (and thermal diffusivity) would be the key parameter



The sharp change in the case of AL & MS pan at transition region is due to increase in the heat transfer rate by conduction from the wall to fuel, where as in the case of SS there is a gradual change in the heat transfer rate at the transition region, i.e. in case of SS the fuel evaporation rate and the heat transfer rate from wall to fuel are comparable

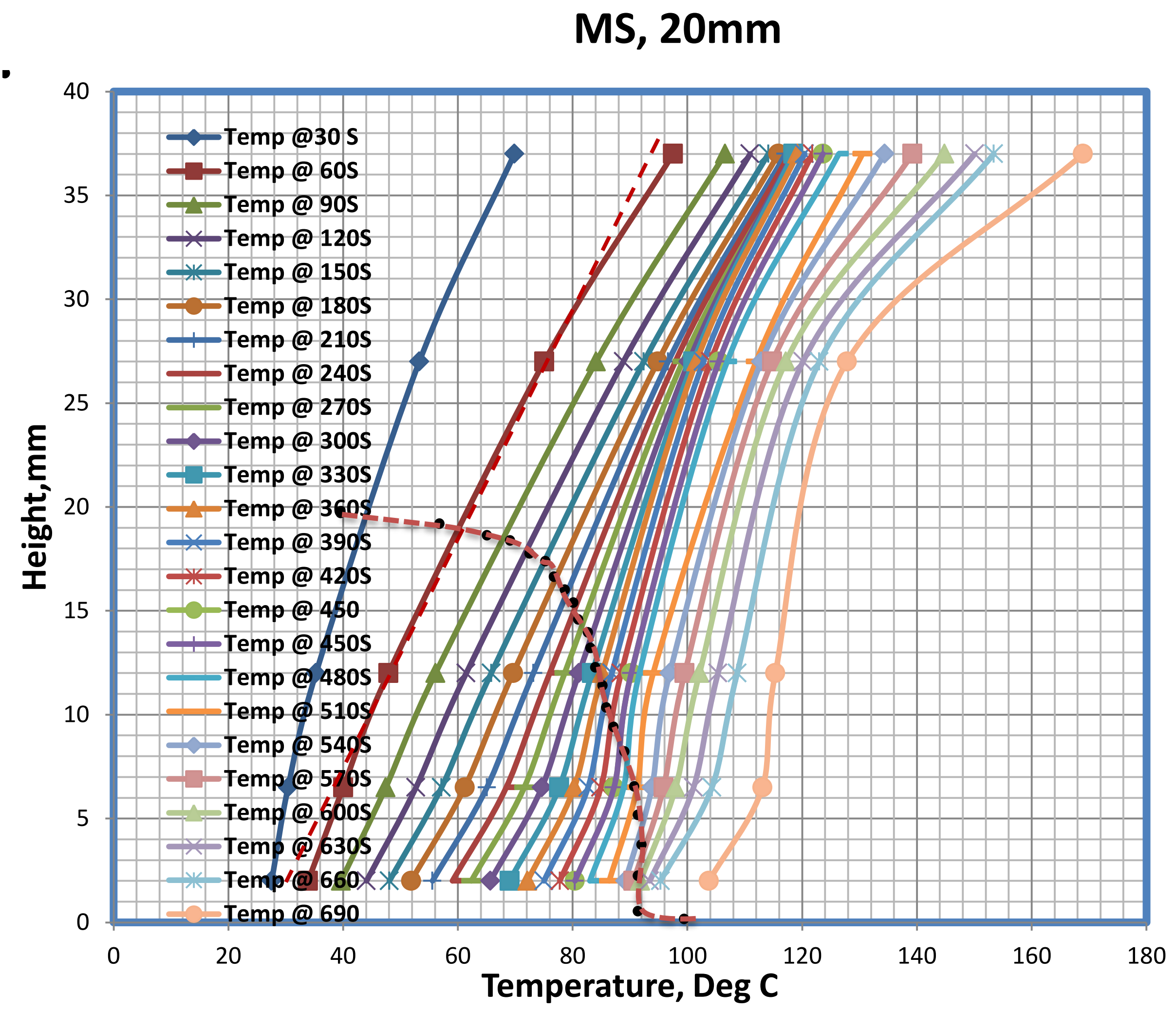
Glass has a near-uniform low fuel flux, but others have at least two segments – low and high flux regions

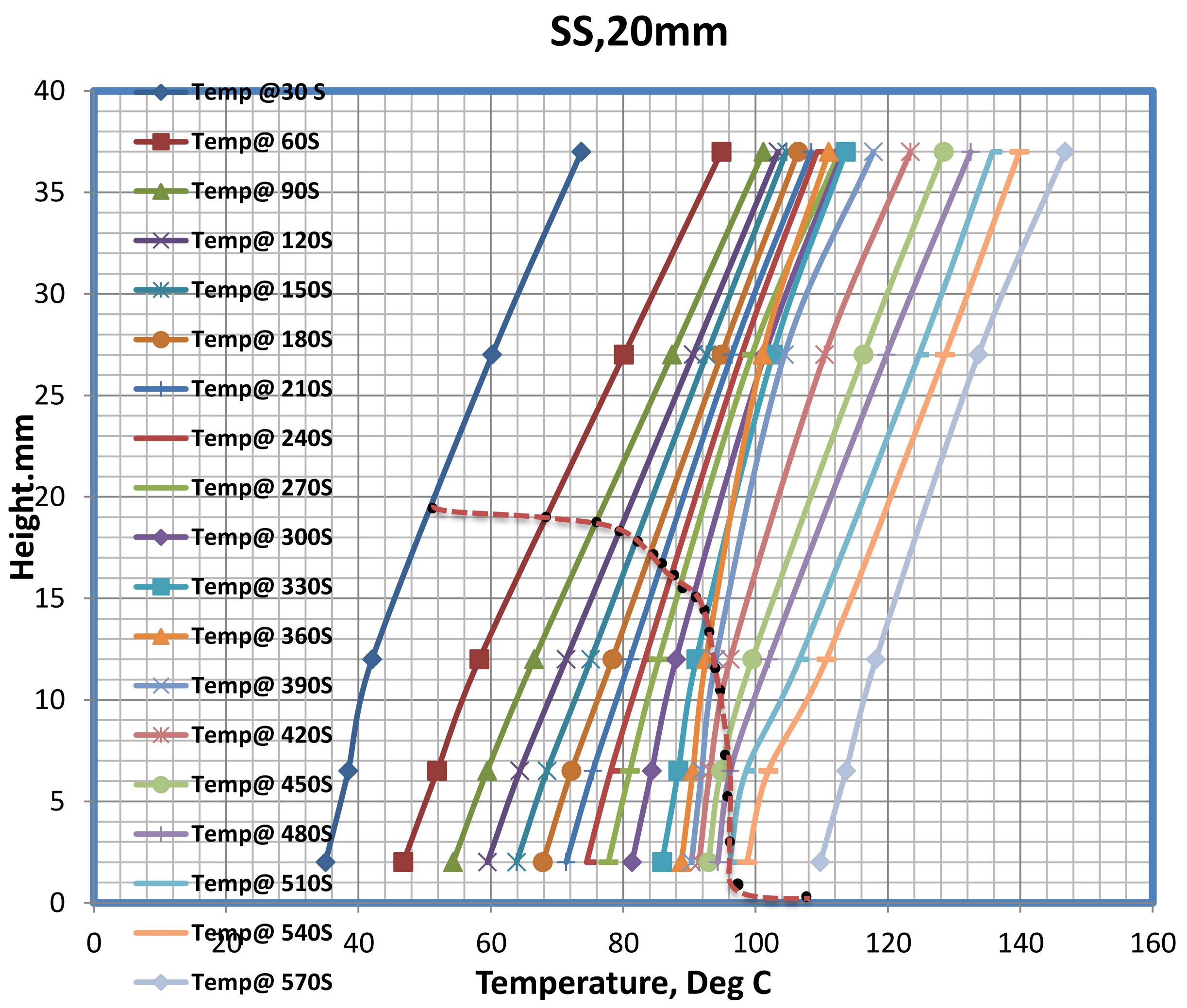
This means that there is only one mode of heat transfer that is effective in glass pan – convective flux

SL.NO	Pan Material	Heptane thickness (mm)	Initial Flux $g/m^2.s$	Time (sec)	Peak Flux $g/m^2.s$	Time (sec)
1	AL	10	11.6	0 to 70	52	110 to 200
2	AL	13	11.6	0 to 60	50	160 to 300
3	AL	20	11.1	0 to 130	60	240 to 410
4	MS	10	10.0	0 to 70	42.8	190 to 310
5	MS	13	11.3	0 to 60	48.2	270 to 400
6	MS	20	10.1	0 to 120	60	350 to 510
7	SS	10	10.4	0 to 70	24.8	240 to 400
8	SS	13	10.1	0 to 60	28.4	320 to 470
9	SS	20	11.1	0 to 120	36.2	460 to 650
10	GL	10	10.0	0 to 280	13.5	415 to 660
11	GL	13	9.1	0 to 180	14.6	520 to 840
12	GL	20	10.6	0 to 120	16.5	340 to 960

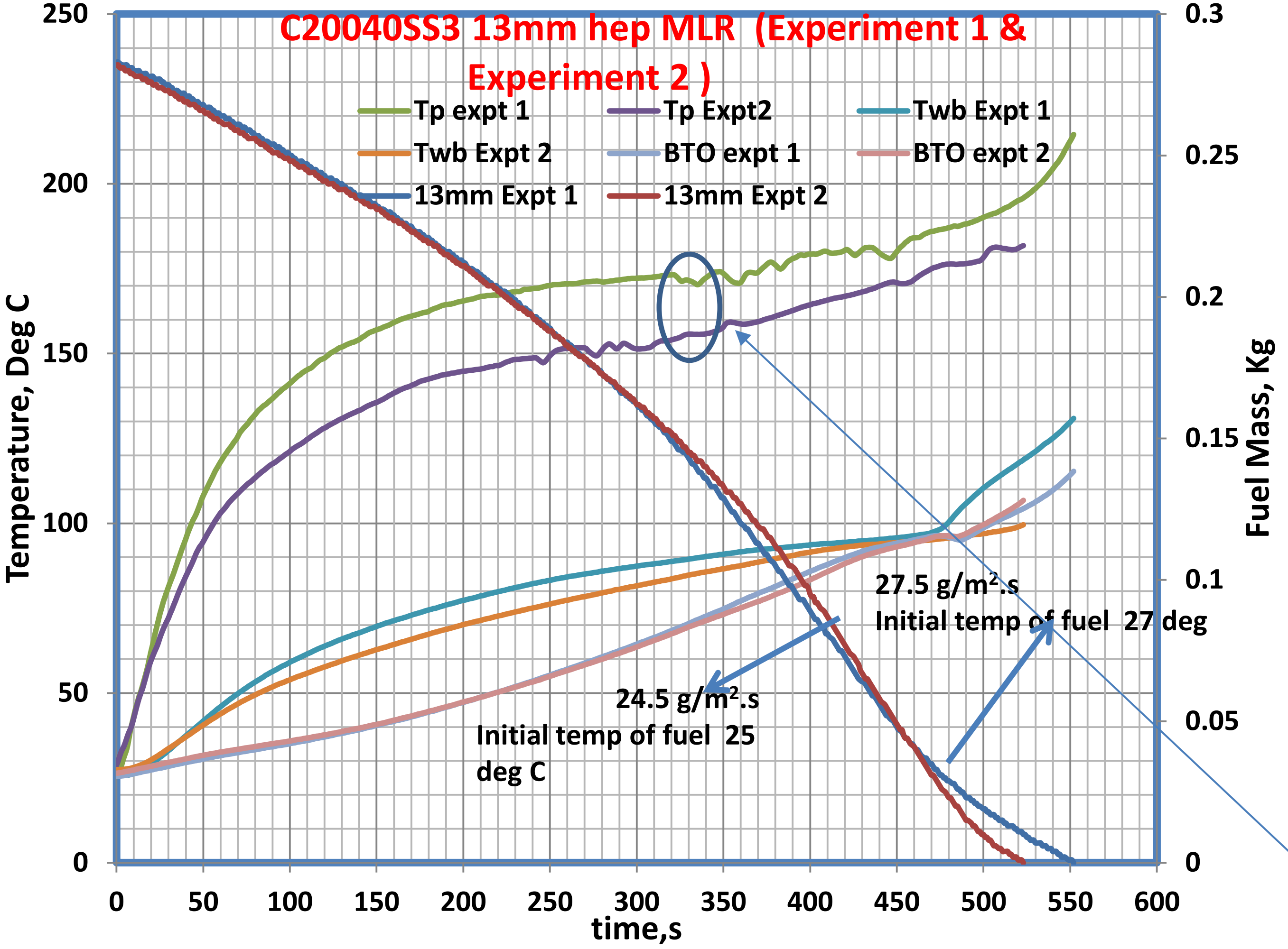
- Initial flux which is largely controlled by the convection is nearly the same (since radiation is less for smaller diameter pans at initial stage), irrespective of fuel thickness and pan material.
- Peak flux varies with the fuel thickness & pan material
- Since it was not yet clear whether the conduction or radiation is responsible for peak flux, experiments were done to measure the wall temperatures at different locations

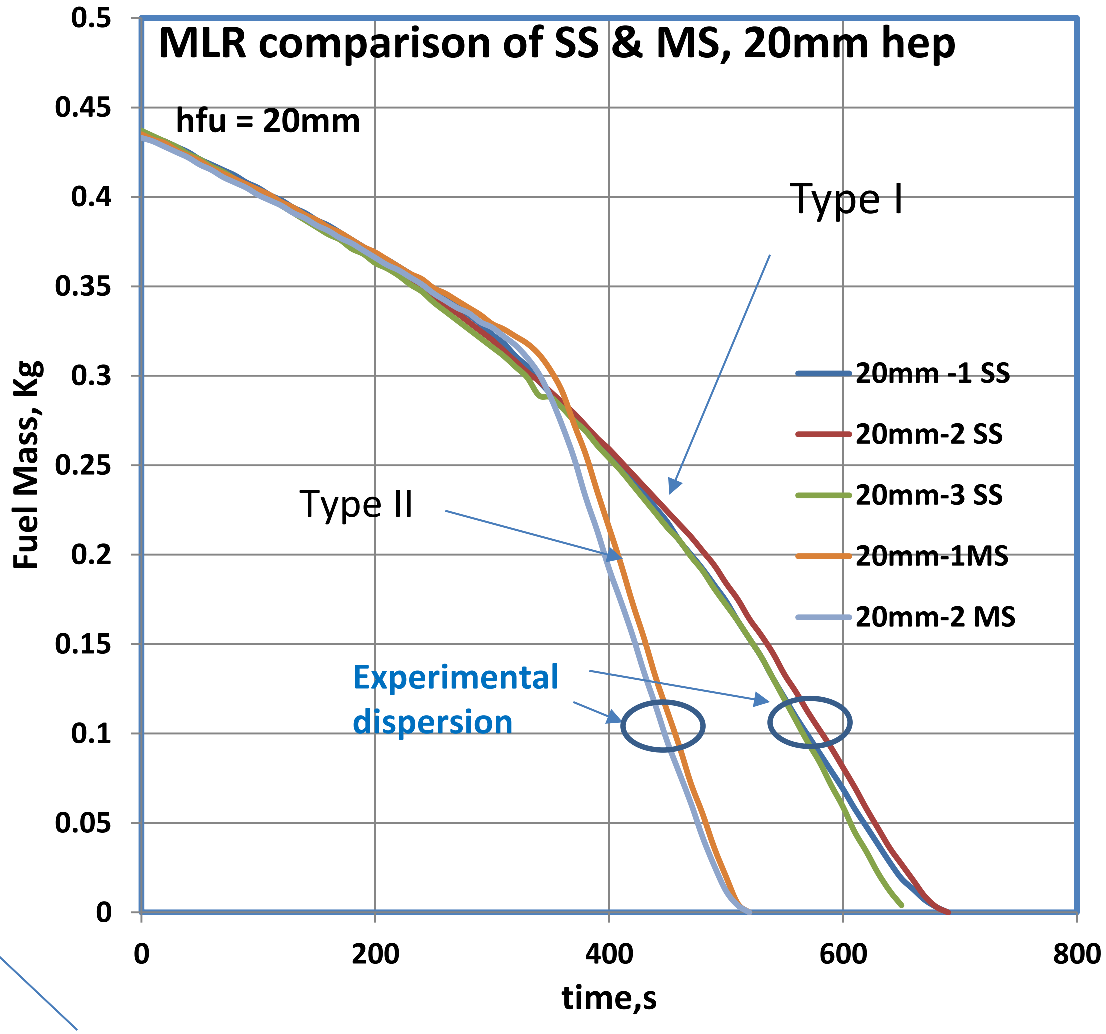
Height VS wall Temperature, 20mm heptane at 2,6.5,13 & 38mm





The wall temperature vs time can be approximated as linear with changes in slope caused by regression





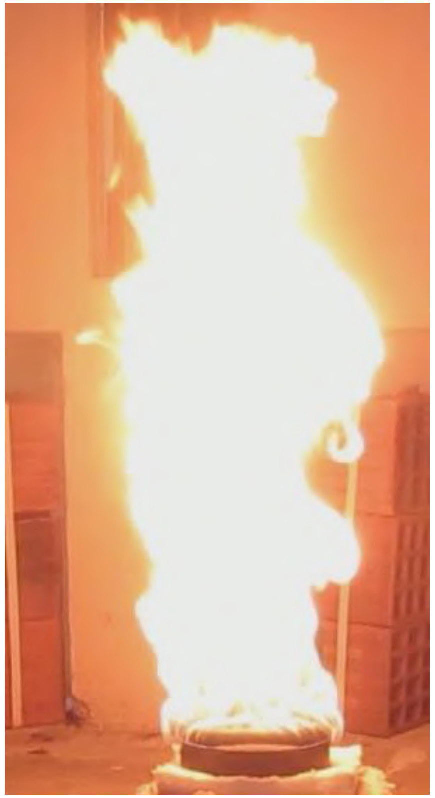
- Even though the pan tip temperature difference is about 15 to 20 °C, the burn time variation of two experiments is not much and there behaviour is about the same (all dispersions are within 5 %)

- The initial flux for both SS & MS pans are about same and the peak flux of same pan experiments does not vary much.

Flame structure at different stages for Glass & MS pan at fuel depth 20mm

- MS 20mm heptane

Steady Phase



Peak phase

Decay Stage

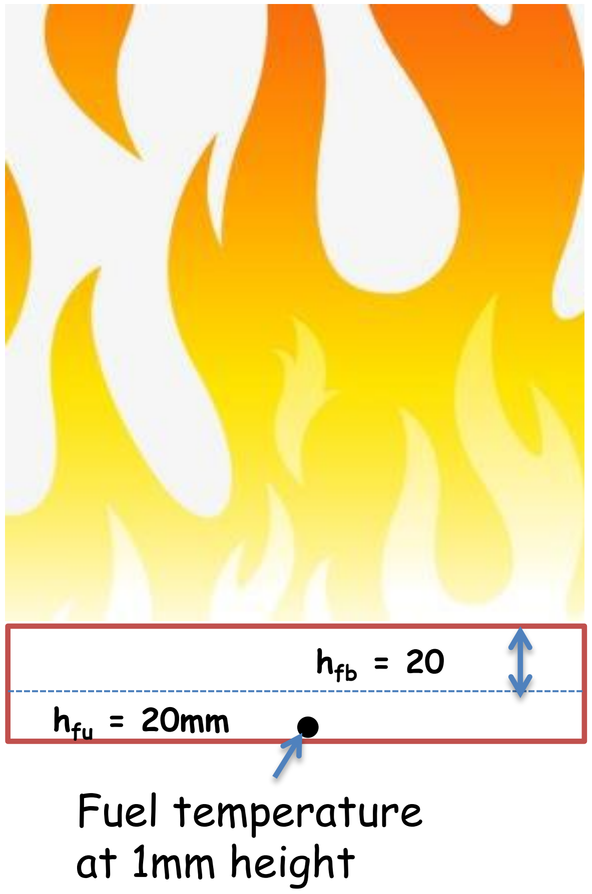
Gl 20mm heptane

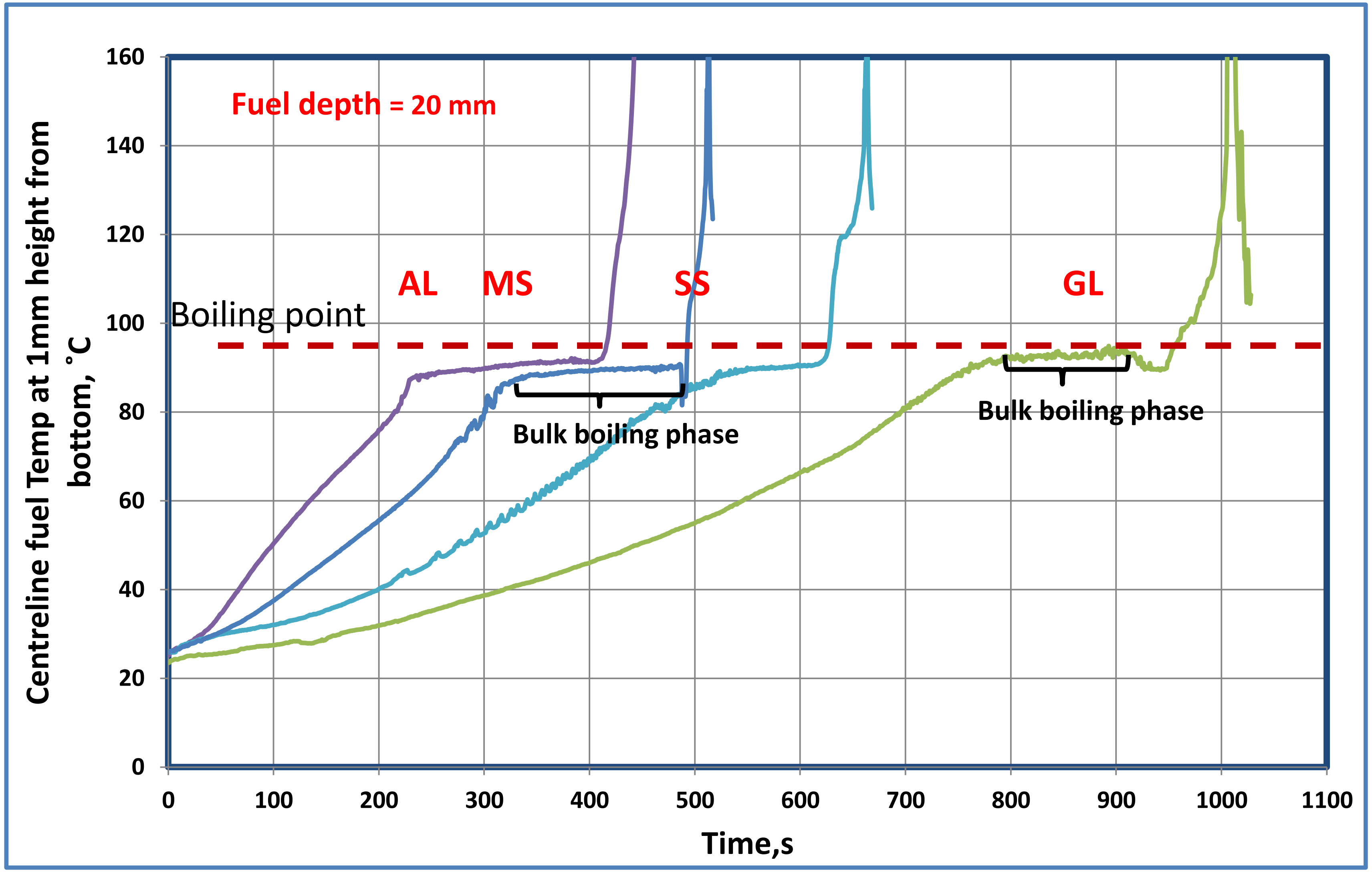
Steady Phase

Peak Phase

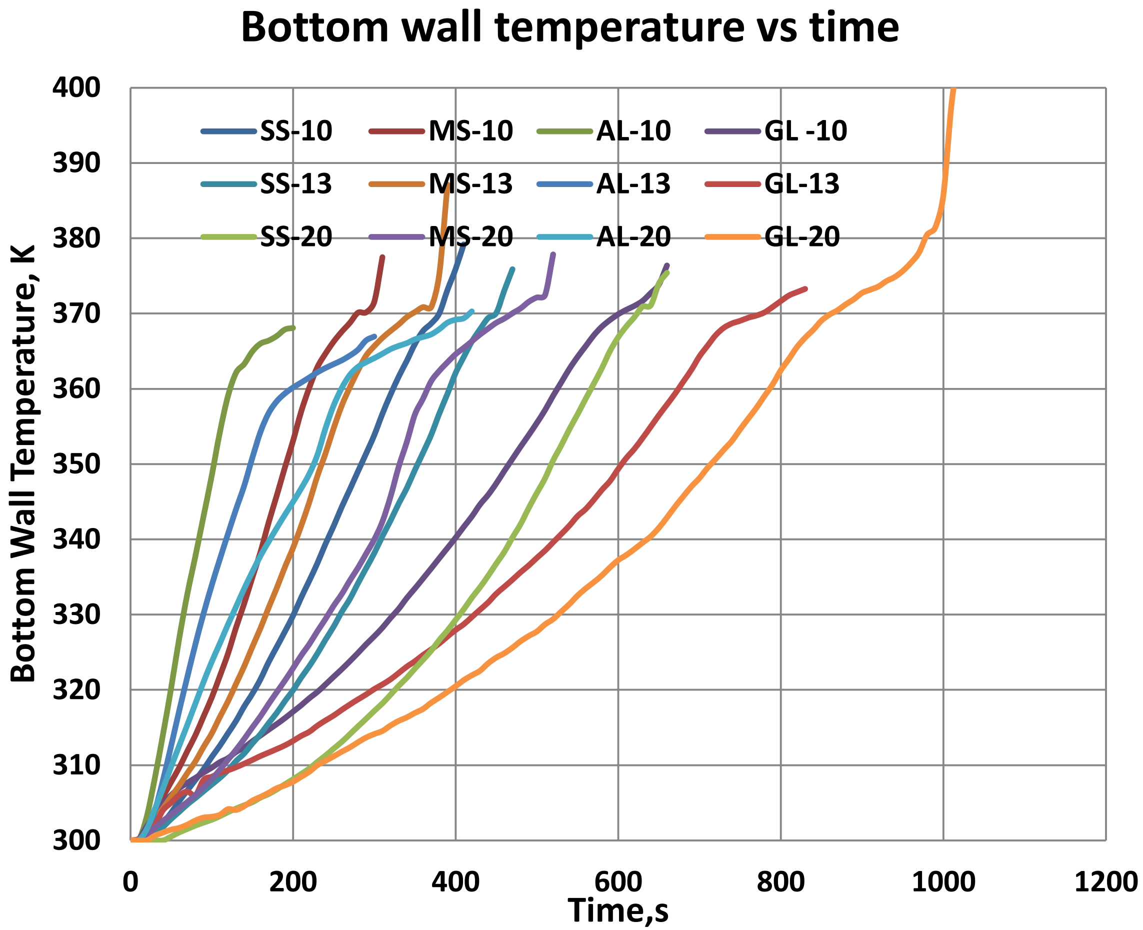
Decay Stage

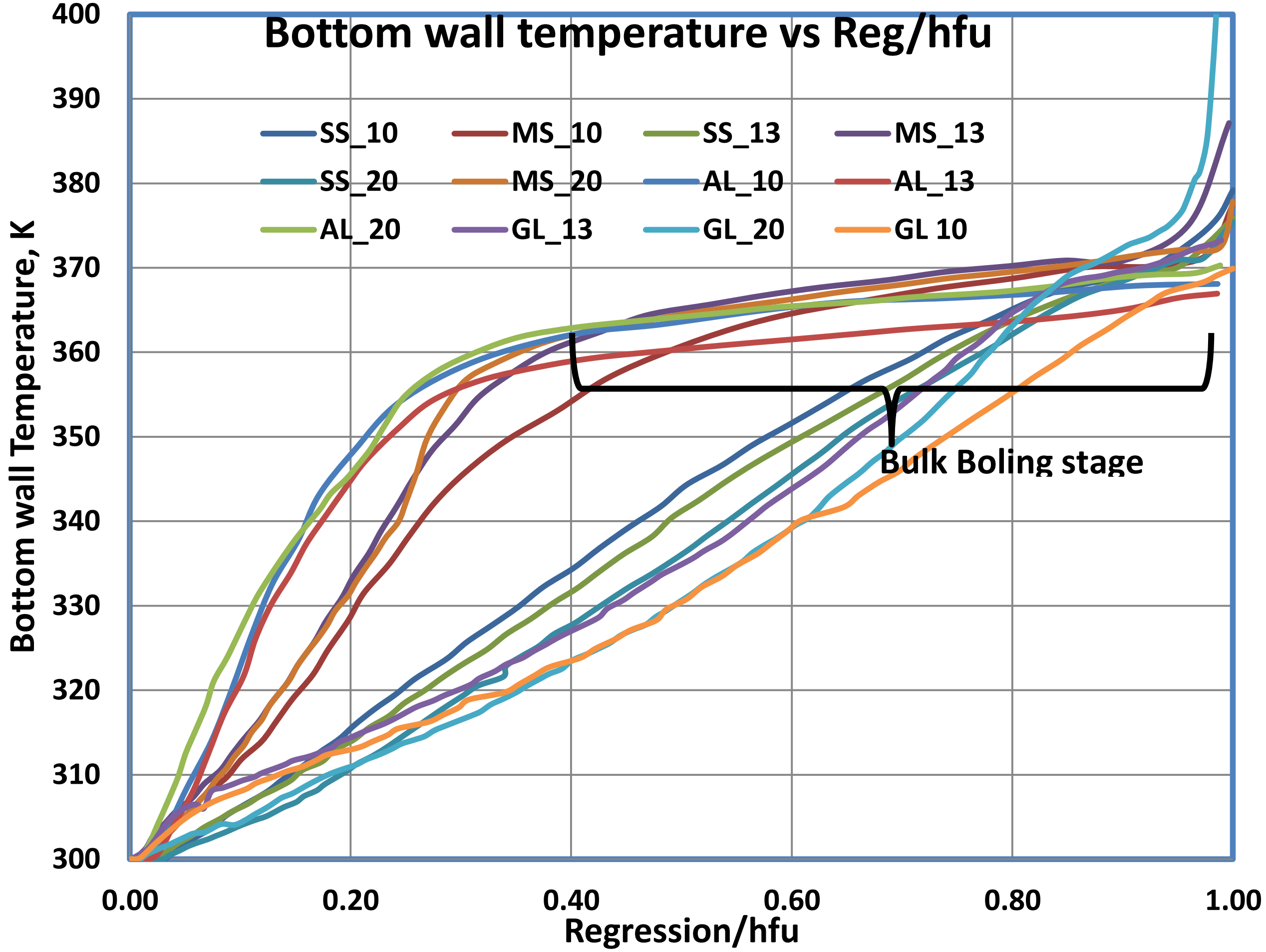
In case of Glass pan the flame size remains nearly same at both steady & peak phase where is in case of MS during peak flux it varies significantly





Fuel reaches boiling in AL pan at 220 s, MS pan at 320 s, SS pan at 530 s & GL pan at 760 s – related to corresponding enhanced gas phase flux basically due to enhancement in conduction heat transfer into the liquid fuel. The burn rate in the subsequent period is due to termed bulk boiling phase





- The bottom wall temperature (BTO), is plotted against time; since regression occurs with time, it appeared interesting to plot with regression itself. The plot shows that major regression occurs in the case of AL and MS in bulk boiling phase largely and some what at all temperatures in the case of SS & GL.
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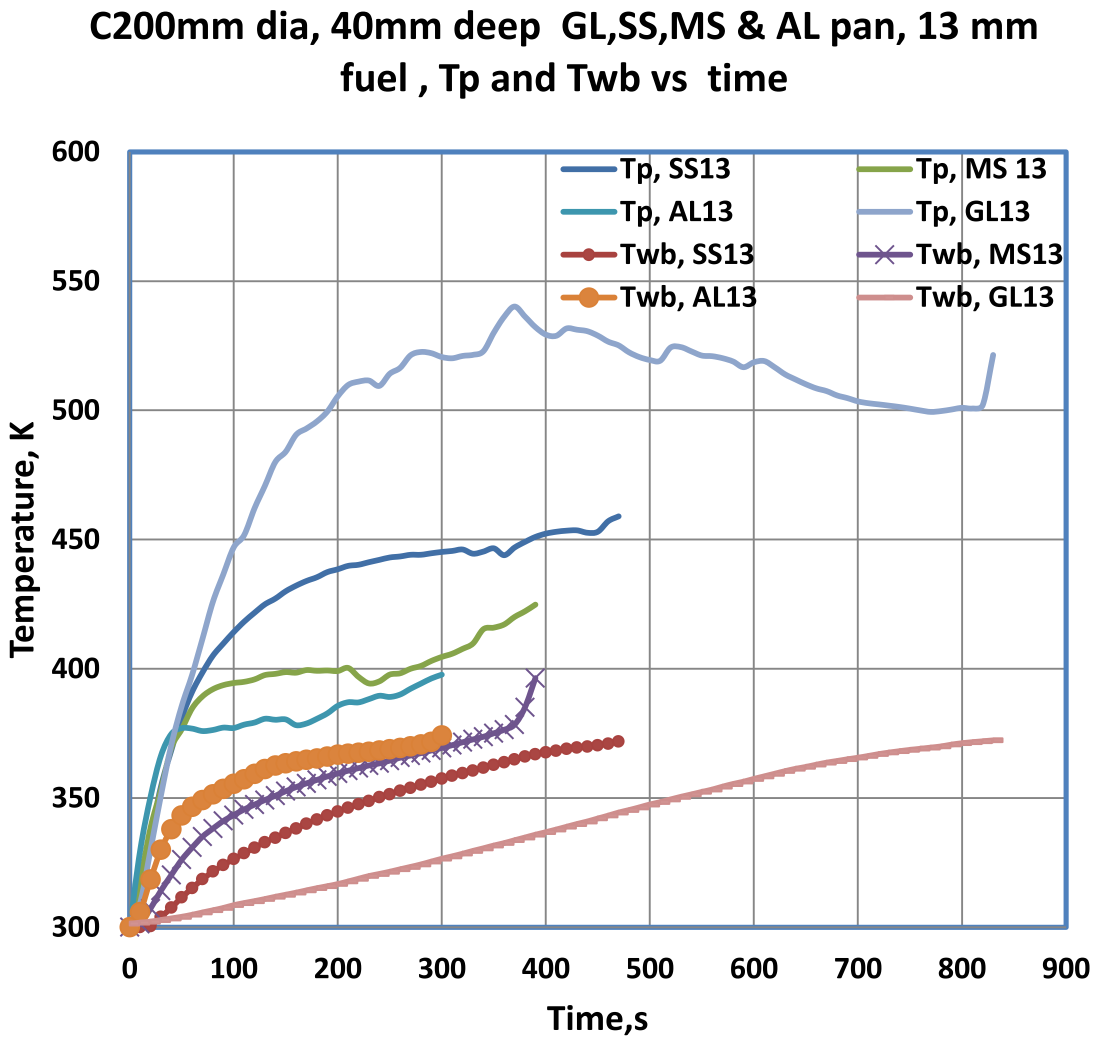
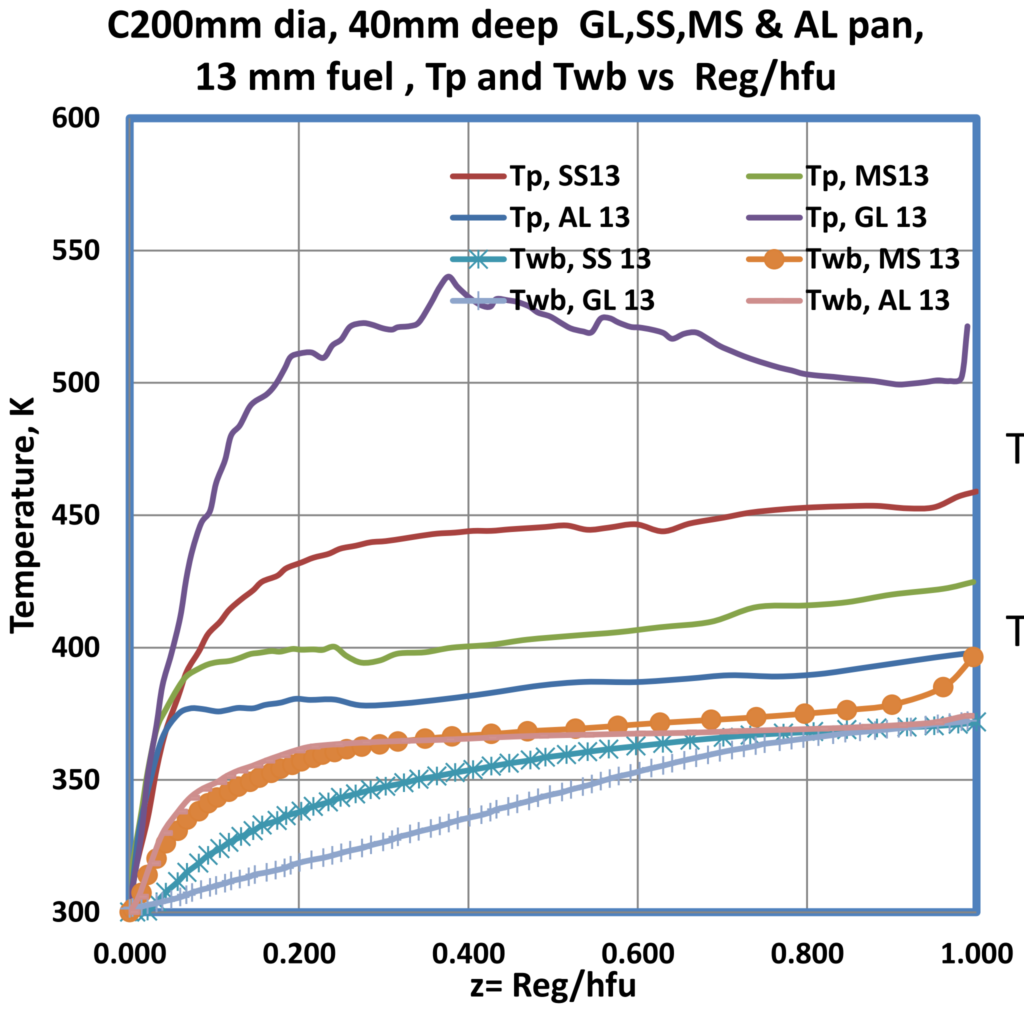
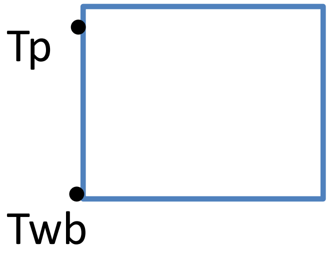
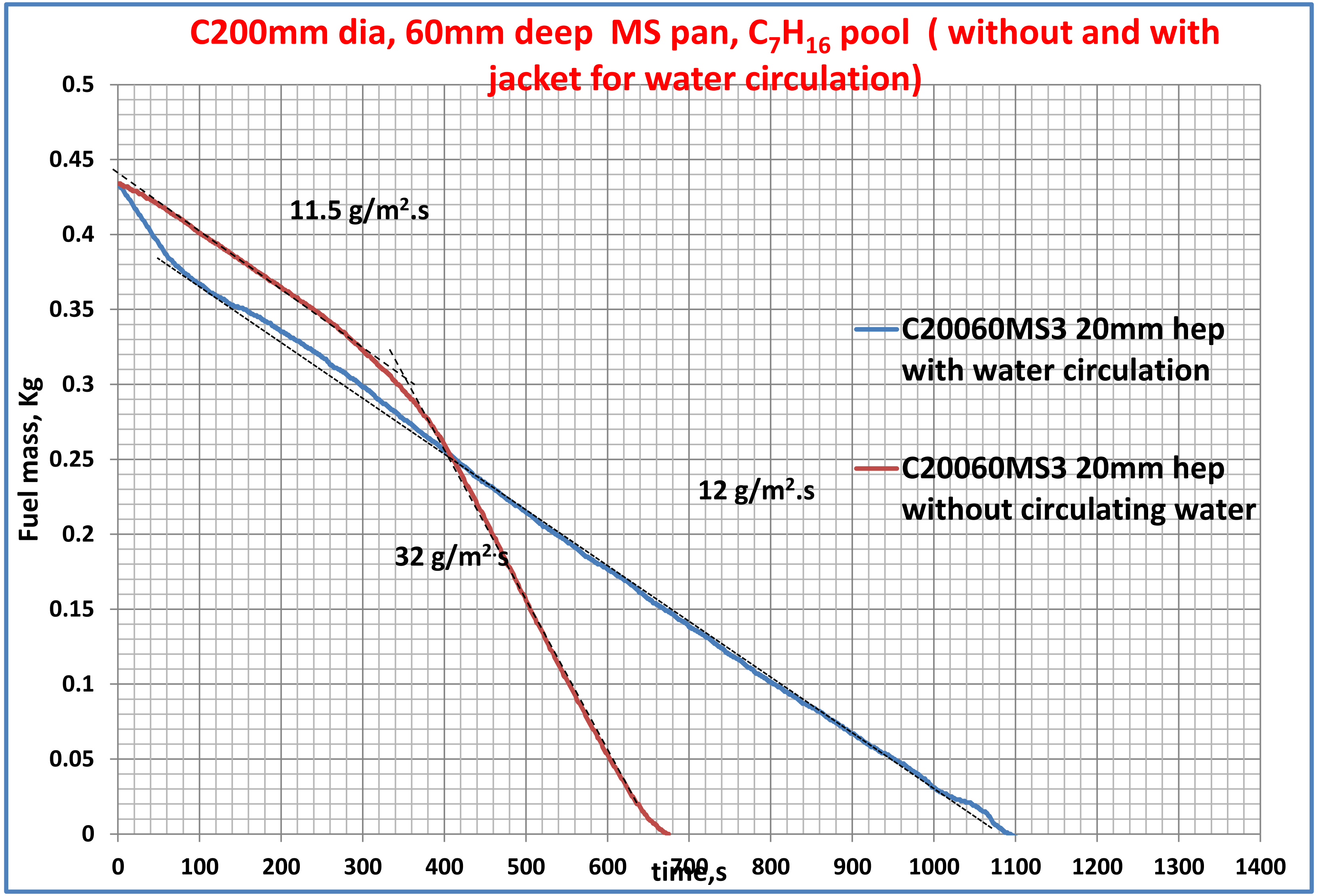
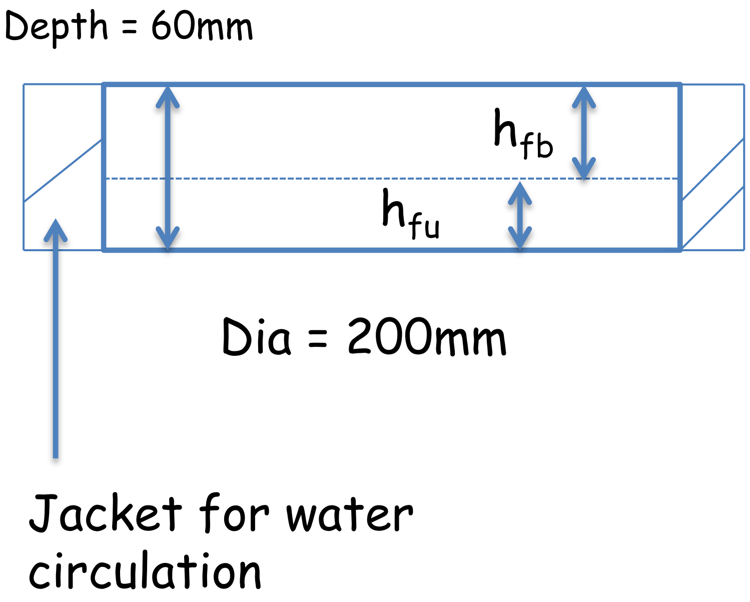




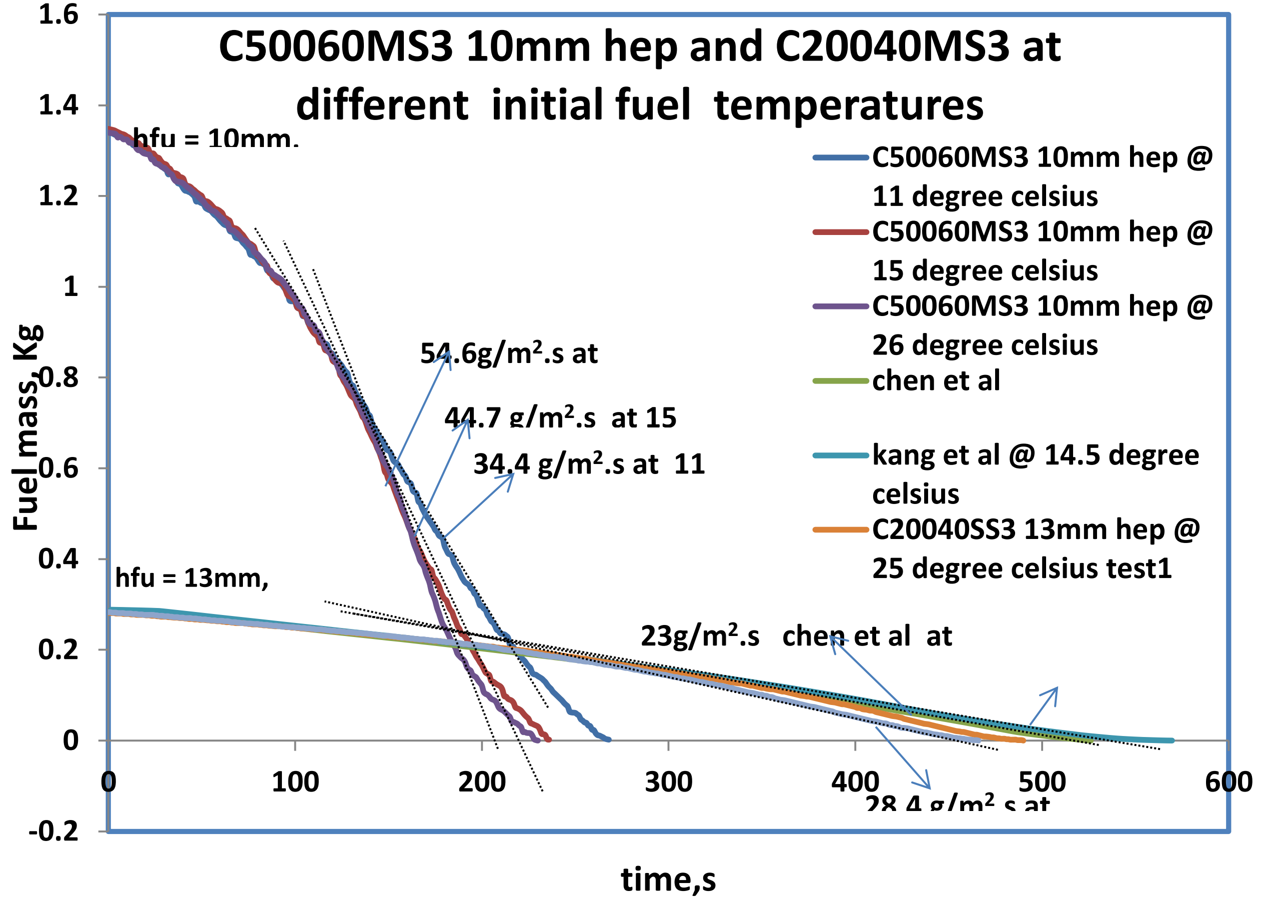


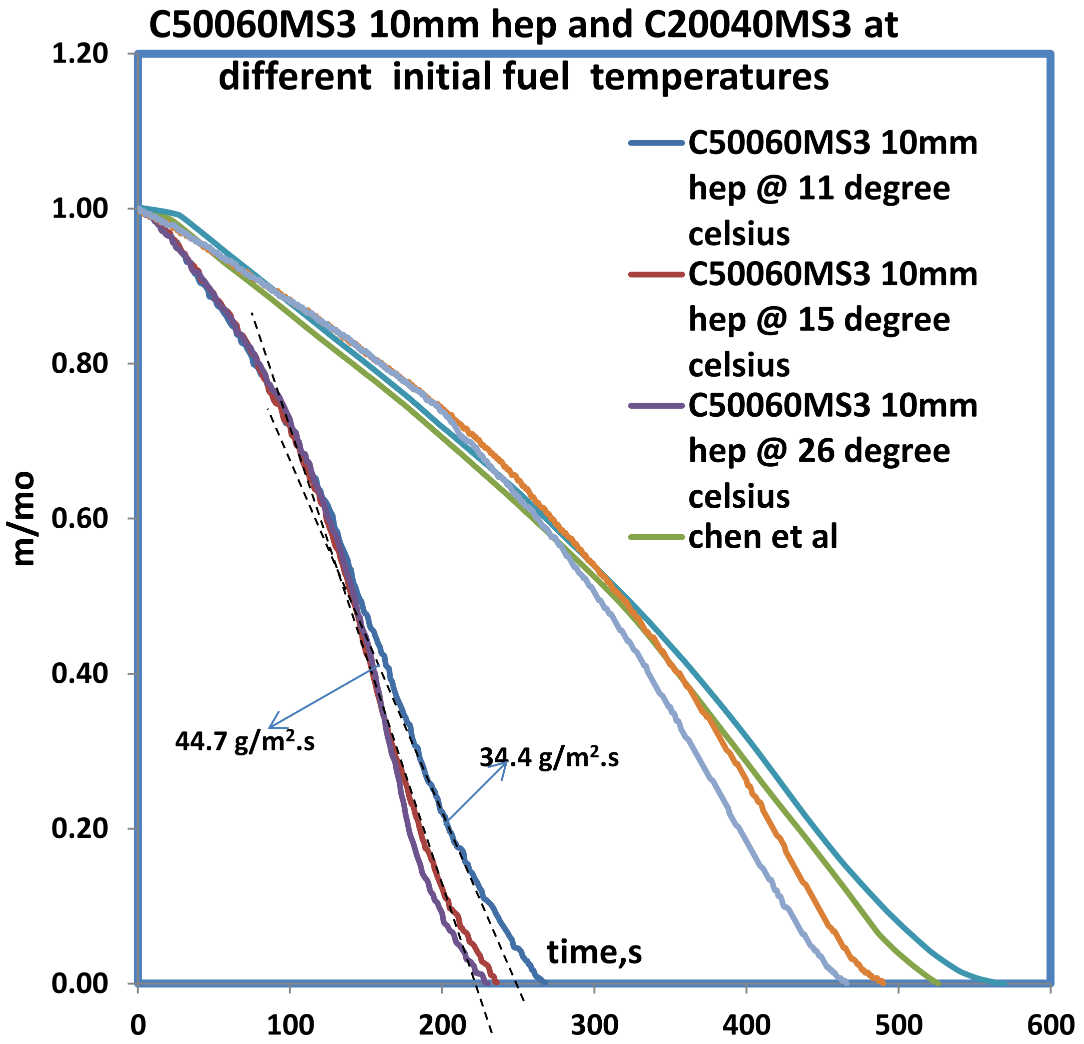
For low conductivity materials the tip temperature (Tp) is high and the bottom temperature (Twb) is much lower, for high conductivity material the tip temperature is less but the bottom wall temperature (Twb) is higher.





Conclusion: If the conduction effects are suppressed the burn rate remains unchanged even during peak condition and so conductive flux is the crucial feature for pans of this diameter





The fuel combustion rate is independent of initial fuel temperature in the early burn period, but varies strongly later.

Key points from the experiments

1. The experiments conducted here and those in China for n-heptane match well over the range tested with 200 mm dia SS pan with 13 mm fuel thickness.
2. The present experiments are with AL, MS, SS and GL with a factor 60 in thermal conductivity change and 24 in thermal diffusivity change and fuel thickness explored are 10, 13 and 20 mm
3. These are a part of extended experimental range that includes 500 mm and 2 m dia pans with and without fuel floating on water as well, not discussed here.
4. With glass, the dominant heat transfer mode is convection. With others, there is increasing role of conduction and at larger diameters and higher fuel fluxes, some radiation as well.
5. Sharp changes in burn rate with MS and AL are thought to be due to very fast conduction through the walls causing sudden appearance of boiling heat transfer all over.

How do we account for the behavior?

- The conductive flux is essentially accounted by using a conductive heat transfer coefficient: k_w/thickness, thickness being either h_{fb} or h_{pan} or (h_{pan} +d_{pan}/2) or $k_w/(h_{fb}$ + reg) (where h_{fb} = free board, reg = regression)
- One should expect that the largeness (or smallness) of this be measured against convective flux that also represents the basic heat flux for combustion (h_{gcv0}, typically about 5 W/m^2 K – in this case it has been determined as 4.5 W/m^2 K)
- We must reference the wall conductive flux to the pan – leading to a factor $\pi d_{pan} t_w / (\pi d_{pan}^2/4) = 4\, t_w/d_{pan}$ (t_w = pan wall thickness)
- Thus the basic dimensionless number that characterizes conductive flux in the pan emerges as $M_{pc} = [k_w/(h_{pan})/h_{gcv0}]\,[4\, t_w/d_{pan}]$. Additional effects of fuel thickness and fuel initial temperature will need to be factored in.

Non-Dimensional Number, M_{pc}

A non dimensional number is introduced to capture the conduction and convection heat transfer so that all the observed effects are captured.

$$M_{pc} = [h_m/h_{gcv0}]\ [4t_w/d_{pan}]\ [(h_{fu}/h_{pan})\ [L_{fu}/\{c_{pfu}(T_{bfu} - T_0)\}]^{0.5}\ [1 - 0.3(h_{pan}/d_{pan})^{0.125}]$$

I II III IV

Where

$h_m = k_w/(h_{pan})$, h_{gcv0} is convective heat transfer coefficient, h_{fu} is fuel depth, hpan is pan depth in mm, L_{fu} is latent heat of vaporization of fuel in kJ/kg, c_{pfu} is specific heat of fuel in kJ/kg K, T_{bfu} is fuel boiling temperature in K, T_0 is initial temperature of fuel in K

I: Ratio of wall heat transfer coefficient to basic convective heat transfer coefficient

II: Converting wall heat flux to that over the pan area $[\pi d_{pan}\ t_w/(\pi d_{pan}^2/4)]$

III: Covering the effects of fuel depth and fuel properties

IV : Taking into account heat loss effects $\{1$ – constant $[\pi d\ h_{pan}/(\pi d_{pan}^2/4)]^n$ n is taken as 1/8 after check with experimental data at 100 mm dia$\}$

The experimental parameters and M_{pc}

$h_{pan} = 0.04$ m, $d_{pan} = 0.2$ m

Matl	kw	ρ_w	c_{pw}	α_w	hfu	T_0	L_{fu}	T_{bfu}	c_{pfu}	$L_{fu}/cp_{fu}(T_{bfu}-T_0)$	Mpc
	W/m K	kg/m³	kJ/kg K	mm²/s	m	K	kJ/kg	K	kJ/kgK		
AL	60	2710	0.91	24.33	0.02	300	322.0	369	2.10	2.2	**15.50**
AL	60	2710	0.91	24.33	0.013	300	322.0	369	2.10	2.2	**13.91**
AL	60	2710	0.91	24.33	0.01	300	322.0	369	2.10	2.2	**13.03**
MS	32	7850	0.5	8.15	0.02	300	322.0	369	2.10	2.2	**8.26**
MS	32	7850	0.5	8.15	0.013	300	322.0	369	2.10	2.2	**7.42**
MS	32	7850	0.5	8.15	0.01	300	322.0	369	2.10	2.2	**6.95**
SS	16	7880	0.46	4.41	0.02	300	322.0	369	2.10	2.2	**4.13**
SS	16	7880	0.46	4.41	0.013	300	322.0	369	2.10	2.2	**3.71**
SS	16	7880	0.46	4.41	0.01	300	322.0	369	2.10	2.2	**3.47**
GL	1.14	2320	0.75	0.66	0.02	300	322.0	369	2.10	2.2	**0.26**
GL	1.14	2320	0.75	0.66	0.013	300	322.0	369	2.10	2.2	**0.26**
GL	1.14	2320	0.75	0.66	0.01	300	322.0	369	2.10	2.2	**0.25**

Conductive heat transfer very High (AL)

Conductive heat transfer high (MS)

Conductive heat transfer marching with convection (SS)

Convective heat transfer most dominant (GL)

L_{fu} = Heat of vaporization of n-Heptane, T_{bfu} = Boiling point of n-Heptane

Modeling the burn process -1

The basic equation for obtaining burn rate flux is

$$\rho_l \dot{r} = \frac{(q''_{conv} + q''_{rad} + q''_{cond})}{[L + C_{pfu}(T_s - T_0)]} \qquad Ts = liquid\ surface\ temperature$$

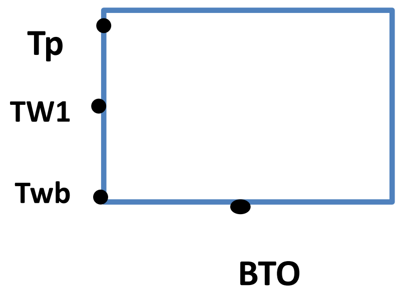
With

$$q''_{conv} = h_{gcv}(T_f - T_s), h_{gcv} = h_{gcv0}\left[1 + \frac{0.02 U_{wind} d_{pan}}{0.000012}\right]^{0.5} \left[1 + \frac{U_{wind}}{\sqrt{9.81 d_{pan}}}\right]^{0.5}$$

$$h_{gcv0} = 0.0045\ kW/m^2.K \qquad h_{gcv} = convective\ heat\ transfer\ coefficient;\ U_{wind} = wind\ speed$$

$$q''_{rad} = 0.2\left[1 - \exp\left\{-0.0002 \rho_l \dot{r} \frac{d_{pan}}{0.000018}\right\}\right]\ 56.78\left[\frac{T_f}{1000}\right]^4\ kW/m^2.K$$

$$q''_{cond} = h_{gwfu}\left[\{T_{wb} - T_{bot}\} + 4\{(h_{fu} - reg)/d_{pan}\{\frac{T_{w1} + T_{wb}}{2} - \frac{T_s + T_{bot}}{2}\}\right]; reg = regression$$



$$T_{w1} = T_p - \frac{(T_p - BTO)(h_{fb} + reg)}{\left(h_{pan} + \frac{d_{pan}}{4}\right)} \qquad T_{wb} = T_p - \frac{(T_p - BTO)h_{pan}}{\left(h_{pan} + \frac{d_{pan}}{4}\right)}$$

$T_{w1} = Temperature\ at\ liquid\ level, T_p = Pan\ tip\ temperature,$

$T_{wb} = Wall\ temperature\ at\ the\ bottom\ corner$

Modeling the burn process -2

$$(\rho_w\, C_{pw} t_w)\frac{dT_p}{dt} = h_{gft}(T_f - T_p) - C_0\left[\frac{k_w}{h_{fb} + reg}\right](T_p - T_0);\ \ h_{gft} = Flame\ to\ tip\ heat\ transfer\ coefficient\ ;$$

$C_0 = 0.8$

Observed $dT_p/dt]_{t=0}$ = dTpdtC *is taken to rewrite the equation as*

$$\frac{dT_p}{dt} = \frac{\left[h_{gft}(T_f - T_p) - C_0\left\{\frac{k_w}{h_{fb} + reg}\right\}(T_p - T_0)\right]}{\left[h_{gft}(T_f - T_p)dT_p dtC\right]};\ dT_p dtC = 0.35\left[1 + \left(\frac{M_{pc}}{4}\right)\exp\left(\frac{-M_{pc}}{4}\right)\right]$$

dTpdtC is ~ 1.3 to 2.4 K/s and the choice is made according to M_{pc} to allow tracking the early variation of Tp.

BTO is determined from: $(\rho_w C_{pw} d^2{}_{pan}/16)\ dBTO/dt = \left[\frac{k_w}{h_{fb}+\frac{d_{pan}}{4}}\right](T_p - BTO);$

Once T_p and BTO are obtained T_{wb} and T_{w1} are obtained as earlier.

Modeling the burn process - 3

The classical expression for radiant heat flux is:

$$q''_{rad} = [1 - \exp\{-K_{ext}\, d_{pan}\}]\ 56.78\left[\frac{T_f}{1000}\right]^4\quad kW/m^2.K$$

Where K_{ext} is the radiation extinction coefficient which is a function of the fuel.

- It has been observed in the present experiments that the mass flux increases significantly at higher depths even with smaller diameter pans.
- The transition from weak radiation to significant radiation is clearly observed.

- Based on these it is conceived that radiation depends on the burn rate flux also. This allows for a simple treatment that expects the radiation flux to depend on the Reynolds number with pan burn flux as the flow variable.

These give: $$q''_{rad} = 0.2\left[1 - \exp\left\{-0.0002\rho_l \dot{r}\,\frac{d_{pan}}{0.000018}\right\}\right]\ 56.78\left[\frac{T_f}{1000}\right]^4\quad kW/m^2.K$$

While it is thought that the current frame work for radiation is adequate, it may well be that additional aspects related to radiation come into play. *Earlier work suggests a weak dependence of smoke yield, $Y_s^{0.25}$* ***(Ditch and DeRis, C & F, 2013)*** *can be accounted for if the results demand such a dependence.*

Modeling the burn process - 4

Regarding hgwfu, burn behaviors of Glass, SS are treated as Type I and MS, Al as Type II

For Type 1, it taken that $h_{gwfu} = h_{gwfu0}\left(1 + C_3 \frac{reg}{h_{fu}}\right);\ \ h_{gwfu0} = 0.0045\ kW/m^2.K$

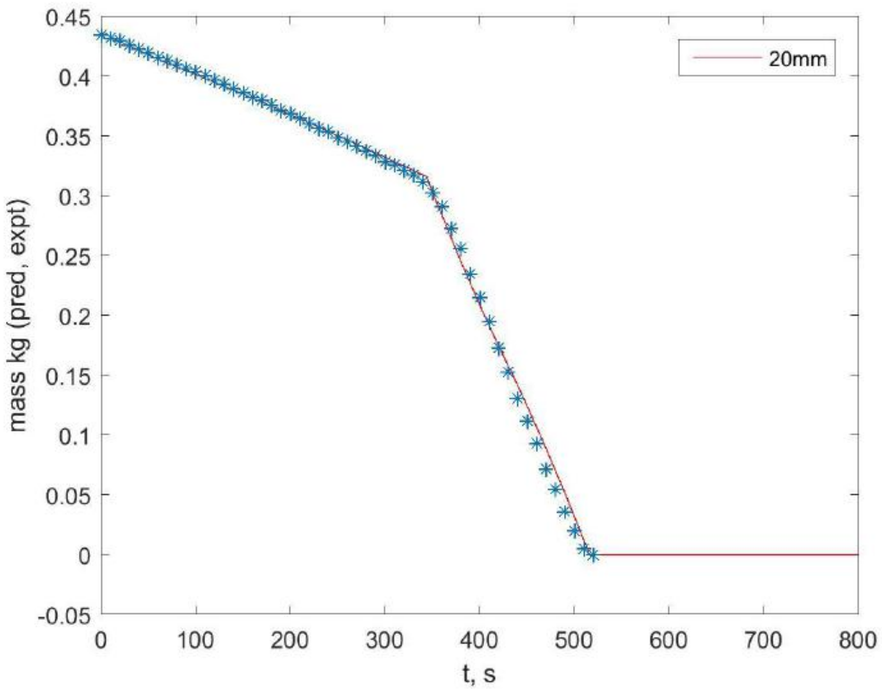
C_3 is taken as a function of M_{pc} as $C_3 = (20M_{pc} - 57)\, for\ all\ M_{pc} > 1\ .\ For\ \ M_{pc} < 1, C_3 = 0$

For Type II, two specifications are needed. The position at which the slope changes and the heat transfer coefficient on slope change. Here again relationships based on Mpc are set out using available information.

Apart from the description above with the parameters chosen above, <u>there no free parameters</u> in the calculation procedure.

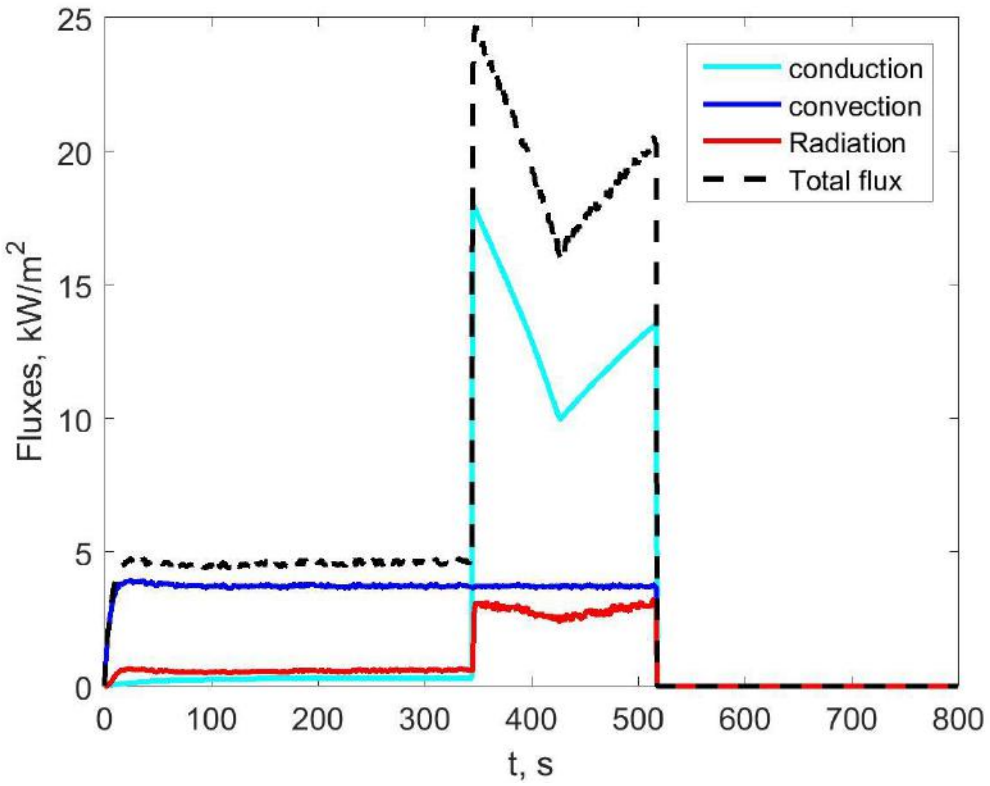
The MATLAB code runs with geometric and thermal parameters and initial conditions of fuel depth and temperature without any free parameters and gives all the parameters as a function of time till burnout….

….. Now on to results



Code predicts:

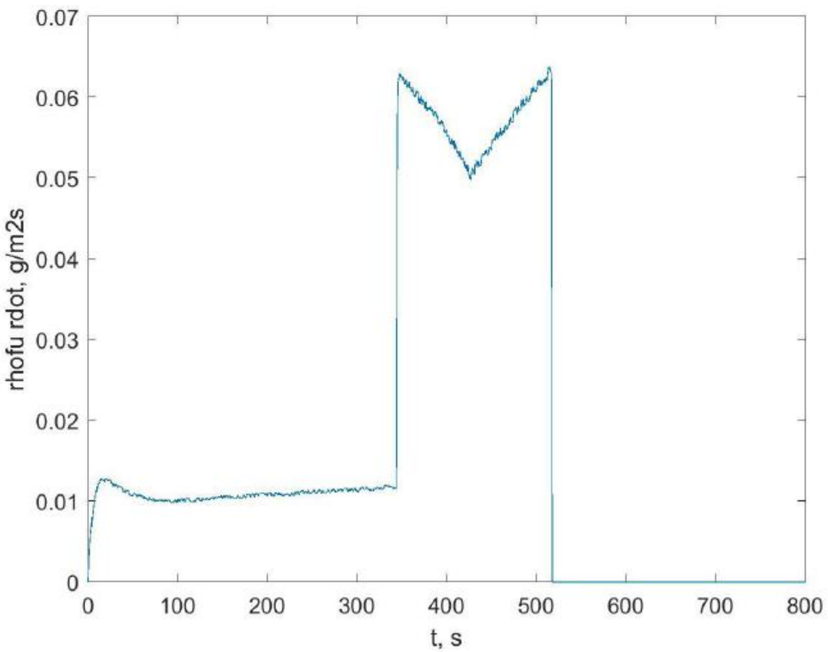
mass vs time, burn rate flux, heat flux components and the temperatures at the pan tip as well as bottom and liquid bottom temperatures

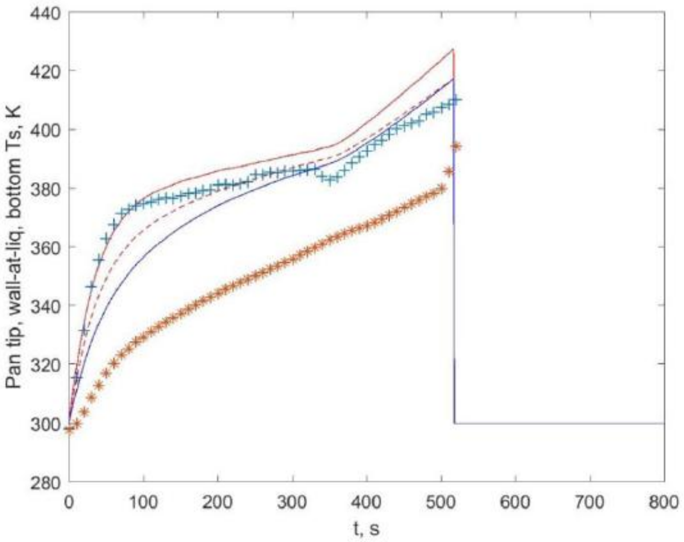


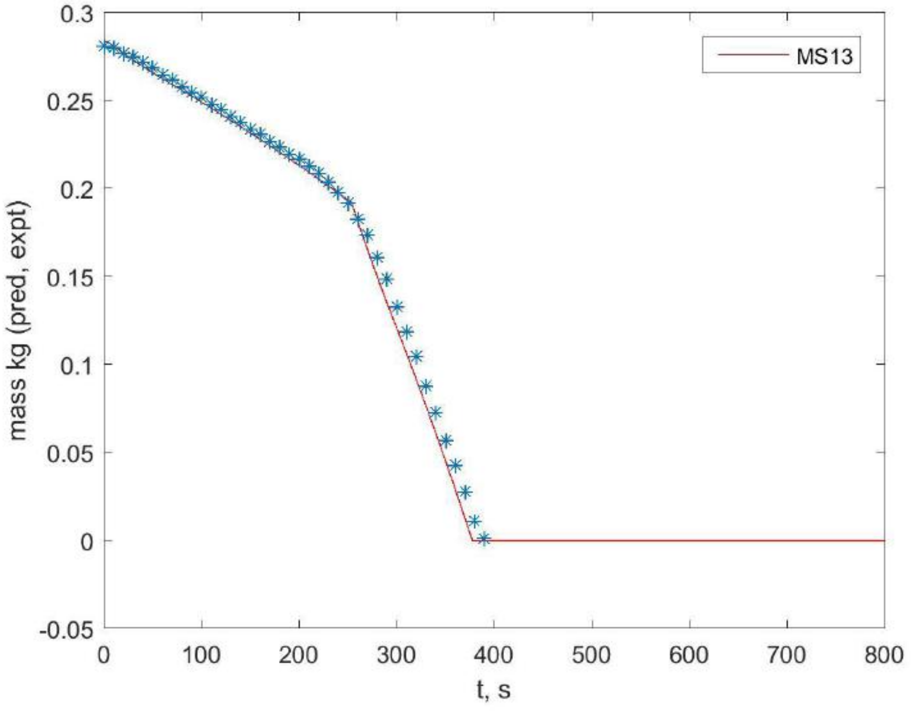
Even though m_{fu} vs t is predicted very well and the qualitative variation of pan tip temperature is indeed very good, quantitative variations are not that good.

Getting this well is not considered important……..

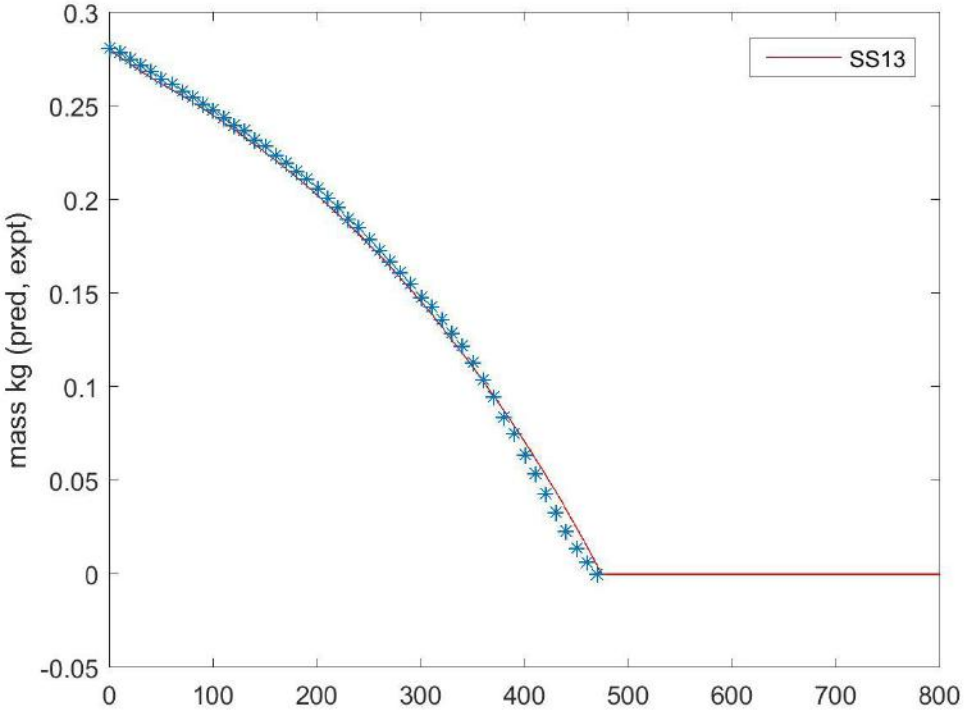
because there is no model in the literature which is anywhere close to what this is able to do at this stage



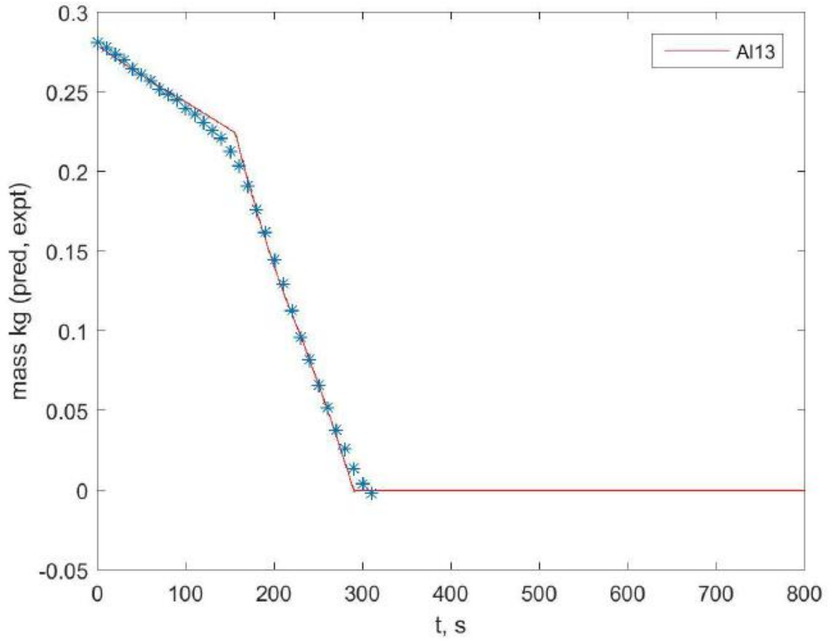




200 mm dia, 40 mm deep pan with 13 mm fuel thickness

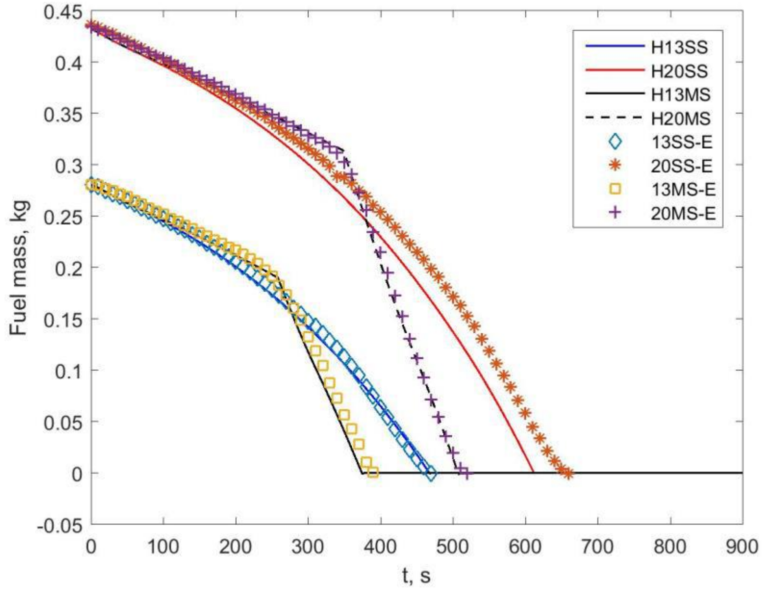


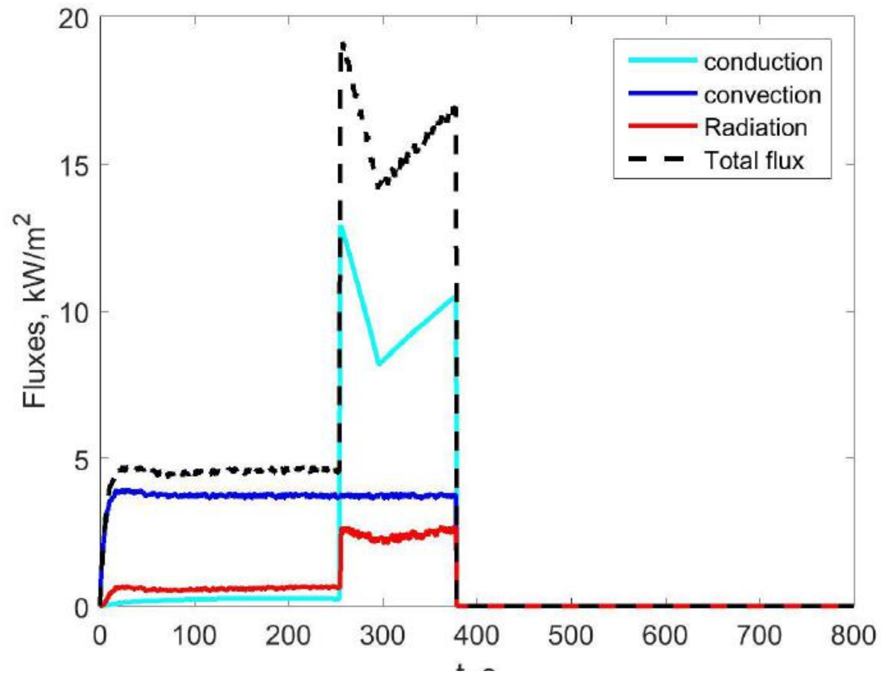
Predictions on mass burn match with experimental data extraordinarily well

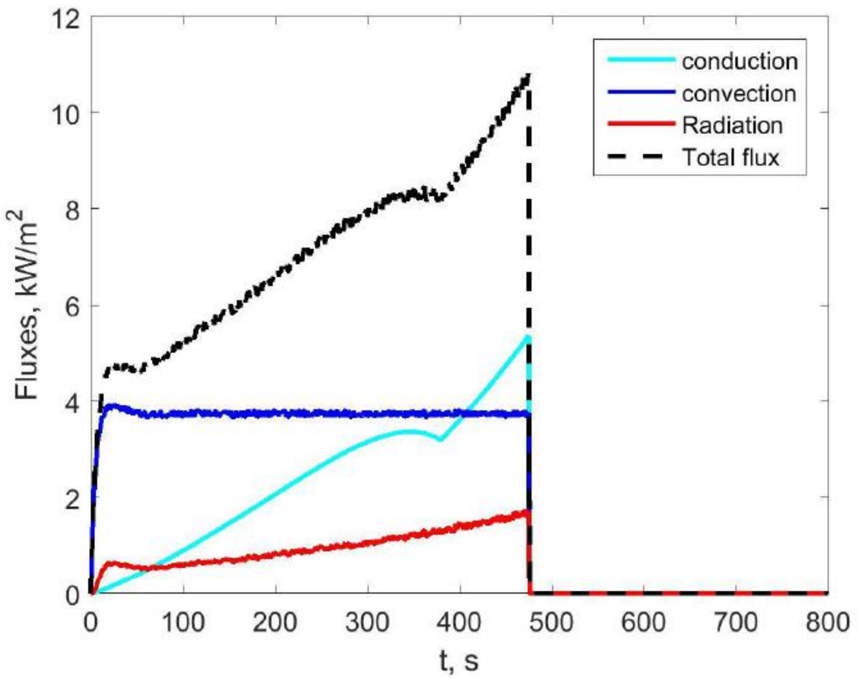


Other results for different fuel thicknesses are also predicted well,

Not just well, "Unreasonably" well



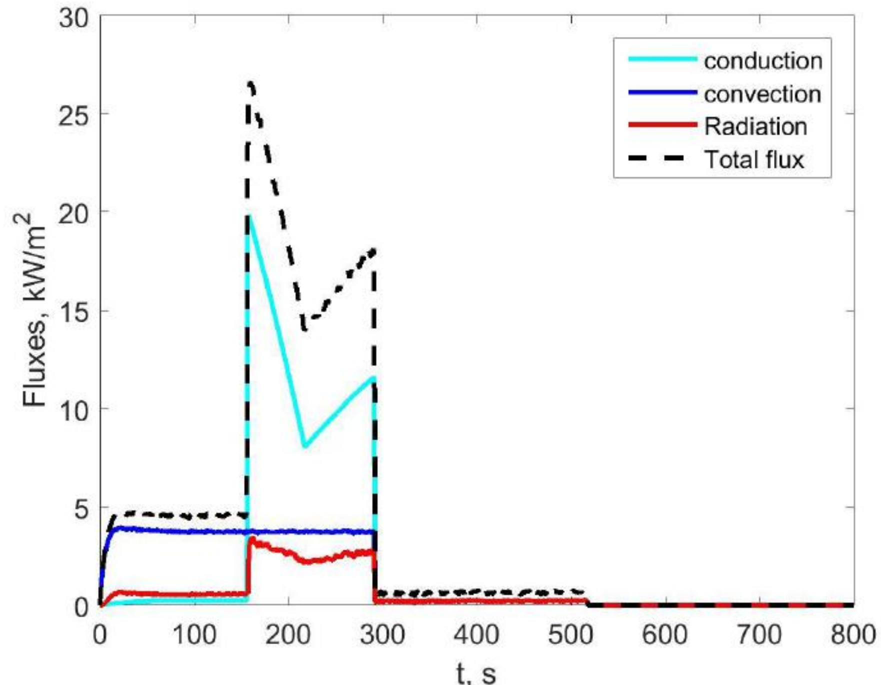


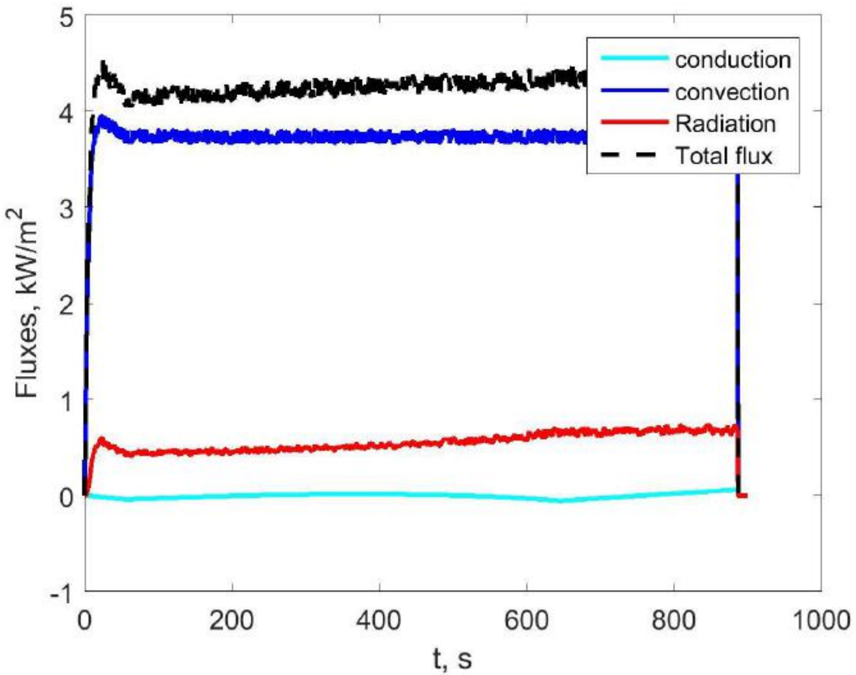


Components of heat flux for 200 mm dia pan, 40 mm deep, 13 mm heptane

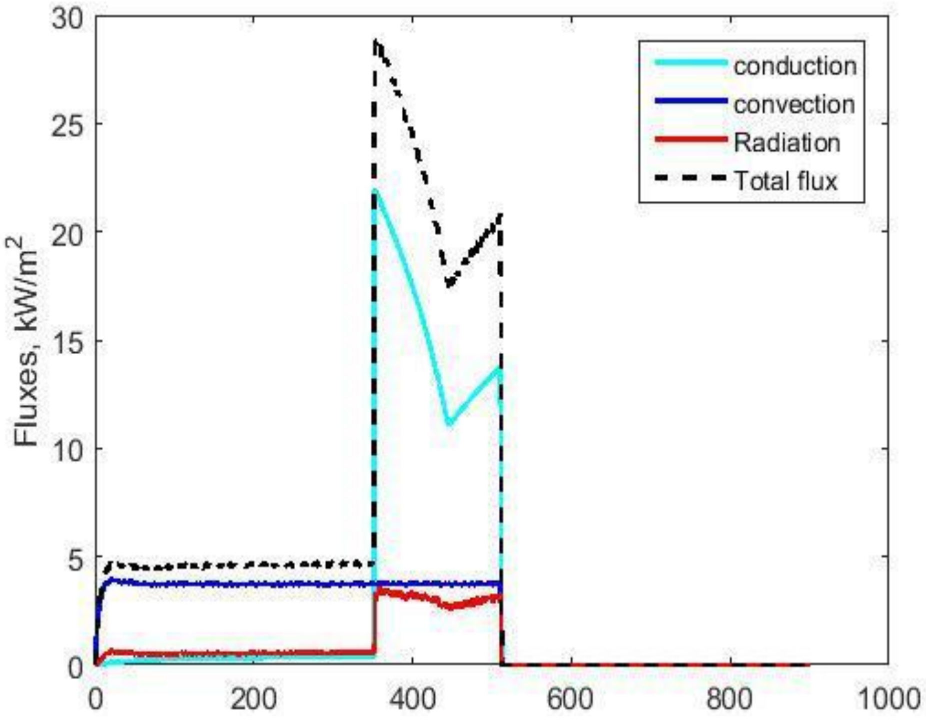
The conductive flux may be slightly negative for glass, but increases in magnitude towards SS, MS and Al.

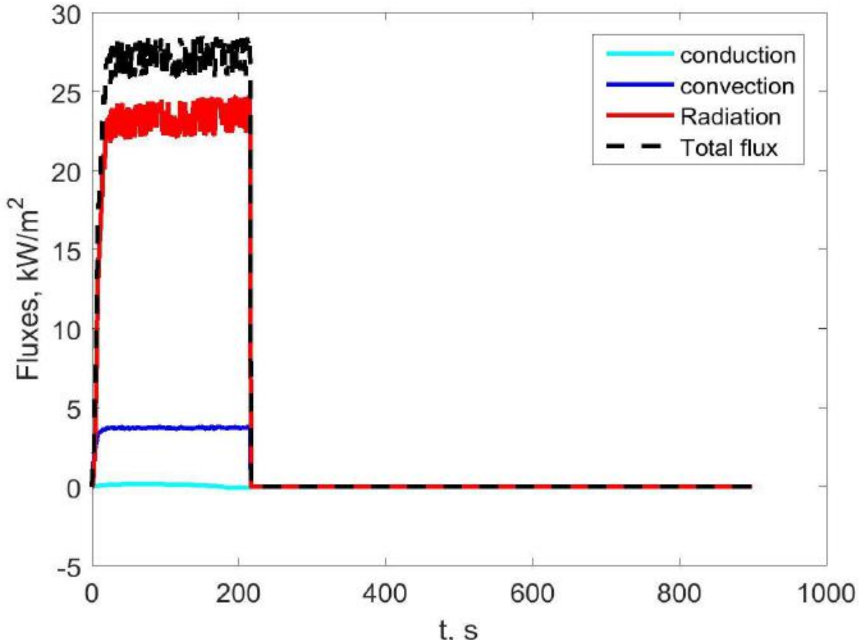
The peak flux also increases from about 4.5 kW/m² K to 27 kW/m² K when we move from Glass through SS, MS to Al pans

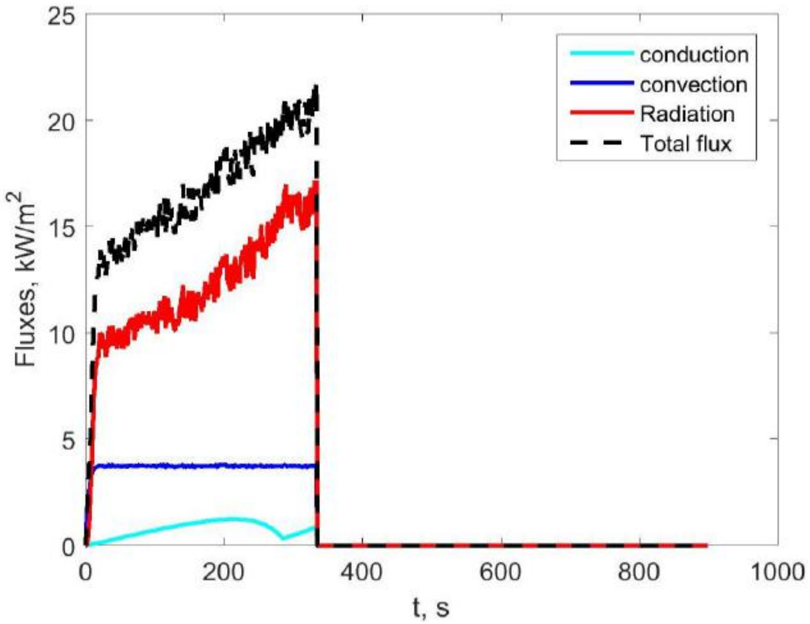


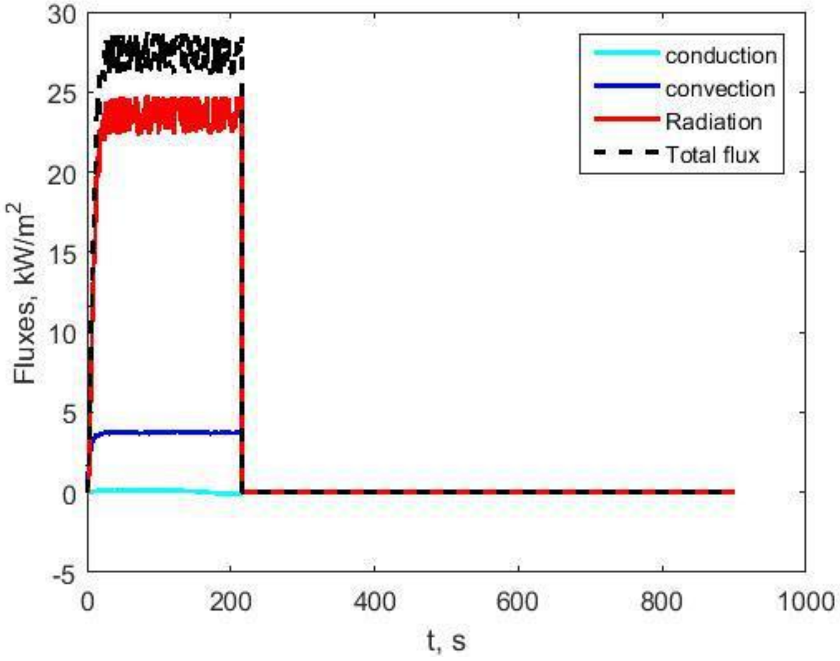


Components of heat flux for 0.2, 0.5, 2 & 3m dia & 40mm depth pans

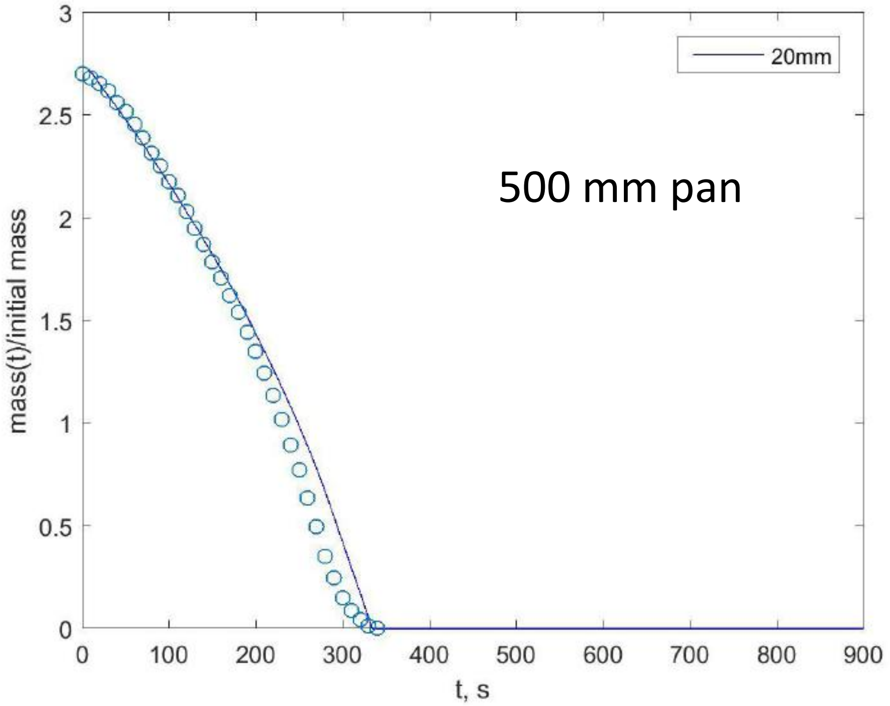






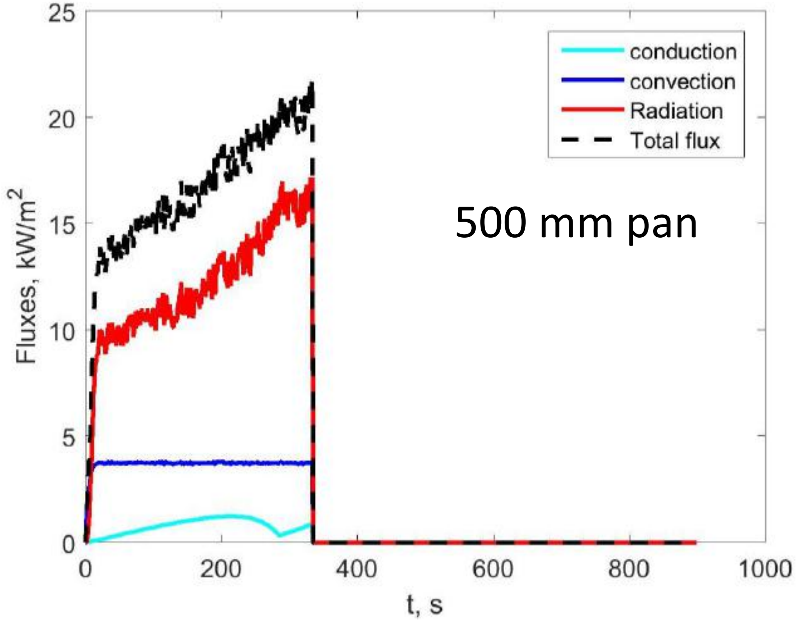


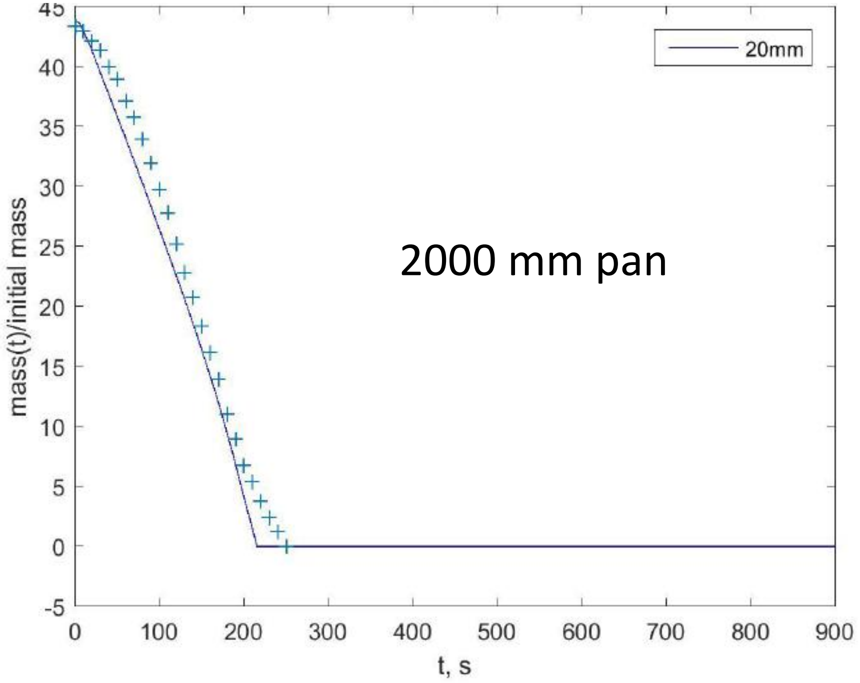
The radiation flux increases with increase in diameter of pans where as the conduction flux reduces, but the convective flux remains same for all the pans



Predictions from the same code 500 mm and 2000 mm pans

The radiation flux for 500 mm Increases with time – implying That convection and conduction have still some role to play

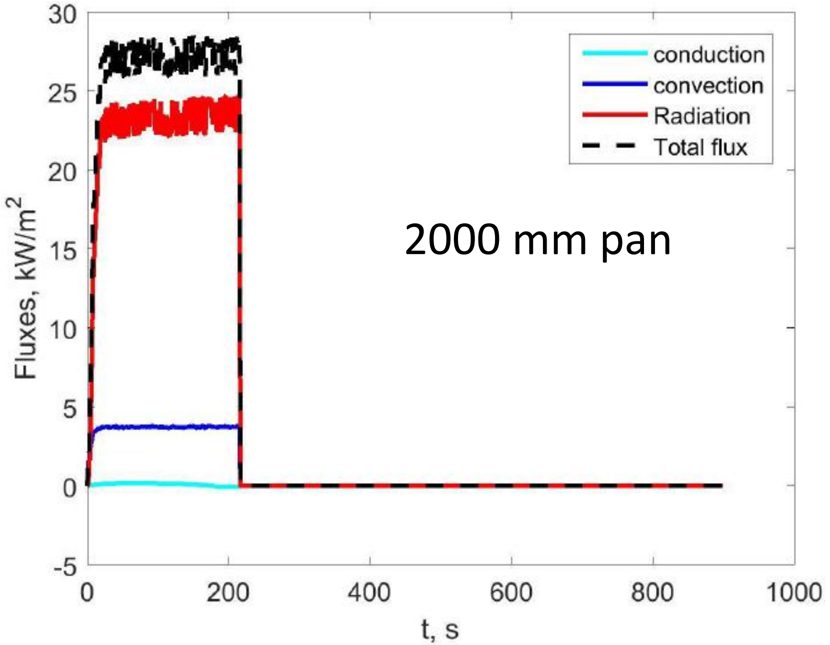




In the case of 2000 mm pan, Radiation flux pick up fast and Is nearly same afterwards.

These are along expected trends.

Quantitative comparison on mass burn is good in both cases.



Conclusions - 1

- Burn rate is strongly dependent on the fuel thickness, pan material and initial temperature of fuel.
- The principal mechanisms governing the burn rate are identified clearly:
- All pan materials have initial burn controlled by convective flux. The initial convective flux for all the pans is described by convective heat transfer coefficient of 0.0045 kW/m^2K.
- Smaller pans have increased contribution of conductive flux depending on the thermal conductivity of wall material.
- Larger pans will in addition get enhanced contribution of radiation. The radiation model is chosen different from classical ones with extinction coefficient since no basis was seen for that.
- High flux which is generally observed in larger diameter pans can be obtained in the smaller pans by increasing the thickness of fuel, this increase is being due to conductive heat transfer.
- An intriguing behaviour of sharp burn rate change caused by high conductivity wall material (like MS, Al) as different from SS is brought out. The interplay of wall thermal conductivity and heat drawn away through the wall is considered the reason.

Conclusions - 2

- A non-dimensional parameter (M_{pc}) to distinguish the burn behaviour of materials of pans, fuel depth and initial fuel temperature is set out. This parameter is used to classify Type I (smooth mass vs time) and Type II (Sharp slope change in mass vs time) behaviours of n-heptane.

- A theoretical unsteady model that includes all modes of heat transfer with sufficient detail with regard to conduction has been developed. The use of all the modes of heat transfer enables one to predict the burn behaviour for a range of pan diameters with confidence.

- These results are consistent with general understanding, but this work goes beyond that – creates a mathematical model that makes quantitative predictions possible. At this stage, on a new pan with a new material, it is speculated that predictions would be within 10 % error margin.

- Model can be considered as "developing" since other fuels kerosene, diesel and methanol and floating over water and flash-burn like situations need to be dealt with. While more work is needed, doubtlessly, this model is the only candidate available for development as no comparable model exists in literature.

……………….Thank you.

Weight data of the pans

Pan	Area	Bottom	side	Total
	m^2	kg	kg	kg
C2K145MS3	3.1415	197	15.10	212.1
C2K90MS3	3.1415	197	9.40	206.4
C2K60MS3	3.1415	197	6.20	203.2
C50060MS3	0.1963	4.46	2.20	6.66
C50050MS3	0.1963	4.46	1.81	6.27
C50040MS3	0.1963	4.46	1.49	5.95
C20060MS3	0.0314	0.72	0.88	1.60
C20040MS3	0.0314	0.72	0.59	1.31
C20040SS3	0.0314	0.78	0.63	1.41

$mc_p \Delta T/\Delta t$ ~ 0.8 kg x 0.5 kJ/kg K x 1.5 K/s
~ 0.6 kW
Initial power ~ 10 g/s x 40 kJ/g x 0.6 (efficiency of heat release) ~ 240 kW