Pan burn behaviour with different fuels & an approach to modelling

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Introduction

ool fire has been a subject of study for six decades from the time Hottel published a review of the Rus
work. Considerable information and understanding has been gained over this period with research, fire sa
echnology and evolution of standards for acceptance of fire safety products have also made progress.

One of the key aspects of importance is the prediction of burn rates from liquid pool fires, particu
ecause pool fires are a part of the standards for fire extinguishment. While unsteady burn process is the
f these tests, *most investigators have used steady arrangement to study the burn rate of li ool fires, both experimentally and for model development.*

n view of this, in the present study, unsteady pool fire experiments has been conducted on n-hep
thanol, methanol, kerosene and diesel by allowing the fuel thickness (h_{fu}) to vary with time for h_{fu} of
0 mm in 200 mm dia pans.

ata on mass loss, wall temperatures and fuel temperatures at several locations have been obtained for
m diameter pans of 40 mm depth with different materials -*Glass (GL), Stainless steel (SS), Mild steel (nd Aluminum alloy (AL)* with a wide range of thermal conductivities.

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

Earlier work

number of researchers have studied pan fires. A large number of them have studied steady pool fire itch, John de Ris, Blanchat and others).

brauskas (1983) summarized the burn rate data from several sources for a number of fuels. He ha ught out that transient effects due to lip height (or free board), the nature of bounding material, fuel laye ckness and wind would need to be accounted. There was no specific data or correlations to allow estimat the effects.

mins et al (1994) used a steady configuration of ring burners to enable obtain various pool diameters (7 300 mm) and have used several fuels including n-heptane and toulene to measure the burn rates an diational characteristics as a function of radius and azimuth and their principal conclusion is that the flu fairly uniform for hydrocarbon fires.

hall pool fires have been studied by Hayasaka (1997) and Chen et al (2011) particularly in the unstead ode - with fixed fuel thickness and mode in which the fuel burns with time was identified as initial phase ady phase, transition phase, peak and decay phase. Even Chen et al have done the experiments in 20 n SS pan at different initial temperatures and found that it affects the burn rate significantly

e present study goes beyond the earlier studies in obtaining experimental data on unsteady pool fires wit fferent geometric parameters and a range of fuels attempting to extract various effects systematically.

Pans used for experiments
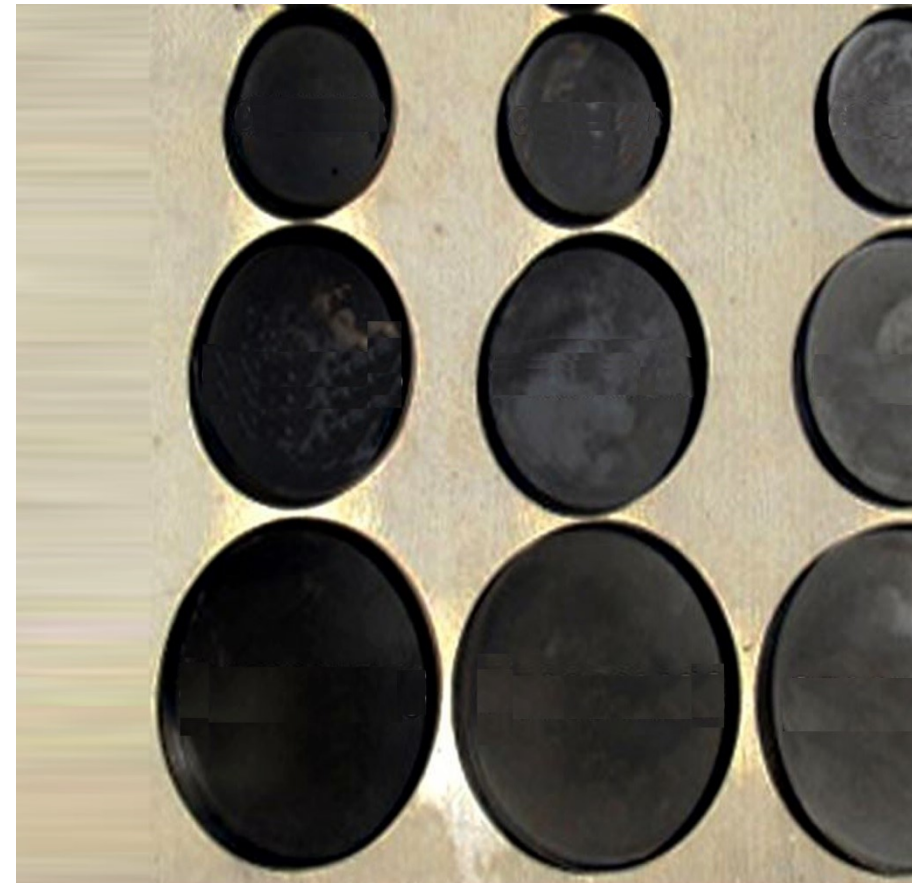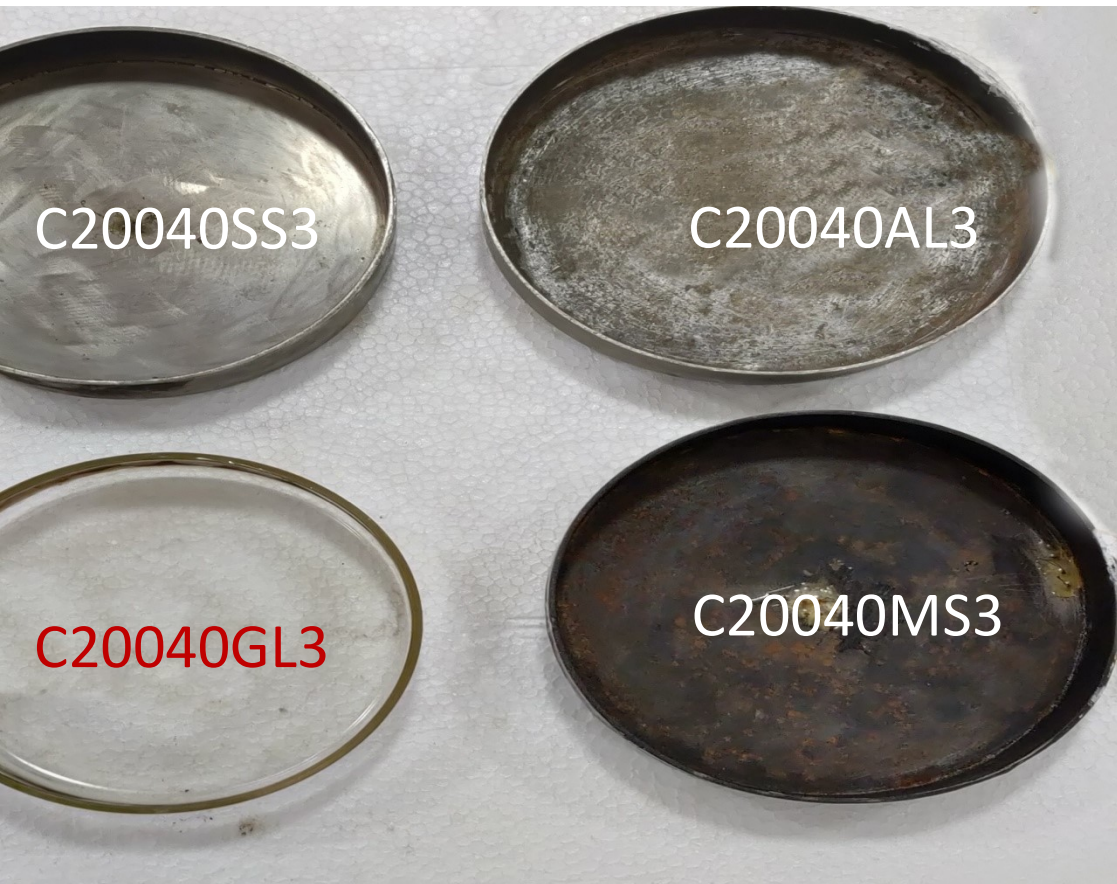
Pans of 200 mm dia, 40 mm depth made of Stainless Steel (SS), Mild steel (MS), Aluminum alloy (Al) and gl(GL) (clockwise from the top) on left side and pans of 300, 400 and 500 mm diameter, 40, 50 and 60 mm demade of MS on the right side

The burn process and measurements in Pool fires
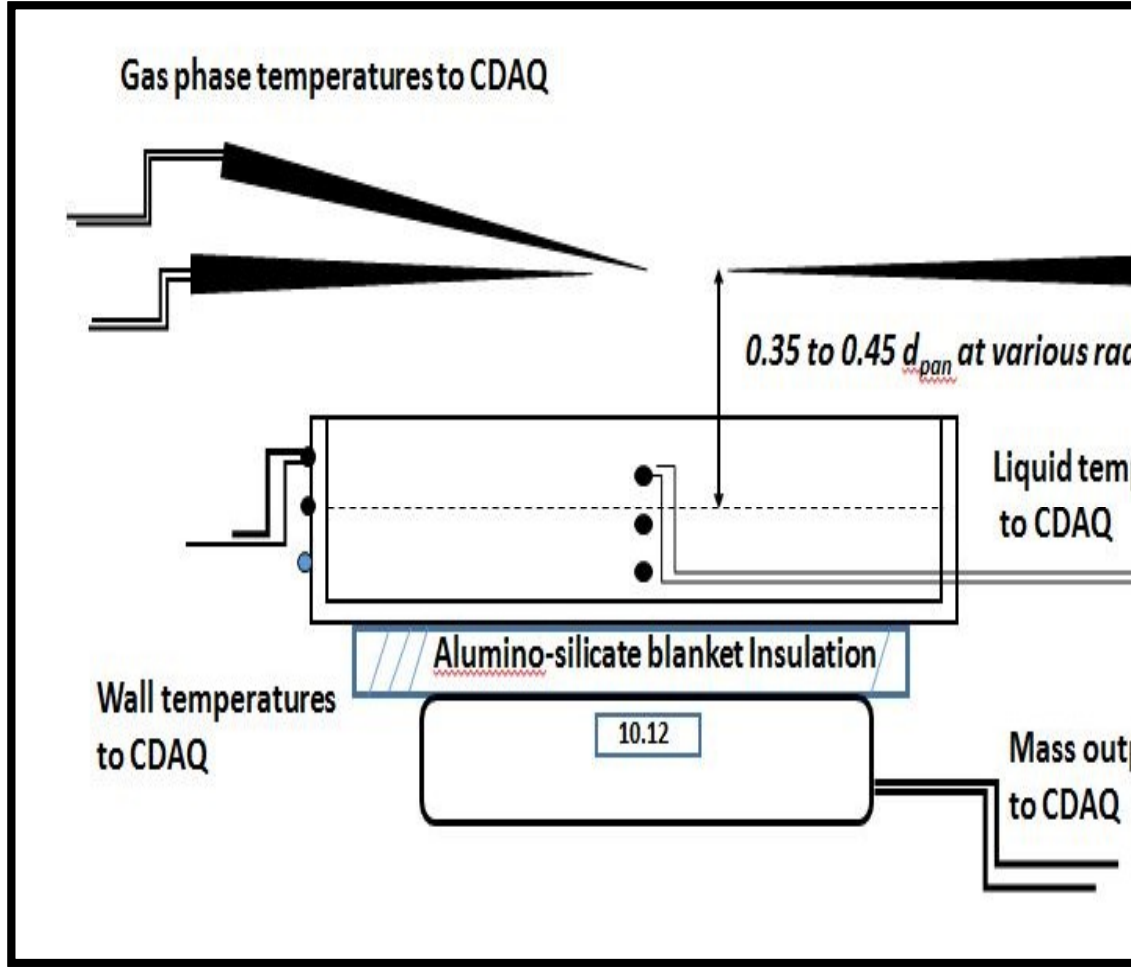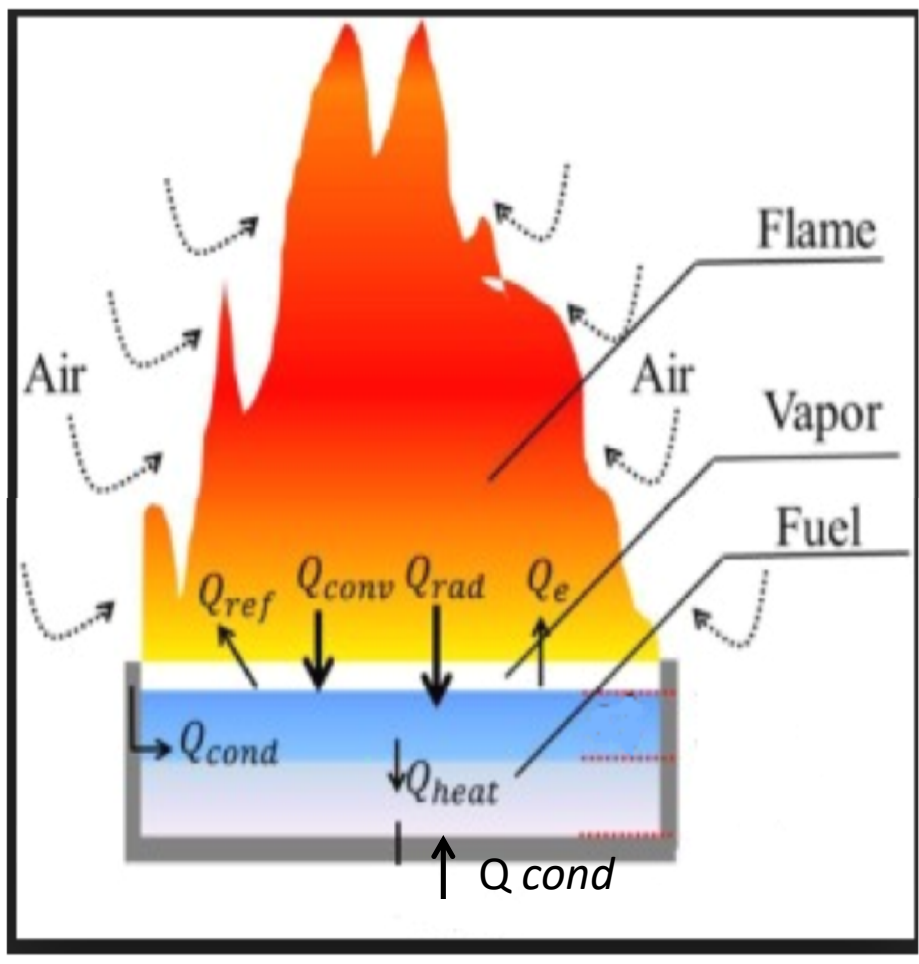
$$\dot{r} = \frac{(\ddot{Q}_{cond} + \ddot{Q}_{conv} + \ddot{Q}_{Rad})}{(L + Cp(T_s - T_0))}$$

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

The experiments….

the experiments were conducted at FCRC fire lab are on n-Heptane, kerosene, diesel and alcohols.

easurements have included fuel mass, centre line in-depth liquid temperature, wall temperatures at
eights on the pan wall, bottom wall temperatures, some in which temperatures across the wall, ga
mperatures vs burn time in several experiments.

uel depths tried were 10 mm, 13mm and 20 mm. The choice of 13 mm was because of earlier stu
hen et al and Kang et al (from China) for 200 mm SS pan. They have been the only studies of sign
tempting to elucidate the unsteady burning behavior in pans.

ore than 180 different experiments have been conducted – with four different pans and different
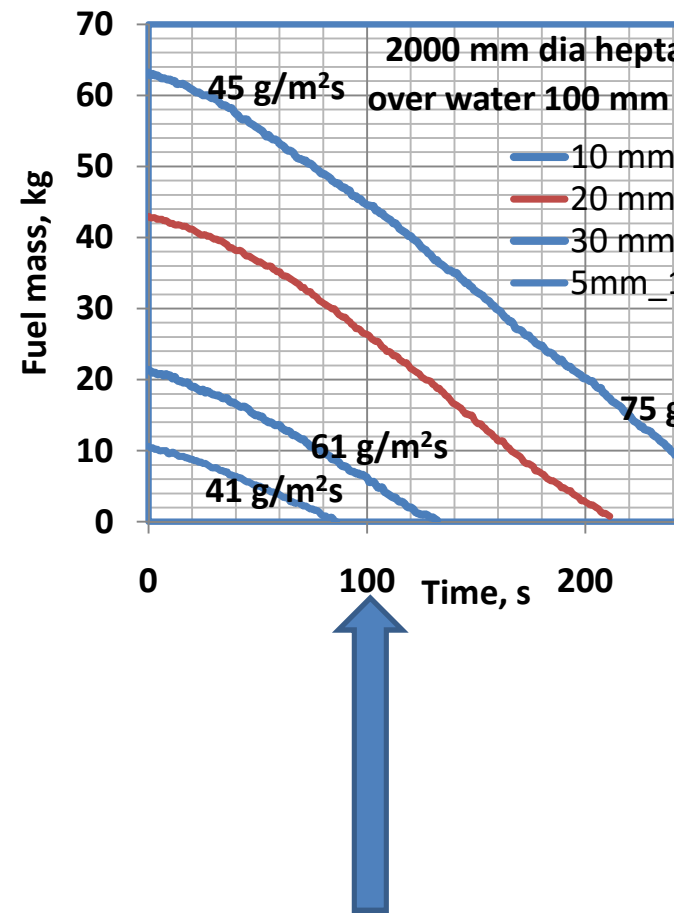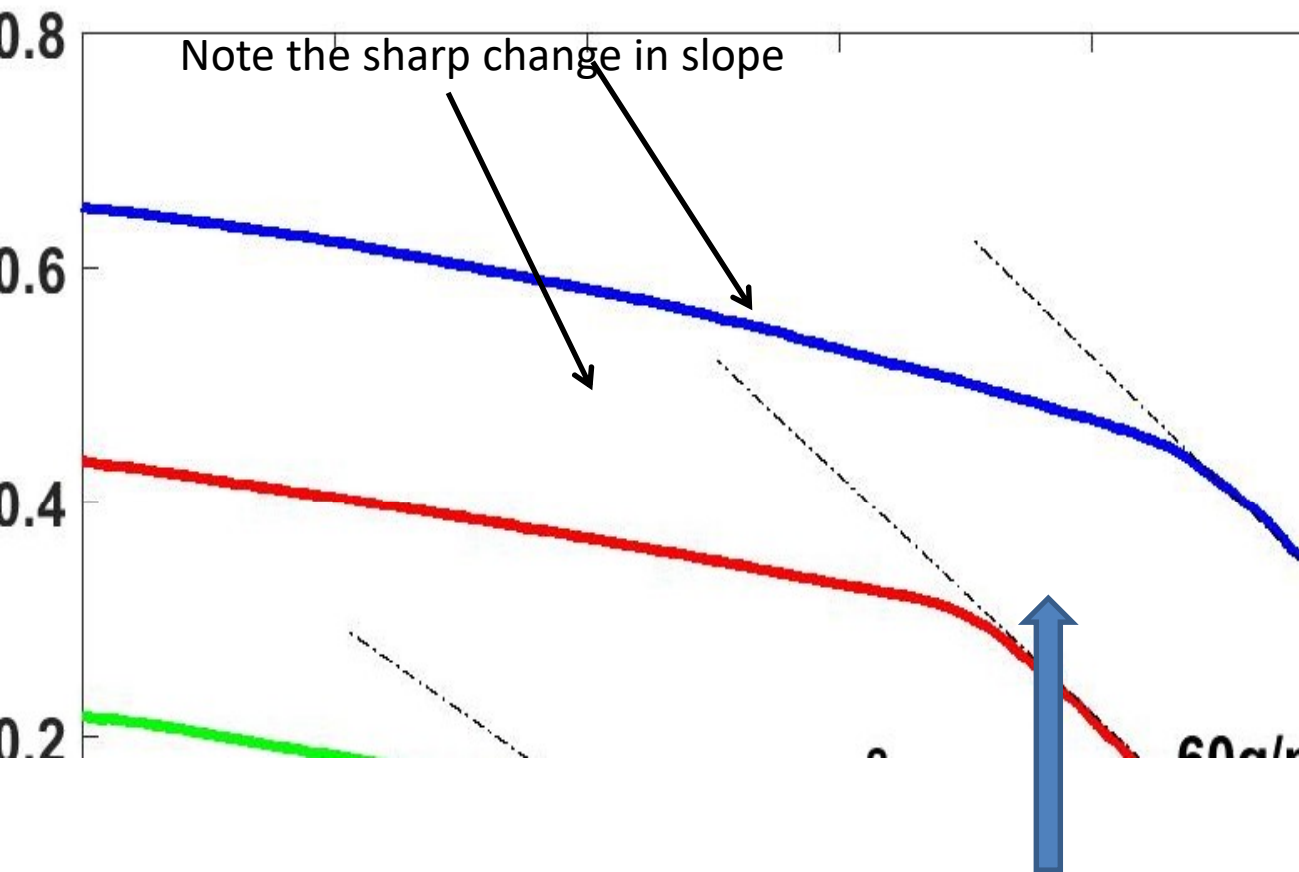d repeats to check on accuracies.

ignificantly new results have emerged……

Comparison of Chen, Kang et al (SS,200 mm pan) data
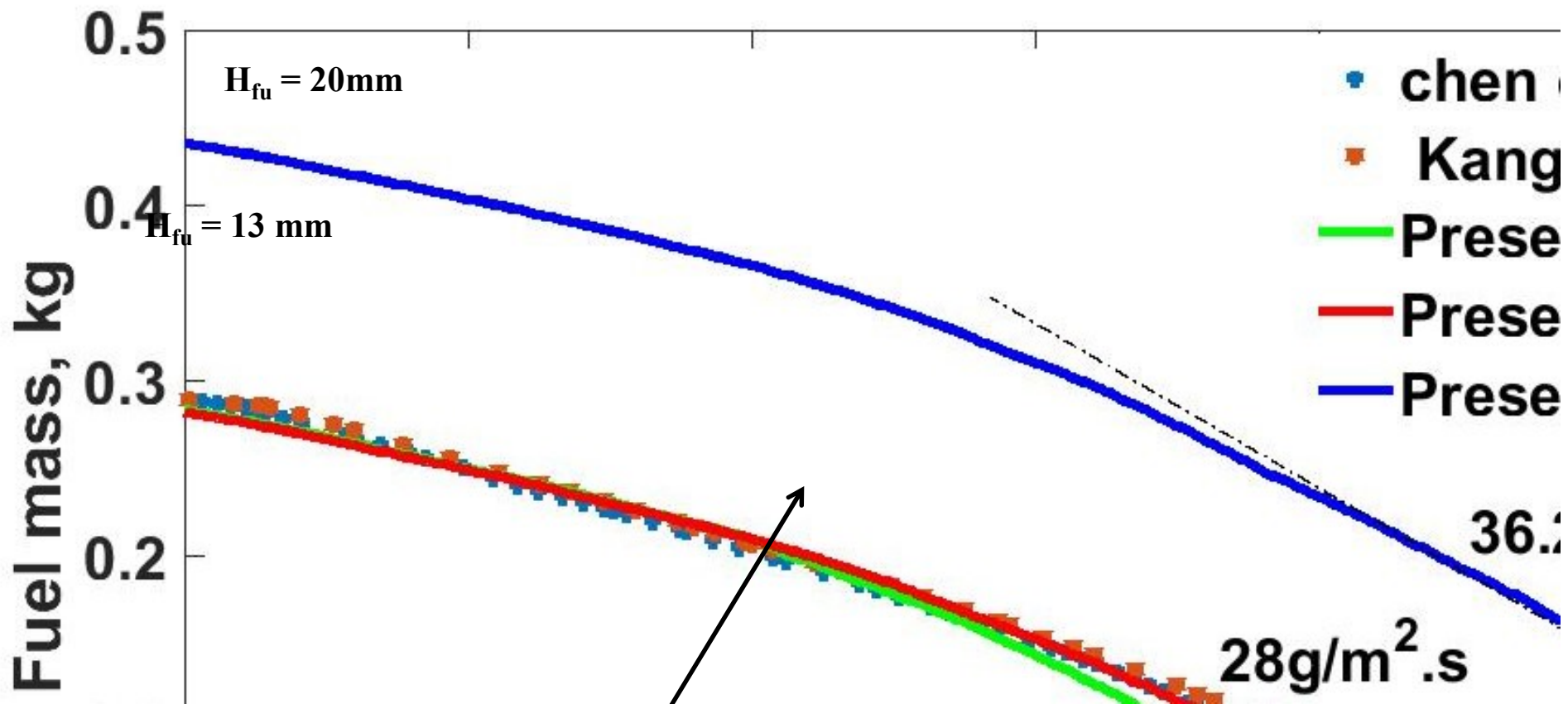
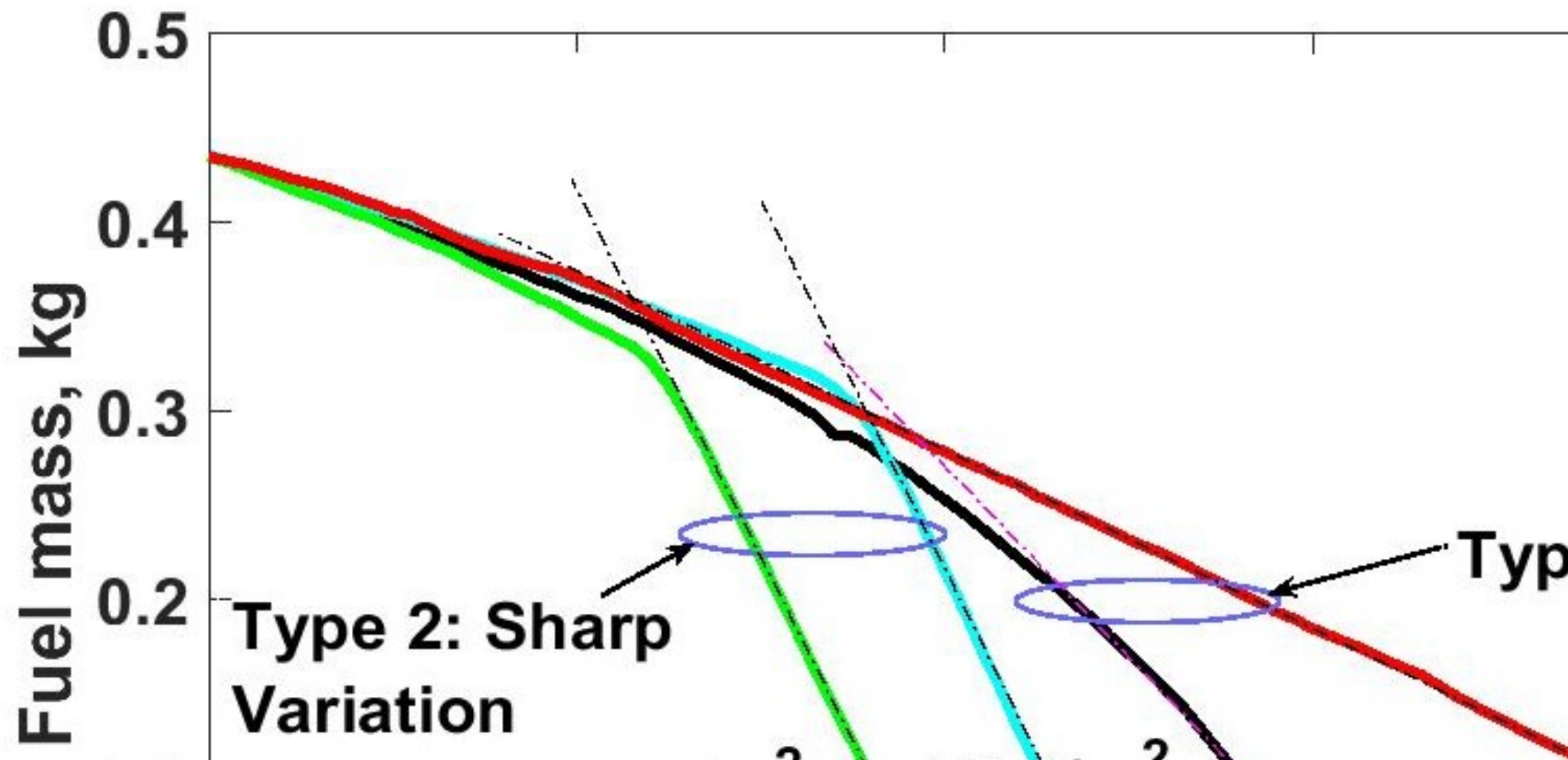comparison is considered "good". The higher slopes are due to enhanced initial temperature at FCRC.

Fuel depth Effect (MS, 200 mm pan) on the mean and Peak Flux for n-hepta

Note the sharp change in slope

At this small pan diameter, the peak flux is 67 g/m^2.s at fuel depth > 20 mm, a flux found only in large pans because of significant radiation flux .

A quick inference is that this behavior is related to the liquid in the pool having reached boiling, a feature that needs further investigation.

At this stage, it is thought useful to examine the burn behavior with pans of different materials.

Type 2: Sharp Variation

Тур

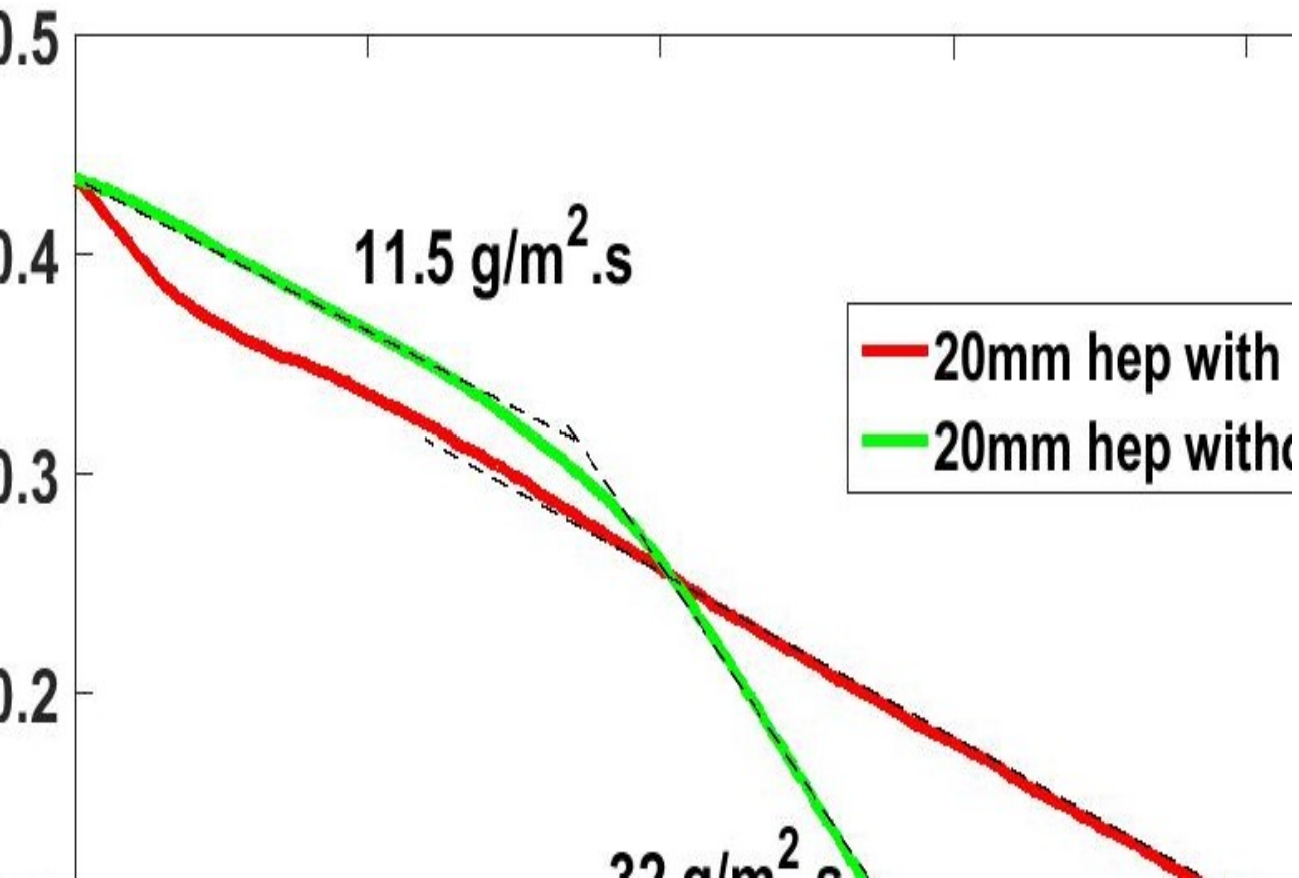| .NO	Pan Material	Heptane thickness (mm)	Initial Flux g/m²·s	Time (sec)	Peak Flux g/m²·s	Time (sec)
1	AL	10	11.6	0 to 70	52	110 to 200
2	AL	13	11.6	0 to 60	50	160 to 300
3	AL	20	11.1	0 to 130	60	240 to 410
4	MS	10	10.0	0 to 70	42.8	190 to 310
5	MS	13	11.3	0 to 60	48.2	270 to 400
6	MS	20	10.1	0 to 120	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

...tial flux which is largely controlled by the convection is nearly the same (since radiation is less for small ...eter pans at initial stage), irrespective of fuel thickness and pan material.

...k flux varies with the fuel thickness & pan material

...ce it was not yet clear whether the conduction or radiation is responsible for peak flux , experiments we... ...to examine the role of wall conduction by suppressing it.........................

Experiment *without* and *with* jacket for water circulation

C200mm dia, 60mm deep MS pan, heptane pool
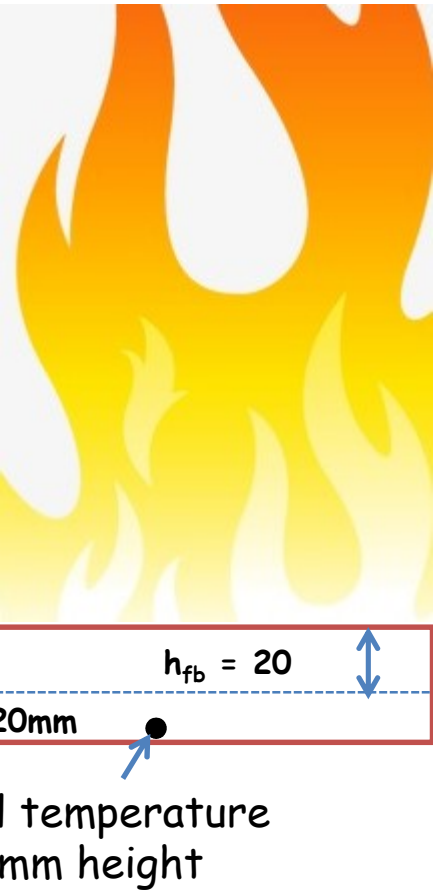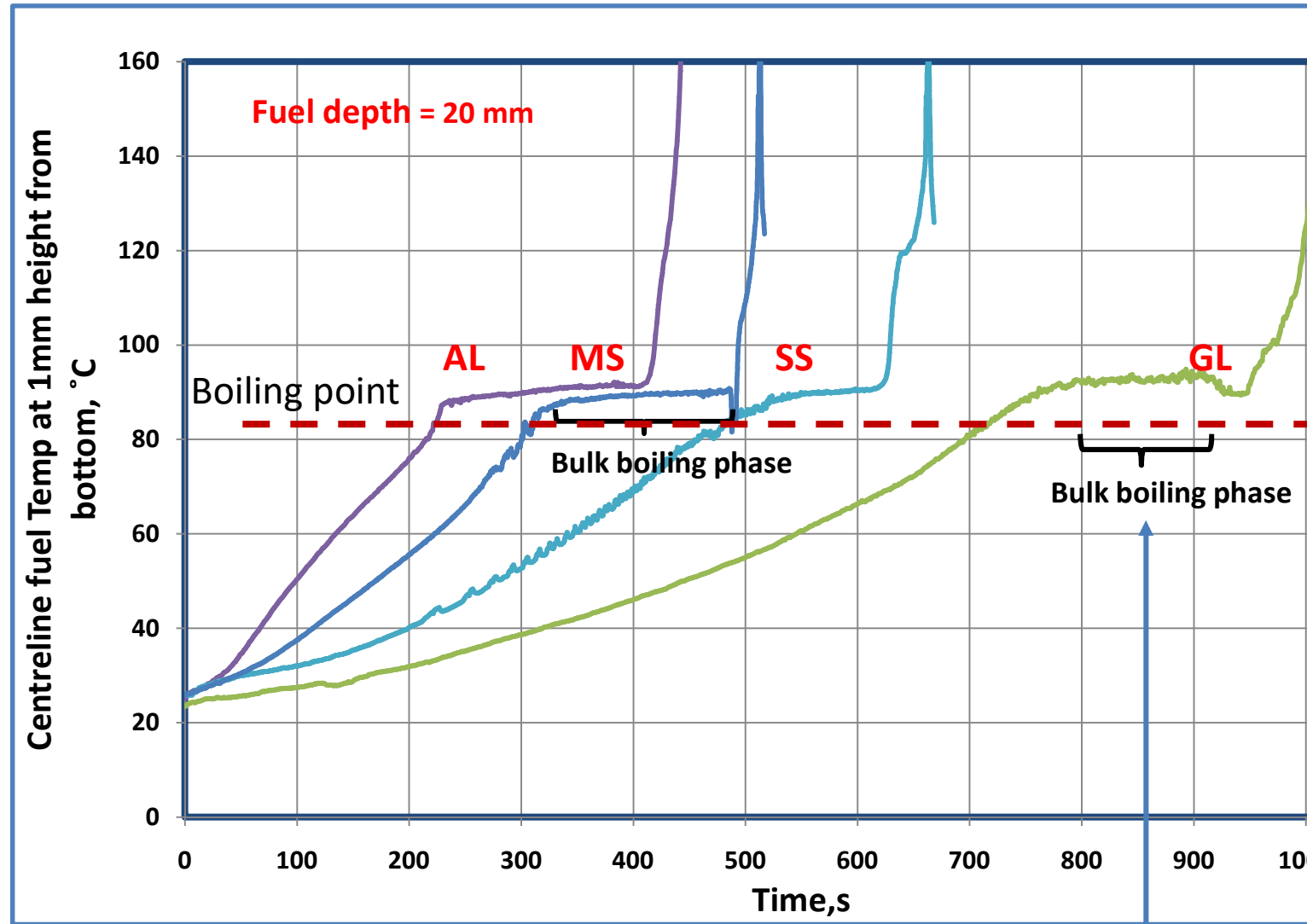

If the conduction effects are suppressed the burn rate remains unchanged even during peak condition and so *conductive flux is the crucial feature for pans of this diameter*

What is happening in the liquid phase with different pan materials?
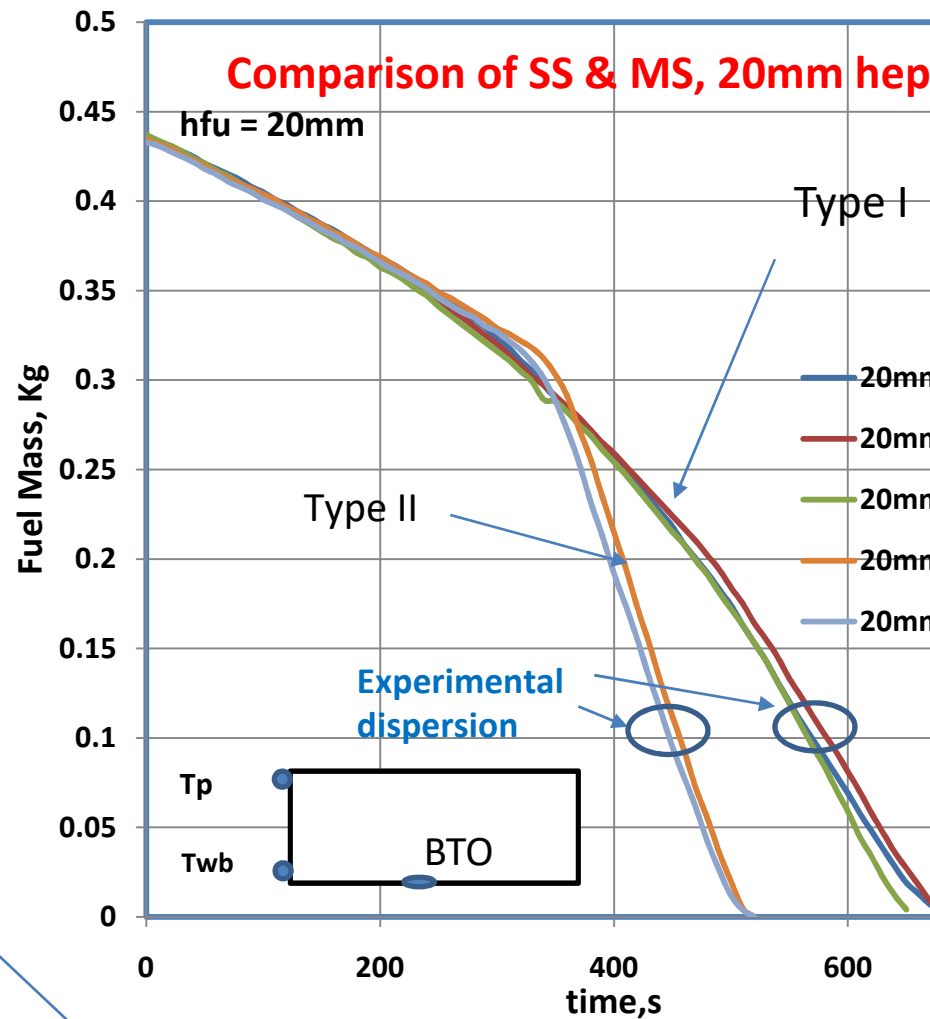
Fuel reaches boiling in materials of higher conductivity earlier – related directly to increased wall conduction heat transfer into the liquid fuel.

The burn rate in the subsequent period is due to bulk boiling

Wall temperature behaviour?

C20040SS3 13mm – Heptane (Expt 1 & Expt 2)

Comparison of SS & MS, 20mm hep
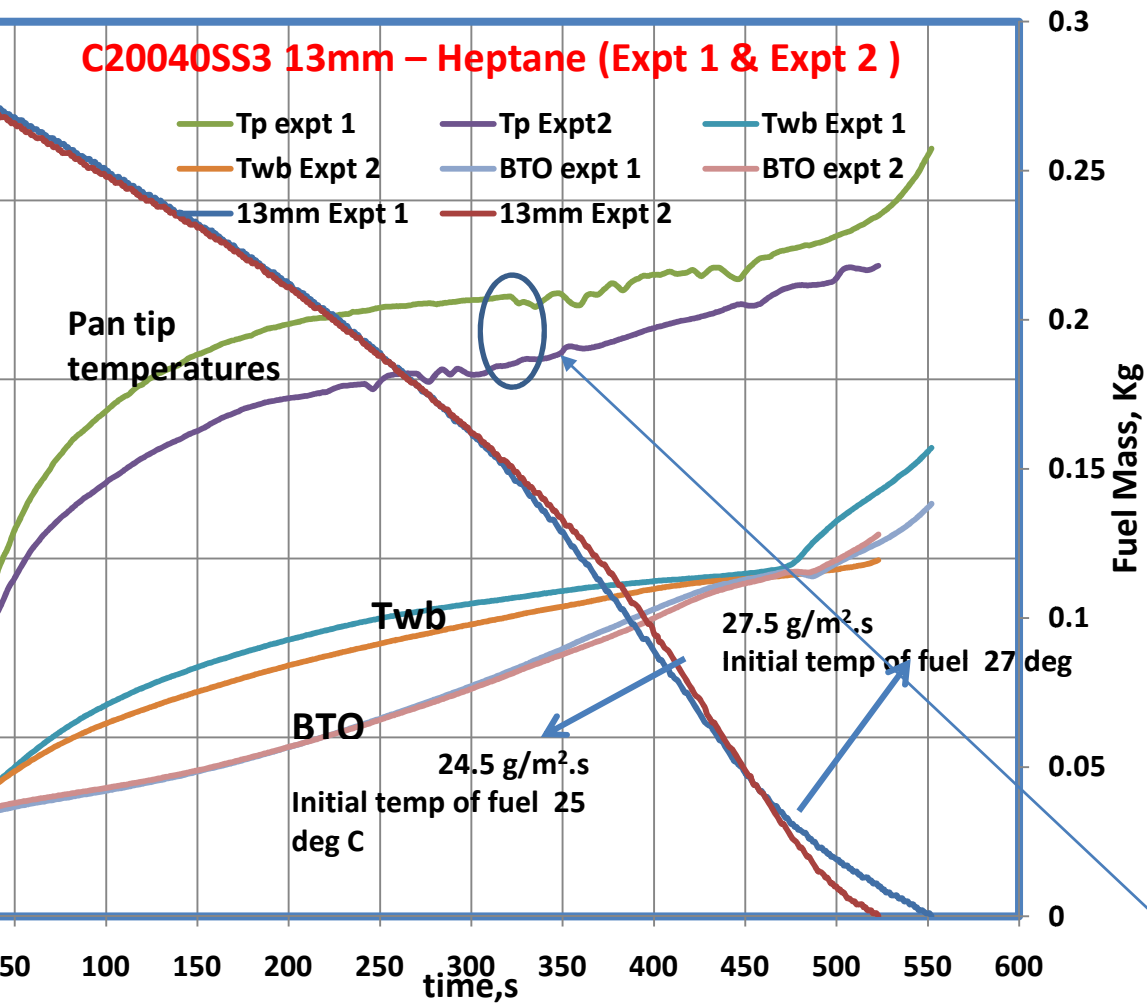
Even though the pan tip temperature difference is about 15 to 20 ℃, the burn time variation of two experim
much and there behaviour is about the same (all dispersions are within 5 %)

initial flux for both SS & MS pans are about same and the peak flux of same pan experiments does not

Other fuels – Kerosene, Diesel and Alcohol

Fuel depth and material effect on burn rate of kerosene
200 mm dia, 40 mm depth MS and SS pan
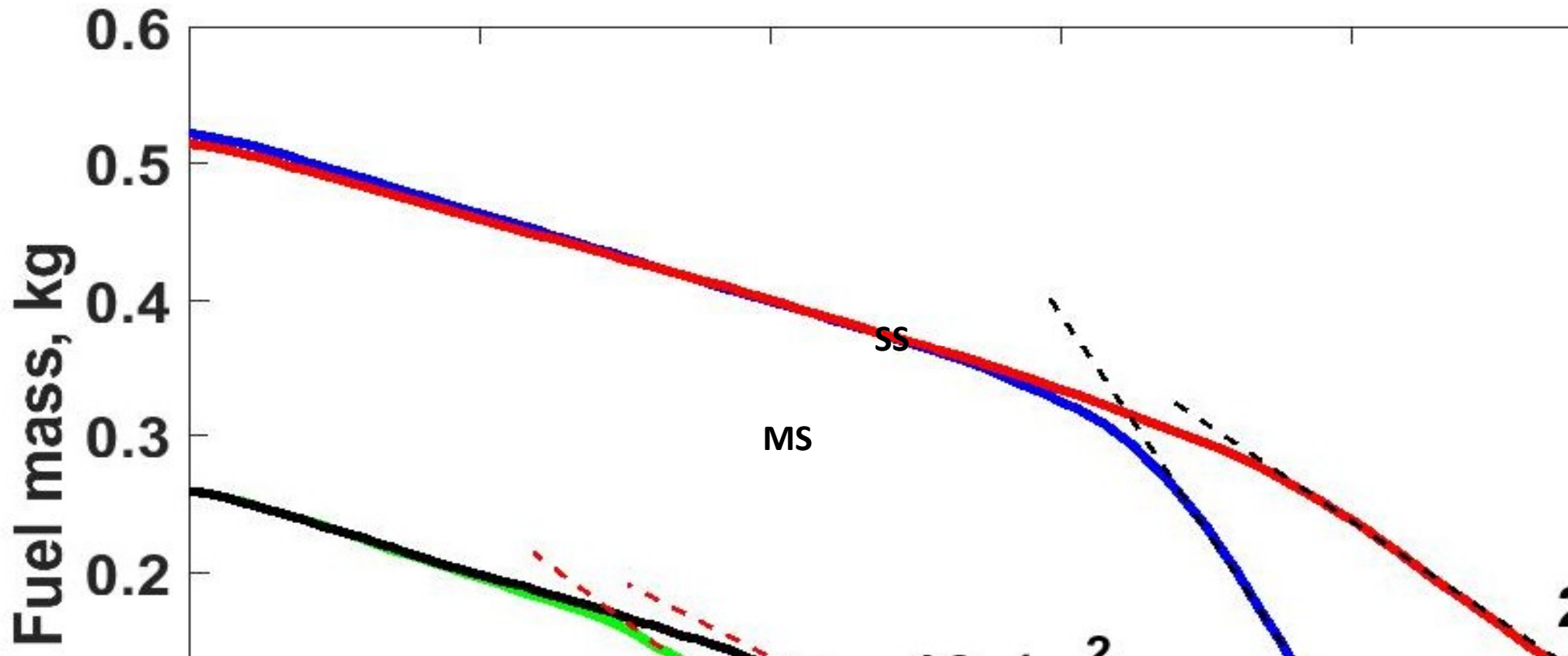
- The burn behavior is similar to n-heptane behavior but with reduced peak flux values

- Mass flux increases with increase in thickness of fuel and MS pan experiment has higher flux compared to SS.

Fuel depth and material effect on burn rate of diesel in 200 mm dia, 40 mm depth MS and SS pan
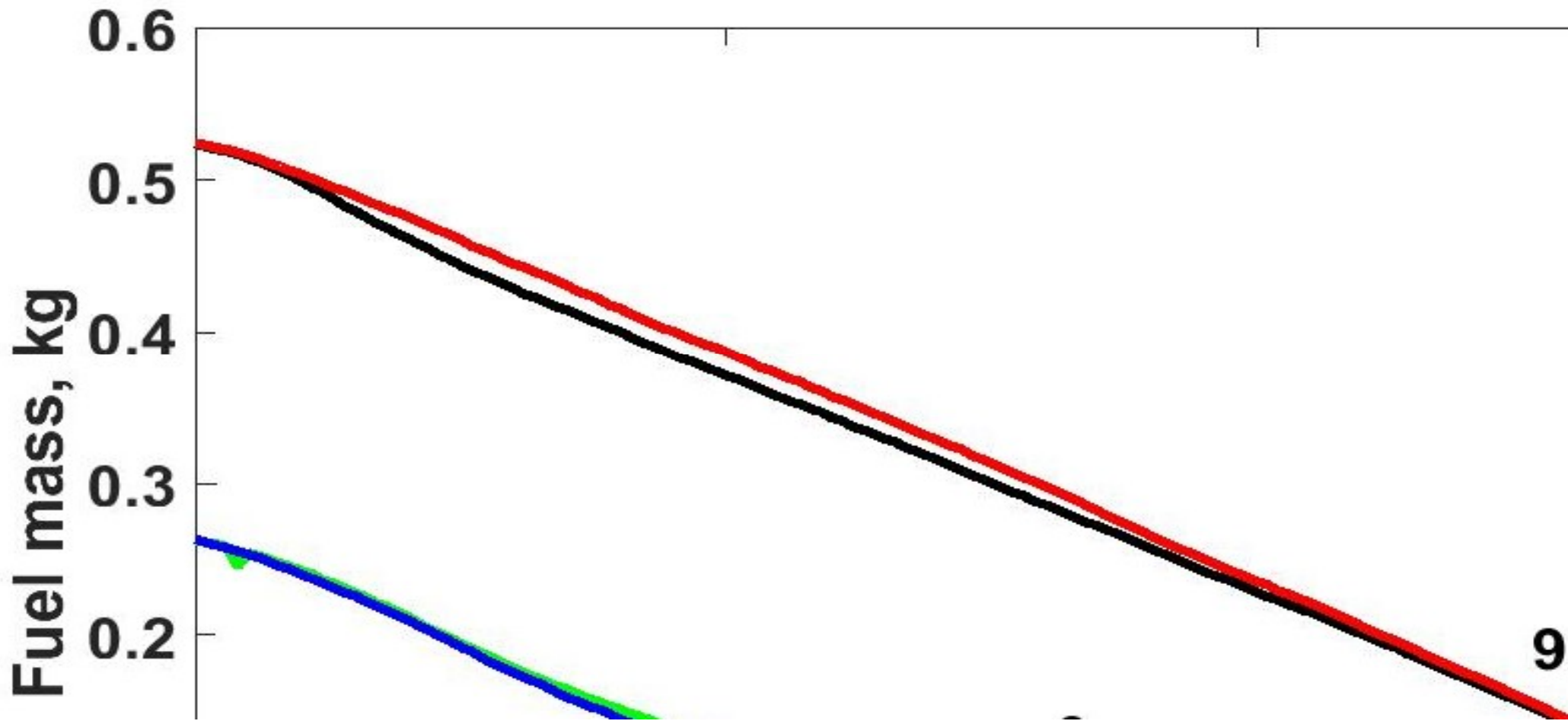
Fuel thickness and material effect on the burn rate is negligible for diesel fuel

Fuel depth effect on burn rate of methanol and ethanol fuel in 200 mm dia, 40 mm depth MS pan
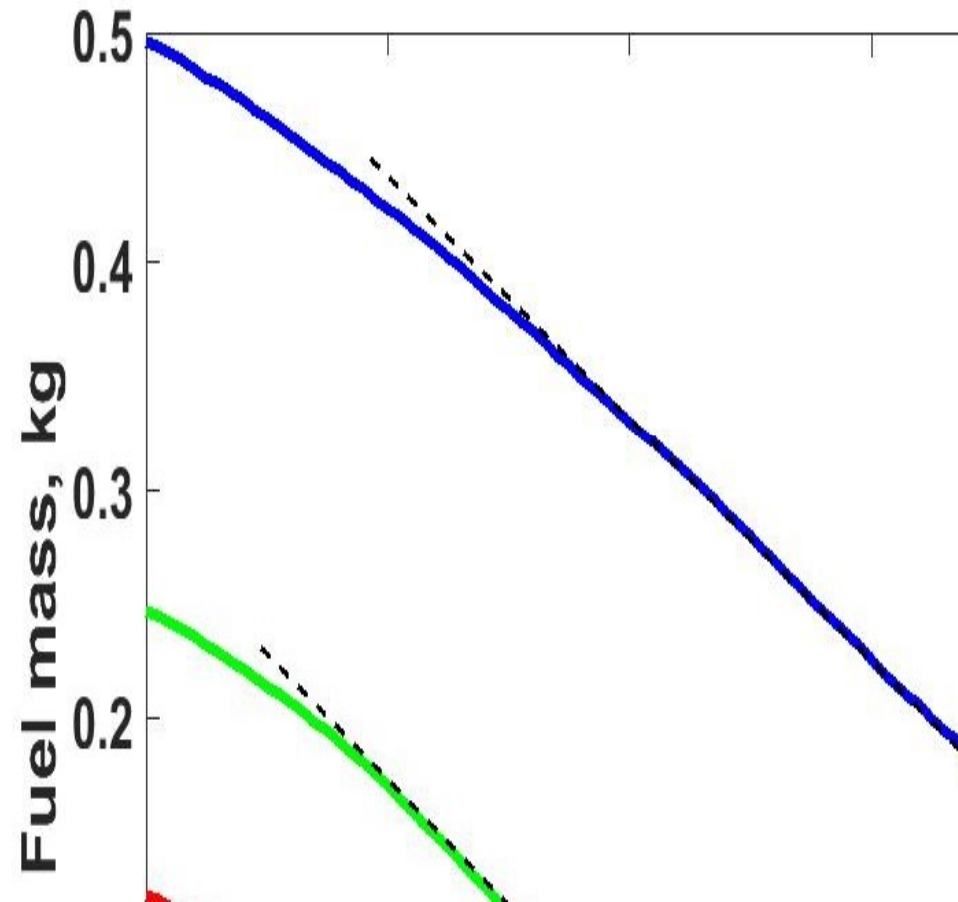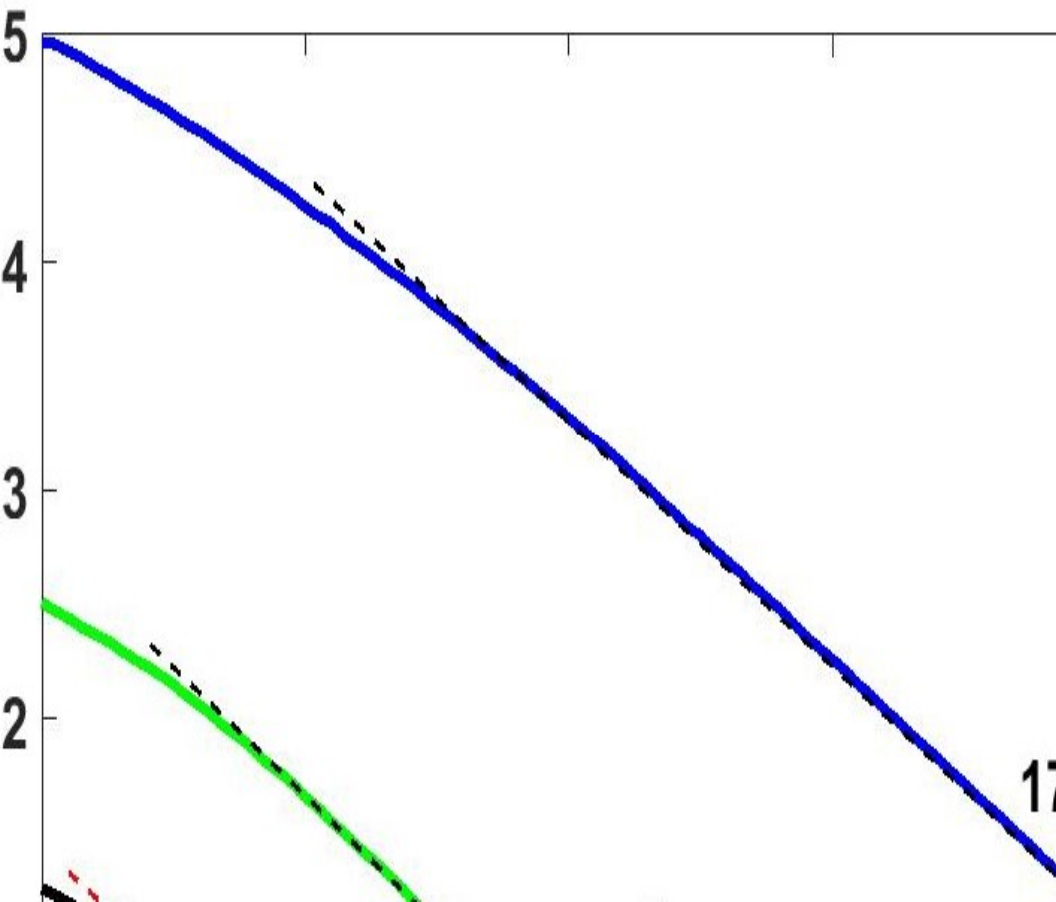
Fuel depth effect on burn rate is negligible for methanol and ethanol

Fuel temperature of different fuels at 1mm height from the bottom of pan
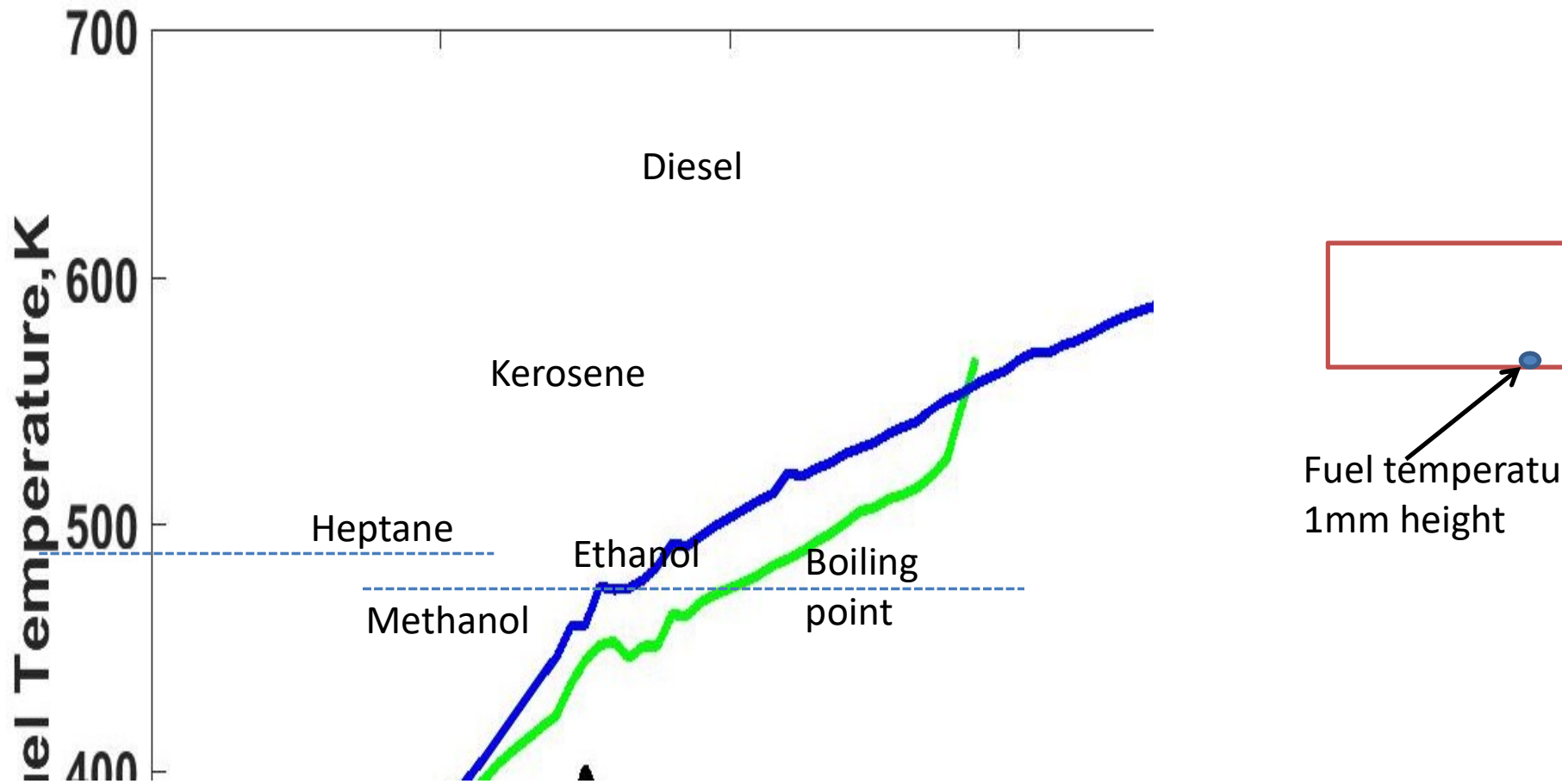
- In case of pure fuels – heptane, methanol and ethanol, the maximum temperature is the boiling point

- In the case of kerosene and diesel, the temperature increases to much larger values

Mass loss rate of different fuels in C200mm dia, 40mm deep MS pan.
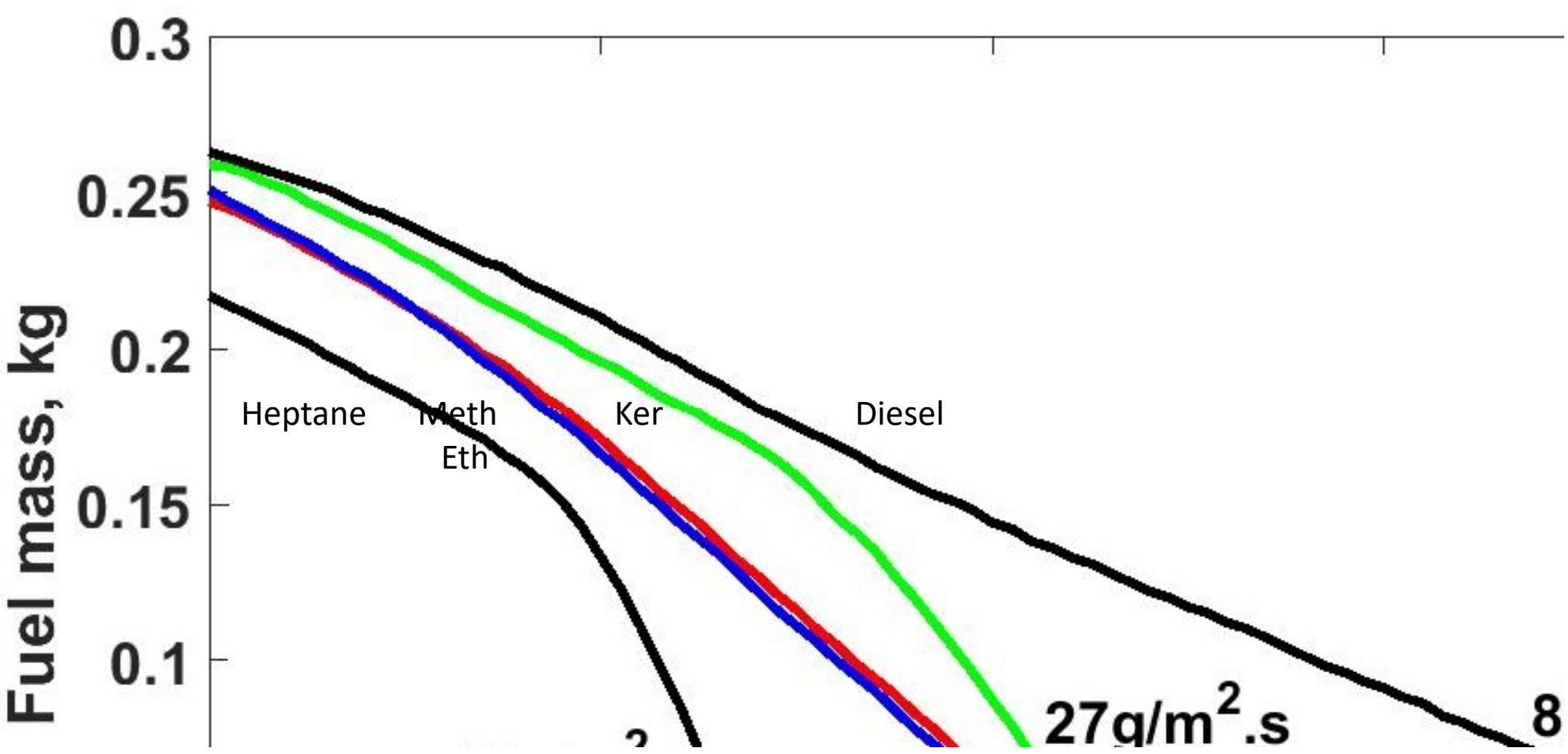
Key points from the experiments

The experiments conducted here and those in China for n-heptane match well over the range tested 200 mm dia SS pan with 13 mm fuel thickness.

The present experiments are with AL, MS, SS and GL with a factor 60 in thermal conductivity ch and 24 in thermal diffusivity change and fuel thickness explored are 10 to 20 mm for n-heptane fuel

In terms increasing order of burn rate fluxes, - diesel, methanol, ethanol, kerosene and heptane

With glass, the dominant heat transfer mode is convection. With others, there is increasing ro conduction and at larger diameters and higher fuel fluxes, some radiation as well.

Sharp changes in burn rate with MS and AL are due to very fast conduction through the causing sudden appearance of boiling heat transfer all over.

Non-Dimensional Number, M$_{pc}$

evolution of a dimensionless number for defining pan conduction, M$_{pc}$ to account the burn rate behavior
lve the following aspects.

**Increase in wall material thermal conductivity (k$_w$) should increase the heat transfer into the pan and
increase M$_{pc}$.**

Increase in free board (h$_{fb}$) and pan depth (h$_{pan}$) should reduce the heat transfer and hence M$_{pc}$.

Increase in fuel thickness (hfu) increases the burn rate and hence M$_{pc}$.

Increase in pan diameter increases the burn rate and must be so reflected in M$_{pc}$.

**Decrease in pan wall thickness should result in reduced conductive flux and should be reflected in r
M$_{pc}$.**

Increase in initial fuel temperature increases the burn rate and hence M$_{pc}$.

ndering conductive heat transfer coefficient, k$_w$/h$_{pan}$ dimensionless is performed using the convectiv
isfer coefficient, h$_{g;conv}$ that is obtained by expecting that the burn rate flux is controlled by convection
y stages in a small diameter pan.

h regard to other dimensions - fuel thickness, free board, pan diameter and pan wall thickness,
ensionless constructions are possible. Amongst these, one candidate for rendering the fuel thickne
ensionless is conduction thickness, k$_{fu}$/h$_{g;conv}$ whose value is about 0.03 m.

Non-Dimensional Number, M_{pc}

candidate for rendering the pan diameter dimensionless should arise from free convective length scale, $[v_g^2/g]^{1/3}$, w
$/\rho_g$ is the dynamic viscosity of the hot gases. With $\mu_g = 1.8*10^{-5}$ kg/m.s, g = acceleration due to gravity, this length s
21m.

ce these dimensions are independent quantities, they can be incorporated into a constant.

er much study, the dimensionless number is grouped into product of four parameters as shown below

$[k_w t_w h_{fu}/(h_{pan} h_{g,conv})]^{1/3}$ - accounts for conductive and convective heat transfer effects

$[\{1-\exp(-7 h_{fu}^{0.2} (h_{fb}/h_{pan})^{0.05} *d_{pan}^{1.3} (1+0.1*h_{wr} d_{pan}^{1.3}/h_{pan}^{2.3}))\}]$ - accounts for pan diameter in addition to free board h $_{fb}$ and
th h $_{wr}$

$= [T_{bfu}/T_o -1]^{0.45}$ - accounts for initial fuel temperature

$= c_{pg}*To/[L+c_{pfu}(T_{bfu}-T_o)]$ - accounts for fuel properties

$M_{pc} = 285* P1* P2* P3* P4$,   The constant 285 is chosen such that the value of M_{pc} corresponds to the flux values for larger diameter

conductive heat transfer coefficient, h_{gcv0} is convective heat transfer coefficient, h_{fu} is fuel depth,
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,
l boiling temperature in K, T_0 is initial temperature of fuel in K

The various values of indices were obtained to reduce the mean square error after extensive comparison wi
ental data

The experimental parameters and M_{pc}

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

| atl	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	**49.4**	
AL	60	2710	0.91	24.33	0.013	300	322.0	369	2.10	2.2	**40.1**	**← Conducti** **transfer**
AL	60	2710	0.91	24.33	0.01	300	322.0	369	2.10	2.2	**35.4**	
MS	32	7850	0.5	8.15	0.02	300	322.0	369	2.10	2.2	**40.1**	
MS	32	7850	0.5	8.15	0.013	300	322.0	369	2.10	2.2	**32.8**	**← Conducti** **transfer**
MS	32	7850	0.5	8.15	0.01	300	322.0	369	2.10	2.2	**29**	
SS	16	7880	0.46	4.41	0.02	300	322.0	369	2.10	2.2	**32**	
SS	16	7880	0.46	4.41	0.013	300	322.0	369	2.10	2.2	**26**	**← Conducti** **transfer** **with con**
SS	16	7880	0.46	4.41	0.01	300	322.0	369	2.10	2.2	**23**	
GL	1.14	2320	0.75	0.66	0.02	300	322.0	369	2.10	2.2	**13**	
GL	1.14	2320	0.75	0.66	0.013	300	322.0	369	2.10	2.2	**10.8**	**← Convecti** **transfer** **dominan**
GL	1.14	2320	0.75	0.66	0.01	300	322.0	369	2.10	2.2	**9.4**	

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

Correlation to predict the mean burn rate

$$\dot{m}_{fu} \ (\text{g/m}^2\cdot\text{s}) = 7.8 + 0.74 M_{pc} \text{ for } M_{pc} < 26.5$$
$$= 213\text{-}7^*M_{pc} \text{ for } 26.5 < M_{pc} < 27.5$$
$$= 0.79^*M_{pc} - 1.2 \text{ for } M_{pc} > 27.5$$
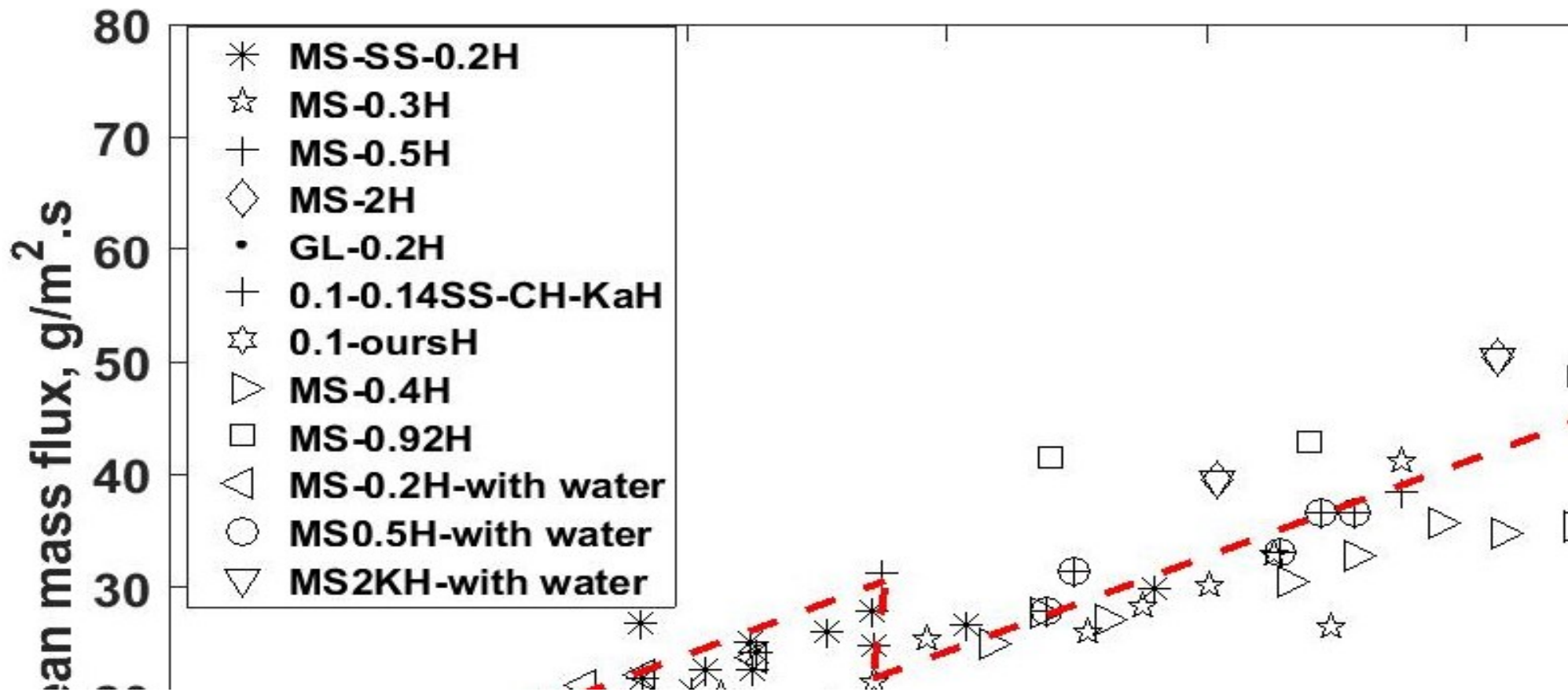
Conclusions - 1

rate is strongly dependent on the fuel thickness, pan material and initial temperature of
ase of n-heptane and kerosene fuel.

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 4.5 W/m²K (this value
obtained from a MATLAB simulation of the burn rate process not discussed here)
maller 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.

flux which is generally observed in larger diameter pans can be obtained in the smaller p
ncreasing the thickness of fuel, this increase is being due to conductive heat transfer.

ntriguing behaviour of sharp burn rate change caused by high conductivity wall material (
Al) as different from SS is brought out in case of n- heptane and kerosene fuels. The inter
all thermal conductivity and heat drawn away through the wall is considered the reason.

Conclusions - 2

n-dimensional parameter (M_{pc}) to distinguish the burn behaviour of materials of pans, fuel depth and init
erature is set out. It is also used to obtain a correlation for the burn rate flux of fuels discussed here.

e results are consistent with general understanding, but this work provides quantitative estimates for the l
given the geometric parameters of the pan and thermochemical parameters of the fuel. It is expected that
ctions would be realistic for other fuels (mixture of the primary fuels, for instance).

……………….Thank you.