Insights into pool fire combustion behavior

- The pool fire? Its features from Sandia lab data and literature
- Pulsations in pool fire – literature and the present experiments
- Experimental data on flame temperatures vs time and spectra
- The “external insight” and its generality
- More experiments and more data and support for the “new” behavior
- What about results from fire dynamics simulator (FDS)?
- Do these results set “Ganga on fire”?

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The pool fire?

- Pan fire constitutes free convective combustion of a "large" layer of fuel in air
- It is essentially a diffusion flame – largely turbulent.
- Pan sizes used for fire safety qualification tests (UL standard) is about 2.1 m x 2.1 m. BARC tests for qualifying "nuclear" sensitive hardware have pan sizes of 4 m x 4 m.
- Heat transfer to the surface of the liquid fuel at large sizes is largely by radiation.
- Simple heat flux balances gives $\rho_p \acute{r} \sim [\varepsilon\sigma T_f^3/c_p]\, B$, where $B = c_p(T_f - T_s)/L$. T_f varies between 900 to 1300 K. The emissivity is close to 1. Any choice of a value for T_f can lead to uncertainty in $\acute{r}$ prediction by ~ 100 %.
- This is the reason for the inability to calculate $\acute{r}$, even if such estimates can be considered credible.
- Further…….

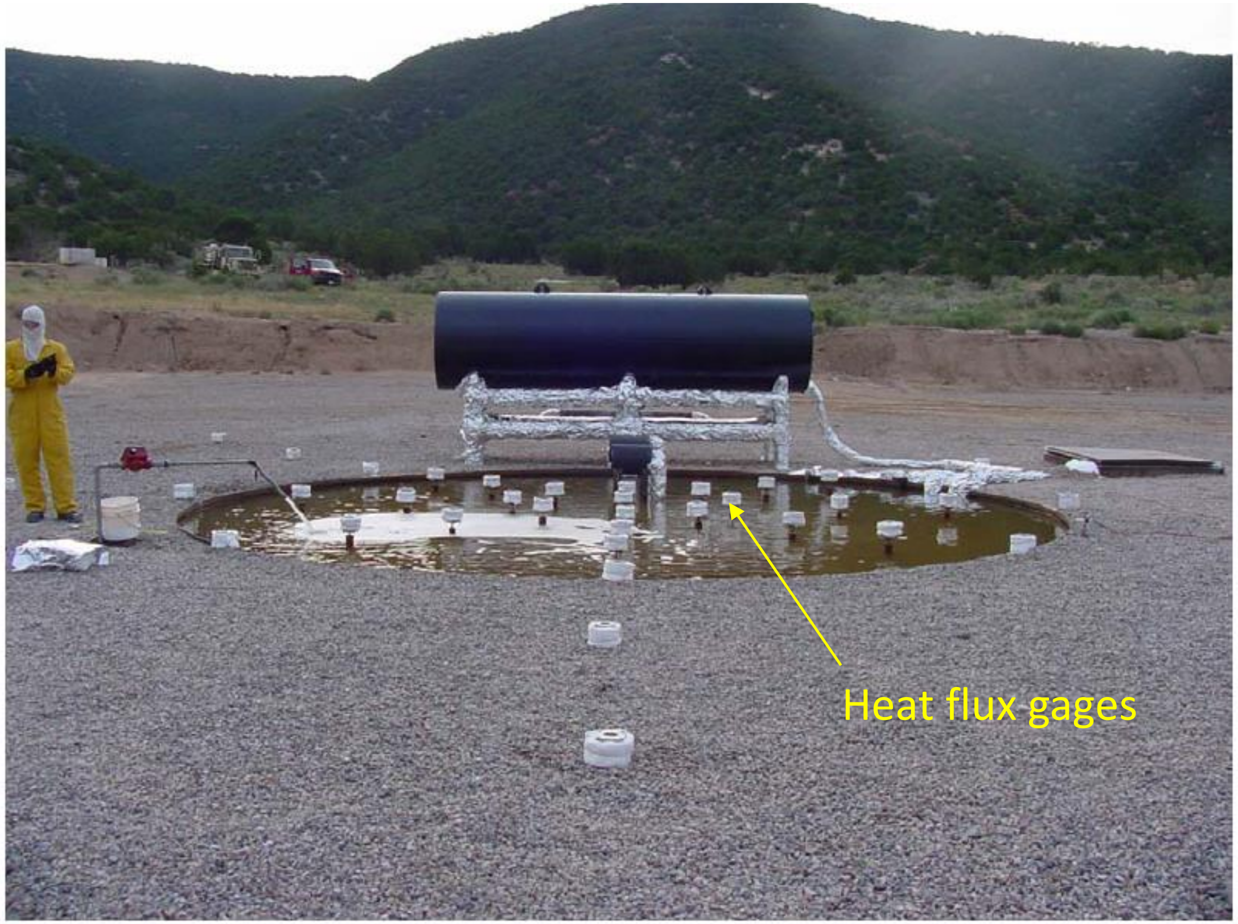
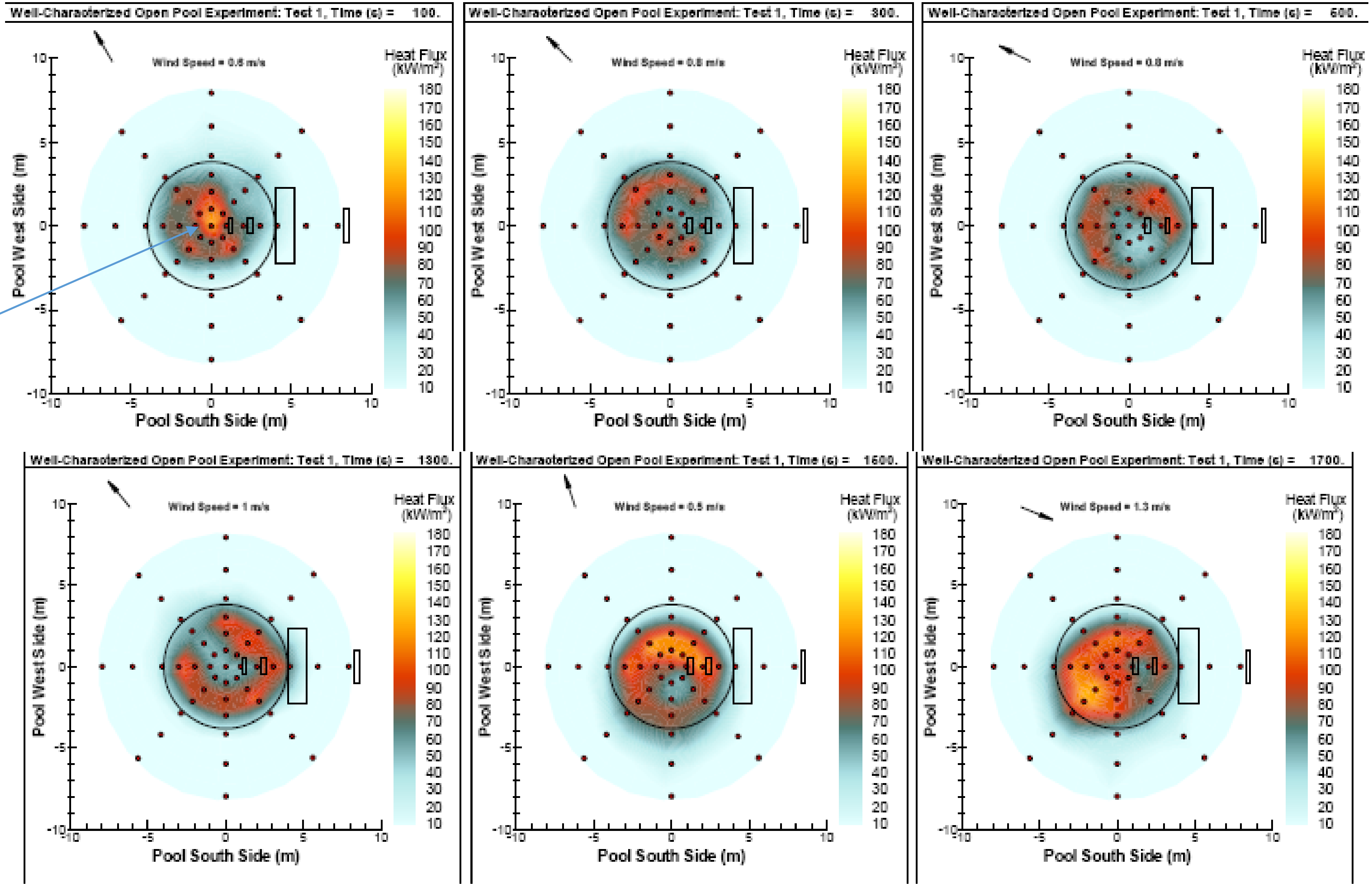


Figure 13. 26-ft diameter open pool with heat flux instrumentation.

Sandia lab tests – 26 ft dia kerosene pool fire showed…

Heat fluxes over the fuel surface at various times for Test – 1, low wind.



Notice that the flux is very small everywhere except in small zones. The assumption of a single mean heat flux over the surface is highly questionable.

Further, Hiroshi and Koseki have shown:

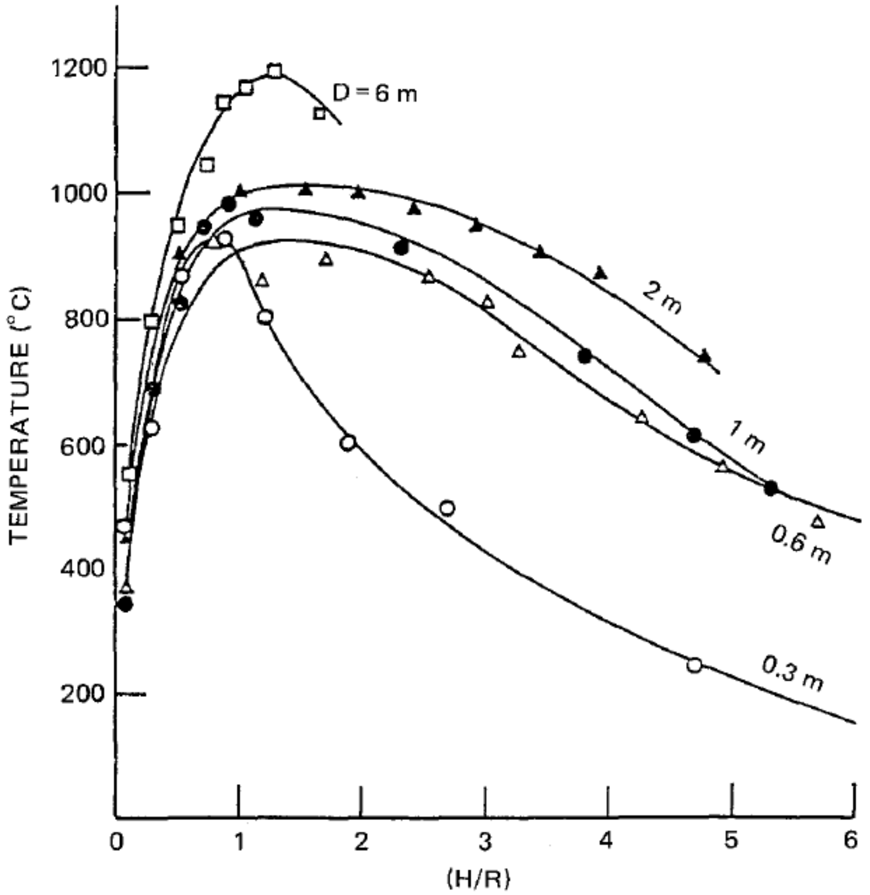
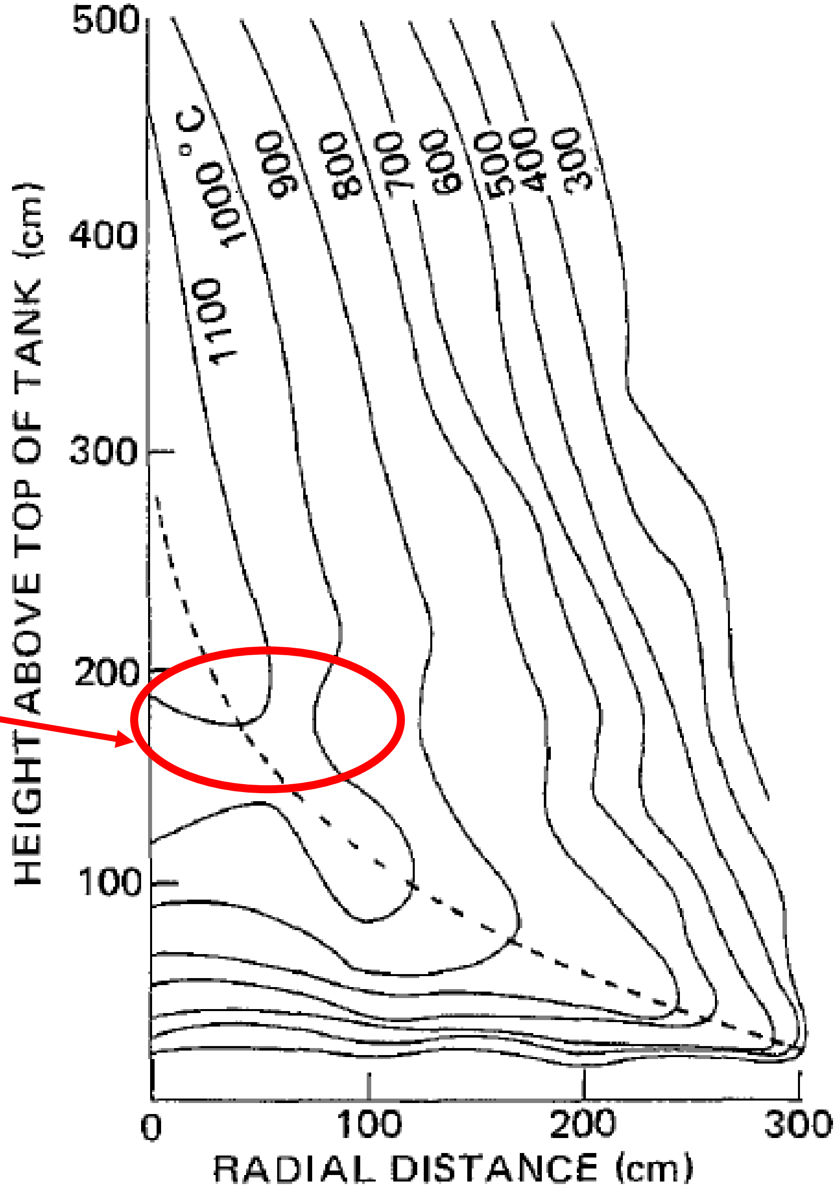


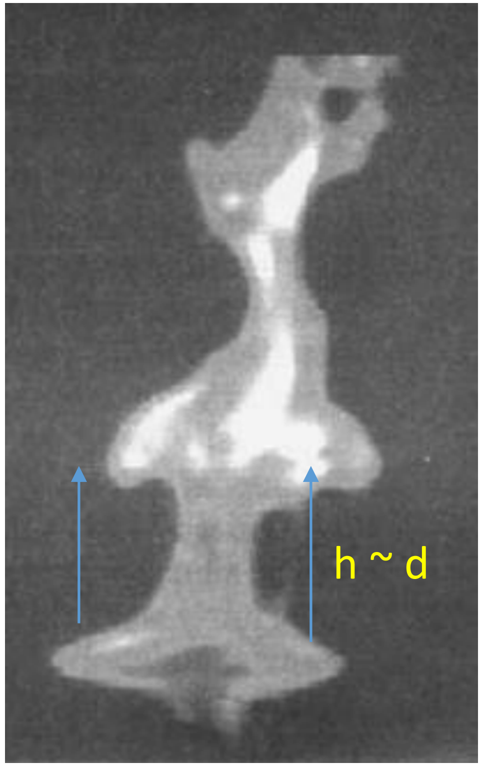
Figure 5. Temperature profiles along the flame axis.

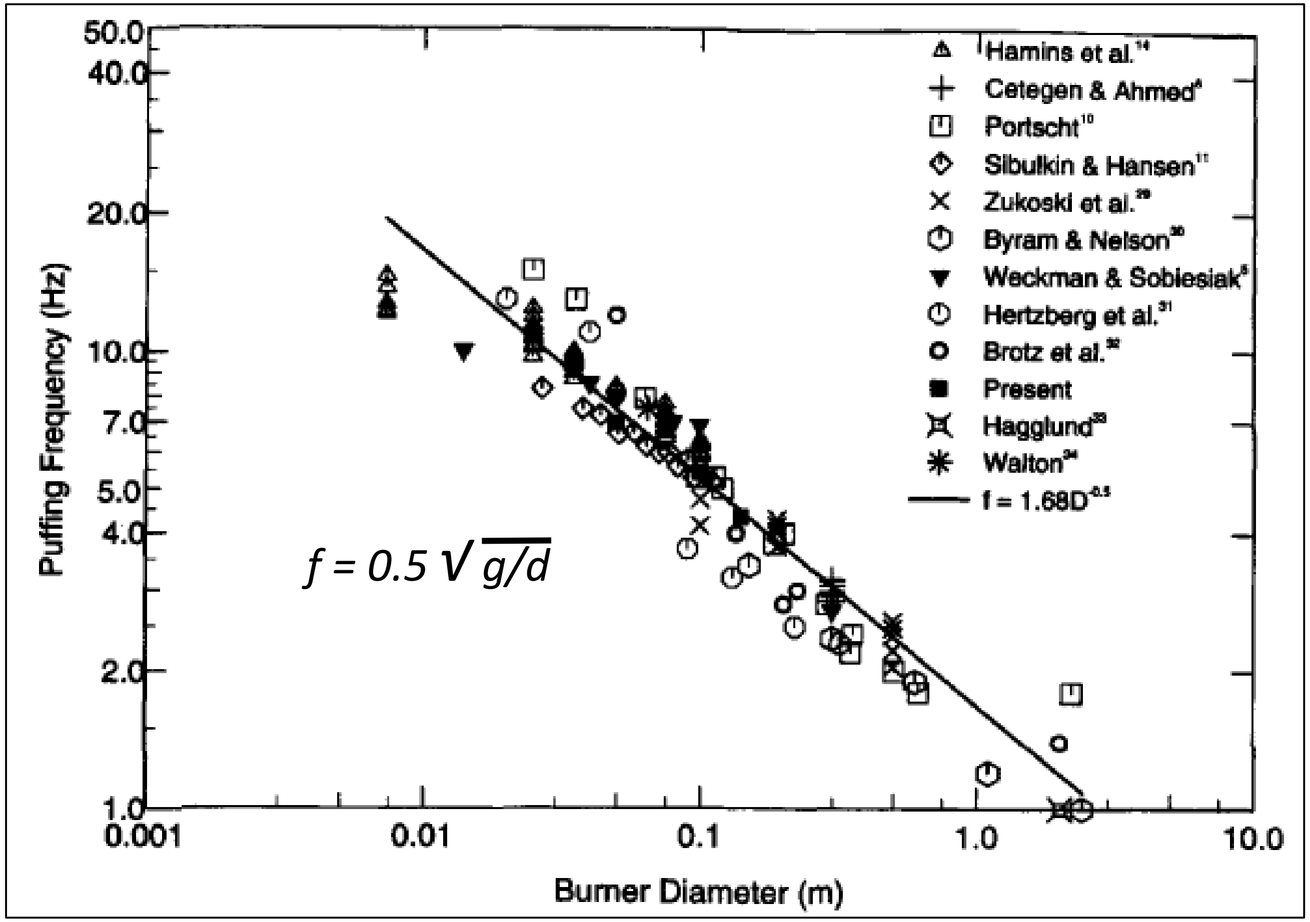
High temperature
Zone Is small.



Trying to use ideas of mean temperature for estimating flux are unsupported by observations

Pulsations in Pool fires





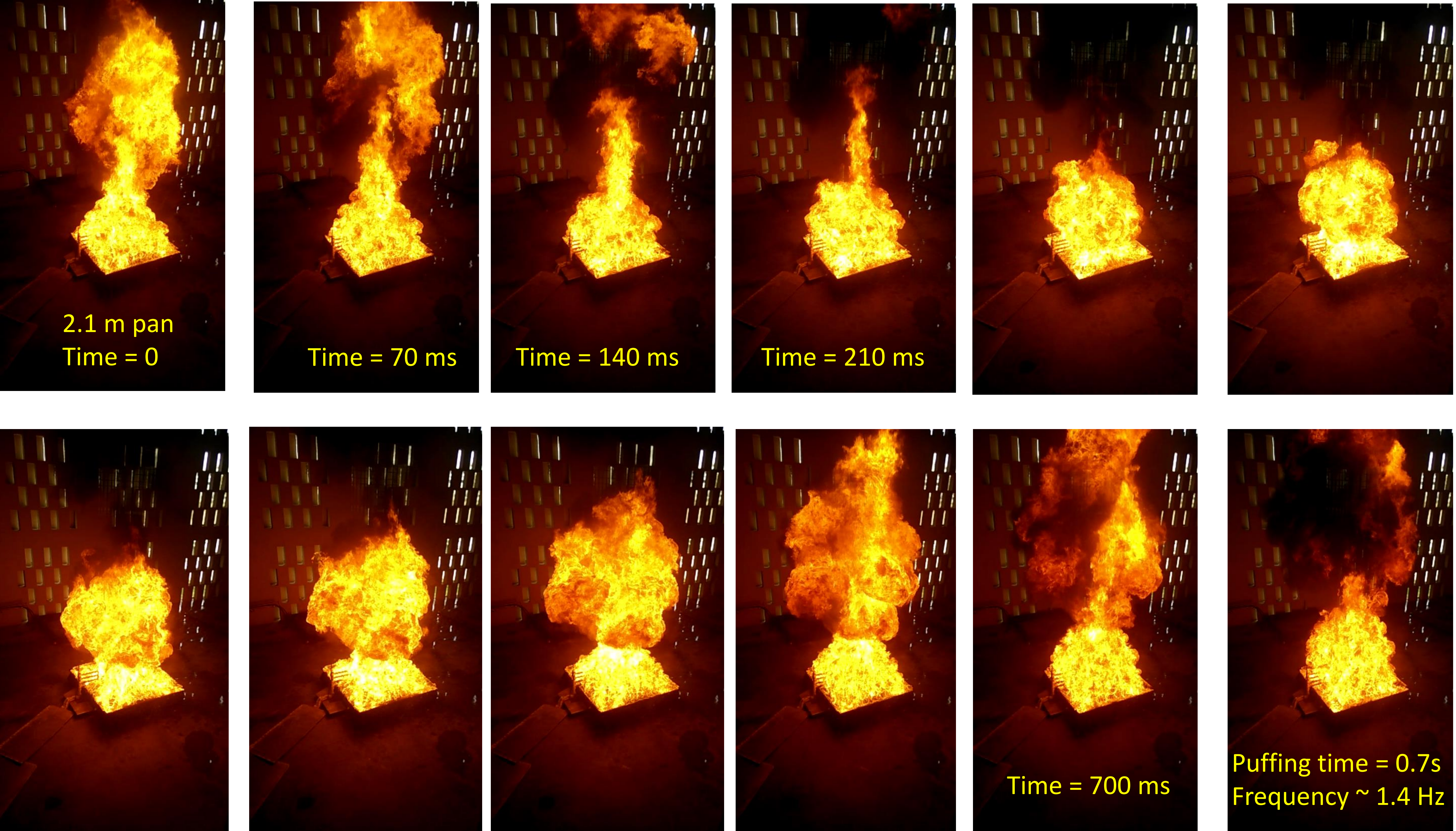
$t = h/V \sim V/g$

$V^2 = gh$ $f \sim V/h \sim V/d \sim \sqrt{g/d}$

The most common notion is that all pool fires are characterized by a puffing frequency.

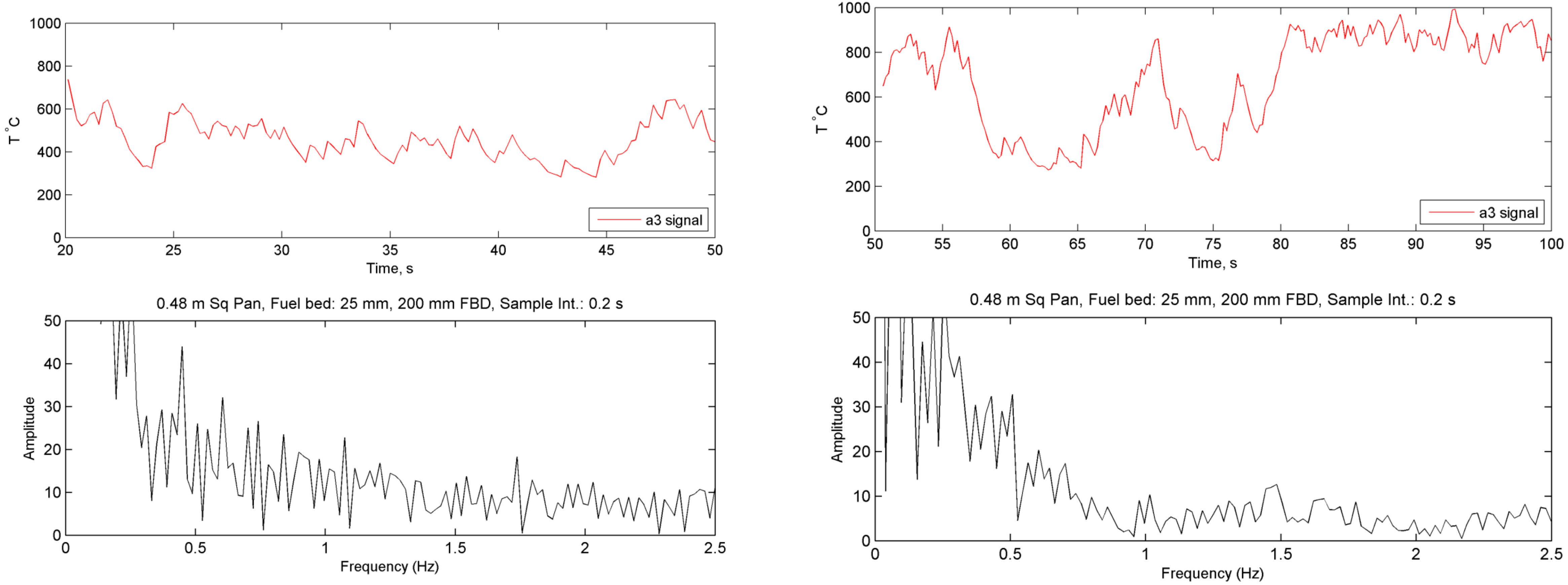
Experiments at FCRC were conducted with 0.48 m, 1.05 m, 1.52 m And 2.15 m square pools at the lab.

Frequencies ~ 2.25 Hz, 1.55 Hz and 1.27, and 1.05 Hz.



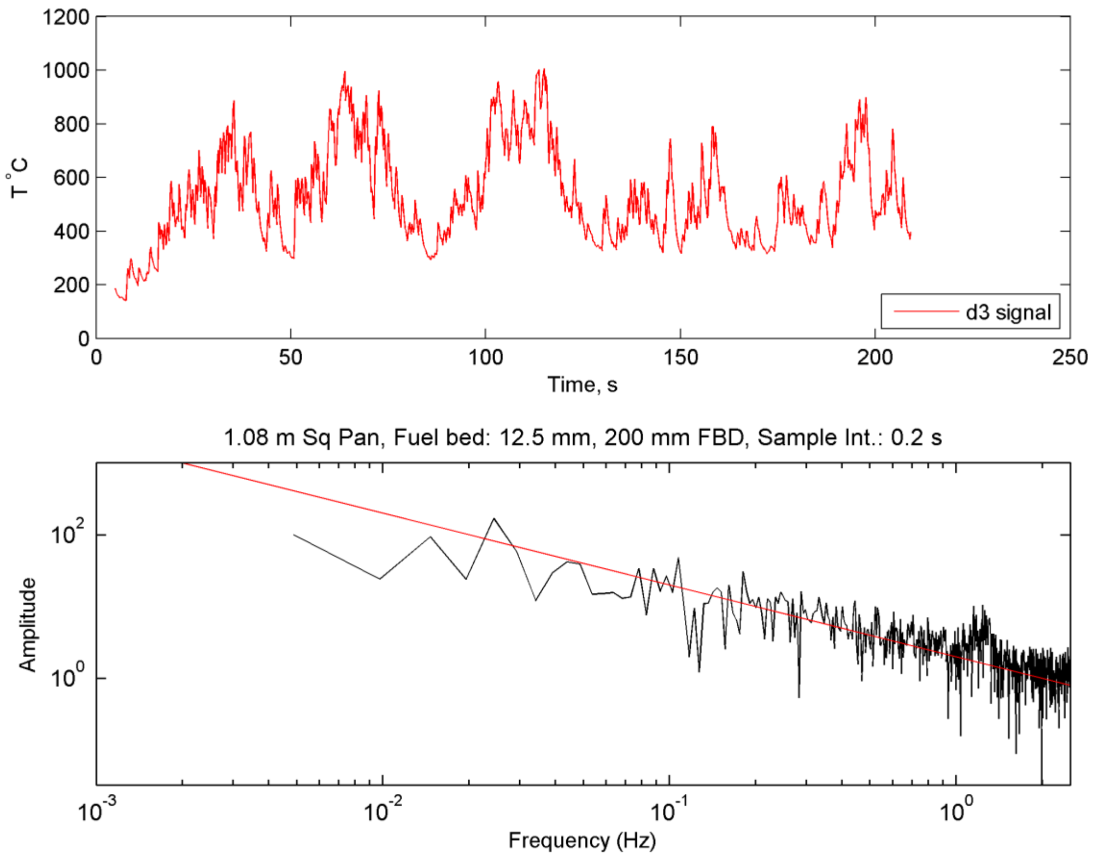
2.1 m pan
Time = 0
Time = 70 ms
Time = 140 ms
Time = 210 ms
Time = 700 ms
Puffing time = 0.7s
Frequency ~ 1.4 Hz

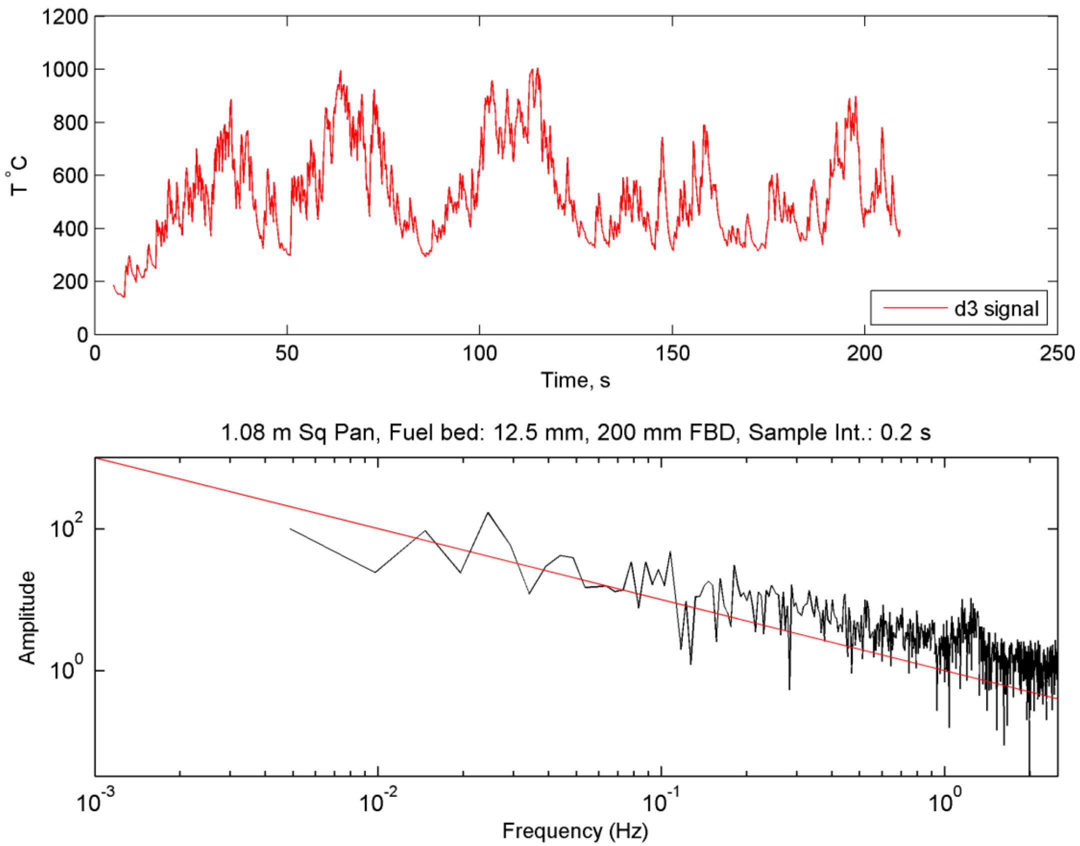
What do thermocouples inside the pan fire show?



Thermocouple data for 0.48 m x 0.48 m pool fire, Expected frequency ~ 2 to 2.2 Hz
What is observed: Varying range of frequencies, smaller ones not insignificant.
Very puzzling….

But, if we plot the data on a log-log scale (thanks to Dr. Shravan Hanasoge),





We get a amplitude ~ 1/f behavior.

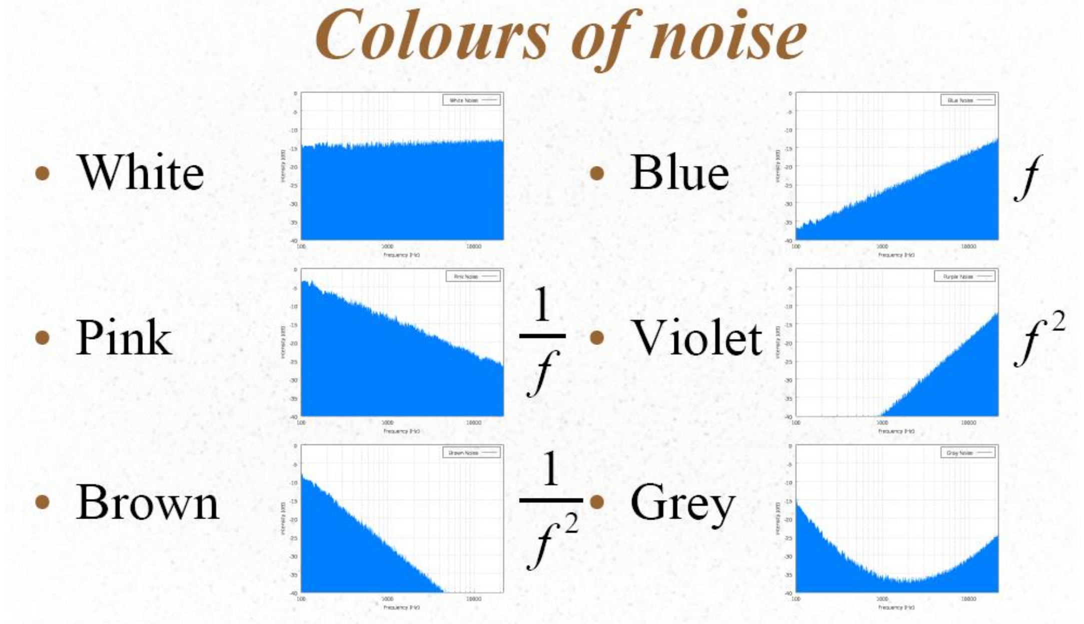
The most important aspect here is that the energy of fluctuations is much larger at lower frequencies over a continuous range. While 1.05 m pool fire should have 1.55 Hz, the fluctuation of 50 K occurs at a frequency 0.1 Hz and it corresponds to a length scale of 4 m! One interpretation of this is that the flame is very sensitive to ambient disturbances, a fact that is generally known. But is this all?

Pink noise or $^1/_f$ noise

From: https://en.wikipedia.org/wiki/Pink_noise

Because pink noise occurs in many physical, biological and economic systems, some researchers describe it as being ubiquitous.[8] In physical systems, it is present in some meteorological data series, the electromagnetic radiation output of some astronomical bodies, and in almost all electronic devices (referred to as flicker noise). In biological systems, it is present in, for example, heart beat rhythms, neural activity, and the statistics of DNA sequences, as a generalized pattern.[9

There are no simple mathematical models to create pink noise. Although self-organised criticality has been able to reproduce pink noise in sandpile models, these do not have a Gaussian distribution or other expected statistical qualities.[18][19] It is usually generated by filtering white noise[20][21][22] or inverse Fourier transform.[23]



log(Noise power density) is plotted vs. log(f)

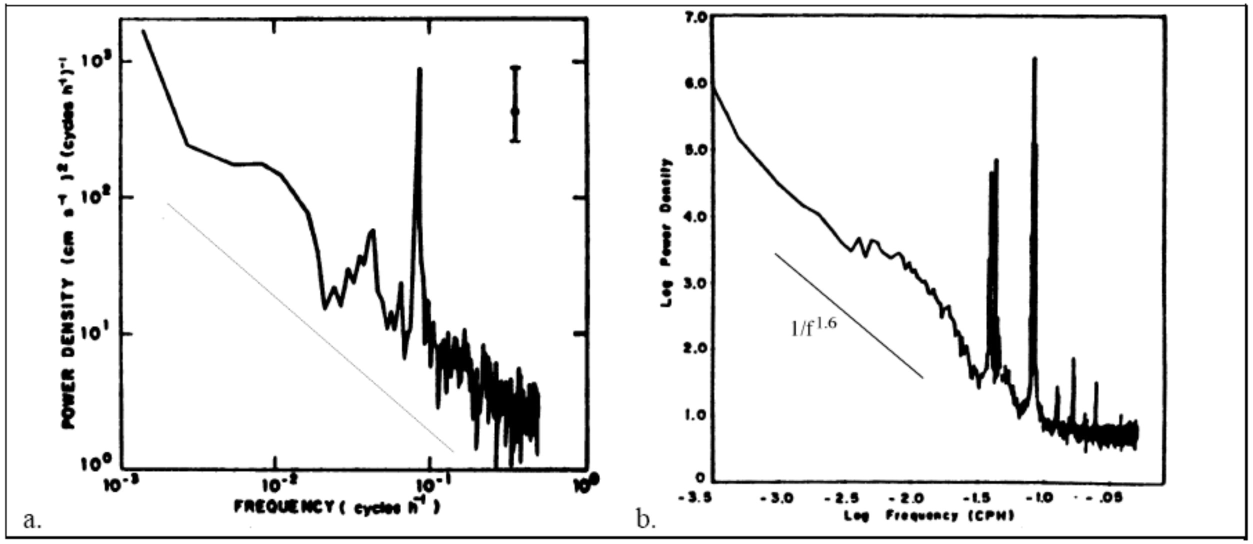


Figure 2: a. power spectrum of the east-west component of ocean current velocity [7]; the straight line shows the slope of a $1/f$ spectrum. b. sea level at Bermuda: this is $1/f^{\alpha}$ spectrum with $\alpha \approx 1.6$ [8].

LOW-FREQUENCY FLUCTUATIONS WITH $1/f$ SPECTRA IN CRITICAL REGIMES WITH PHASE TRANSITIONS

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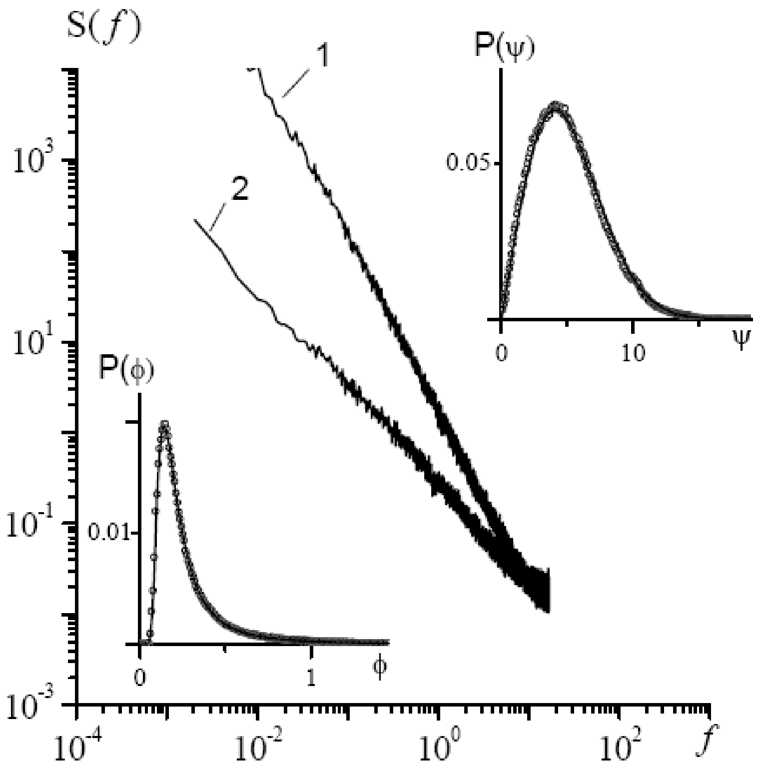


$$\frac{d\phi}{dt} = -\phi\psi^2 + \psi + \Gamma_1(t)$$
$$\frac{d\psi}{dt} = -\phi^2\psi + 2\phi + \Gamma_2(t)$$

All the studies now are based on model mathematical equations. They are good Enough for publications and not for unraveling the right physics.

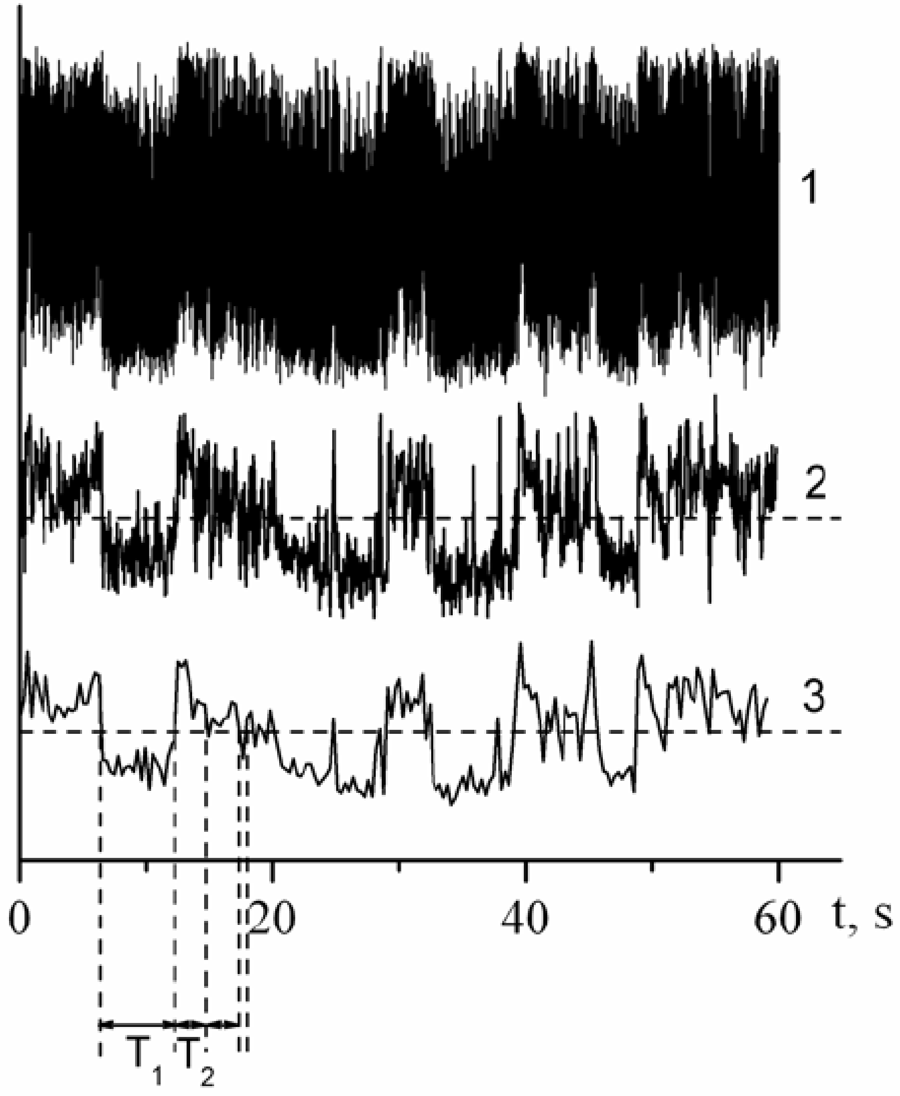


Figure 5. Initial (*1*) and roughened time series of fluctuation at water acoustic cavitations. Durations of low-frequency bursts T_i are shown on the roughened time series.

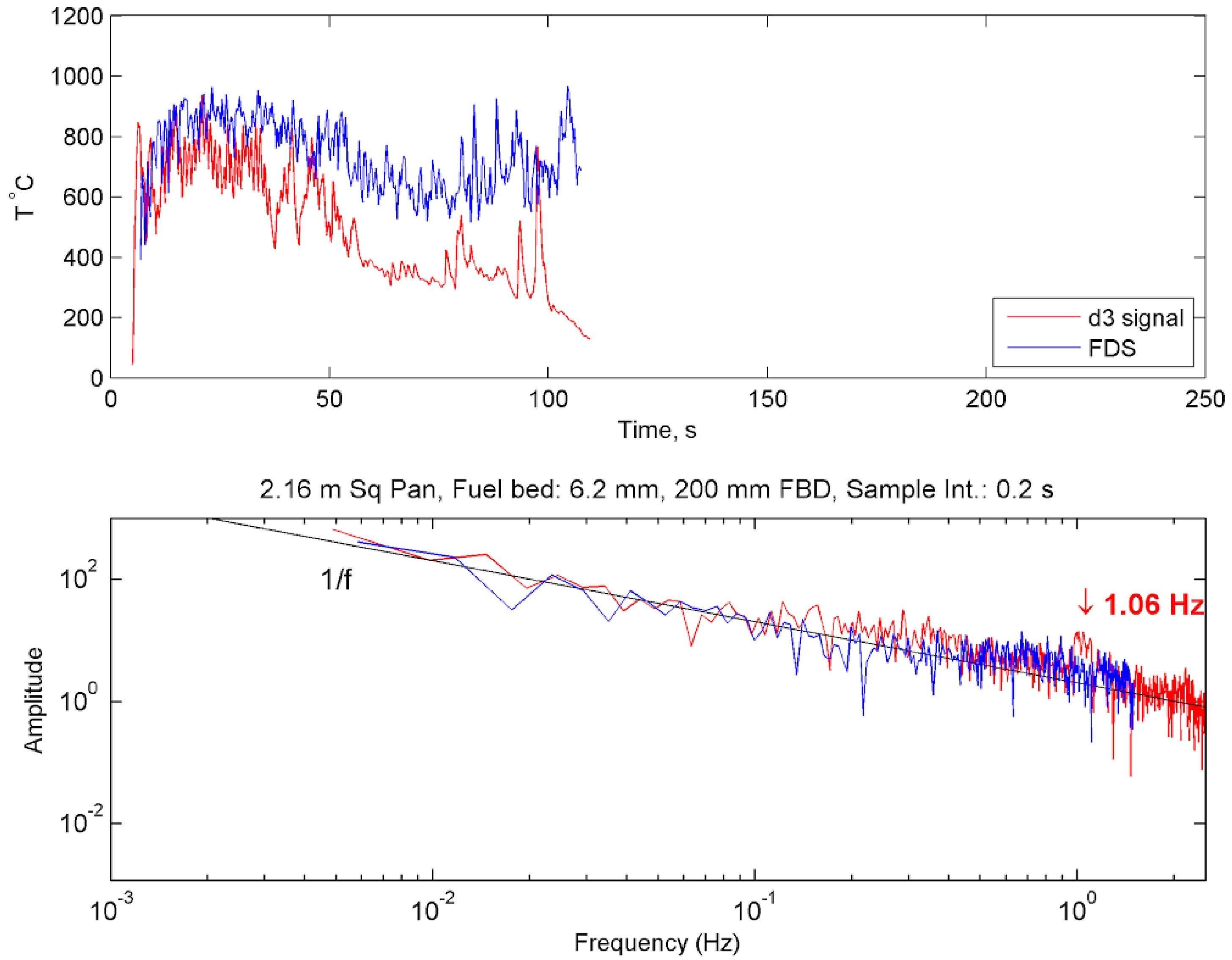
Can we create similar equations based on the physics of pan fires?

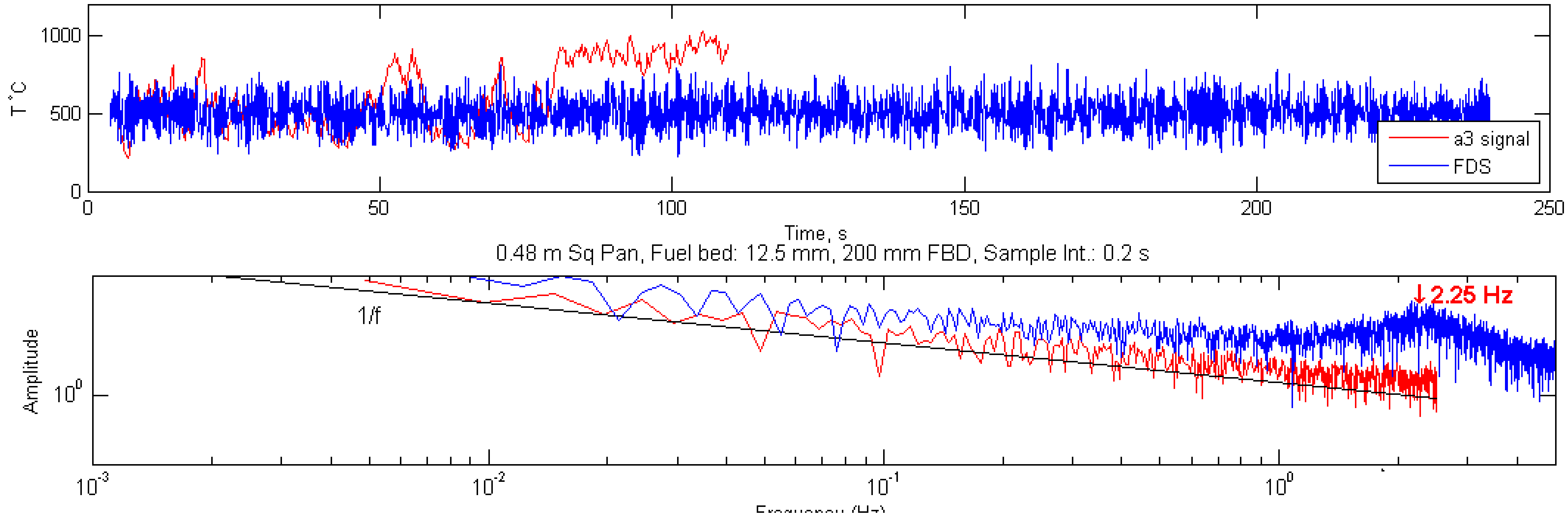
Can FDS predict puffing frequency and 1/f noise?

NIST based FDS does not predict the familiar pulsing frequency – "…results have shown the limitation of the code in predicting the puffing frequency, this is thought to be due to some approximation in FDS which is to be there in order to obtain the high efficiency of FFT-based fast solver for the Poisson equation.." Wen et al, Fire safety Journal, 2007, p 127

Is this justified at all?

Is it worth looking for it because The energy contained in it is Not so large as in lower frequencies?





A more refined calculation on a 0.48 m x 0.48 m pool fire with 40 mm grid size all around and calculation size of 3 m x 3 m x 3 m has resulted in the above plots. The 1/f relation is obeyed with a peak (somewhat broad that is suspected to be due to a slightly coarse grid) which is at the puff frequency.

Thus, both puff frequency stands captured and the 1/f relation stands established.

These are new results in the field of fire research….. What is the physics behind the phenomena?

a. Puffing, b. subharmonic wave propagation to wavelengths much larger than the size of the pan!

From: Ghoneim et al, Numerical simulation of the dynamics of large fire plumes and the phenomenon of puffing, 26th International Symp. combustion, 1996, pp. 1531 – 1539

From: Modeling of temporal combustion behavior In a large buoyant pool fire with detailed chemistry Consideration: 20th int congress on modeling and Simulation; Hu, Yuan Cheung, Lappas, Chow, Yeoh

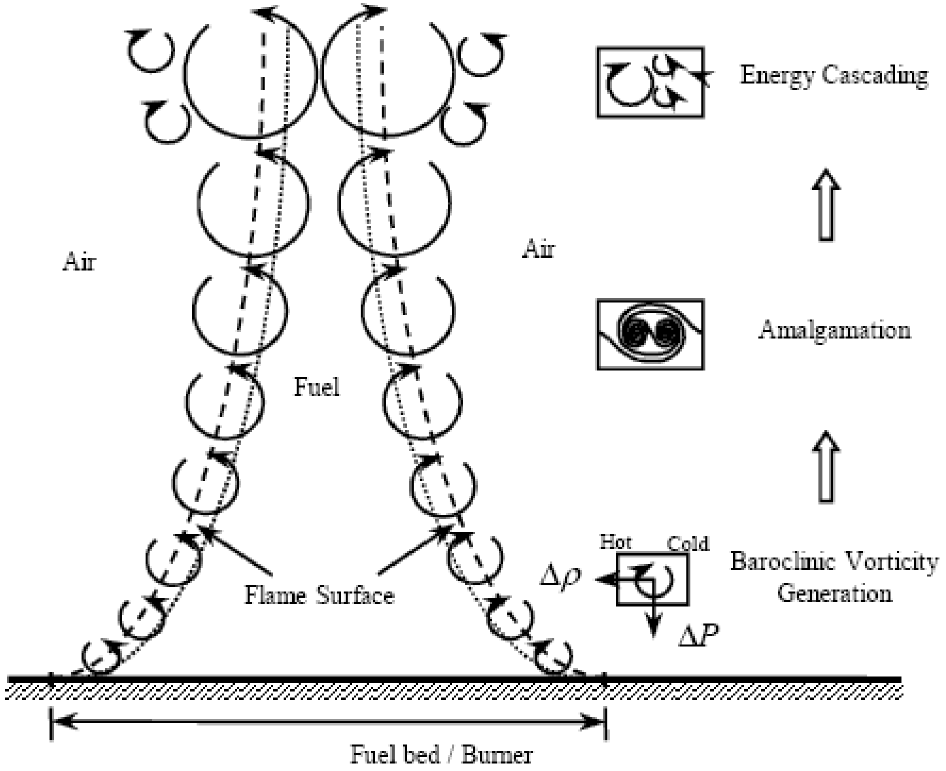
Important

Also unimportant

Unimportant

$$\frac{D\omega}{Dt} + (\nabla \cdot u)\omega - \frac{u\omega}{r} = \frac{1}{\rho^2}\left(\frac{\partial p}{\partial r}\frac{\partial \rho}{\partial z} - \frac{\partial p}{\partial z}\frac{\partial \rho}{\partial r}\right) + \frac{1}{\rho^2}\frac{\partial \rho}{\partial r} + \frac{1}{R_e}\left(\nabla^2\omega - \frac{\omega}{r^2}\right) \quad (4)$$

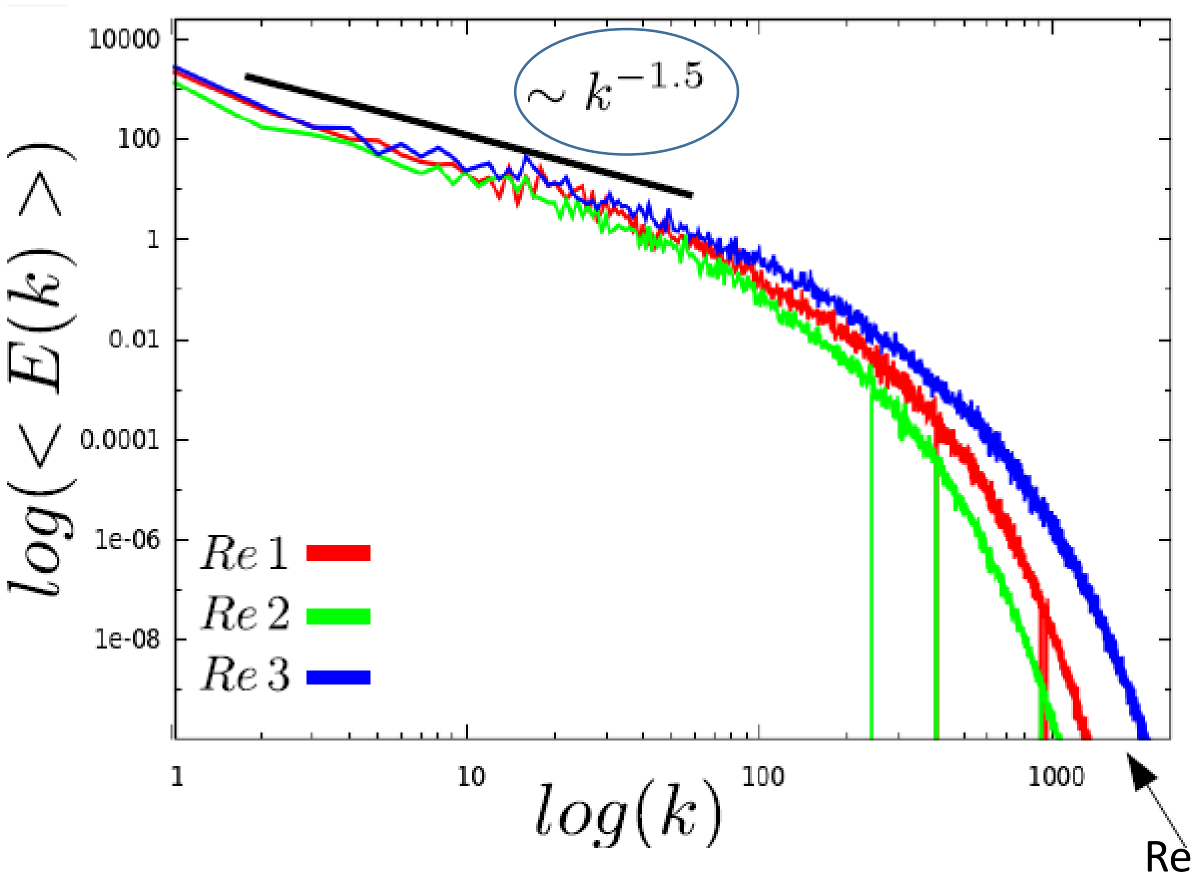
where p is pressure. The second and third terms on the left-hand side and the last term on the right-hand side correspond, respectively, to vorticity modification caused by volumetric expansion, stretch as the ring radius changes, and molecular diffusion. None of these terms can create or destroy rotation, the total circulation associated with a material volume remains constant under their action (diffusion spreads vorticity over a larger material volume). On the other hand, the first two terms on the right-hand side can generate vorticity because of the interaction between the density gradient and the hydrodynamic pressure gradient and the density gradient and gravity. Starting from rest, they are responsible for converting potential energy into kinetic energy, as will be shown in the results.

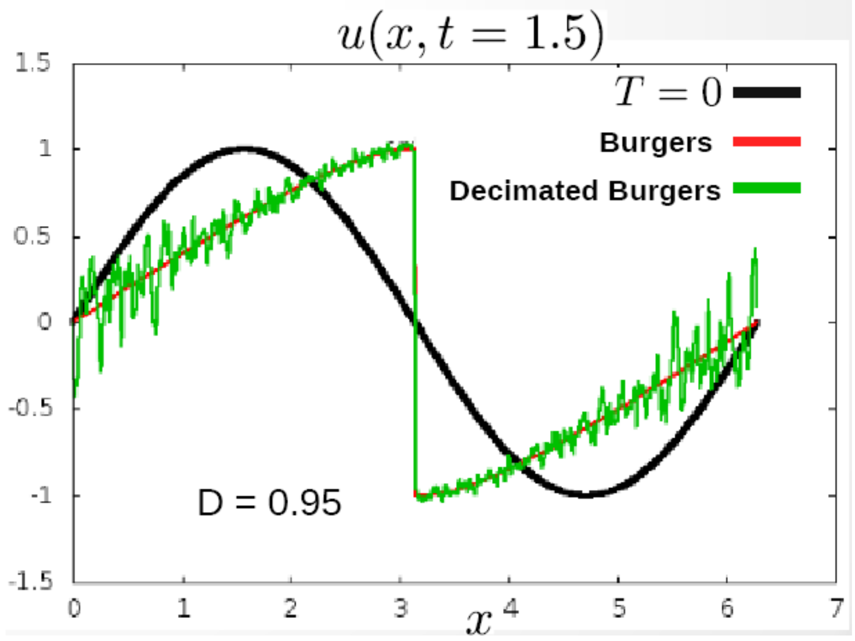


Constructing meaningful low-dimensional Dynamical models that can replicate the 1/f phenomenon as well puffing frequency is the task ahead!

The classical Burger's equation as a model?

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \nu\frac{\partial^2 u}{\partial x^2} + f(x,t)$$





In the light of the observations by Ghoneim et al, this route does not seem appropriate.

Summary

(do these results set Ganga on fire? – you decide!)

- Predictions of burn rate of pan fires from well grounded physics was the intent.
- There are enough experimental evidence to infer that unless physics is properly accounted we cannot predict the burn rate.
- The gas phase physics is embedded in puffing. It was thought initially that this is one of the discrete phenomenon hinted as such in the literature.
- Recent experimental studies showed that w aide range of frequencies (and so physical scales) are involved in the phenomenon
- Old calculations had actually shown wide range of frequencies (and being misled by literature as well) it was thought that these are the ghosts of numerical error (though not with true conviction)
- The observation on 1/f scaling, thanks to Dr. Hanasoge Shravan who simply identified the possibility and its subsequent demonstration both experimentally and "mercifully" through FDS has resolved multiple issues of misconception in literature.
- Dynamic low dimensional model is calling for conceptualization!

- Many staff of FCRC have contributed to the experimental and simulation study. Thanks to them.

……Thanks to all of you.