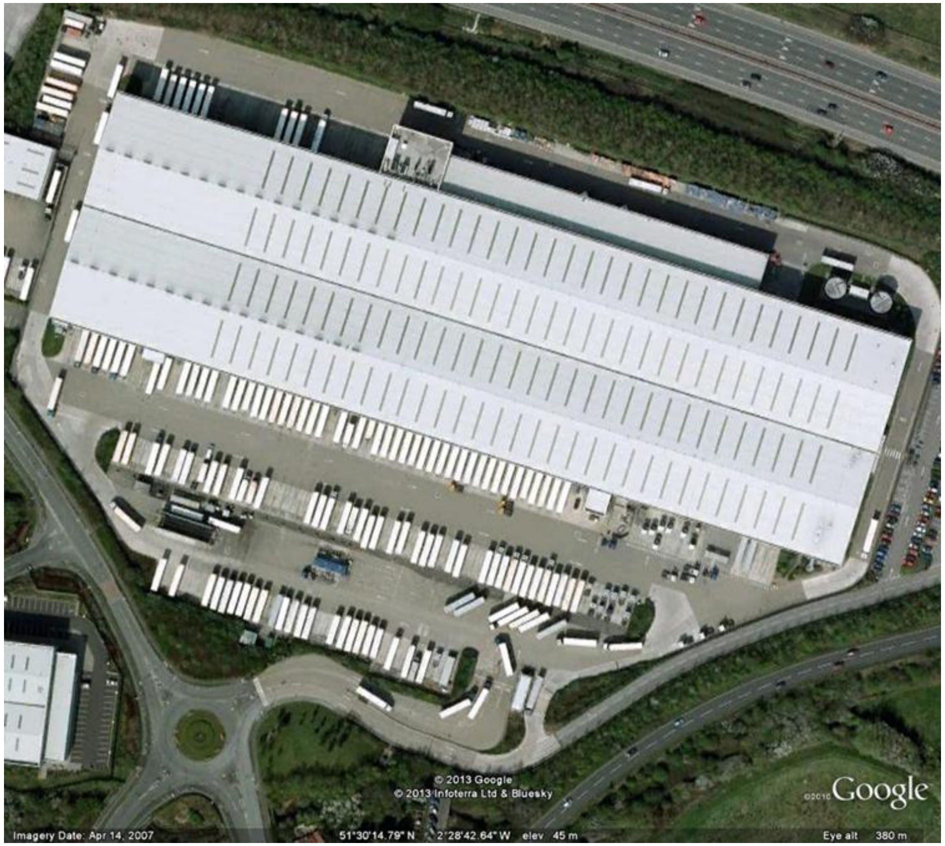
Explosions in linear congested arrays

Graham Atkinson (Health and Safety Laboratory)

Examples of significant problems:

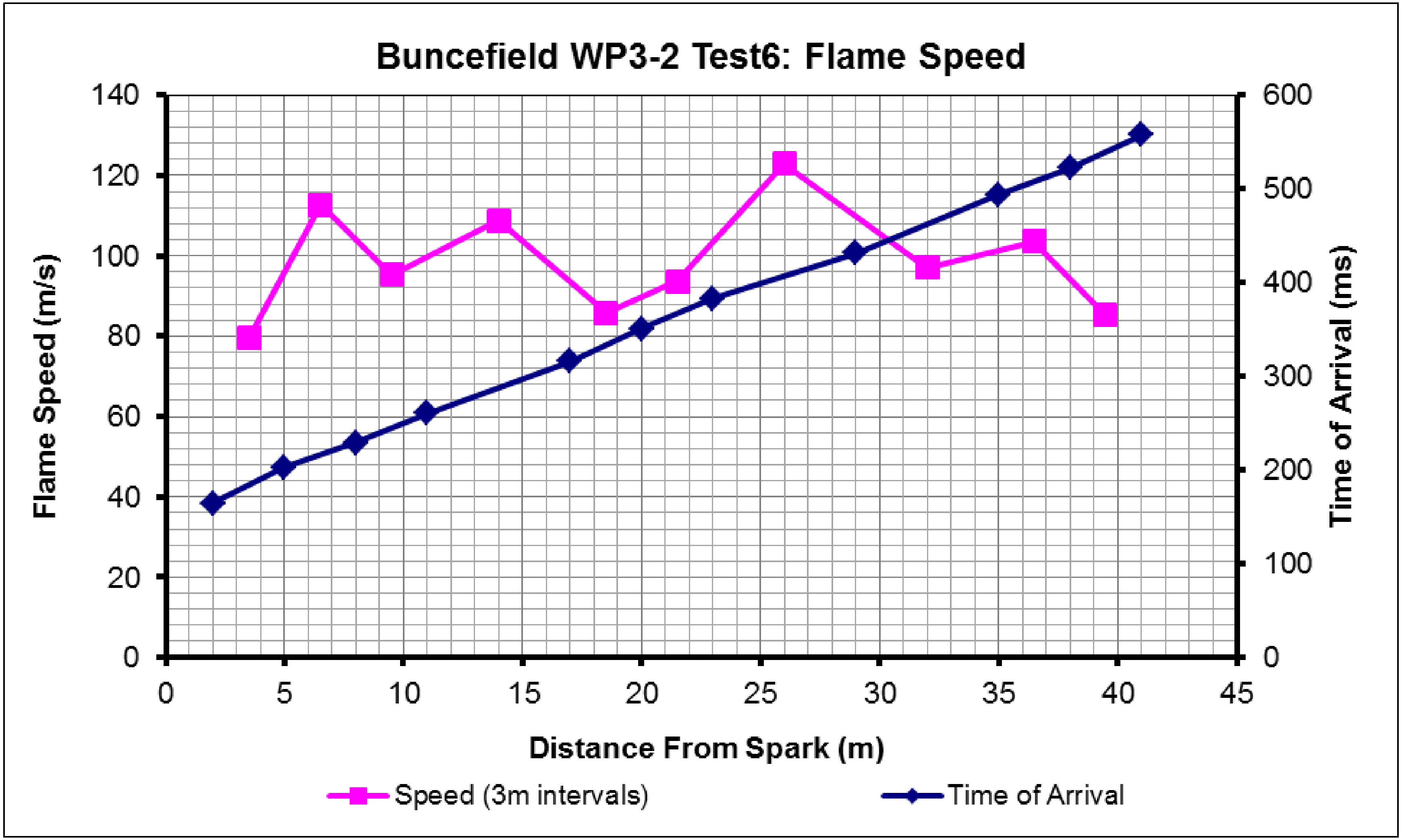
Lines of vehicles



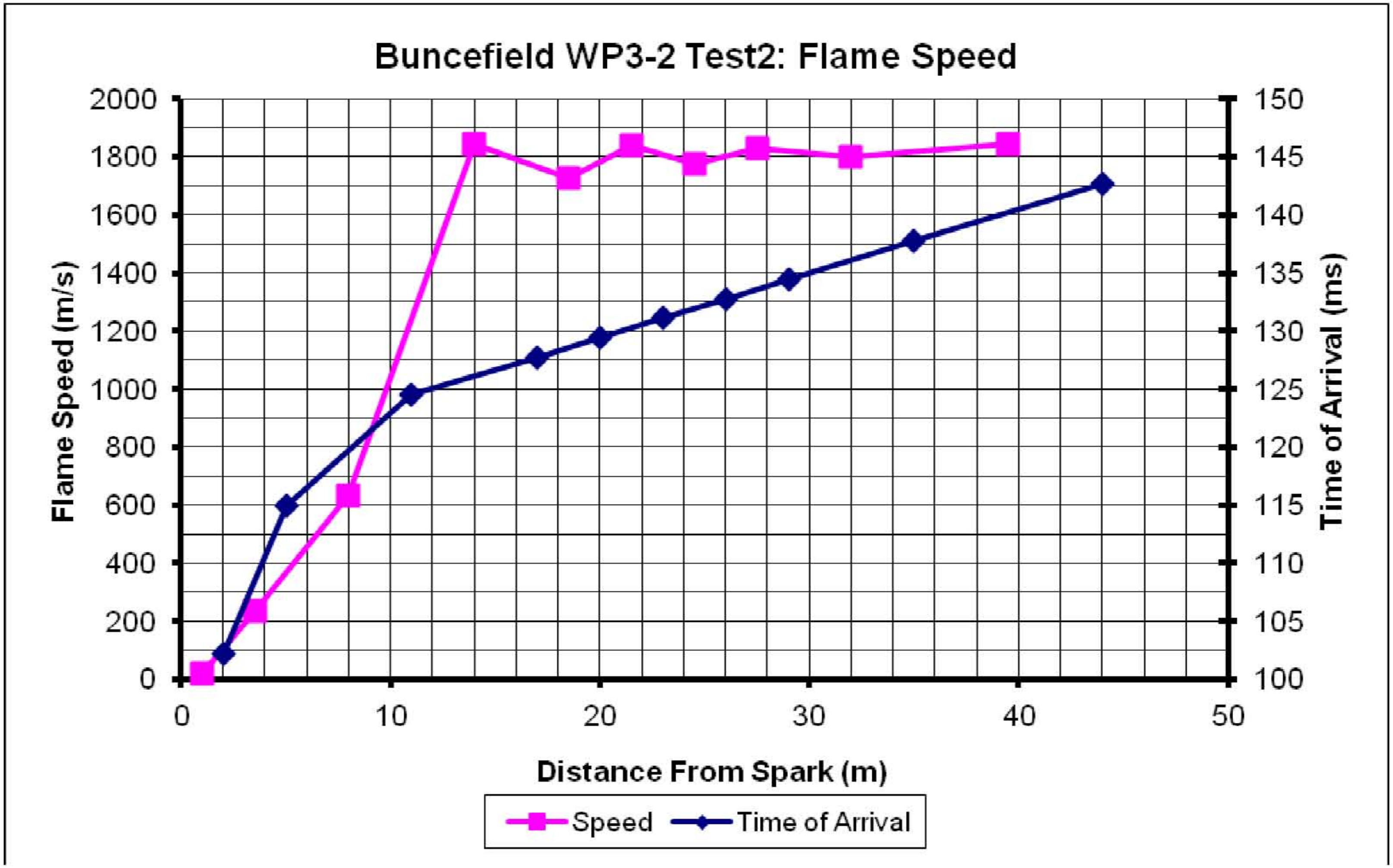
Hedges

Pipe racks

Pattern of flame spread 1: Steady subsonic propagation



Pattern of flame spread 2: Runaway flame acceleration and DDT



Array that shows steady flame propagation

Array that shows flame runaway and eventually DDT

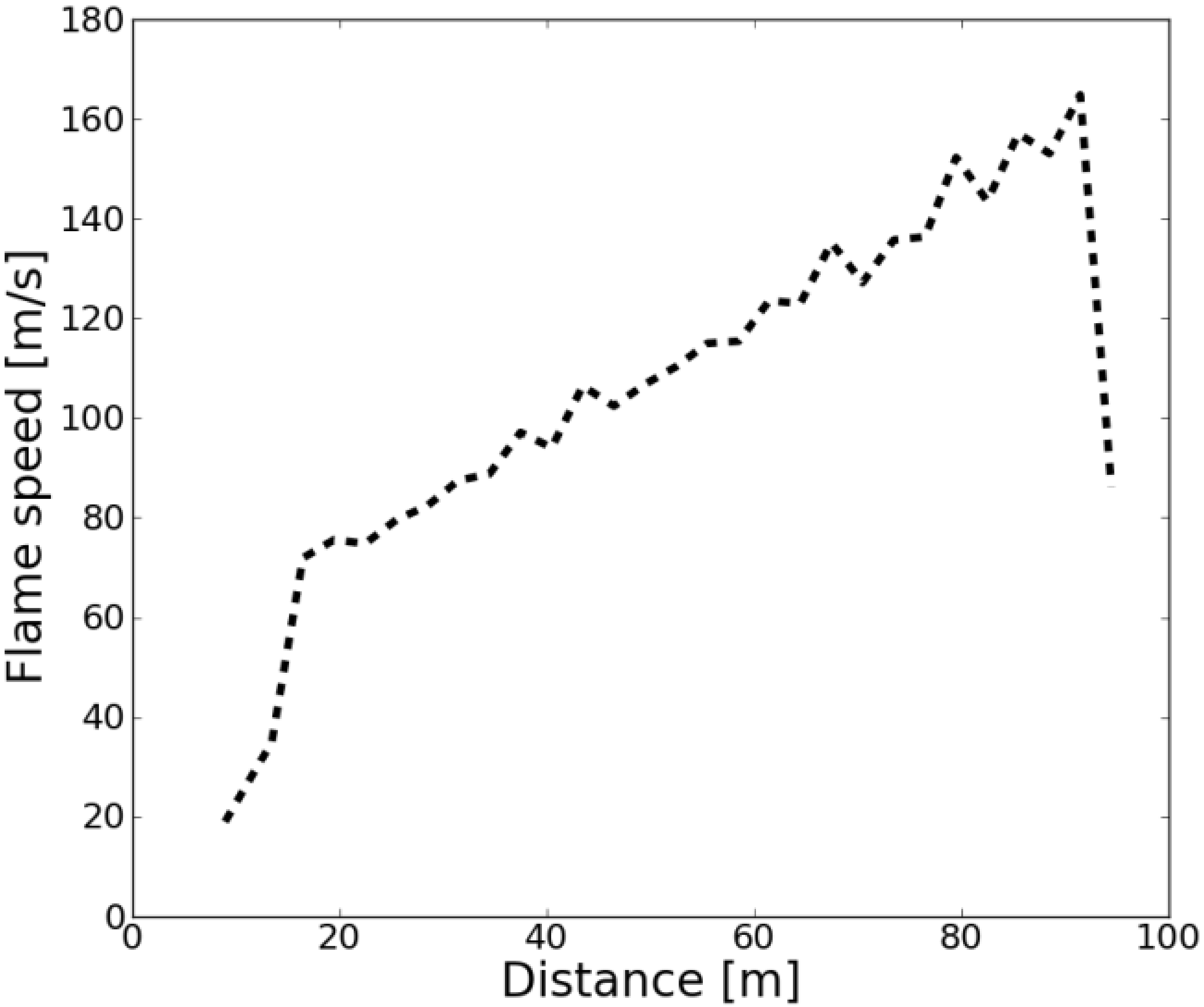
Attempts to investigate the boundary between steady flame propagation and runaway yielded:

- 6 tests with steady flame speed <150 m/s
- 2 tests with flame speeds increasing in a quasi-exponential manner – followed by DDT
- No tests with steady flame propagation flames speeds >150 m/s

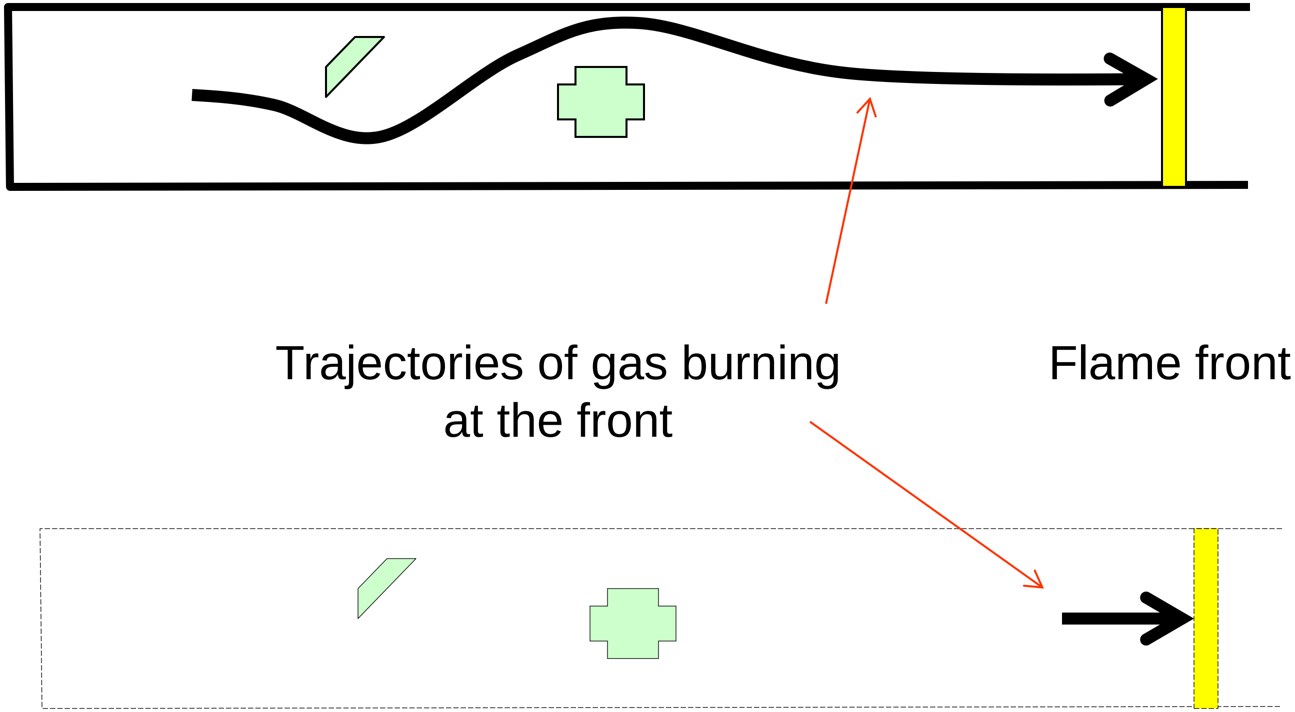
Challenge:

Predict whether flames in a given linear array will runaway and (if they do not) what the steady flame speed will be.

Are existing CFD explosion models suitable?



Problem 1: Flow history of unburned gas



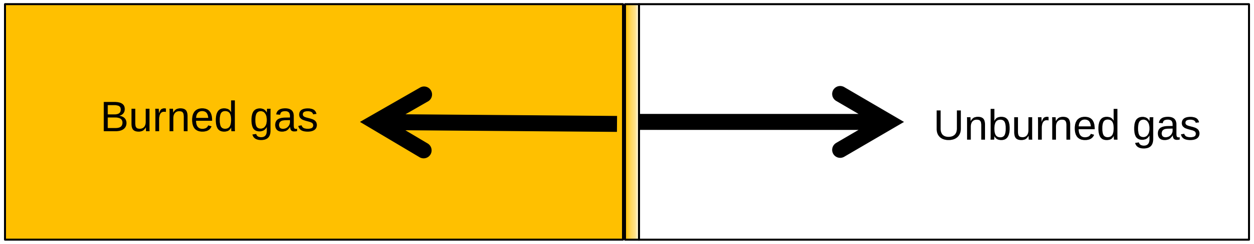
Confined linear array

Open linear array

Trajectories of gas burning at the front

Flame front

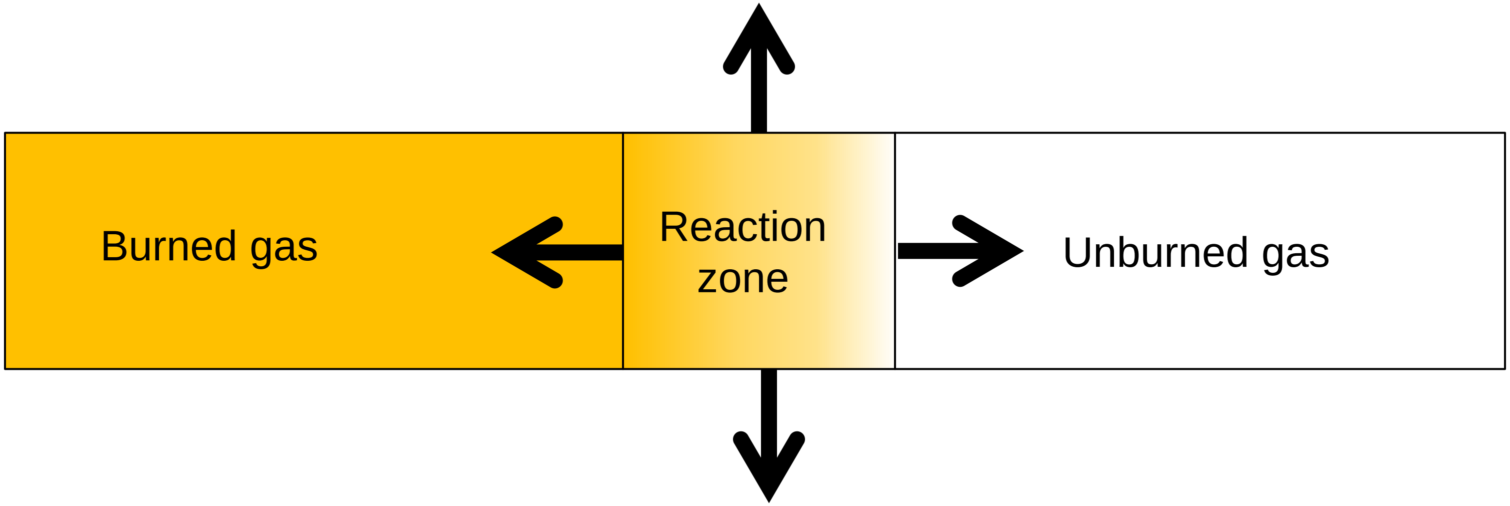
Problem 2: Side venting



Burned gas

Unburned gas

Narrow combustion zone



Burned gas

Reaction zone

Unburned gas

Wide combustion zone – forward flow of unburned gas and turbulence generation is reduced

Typical experimental finding :

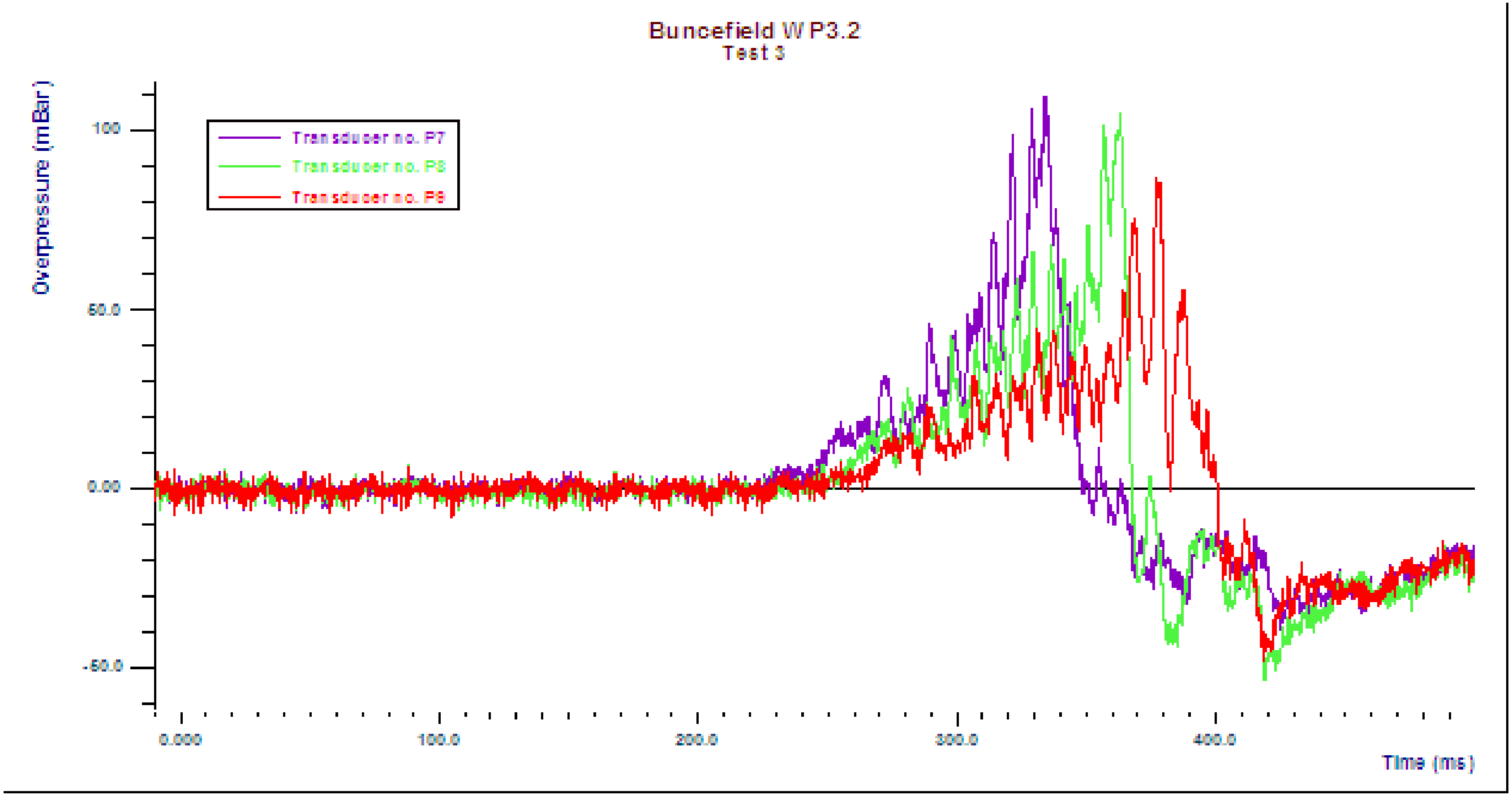
Flame speed in 1m wide array	65 m/s
Flame speed in 2m wide array	115 m/s

(Similar obstacles and arrangement)

Potential CFD approach

“The numerical flame is artificially thickened, i.e. typically 3-5 control volumes…”

Typical pressure variation - Flame speed around 100 m/s



A first step: fix the burning velocity

$$E = E_0 \left(\frac{P_u}{P_b} \right)^{\frac{1}{\gamma}}$$

Pre-compression of unburned gas increases expansion ratio across the flame

$$\left(\frac{\rho_u}{\rho_0} \right) = \left(\frac{P_u}{P_0} \right)^{\frac{1}{\gamma}}$$

$$P_u - P_b = (E-1).\rho_u S_u^2$$

Momentum conservation across the flame front

$$P_u - P_0 = f\,(P_u - P_b)$$

f approximately 1

$$S_u = S_u^{ref}.\,(P_u / P^{ref})^{0.347}$$

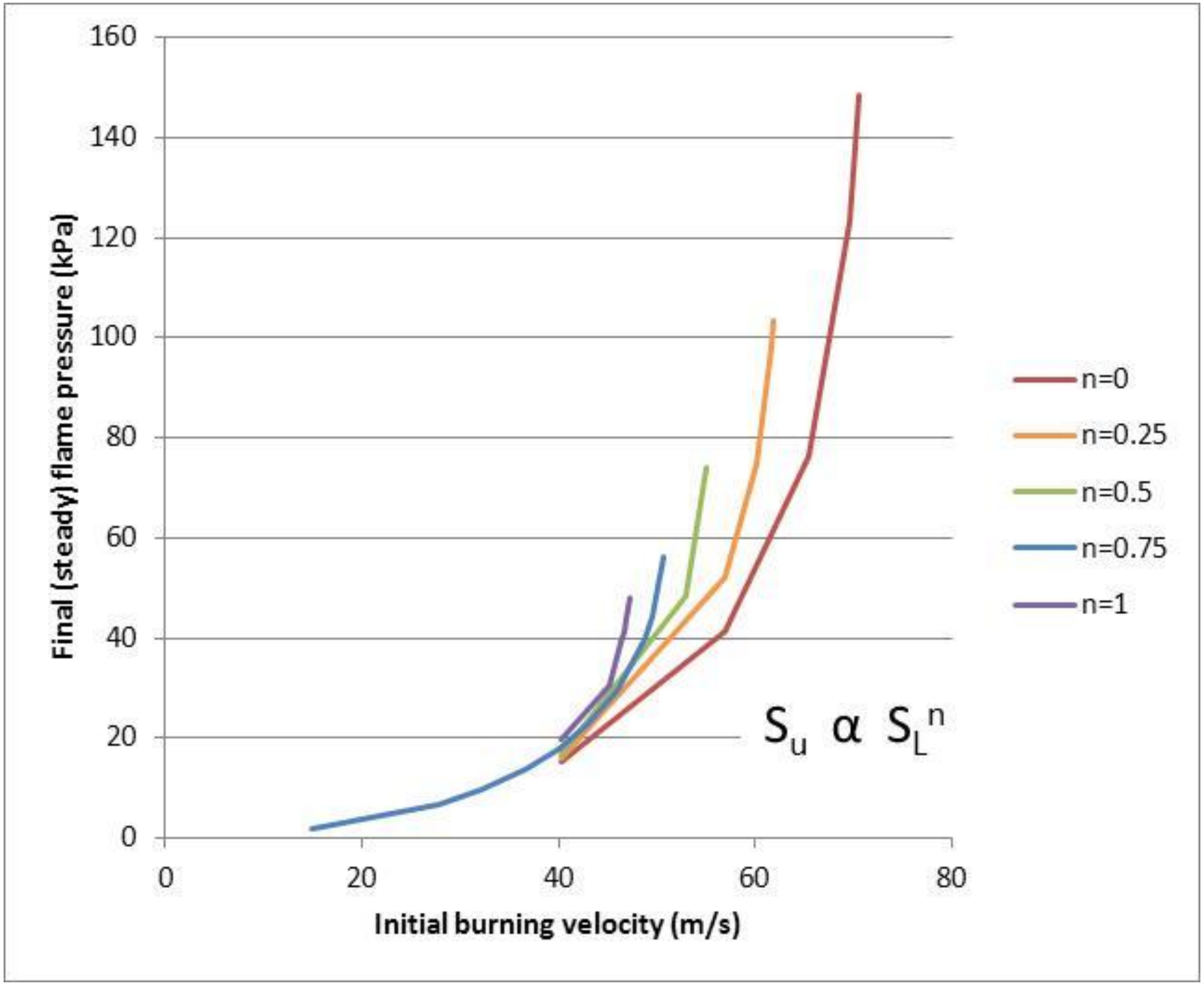
For propane – Assuming S_u proportional to $S_L^{0.75}$

$$S_u = S_u^{ref}.\,(P_u / P^{ref})^{0.0645}$$

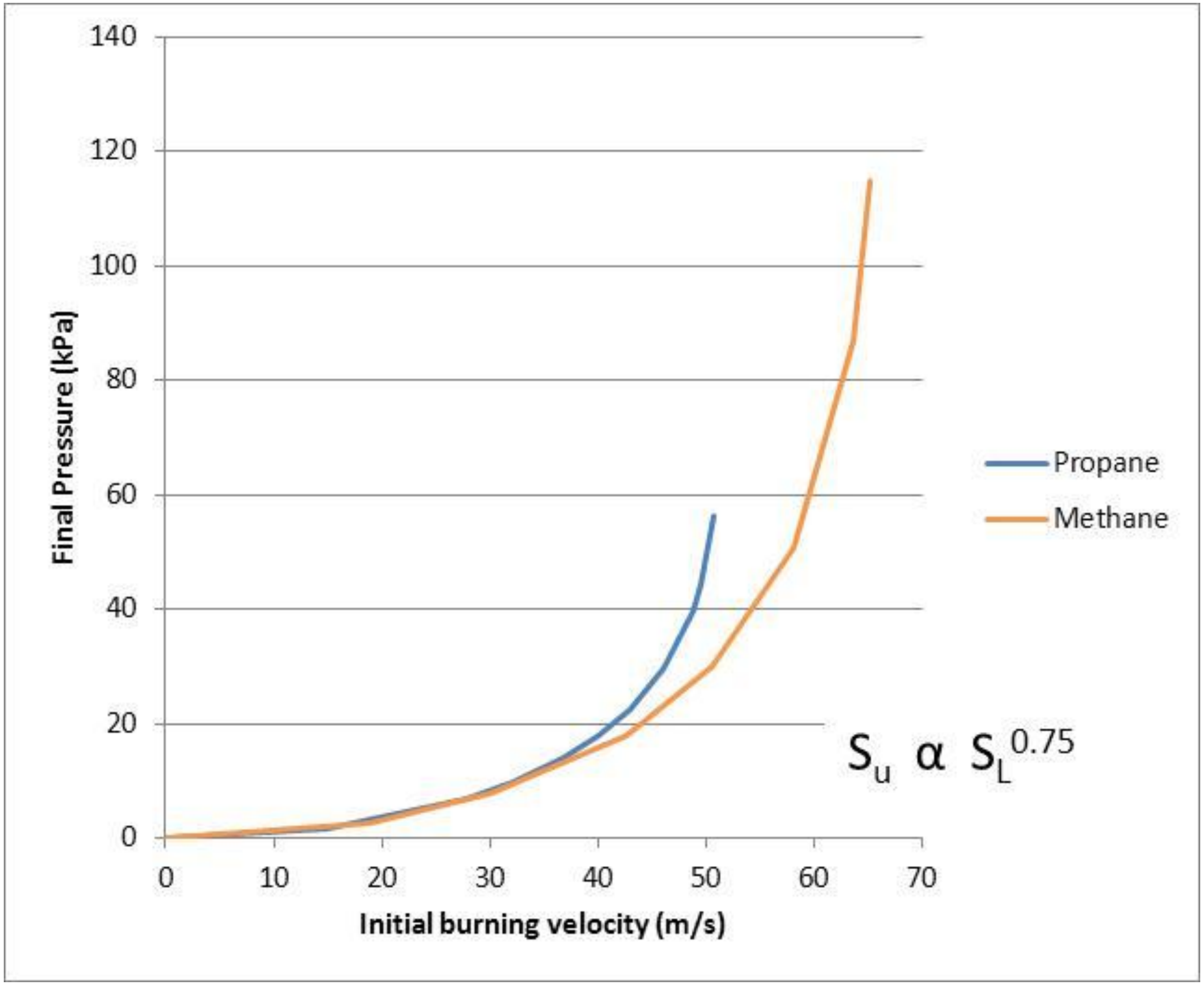
For methane – Assuming S_u proportional to $S_L^{0.75}$

Variation of laminar flame speed during adiabatic compression from: Poinsot and Veynante "Theoretical and Numerical **Combustion"**, 2nd Edition

Possible solutions for pressure in a steady flame

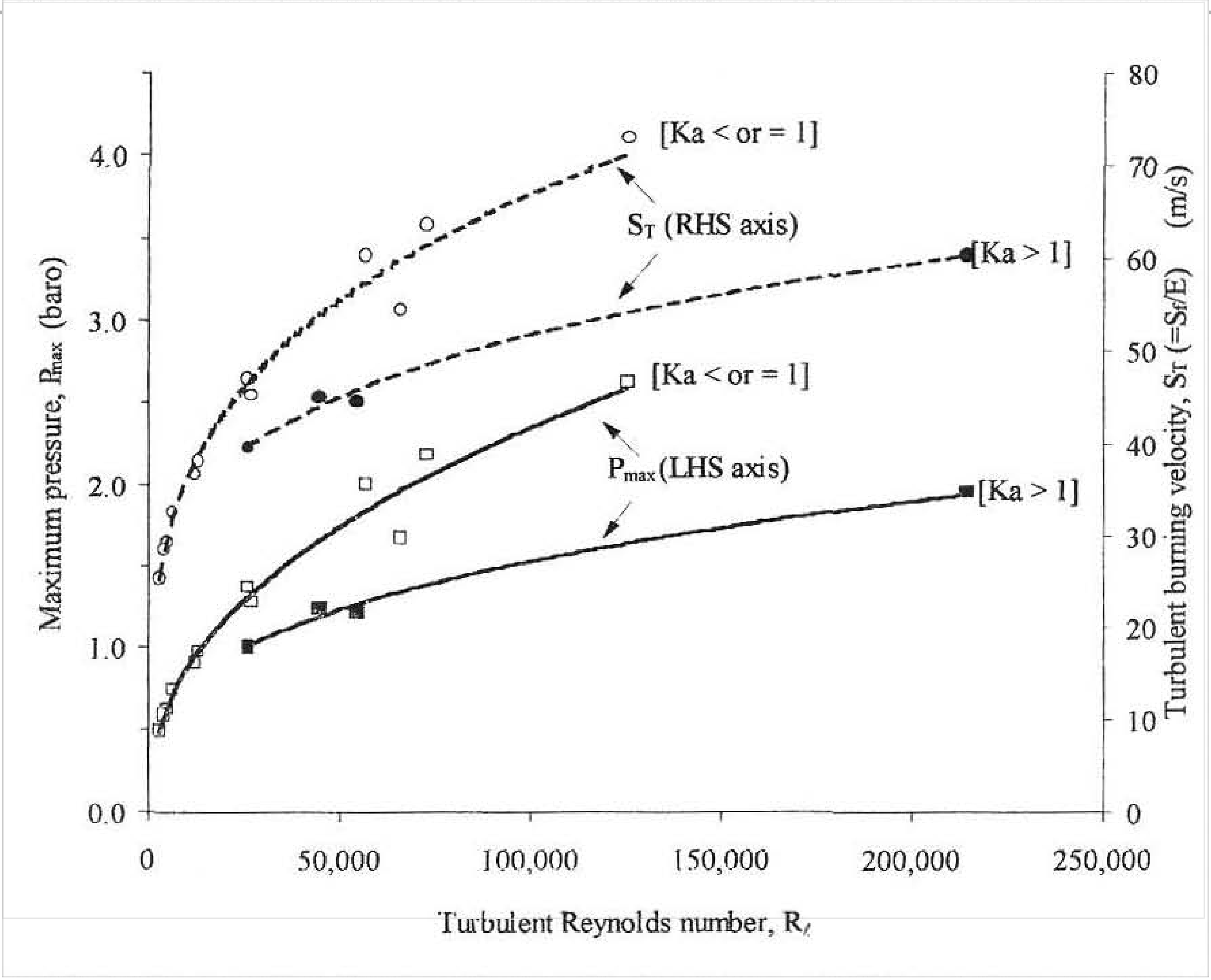


How does sensitivity of laminar flame speed to adiabatic compression affect the possibility of steady flame propagation ?



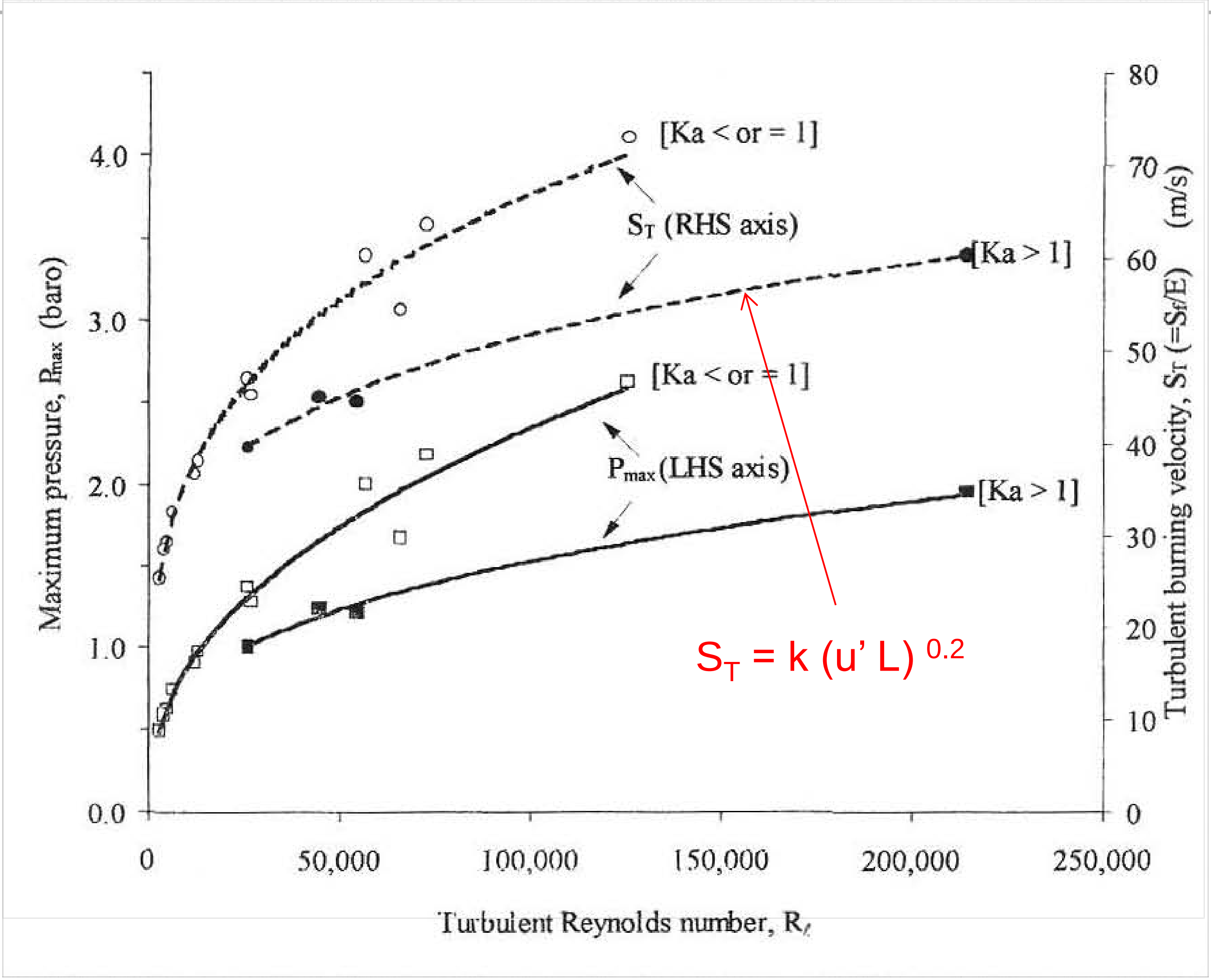
$S_u \propto S_L^{0.75}$

Step 2 (very much more difficult): Linking burning velocity back to the flow field in a developing explosion



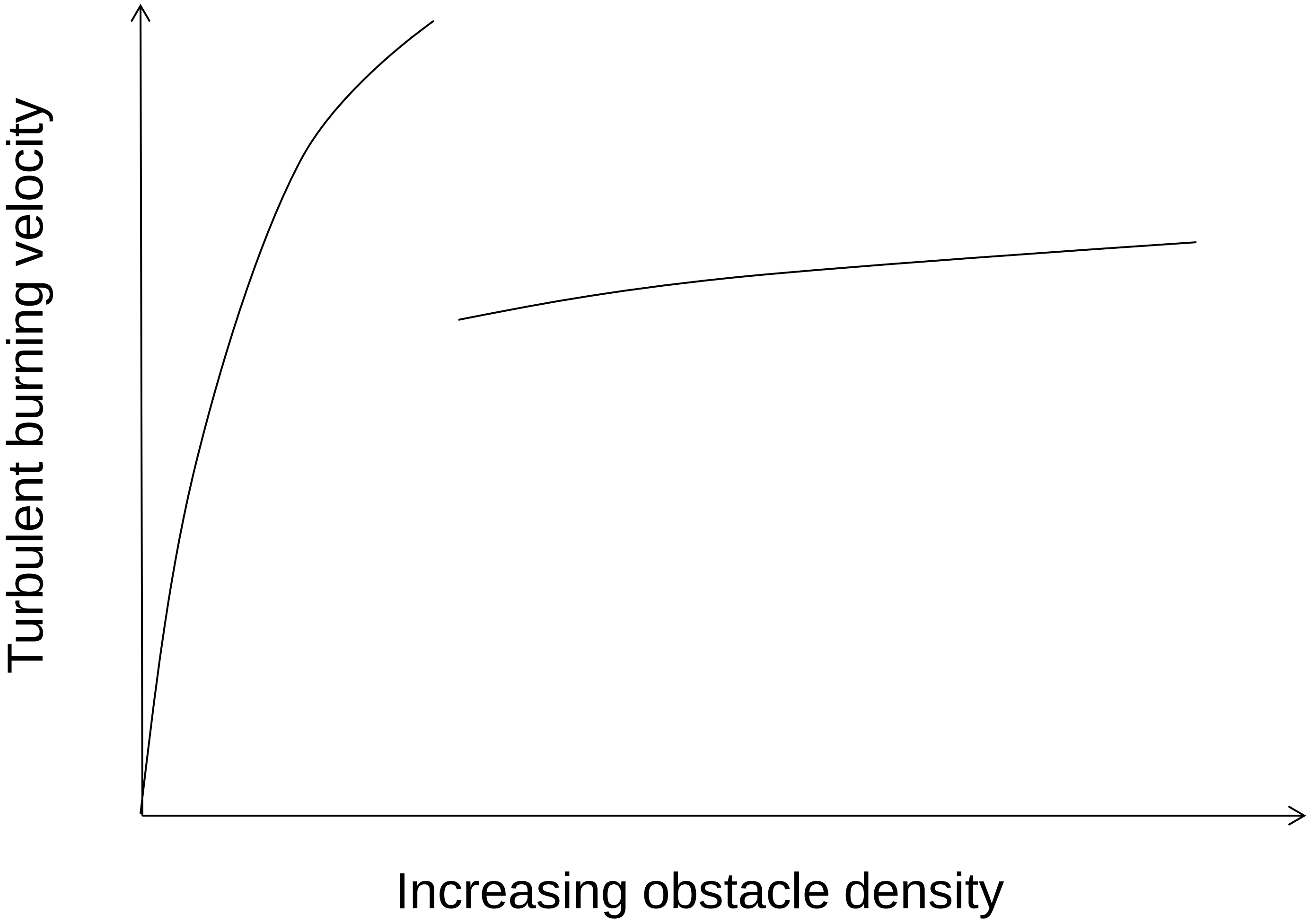
Gardner, Phylaktou and Andrews – IChemE Symposium Series No. 144

Step 2 (very much more difficult): Linking burning velocity back to the flow field in a developing explosion

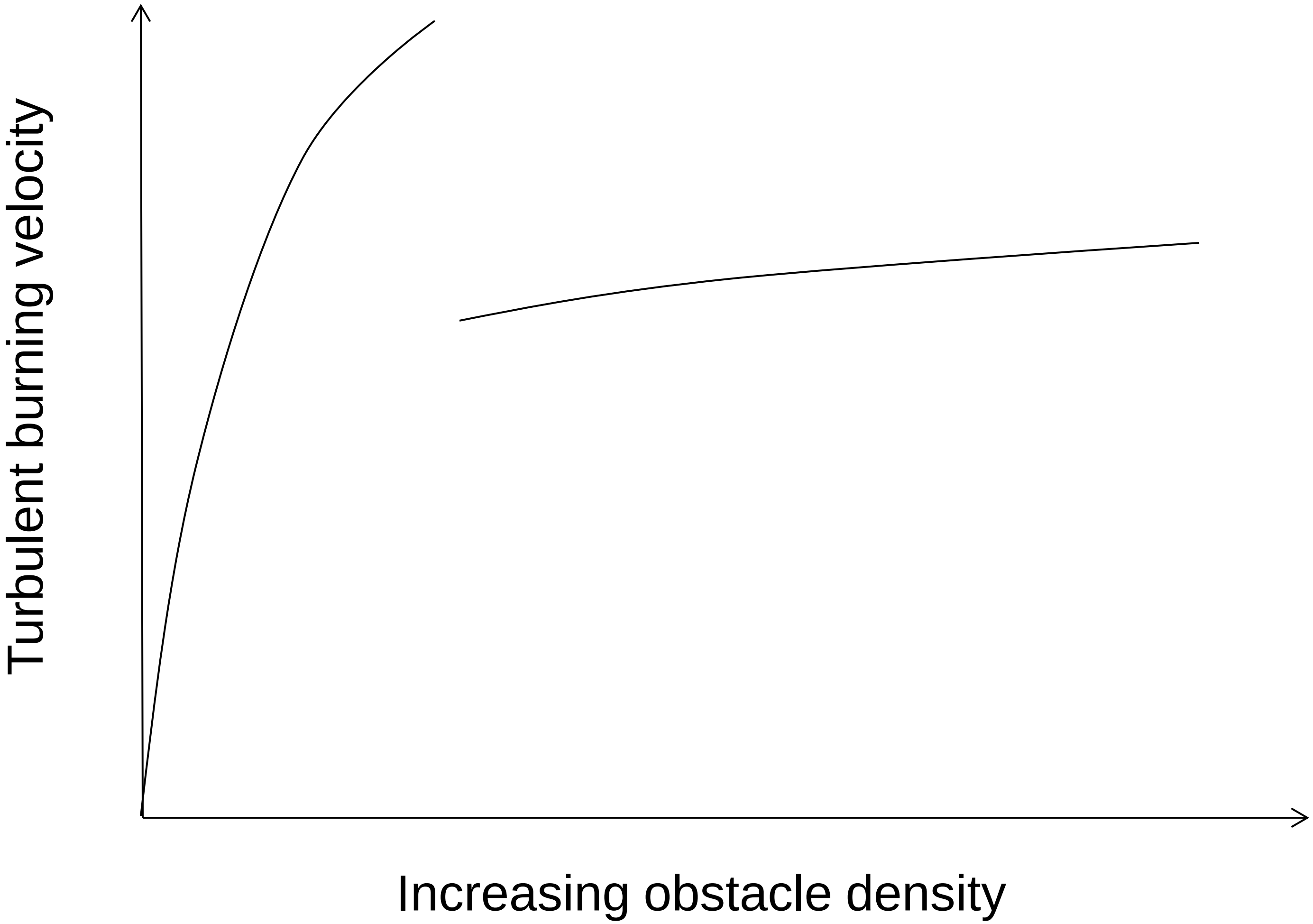


$S_T = k\,(u'\,L)^{0.2}$

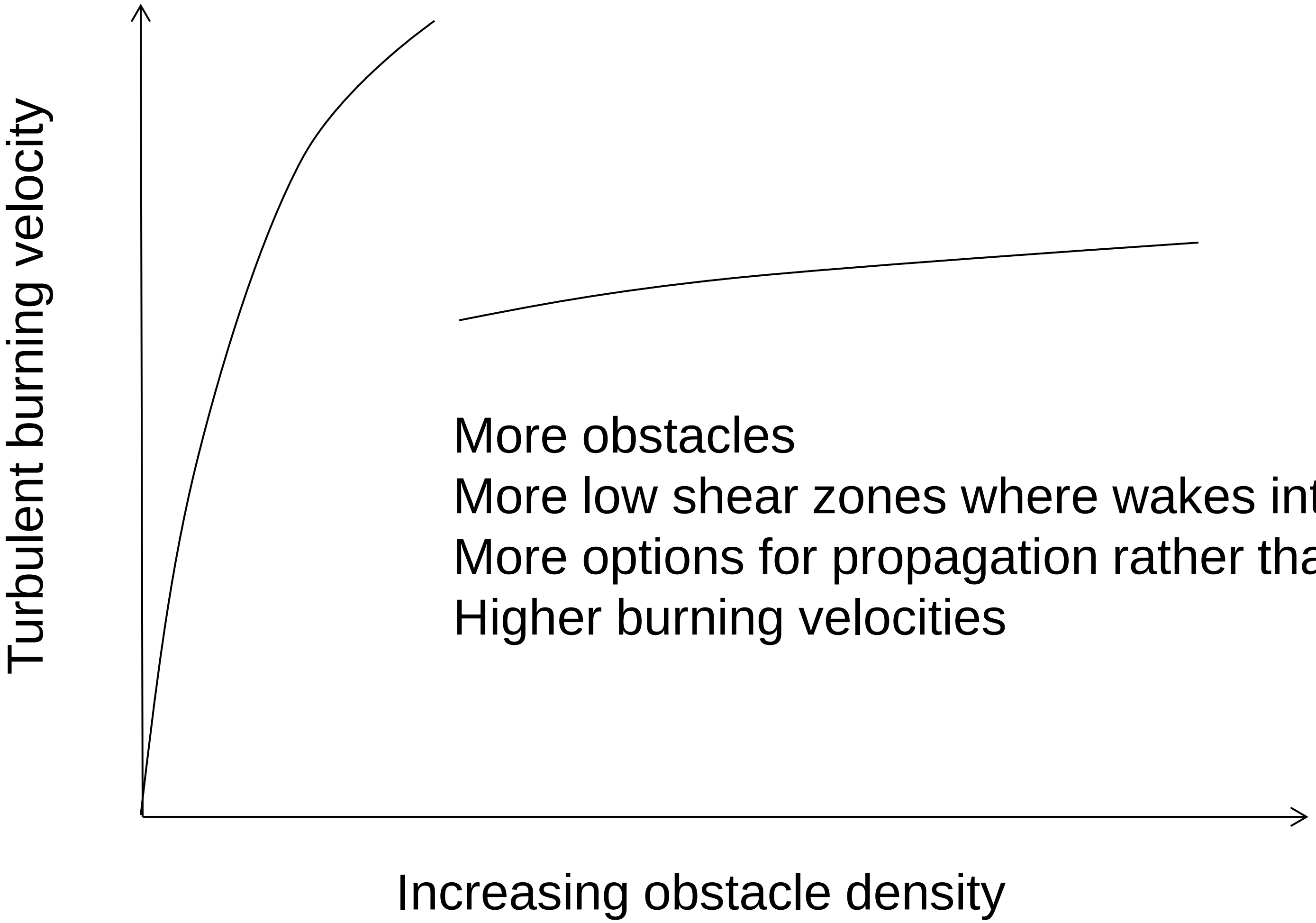
Gardner, Phylaktou and Andrews – IChemE Symposium Series No. 144


Turbulent burning velocity
Increasing obstacle density

More obstacles
Higher general turbulence levels
Higher burning velocities

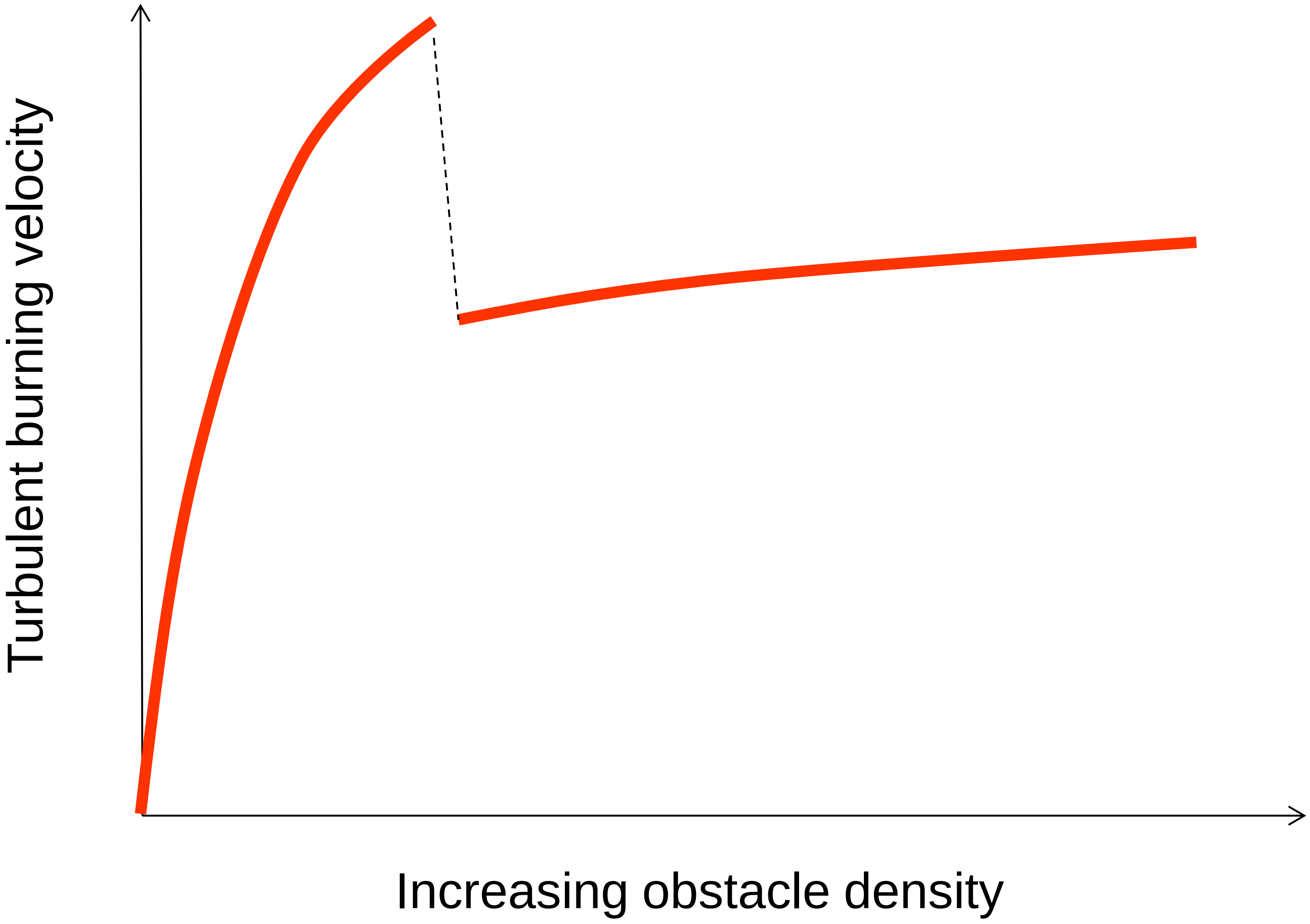


More obstacles
Higher general turbulence levels
Higher burning velocities

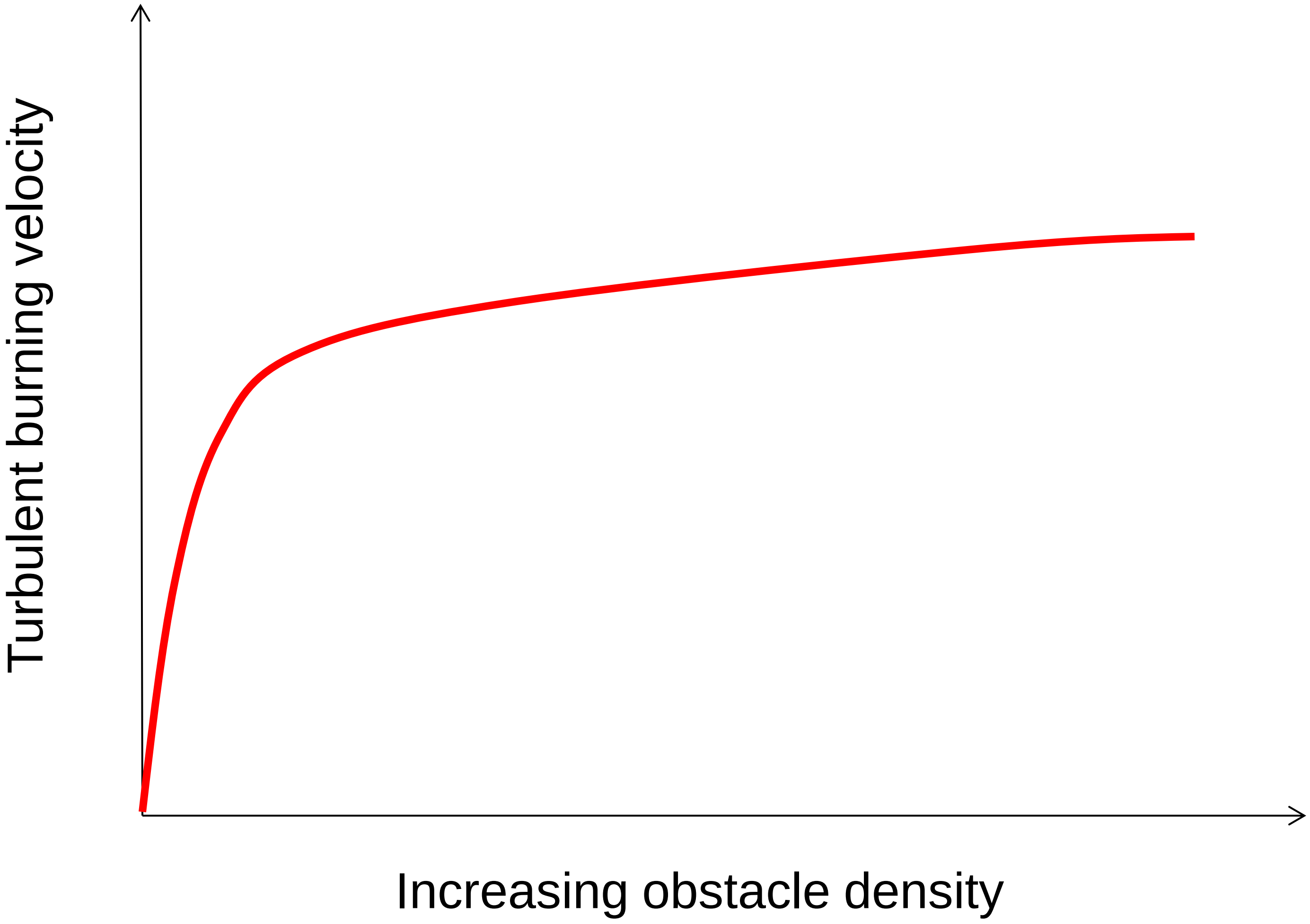


More obstacles
More low shear zones where wakes interact
More options for propagation rather than extinction
Higher burning velocities

Unburned gas flow externally driven



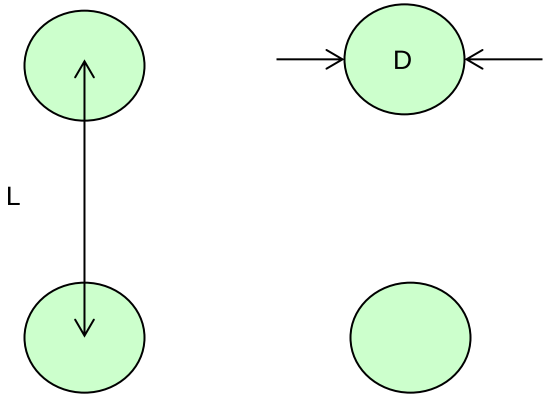
Explosion propagating in the open



Specification of burning velocity

$Su = 29.5\,(u')^{0.2}$

$u'/U_o = 0.7\,ABR$



ABR is the area blockage ratio (D/L) of the equivalent regular array of right circular cylinders

For an array with a range of sizes measureable quantities are Volume Blockage Ratio VBR and Area Blockage Density ABD (m2/m3)

D/L is calculated as $D/L = (4\,.VBR / \pi)^{1/2}$ (Note $ABD = D / L^2$)

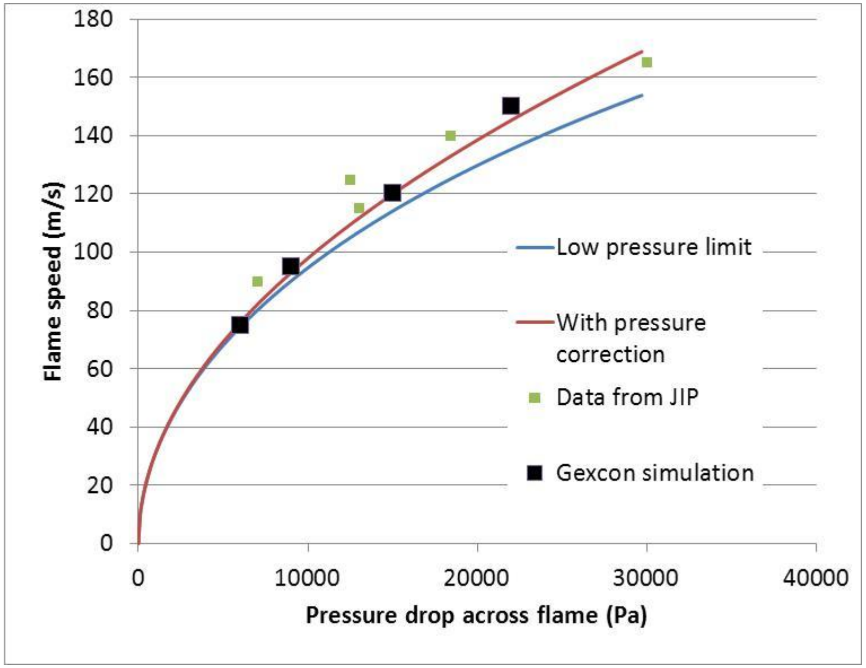
Flame speed

$$V_f = S_u\left(\sqrt{E}\right)$$

$$V_f = \left[\left(\frac{P}{P_0}\right)^{\frac{1}{2\gamma}}.\sqrt{E}\right]S_u$$

Low pressures

Moderate pressures (<400 mbar)



Forward flow of unburned gas (thin flame)

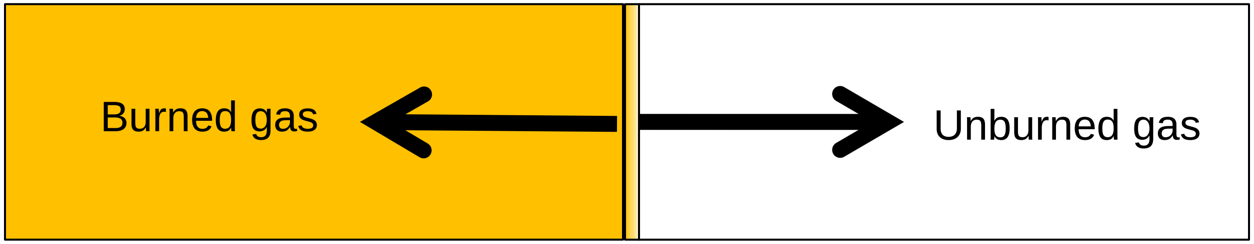
$$U_0 = S_u\left(\sqrt{E}-1\right)$$

$$U_0 \approx \left[\left(\frac{P}{P_0}\right)^{\frac{1}{2\gamma}}.\sqrt{E}-1\right]S_u$$

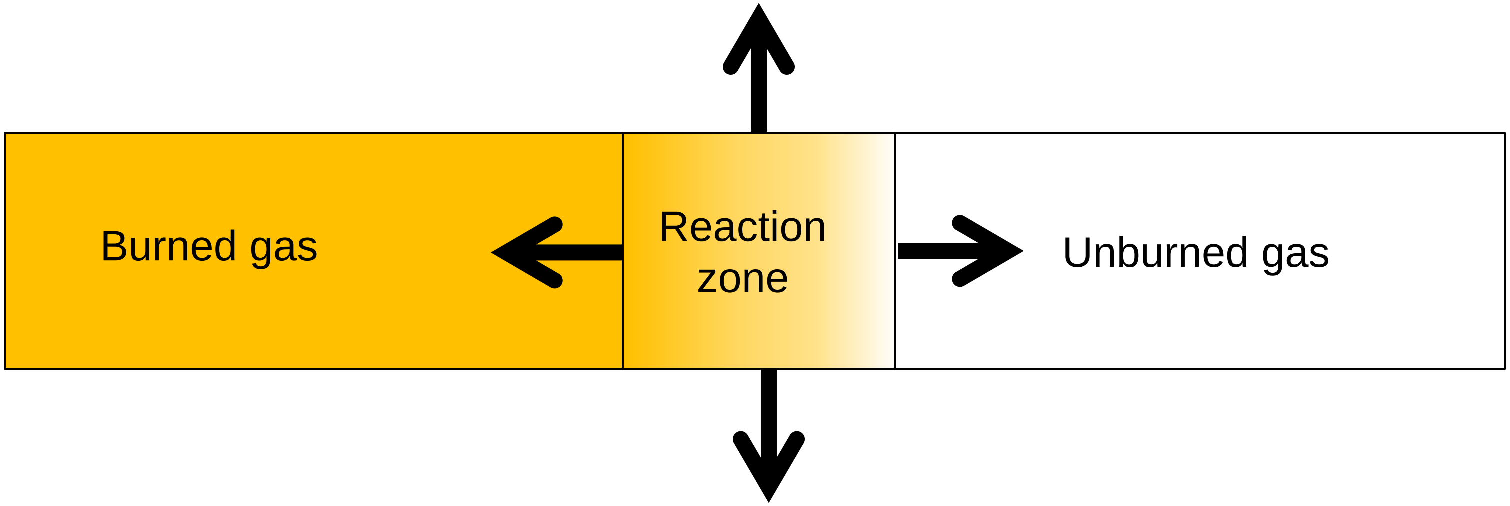
Low pressures

Moderate pressures (<400 mbar)

Flows driven by expansion during combustion

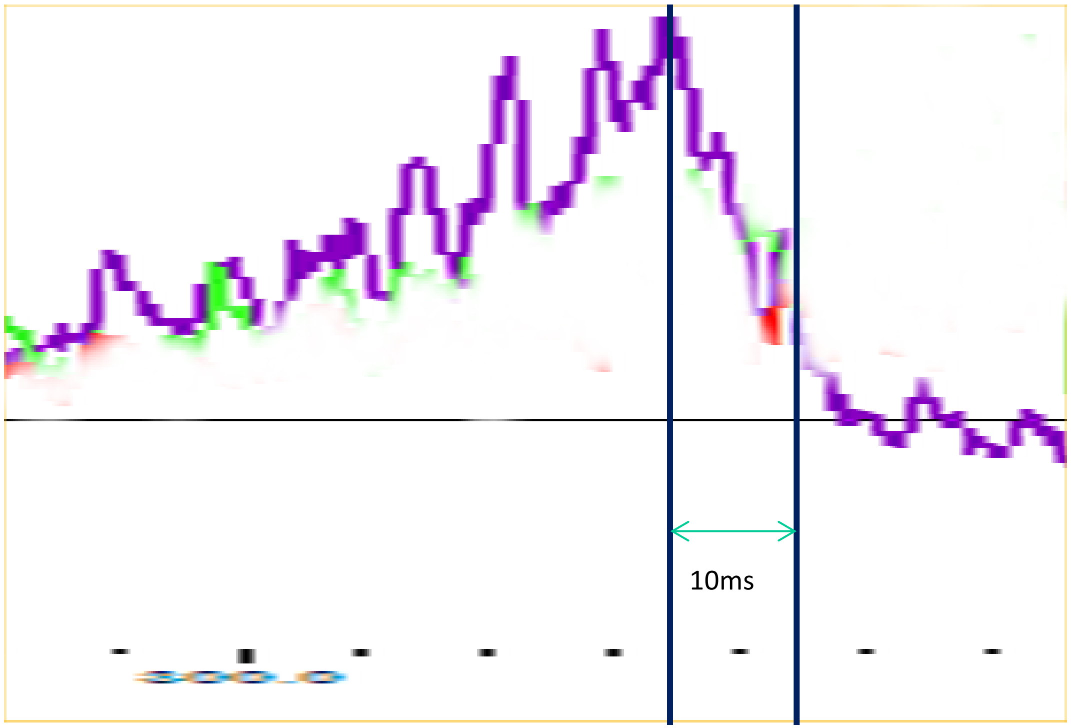


Narrow combustion zone



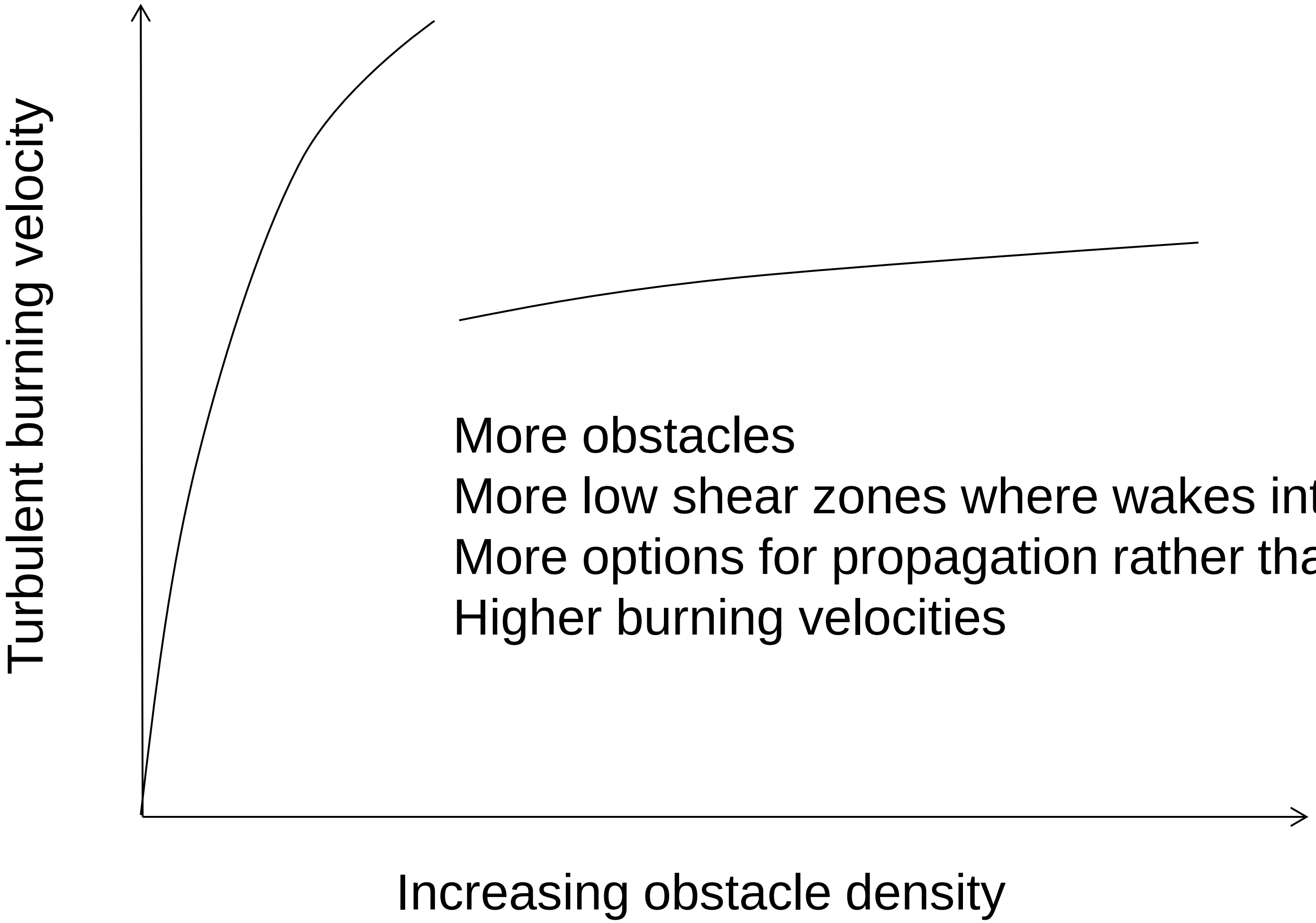
Wide combustion zone – forward flow of unburned gas and turbulence generation is reduced

Thickness of reaction zone



Distance over which pressure drops suggests thickness of RZ is 1.5m in this case

More obstacles
Higher general turbulence levels
Higher burning velocities



More obstacles
More low shear zones where wakes interact
More options for propagation rather than extinction
Higher burning velocities

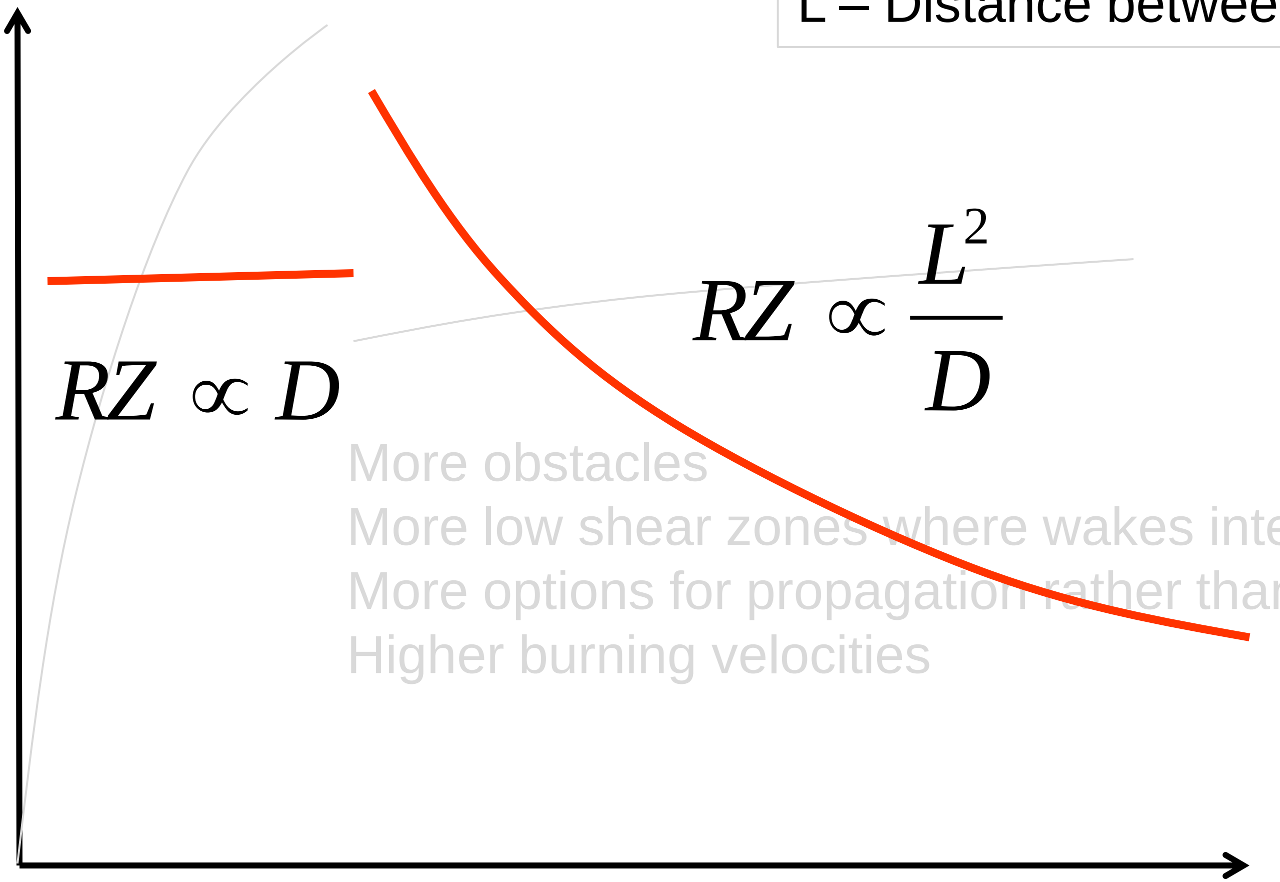
More obstacles
Higher general turbulence levels
Higher burning velocities

Regular arrays

D – Obstacle diameter
L – Distance between obstacles

Turbulent burning velocity

Thickness of reaction zone



$$RZ \propto D$$

$$RZ \propto \frac{L^2}{D}$$

More obstacles
More low shear zones where wakes interact
More options for propagation rather than extinction
Higher burning velocities

Increasing obstacle density

Small L

Why $RZ \propto \frac{L^2}{D}$?

$$\frac{L^2}{D}$$

It is 1/ ABD (area blockage density m^2/m^3)

Average distance travelled along a stream line between obstacles

A good measure of the prevalence of wake overlap

Why $RZ \propto \frac{L^2}{D}$?

$$\frac{L^2}{D}$$

Is 1/ ABD (area blockage density m^2/m^3)

Average distance travelled along a stream line between obstacles

A good measure of the prevalence of wake overlap

Other methods of calculating RZ will be required for other types of obstruction e.g. widely spaced grids

Assumptions about reaction zone thickness

RZ proportional to 1 /ABD

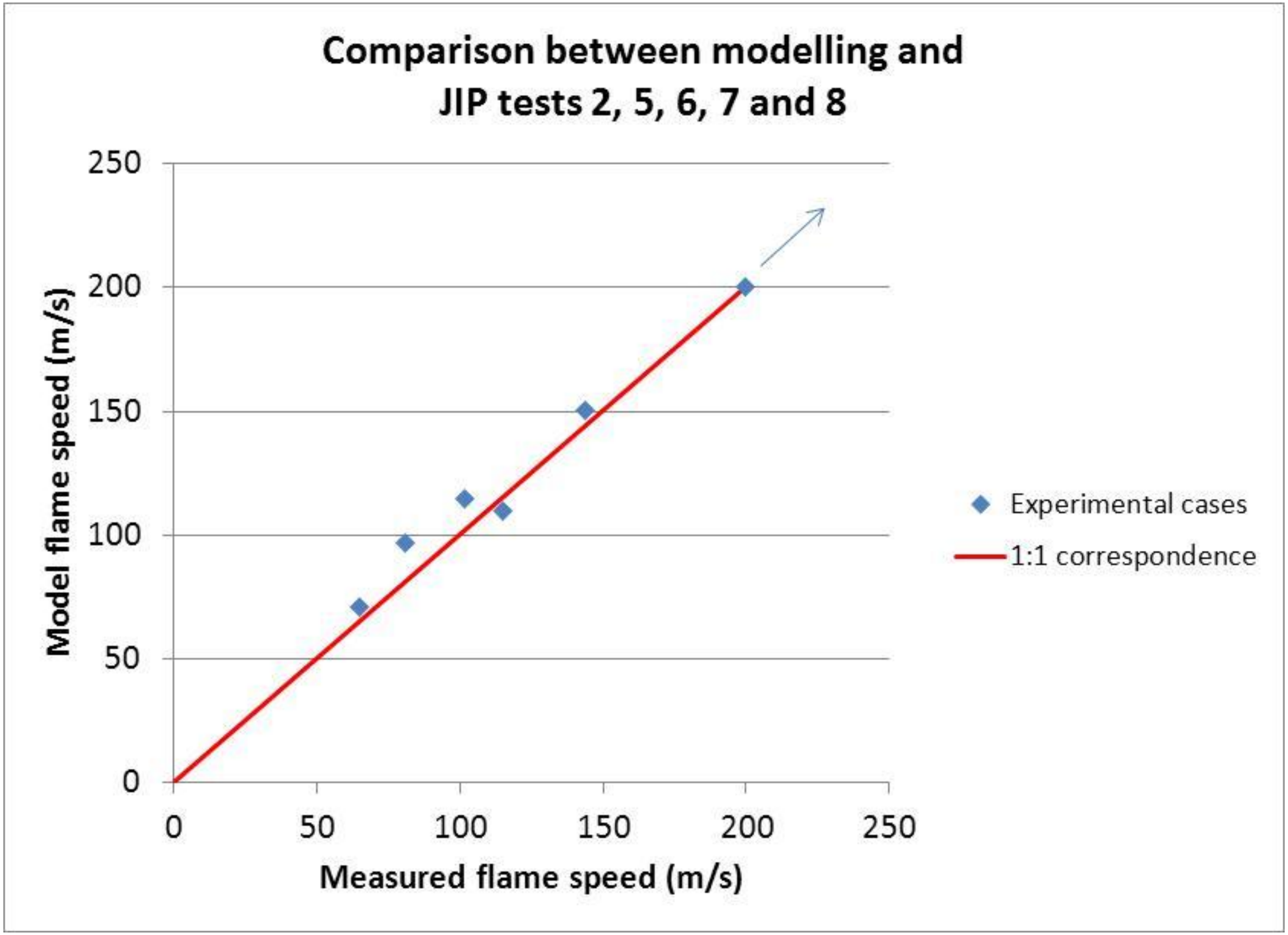
Also expect RZ to be shortened by any increase in fundamental burning rate linked to increased pressure.

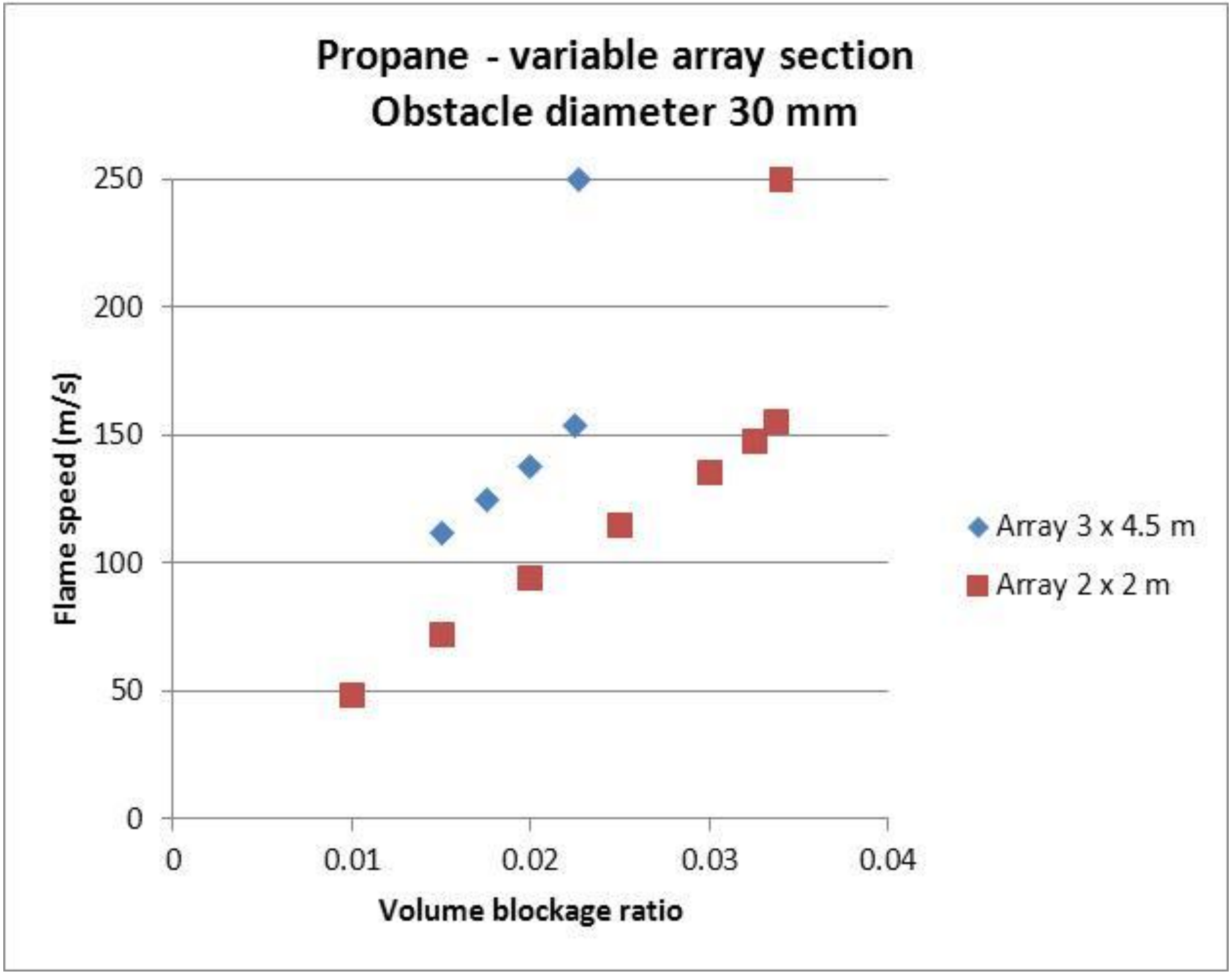
Allowing for side (and top) venting

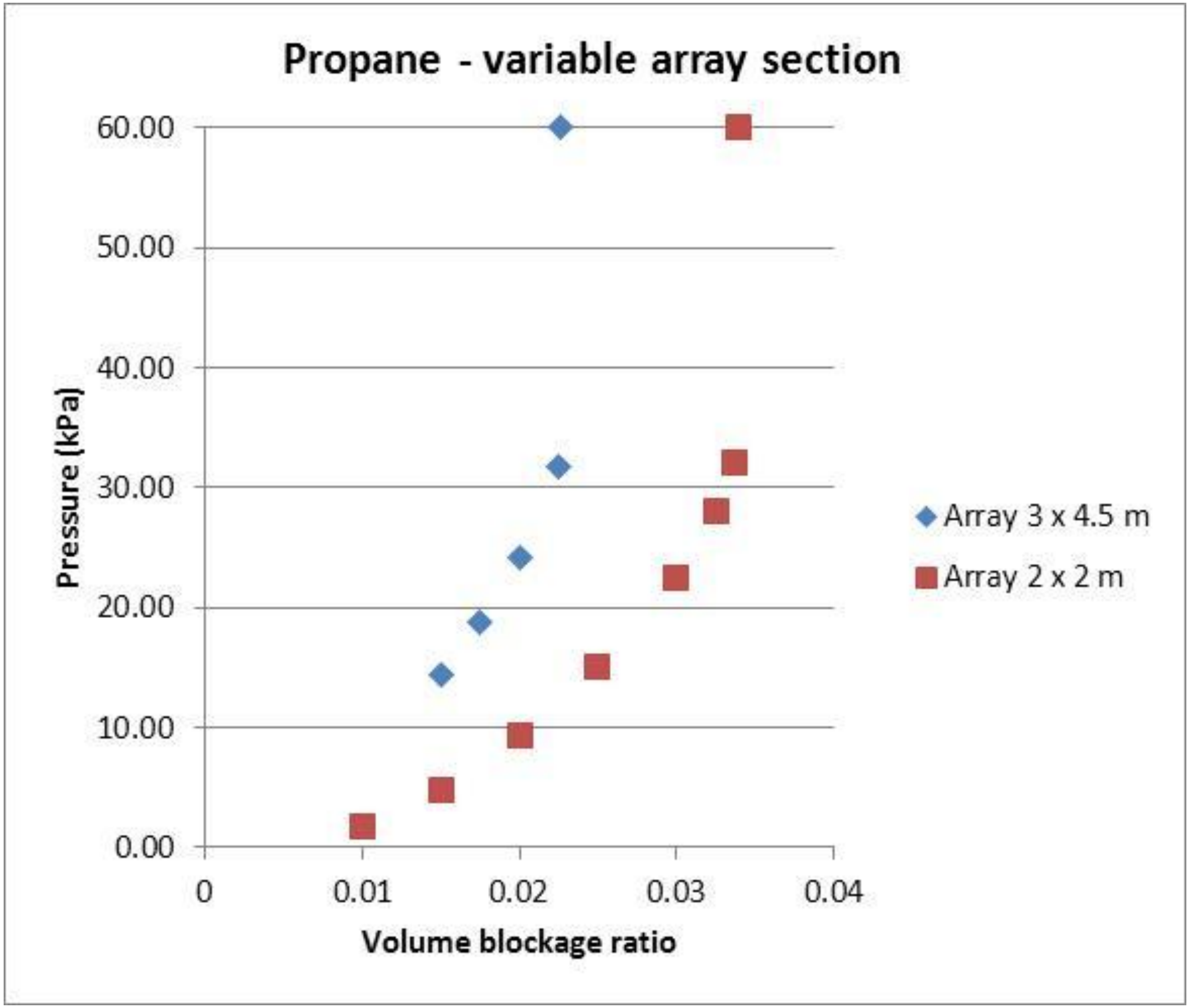
1. Reaction zone assumed to be a cuboid

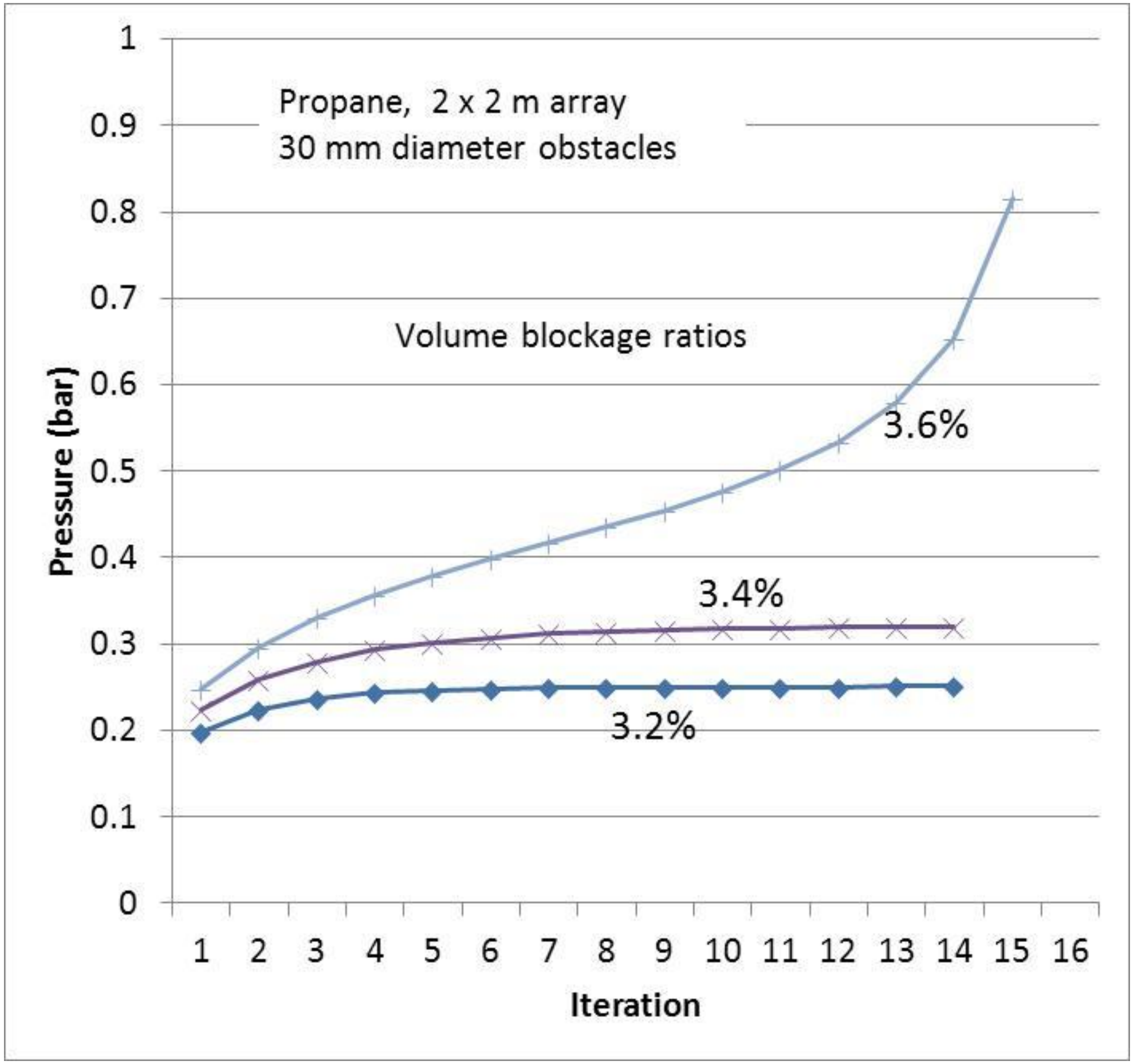
2. Flow through each face of the cuboid is in proportion to the area of each face divided by the average distance (through the congested array) that the outflow has to pass.

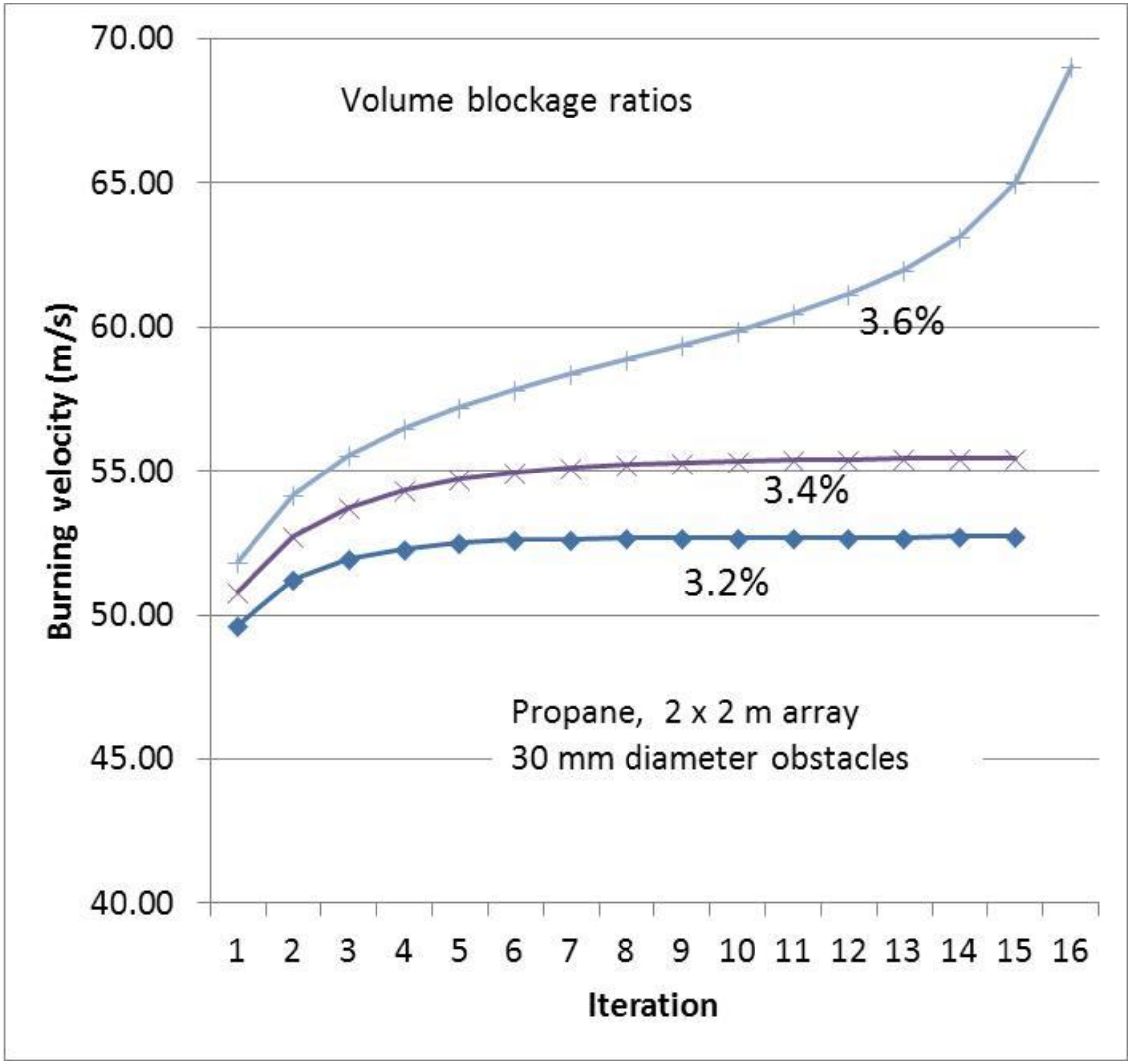
Results of modelling



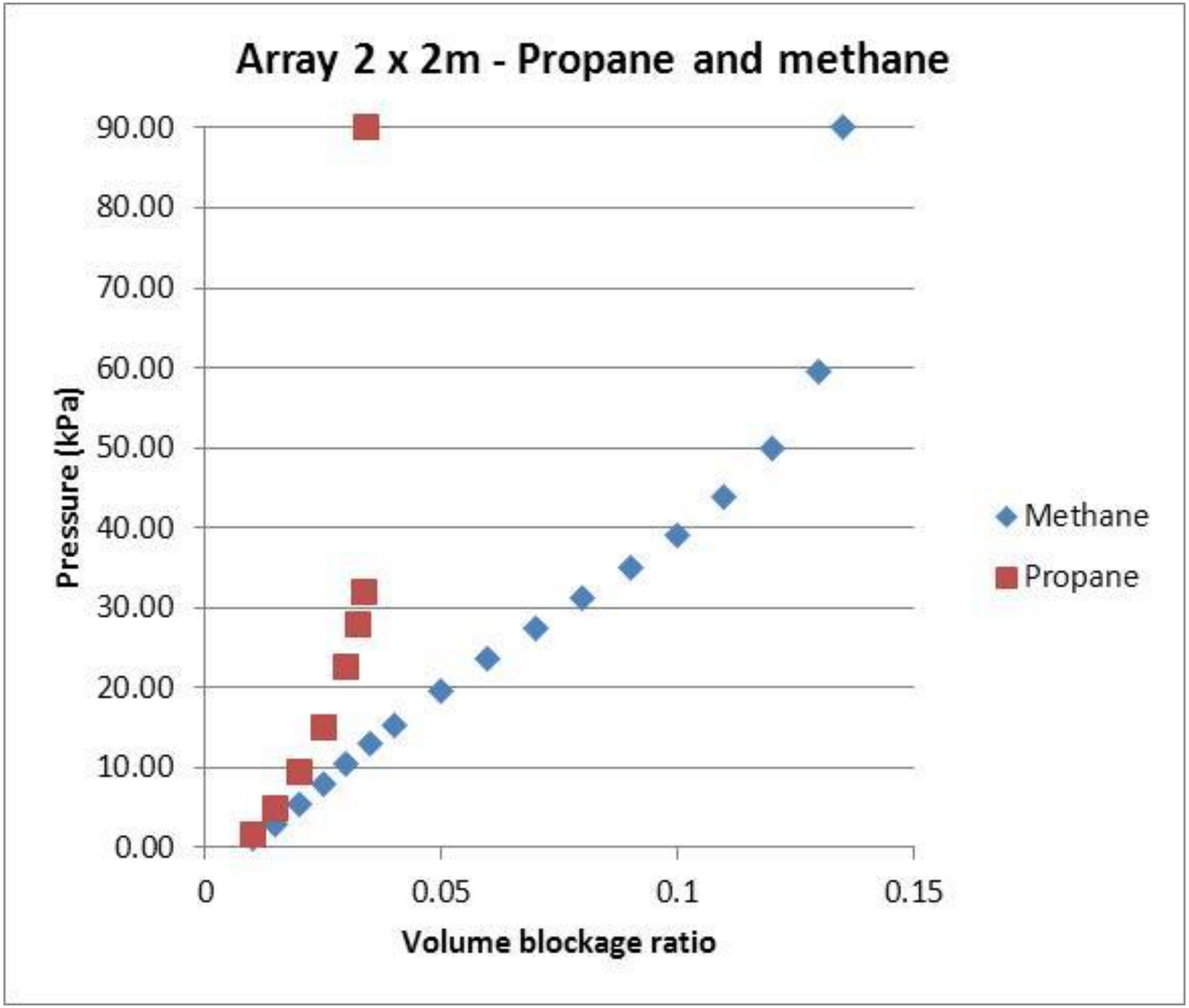

Propane - variable array section
Obstacle diameter 30 mm
Flame speed (m/s)
0
50
100
150
200
250
0
0.01
0.02
0.03
0.04
Volume blockage ratio
◆ Array 3 x 4.5 m
■ Array 2 x 2 m


Propane - variable array section
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Pressure (kPa)
0
0.01
0.02
0.03
0.04
Volume blockage ratio
Array 3 x 4.5 m
Array 2 x 2 m


Propane, 2 x 2 m array
30 mm diameter obstacles
Volume blockage ratios
3.6%
3.4%
3.2%
Pressure (bar)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Iteration
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


Volume blockage ratios
3.6%
3.4%
3.2%
Propane, 2 x 2 m array
30 mm diameter obstacles
Burning velocity (m/s)
70.00
65.00
60.00
55.00
50.00
45.00
40.00
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Iteration

HEALTH & SAFETY LABORATORY



Summary

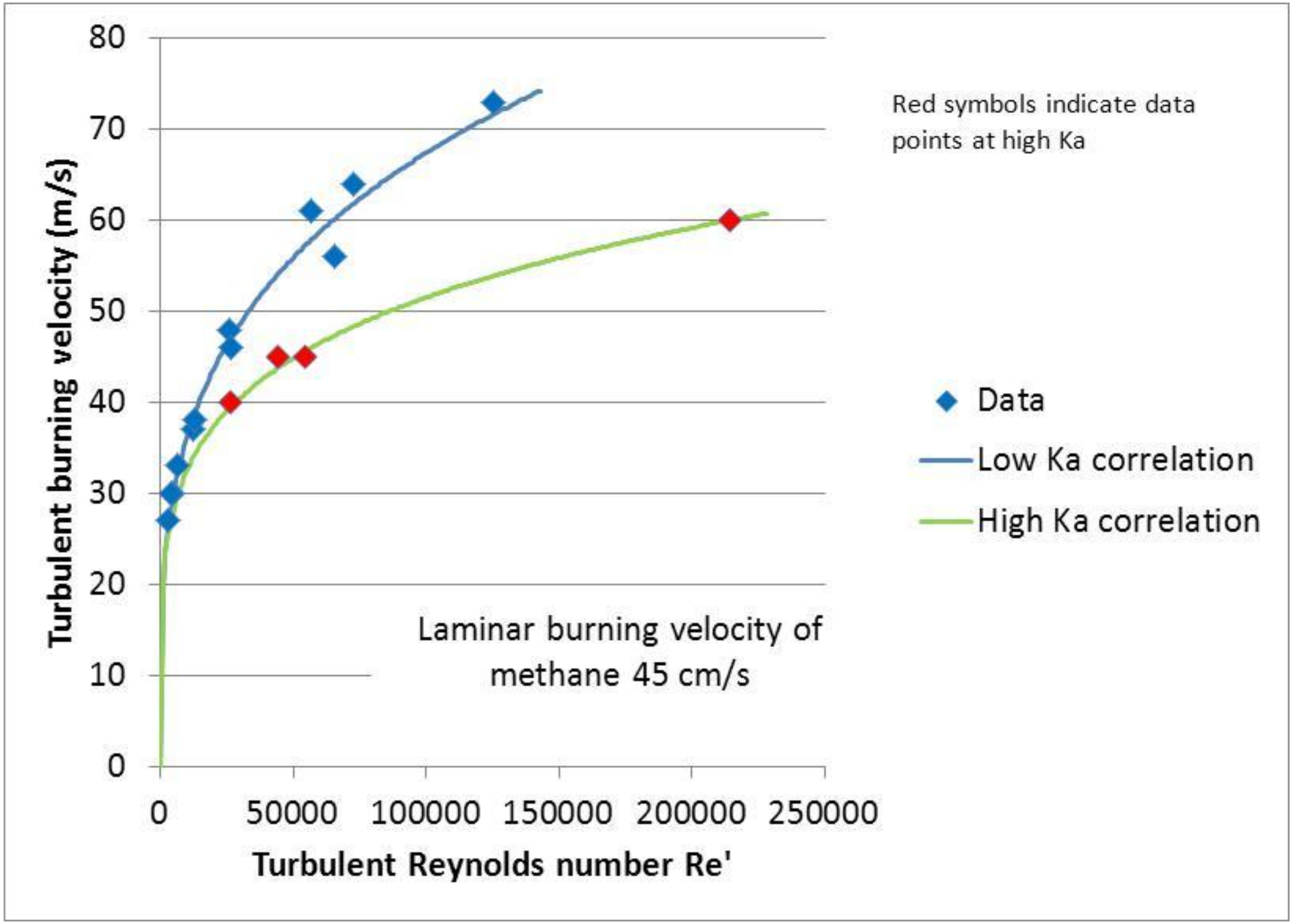
1. Explosions in dense linear arrays rapidly reach a stable sub-sonic speed or run away. Slow build up of flame speed does not occur.

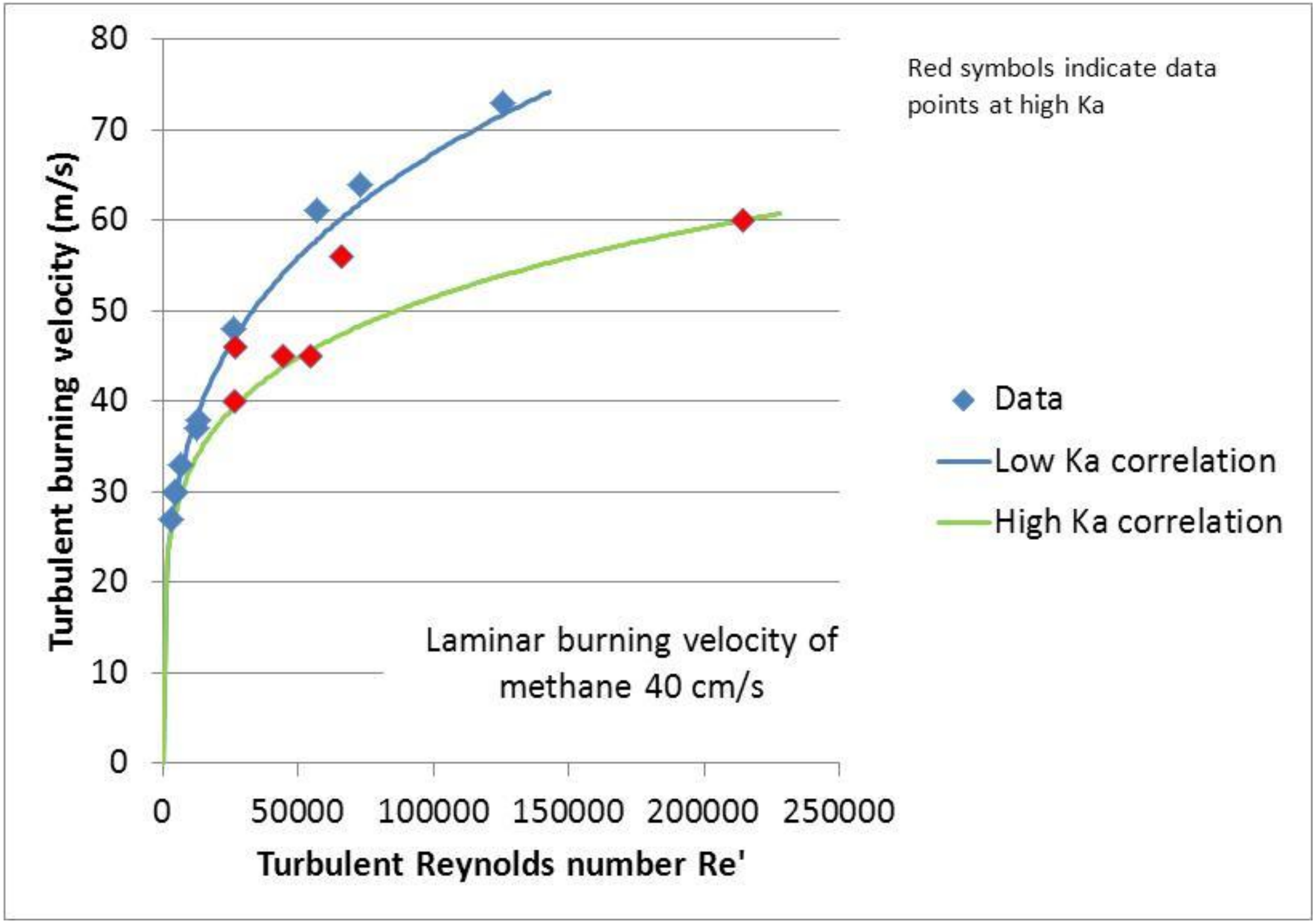
2. Flame speed and pressure for different fuels is affected by laminar flame speed – and especially how this flame speed varies during adiabatic compression.

3. Simple modelling of flame propagation can match both the variation of steady flame speed and the onset of runaway.

4. For near stoichiometric propane and gasoline flames runaway is likely to be followed by DDT. The critical part of any practical assessment may be the prediction of initial runaway. If so, we may not need to understand much about kinetics or the final mechanism of DDT.

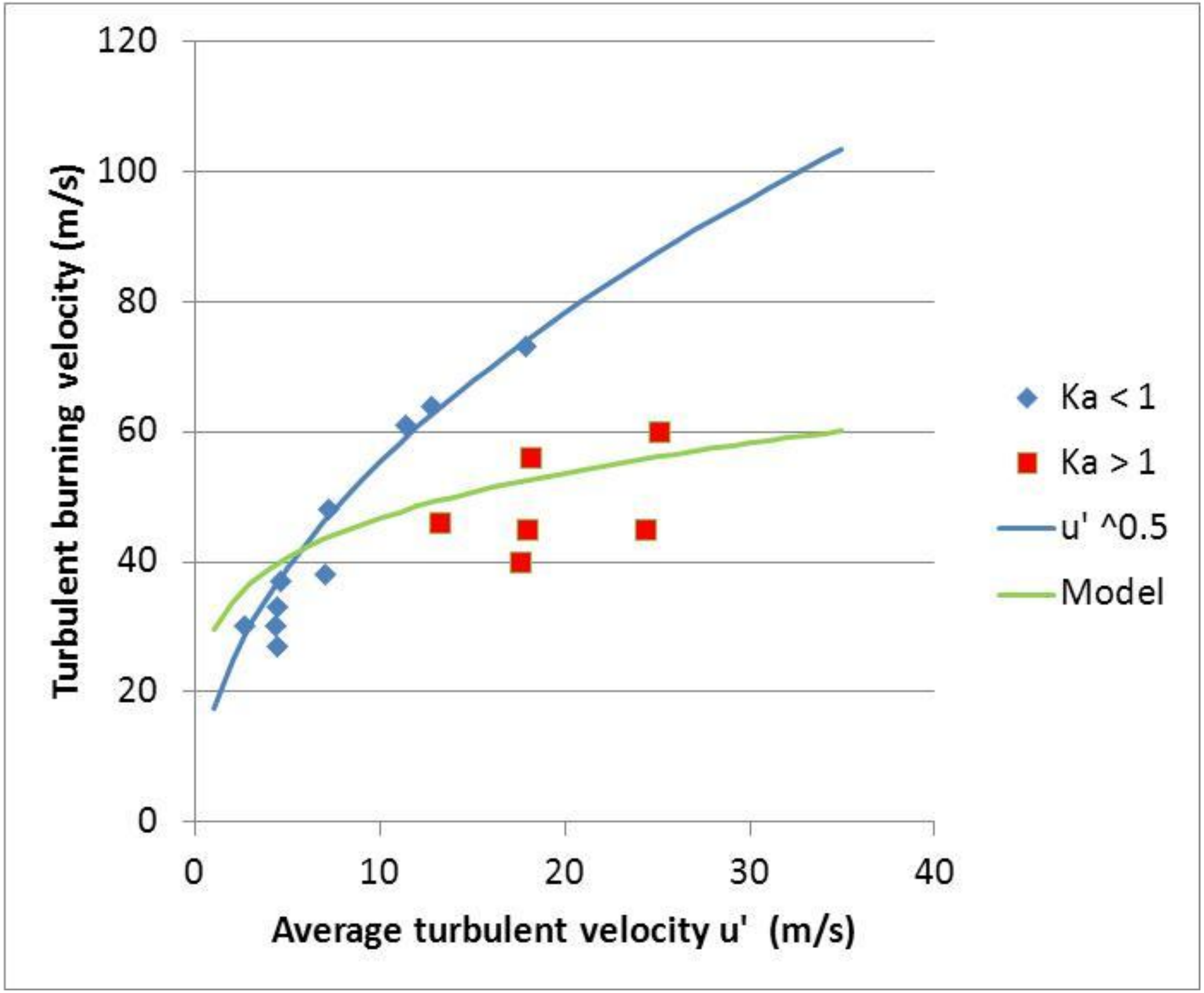
Re-interpretation of Gardner et al’s data



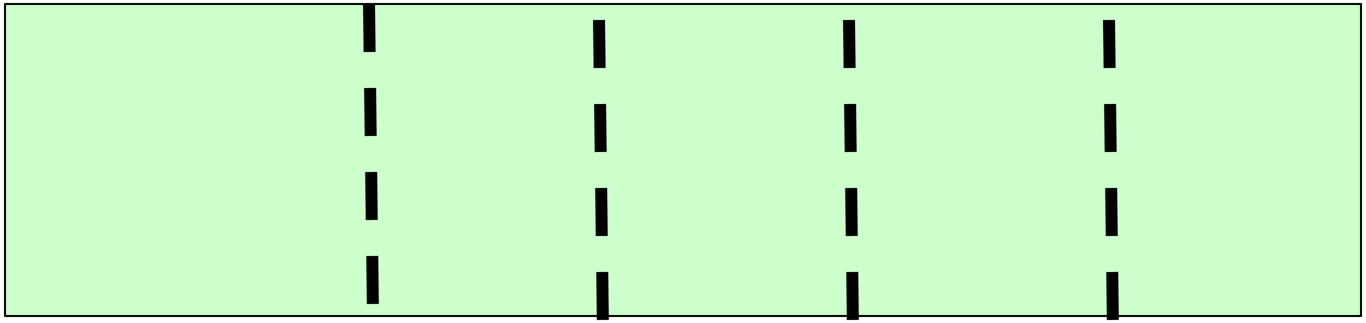


Red symbols indicate data points at high Ka

Laminar burning velocity of methane 40 cm/s


Turbulent burning velocity (m/s)
120
100
80
60
40
20
0
0
10
20
30
40
Average turbulent velocity u' (m/s)
Ka < 1
Ka > 1
u' ^0.5
Model

Buncefield JIP Phase II results



ABR required to get 800-1000 mbar overpressure

4mm obstacles	0.073
20mm obstacles	0.083
100 mm obstacles	0.17

Burning rate did not appear to increase with obstacle size – for fixed ABR