HEALTH & SAFETY LABORATORY

Flammability of Hydrocarbon/CO_2 Mixtures Part 2 - Predictive Models for Gas Jet Ignition

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Introduction

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- **Objective**: to investigate hazards posed by gas releases of mixtures containing hydrocarbons and CO_2 gas

- **Applications**:
  - carbon capture and storage
  - inerting of hydrocarbon processing plant

- **Methodology**: joint experimental and modelling study involving:
  - confined explosions
  - jet ignition tests. 

Flammable Cloud Extent

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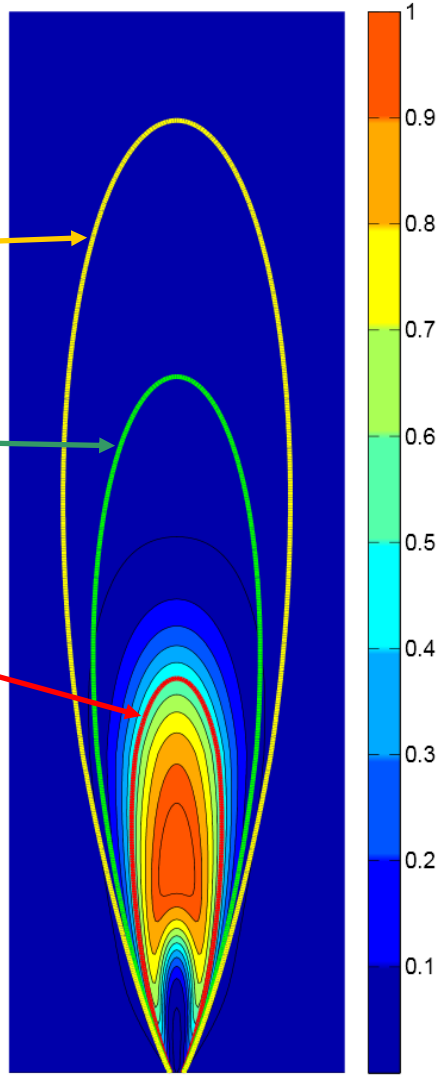
- Many definitions:

Vz (average conc. 50% LEL)

50% LEL contour

100% LEL contour

Flammability Factor (FF)



Flammability Factor

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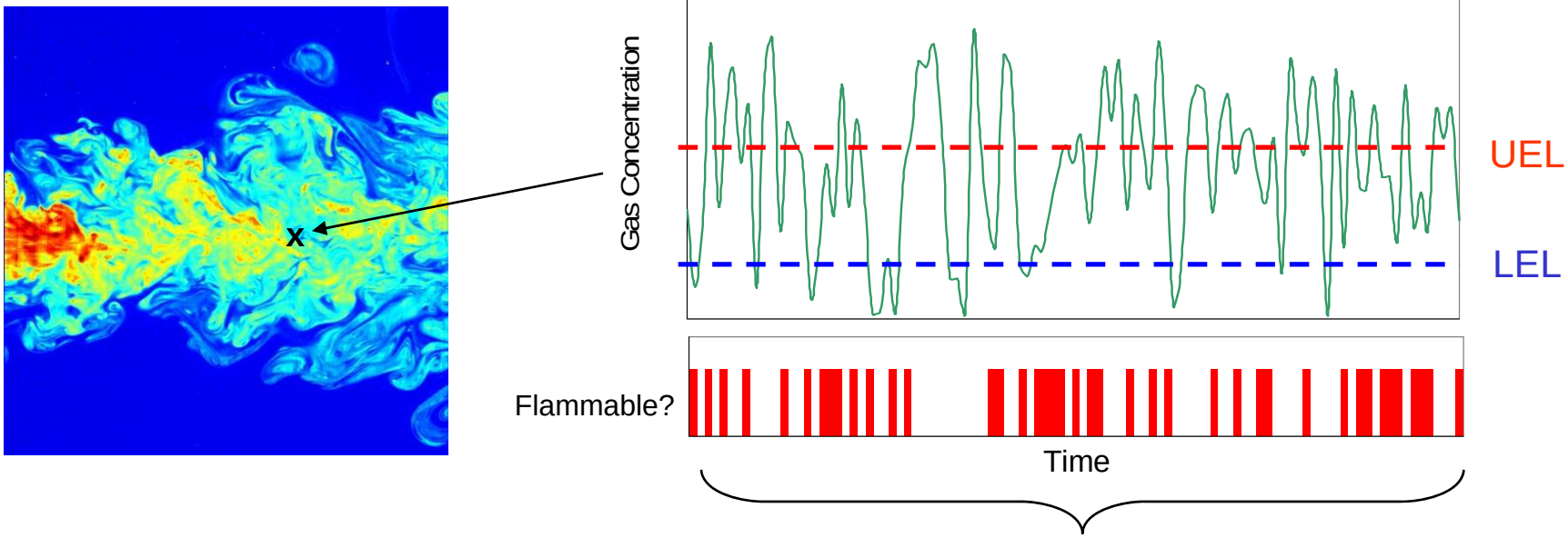
- Definition: proportion of time that the gas concentration is within the flammable range



Flammable at this position for 40% of the time

(Flammability Factor = 0.4)

Ignition Probability

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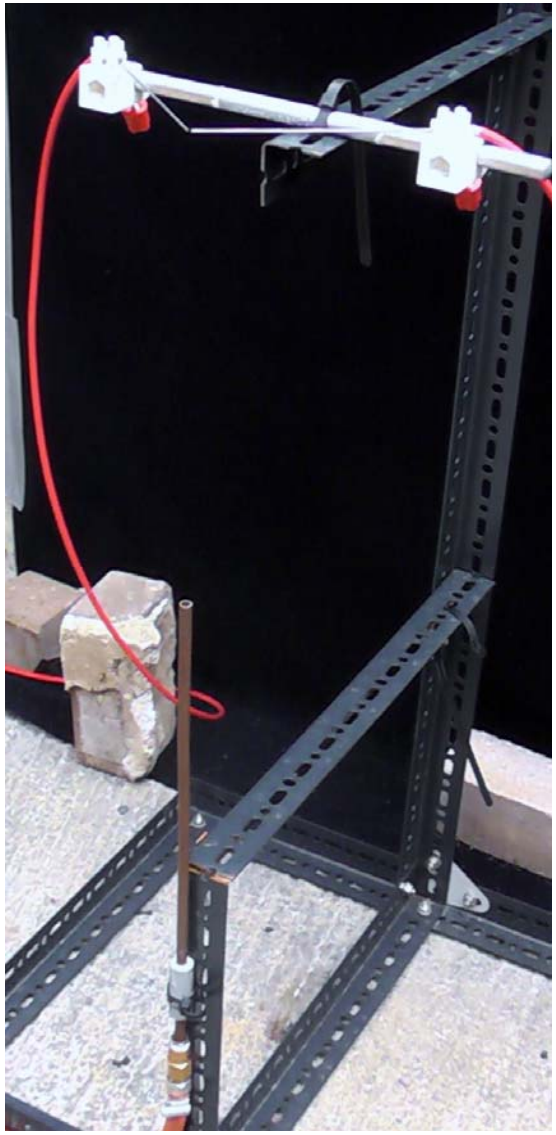
- At each measurement point, a spark is produced several hundred times
- Ignition probability determined from proportion of spark ignitions that produce a flame kernel
  (not necessarily full jet light-up)
- Ignition prob. = flammability factor provided:
  - Sufficiently energetic spark
  - Enough repeats for good statistics



Predicting Flammability Factor

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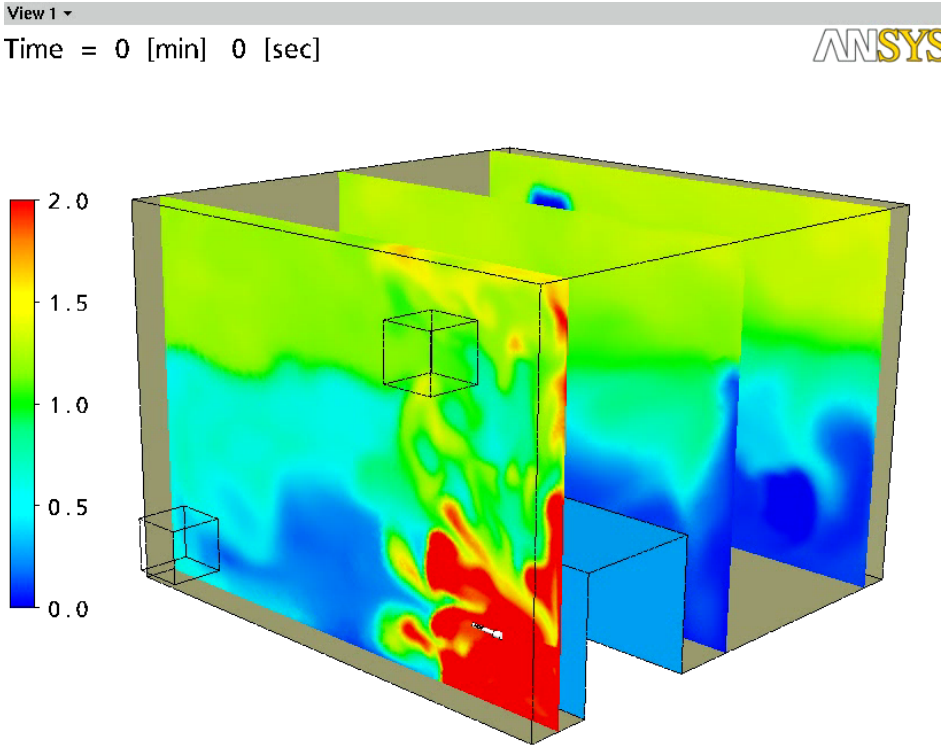
- Sophisticated CFD models that resolve time-varying gas concentrations can be used to calculate FF



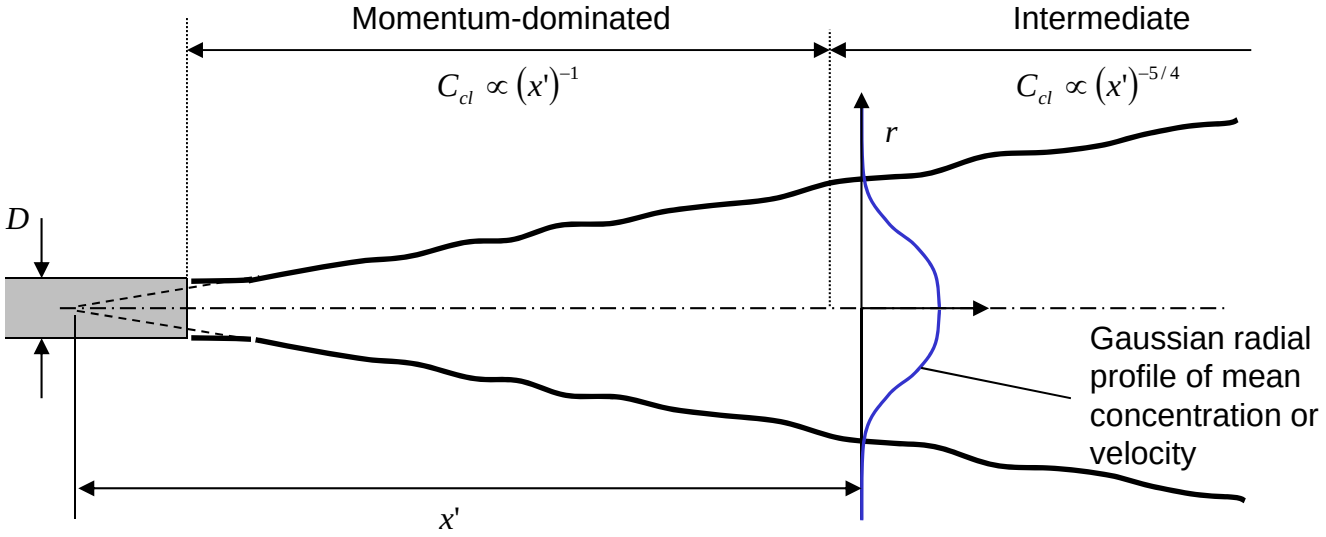
- Problem: computing time can be lengthy!

  (Detached Eddy Simulation of a gas release in a room took 134 CPU-days)

Predicting Flammability Factor

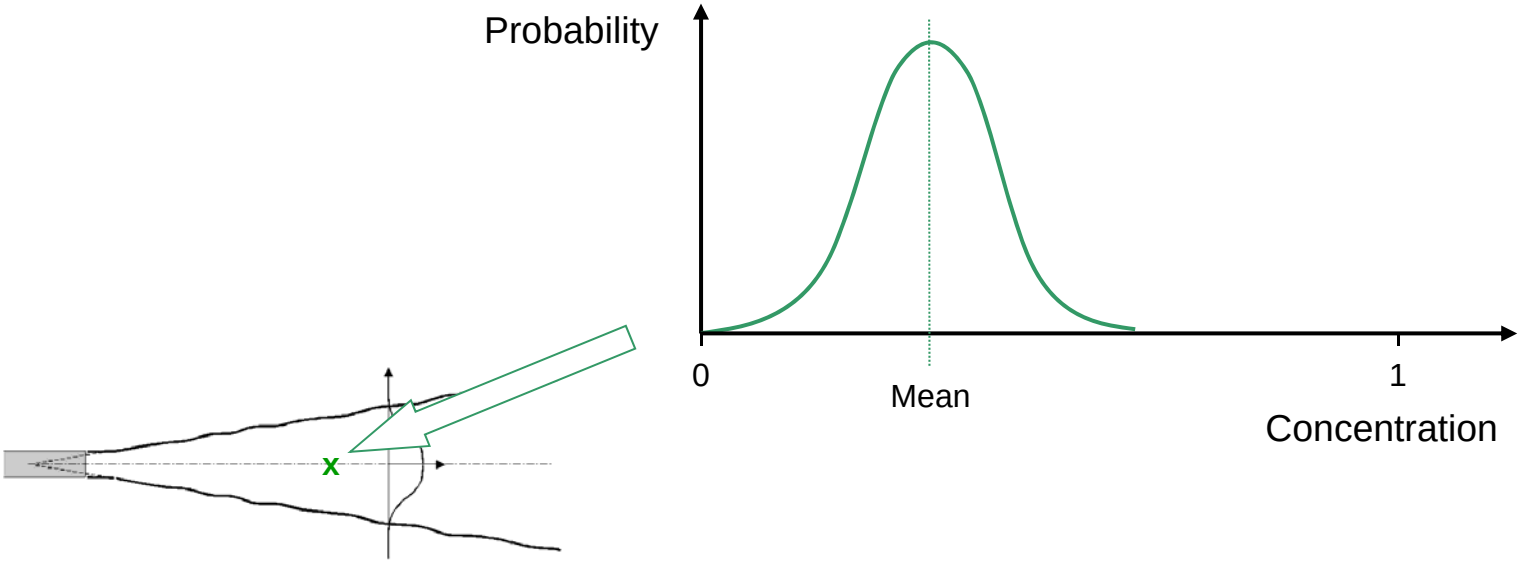
- Pragmatic engineering approach:
  - Empirical profiles for free jets
  - Solved in MatLab (or Excel even) in seconds
  - Based on work at British Gas in 1980's

    (Birch *et al*., 1981, 1988, 1989, Smith *et al*. 1986)



Predicting Flammability Factor

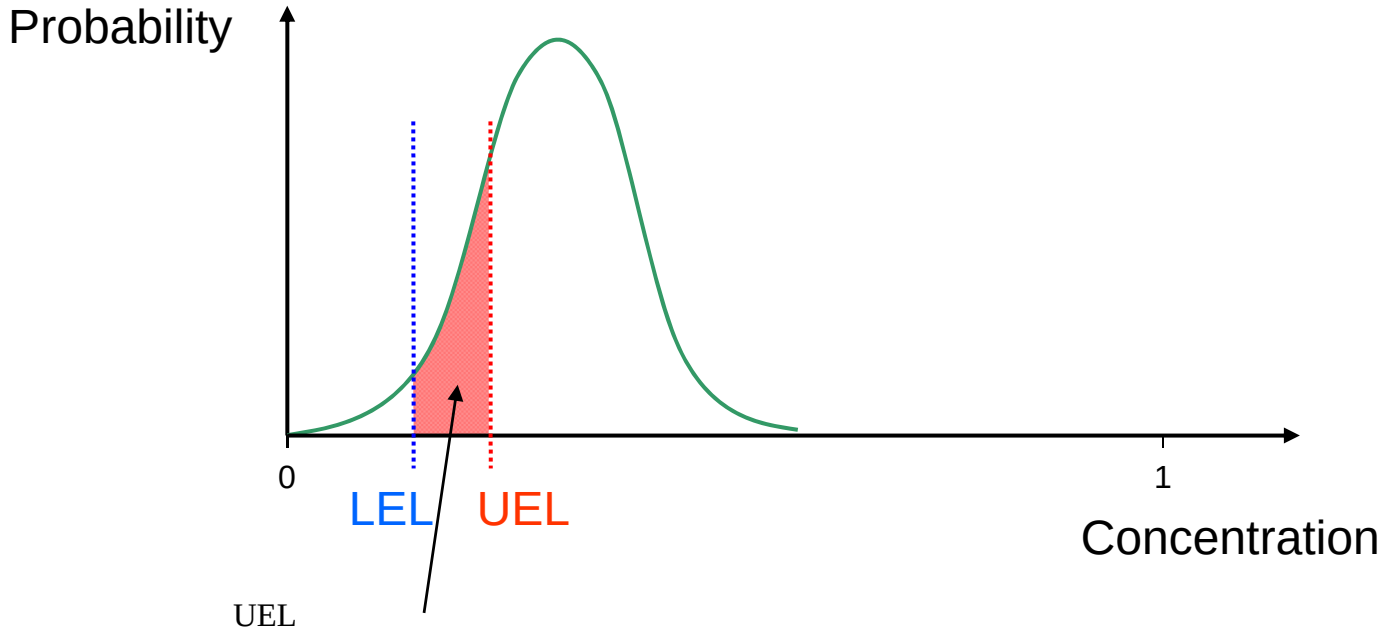
- Probability Density Function (PDF) describes the likelihood of the gas concentration taking a particular value



- PDFs for gas jets measured by Birch *et al*. (1979)

Predicting Flammability Factor

- FF is the fraction of time that mixture is flammable, i.e. the area under curve between LEL and UEL



$$FF = \int_{LEL}^{UEL} P(c)\,dc = 0.2$$

There is a 20% chance of gas mixture being ignitable

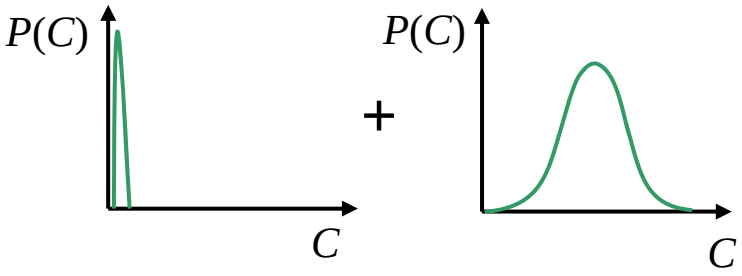
Determining the PDF

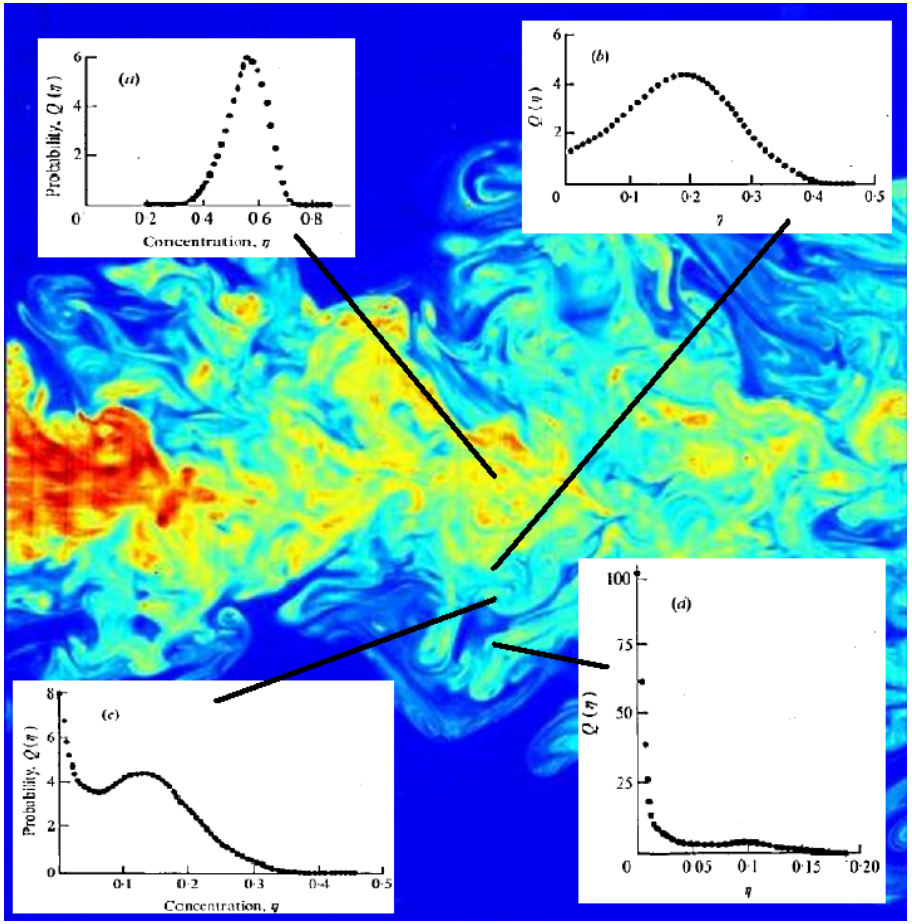
- PDF changes shape across the jet

- Approximated as :

$$P(\tilde{c}) = (1-I)\delta(\tilde{c}) + \frac{IA}{\sqrt{2\pi\overline{c_c^2}}}\exp\left[-\frac{(\tilde{c}-C_c)^2}{2\overline{c_c^2}}\right]$$

Delta Truncated Gaussian





Determining the PDF

- Peak and spread of PDF specified by empirical profiles of mean and RMS concentration

Centreline Mean Concentration:

$$C_{cl} = 5C_0\left(\frac{\rho_0}{\rho_a}\right)^{-1/2}\left(\frac{x'}{D}\right)^{-1} \qquad C_{cl} = a_C C_0 Fr^{1/8}\left(\frac{\rho_0}{\rho_a}\right)^{-7/16}\left(\frac{x'}{D}\right)^{-5/4}$$

Radial Mean Concentration:

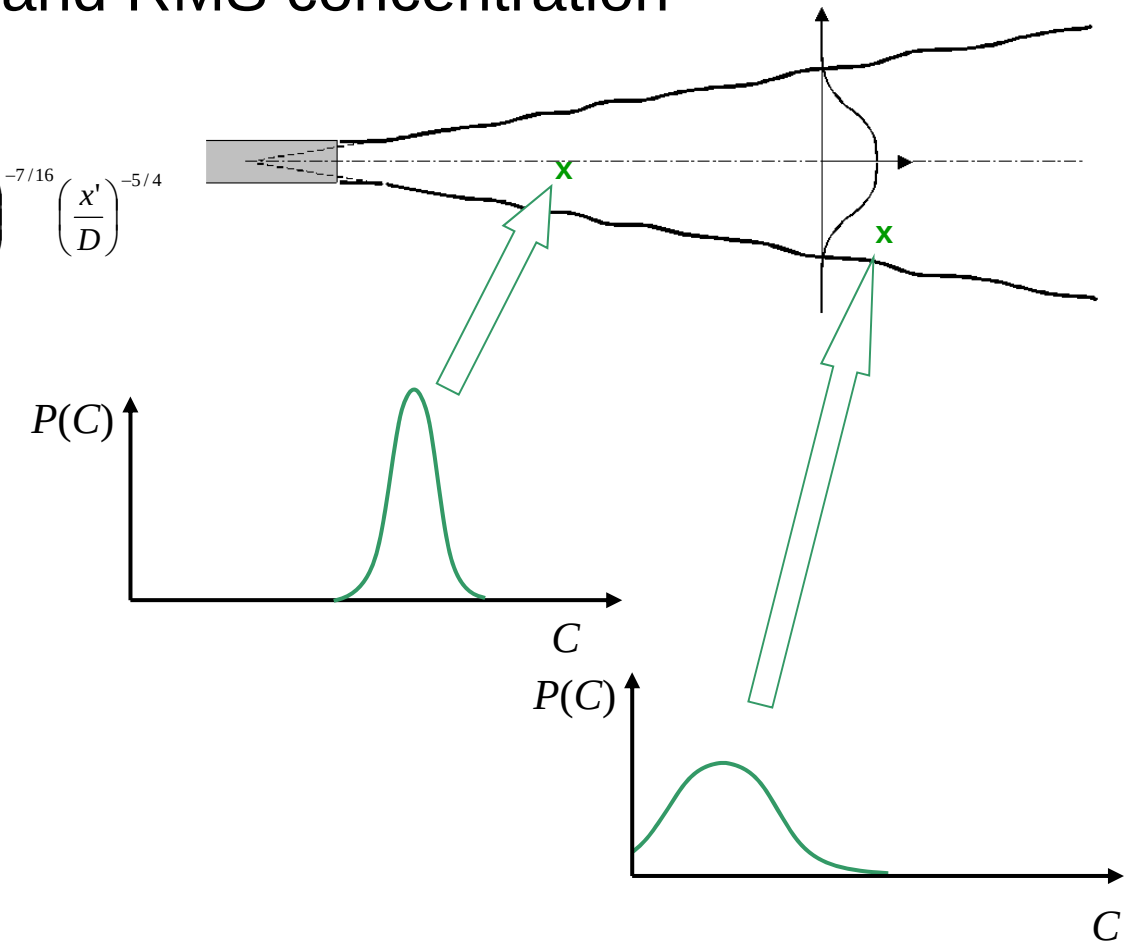
$$\frac{C}{C_{cl}} = \exp\left[-K_C\left(\frac{r}{x'}\right)^2\right]$$

RMS Concentration:

$$\overline{c^2} = \beta C\left(\alpha C_{cl} - C\right)$$

Turbulent Intermittency:

$$I = \frac{K+1}{\left[\left(\frac{\overline{c^2}}{C^2}\right)+1\right]}$$



Model Validation

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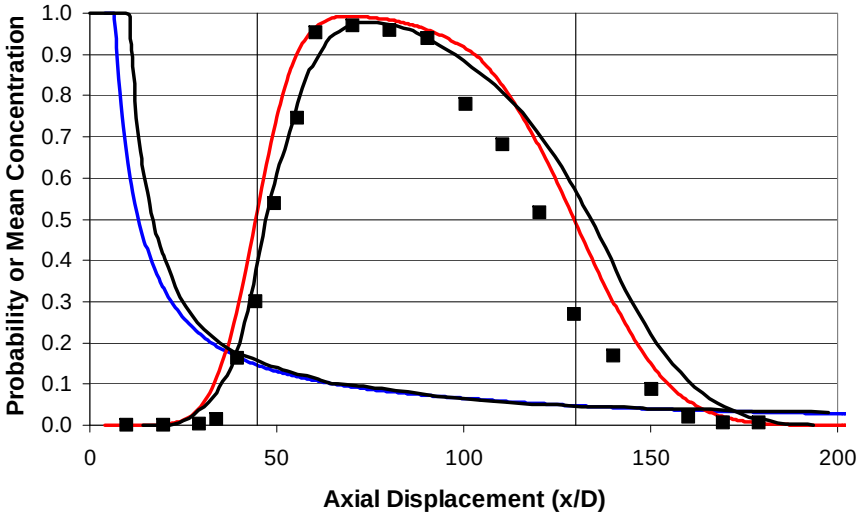
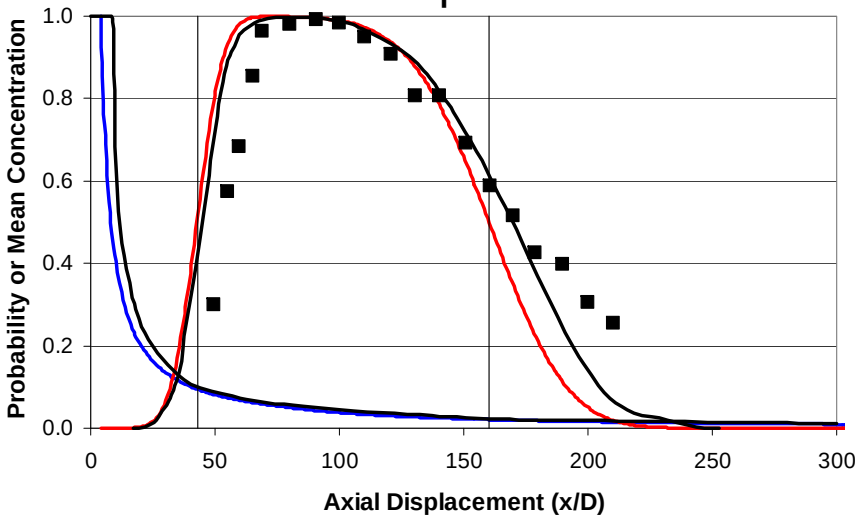
- Smith *et al*. (1986) experiments and new model predictions

Natural Gas



U_0 = 50 m/s, D = 6.35 mm

Propane



U_0 = 20 m/s, D = 6.35 mm

■ Measured ignition probability (Smith *et al*., 1986)

Model predictions from Smith *et al*. (1986)

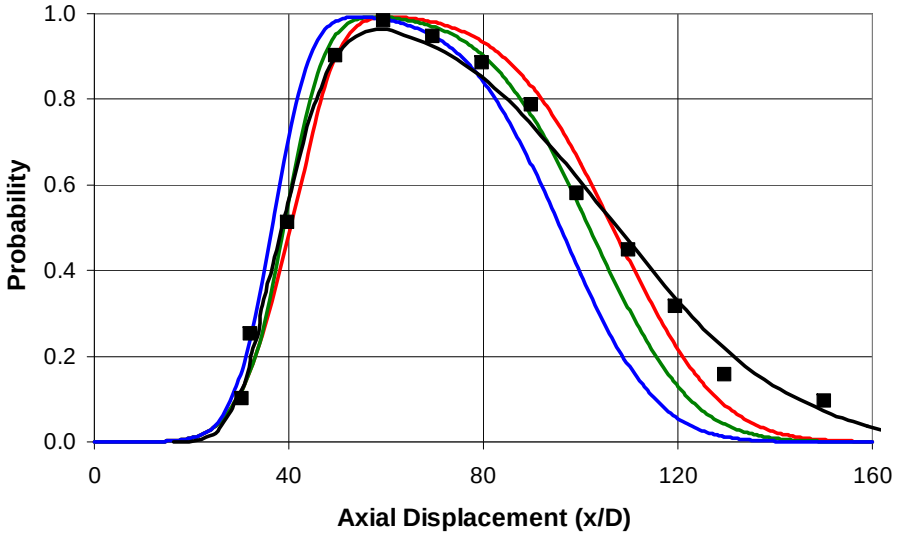
Centreline mean concentration (new model)

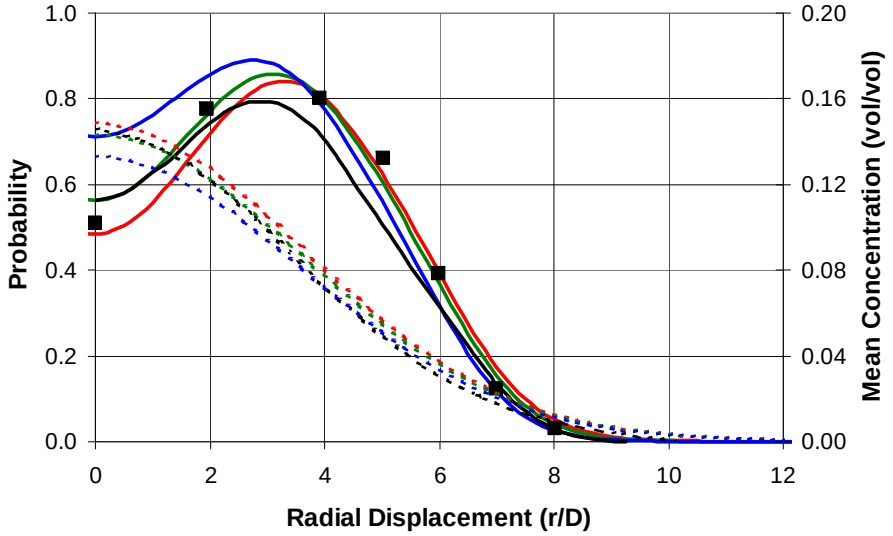
Centreline flammability factor (new model)

Model Validation

HEALTH & SAFETY LABORATORY

- Birch *et al*. (1981) experiments and new model predictions





■ Measured ignition probability (Birch *et al*., 1981)

Flammability factor predictions from Birch *et al*. (1981)

32.2 m/s

25.7 m/s

19.2 m/s

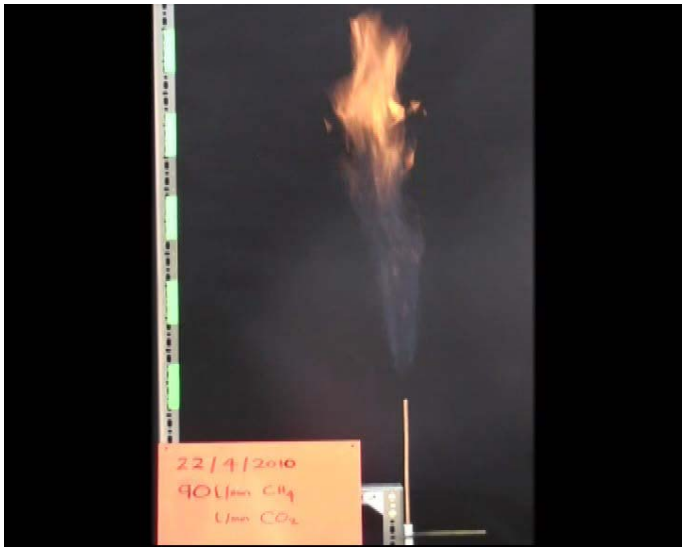
} Flammability factor (new model)

New Measurements

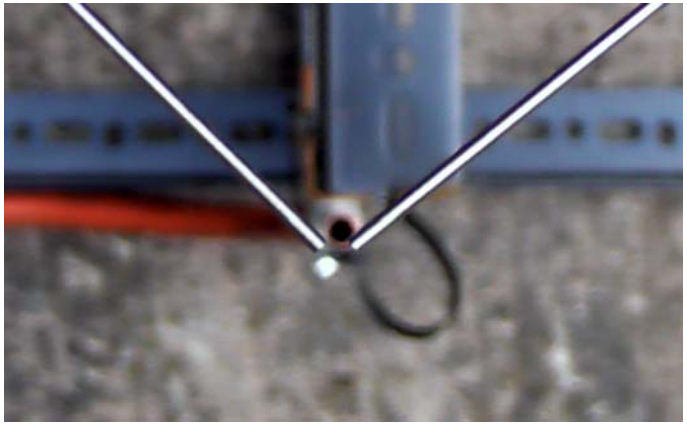
- Ignition probability and mean concentration

100% CH_4
80% CH_4, 20% CO_2

Q = 90 litres/min
U_0 = 53 m/s
D = 6 mm
Re_0 = 19,000



On average 250 ignition attempts at each measurement point



Model Predictions

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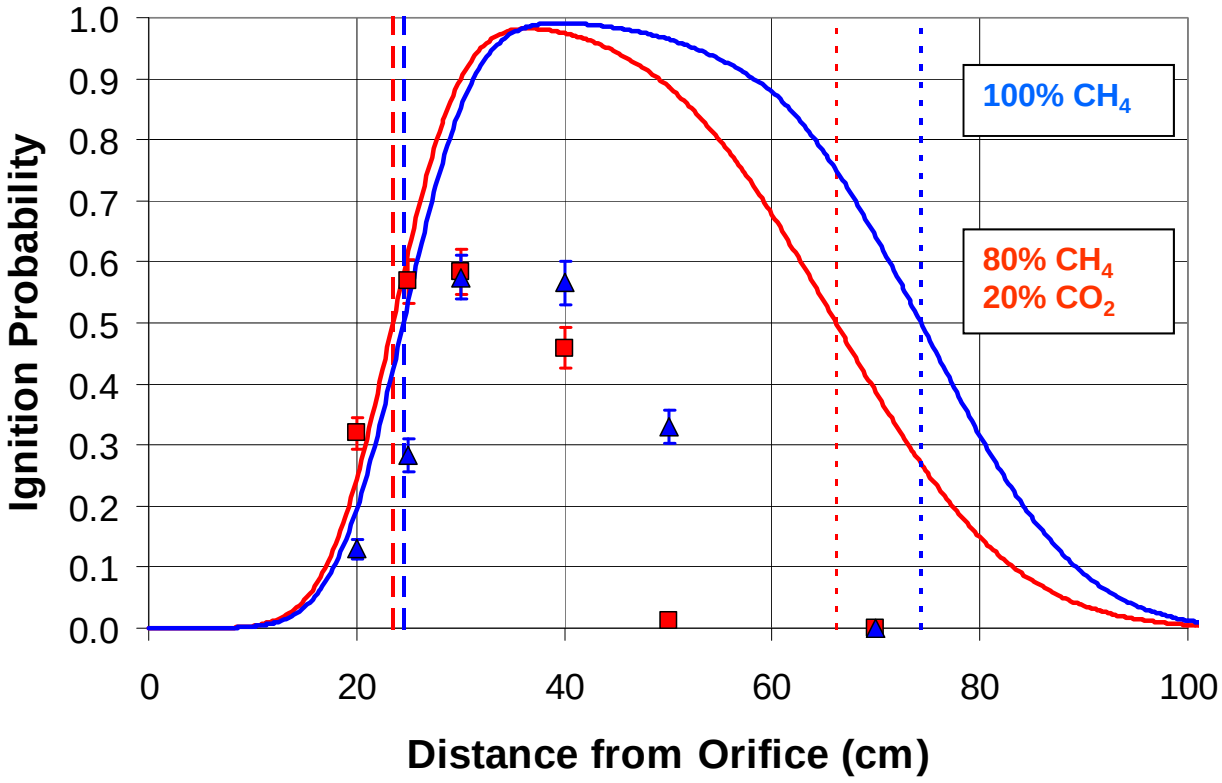
- Flammability factor on jet centreline



- LEL and UEL determined from model of Kondo *et al*. (2006)

Model Predictions

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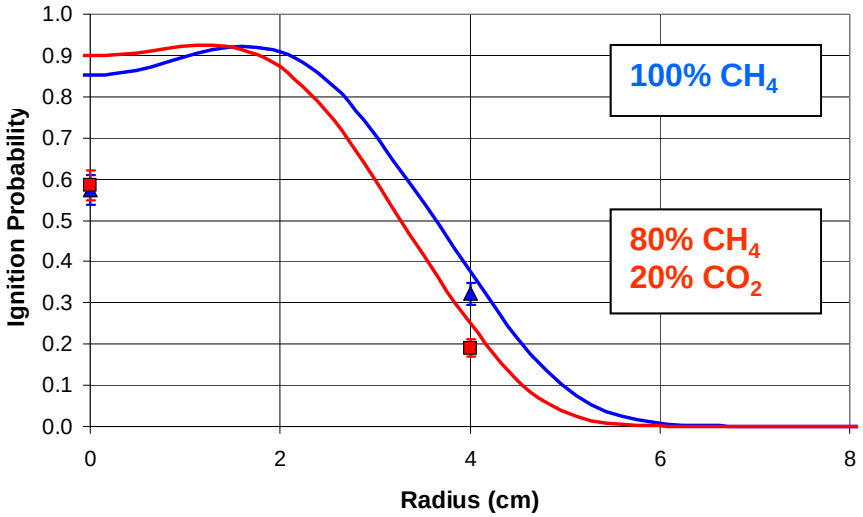
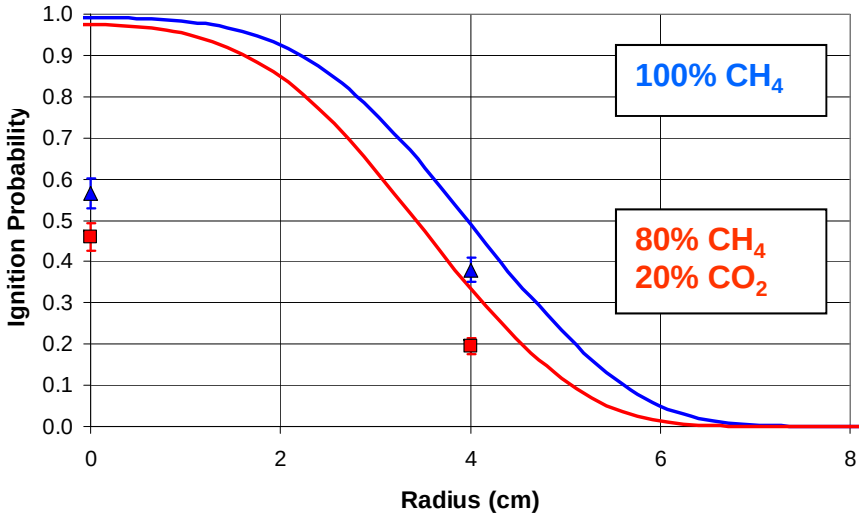
- Flammability factor at radial positions



Distance from orifice = 30 cm



Distance from orifice = 40 cm

Model Predictions

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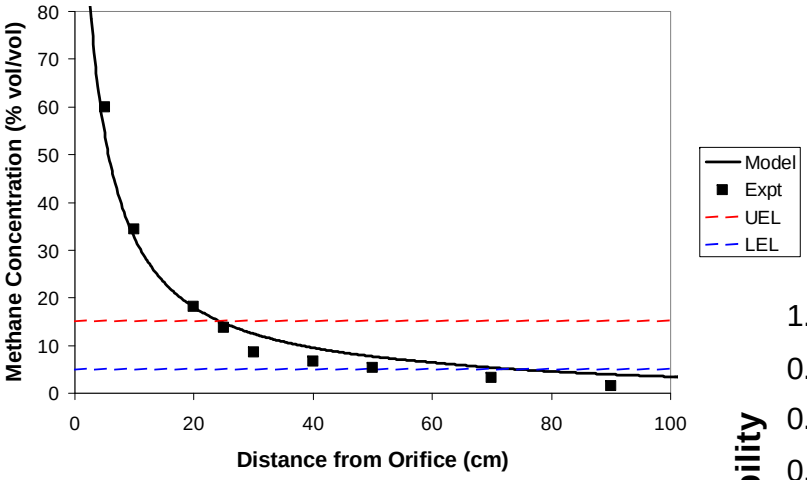
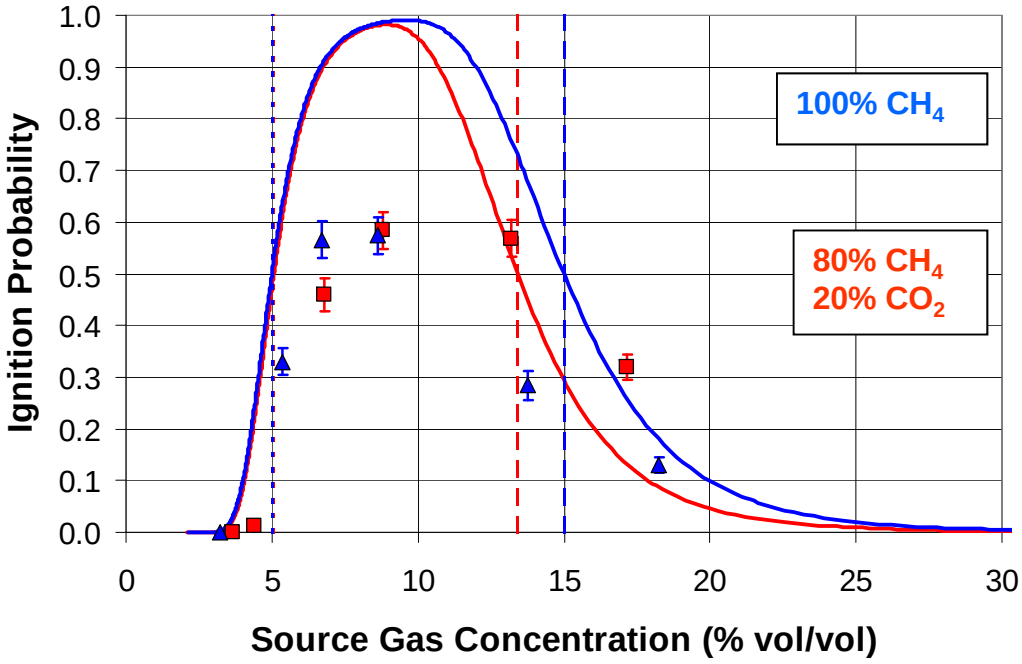
Mean centreline concentration



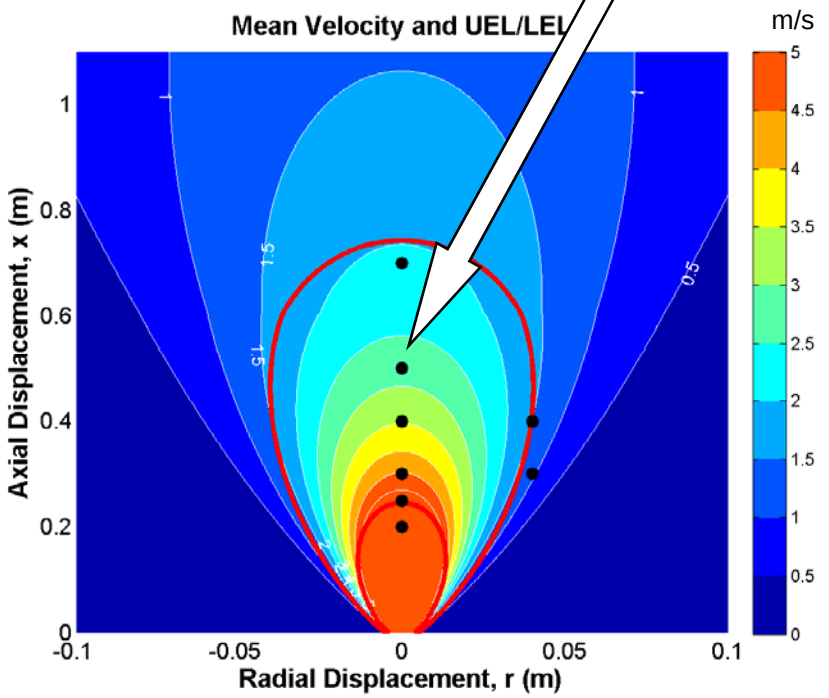
- Flammability Factor plotted in terms of mean concentration



Other Factors

- Not all flame kernels detected
  - Observation, Schlieren shadow, audible
- Spark of insufficient energy
- Jet disturbed by ambient wind

Jet velocity below 5 m/s



Model Predictions

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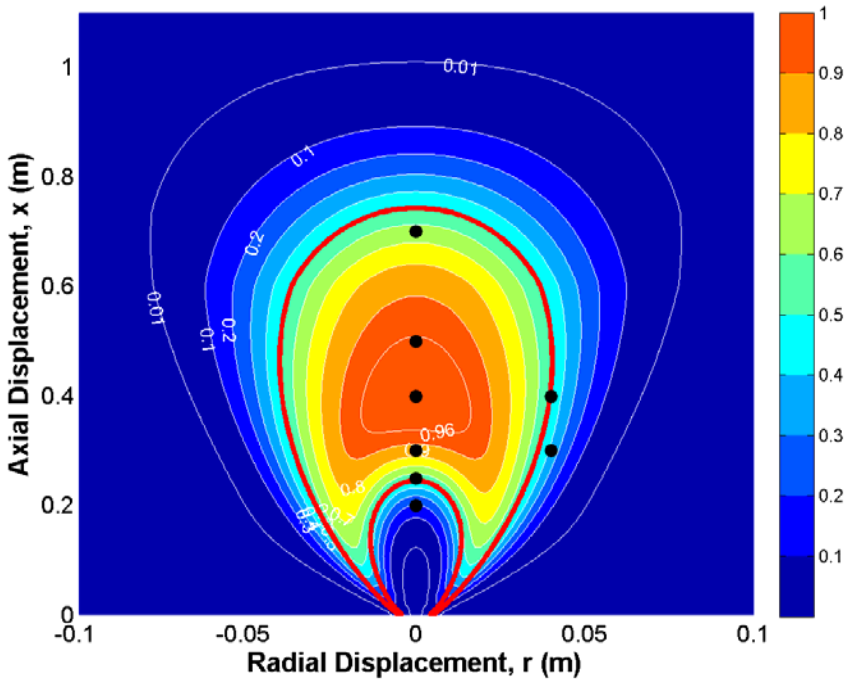
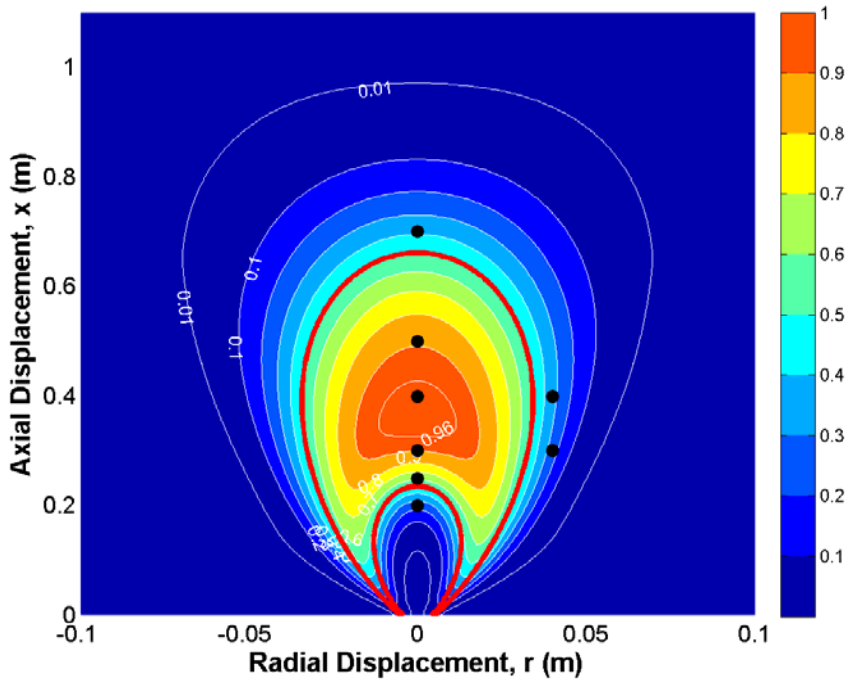


100% CH_4



80% CH_4, 20% CO_2

— UEL and LEL based on predicted mean concentration

Conclusions

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- Empirical Flammability Factor model presented
- Validated for free jets in quiescent environment
- Results from new experiments appear to show that FF is sensitive to ambient wind effects
- Effect of 20% CO_2 on flammable extent shown
- Potential applications:
  - Examine flammability of discharges from hydrocarbon storage tanks with inerting systems
- Future Work:
  - Extend model to consider other flammable or inert gases (only requires UEL/LEL data and density)
  - Toxic load calculation: incorporating the effects of concentration fluctuations (particularly important for CO_2)
  - Develop CFD models for flammability factor

Further Information

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- HSL Report MSU/2010/21:

  "Flammability of Hydrocarbon and Carbon Dioxide Gas Mixtures: Measurements and Modelling"

  by Gant, Lea, Pursell, Fletcher, Rattigan & Thyer

  - Sensitivity to model constants examined
  - Implementation explained
  - CFD models based on PDF approach investigated

Acknowledgements

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