FACULTY OF ENGINEERING AND ARCHITECTURE

# Fire and smoke modelling: Where are we (going)?

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## Introduction

- Experiments – Numerical simulations
- Issues in calculations / numerical simulations
- Smoke modelling
- Fire modelling
- Discussion

## Experiments – Numerical simulations

- Fire: extremely complex.
- Fire development strongly depends on ‘details’:
  - Initial conditions
  - Boundary conditions
  - Material properties
  - Geometry
- Fundamental issue: repeatability in experiments → quid validation of models?



## Experiments – Numerical simulations

- Different types of experiments required:
  - ‘Realistic’ (or ‘heroic’?) large-scale experiments. Examples: Dalmarnock (Edinburgh), car park experiments (BRE, UGent), Rabottoren (UGent), traveling fires (Edinburgh).





## Experiments – Numerical simulations

- Different types of experiments required:
  - ‘Realistic’ (or ‘heroic’?) large-scale experiments. Examples: Dalmarnock (Edinburgh), car park experiments (BRE, UGent), Rabottoren (UGent), traveling fires (Edinburgh).
  - Repetitive experiments, for model validation.
- It needs to be accepted that there will always be spreading in the measurements and it is important to have an estimate on this spreading.
- Deterministic models can, at their best, only reproduce the ‘average’ scenario.



## Experiments – Numerical simulations

- Numerical simulations: are we happy with the state-of-the-art?
- Correlations – zone models – CFD.
- Reliability of numerical simulations:
  - Numerical issues (computational mesh, solver, convergence checks);
  - Modelling issues.

## Experiments – Numerical simulations

- Sensitivity of numerical simulations:
  - Initial conditions
  - Boundary conditions
  - Material properties
  - Geometry



## Issues in calculations / numerical simulations

- Empirical correlations – example: fire/smoke plume.
- Axisymmetric plume → entrainment of air:
  - Zukoski
  - Heskestadt
  - McCaffrey
  - Thomas
- Not entirely 'empirical', yet based on curve fitting for 'idealized' situations → care to be taken about applicability!
- Reliable? Yes, if geometry and conditions not too far off from original situation on which correlations are based.

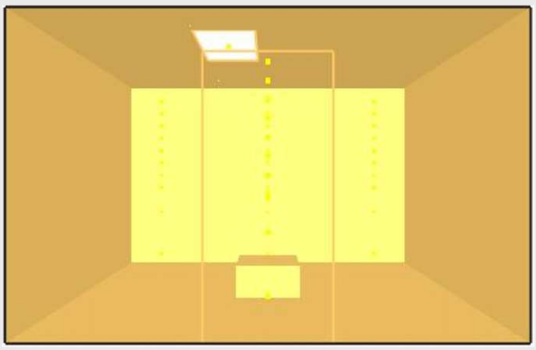
## Issues in calculations / numerical simulations

- Caveat:
  - Position of fire close to wall / corner: not taken into account.
  - Effect of ceiling: not taken into account (→ other correlations for ‘ceiling jet’).
  - Effect of single-sided ventilation: not taken into account (see example).
- Zone modeling:
  - Same limitations (empirical correlations are in there!).
  - Not applicable if transport times are important, if flow field is complex or if there is no clear smoke layer/region.
- CFD: in principle reliable for smoke plumes, if user reliable.



## Issues in calculations / numerical simulations

- Example single-sided ventilation: Van Maele and Merci, Fire Safety Journal 43, pp. 495 – 511 (2008)



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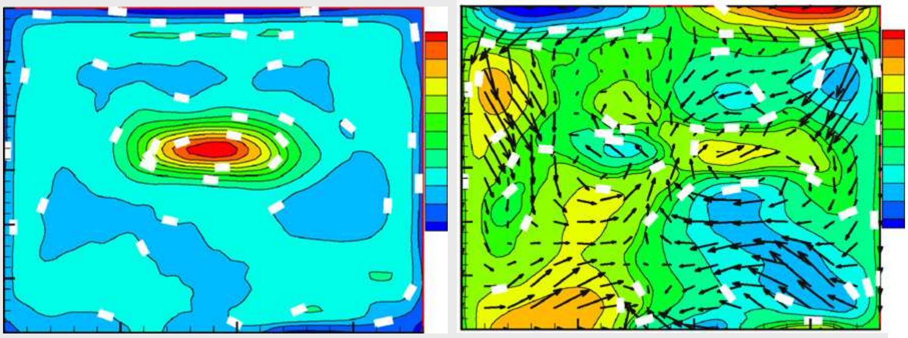


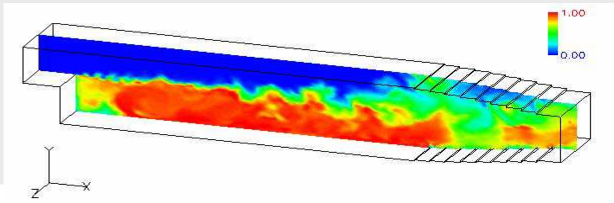


## Issues in calculations / numerical simulations

- Some numerical issues in CFD:
  - Computational mesh:
    - Required mesh size depends on turbulence model (RANS vs. LES).
    - LES: 80% of turbulent kinetic energy to be resolved in principle → related to integral length scale. Practice: hardly ever obtained in fire simulations.
    - RANS: solution becomes grid independent if mesh fine enough. LES: at best grid 'insensitive' (if mesh is used as filter, which is common practice).
    - Papers:
      - Van Maele and Merci, FSJ 41, pp. 122 – 138 (2008)
      - Tilley, Rauwoens and Merci, FSJ 46, pp. 186 – 193 (2011)

## Issues in calculations / numerical simulations

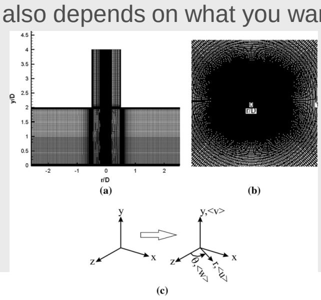
- Some numerical issues in CFD:
  - Computational mesh:
    - Required mesh size depends on fire size (e.g. D* criterion in FDS).
    - Required mesh size depends on geometry. Example backward-facing step LES calculation: typical to have at least 20 cells in step (example from combustion community: Park and Ko, J. Mech. Sci. and Techn. 25, pp. 713 - 719 (2011)) → quid flow around beams in fire simulations?






## Issues in calculations / numerical simulations

- Some numerical issues in CFD:
  - Computational mesh:
    - Required mesh size depends on phenomena to be resolved. Example: impinging jet – ceiling jet. 10 million cells focused on jet (to study heat transfer) → quid fire simulations (ceiling jet)? (Work in progress).
    - Note: the mesh also depends on what you want to see!



## Issues in calculations / numerical simulations

- Some numerical issues in CFD:
  - Numerical discretization:
    - Interacting errors between (turbulence) modeling and numerical scheme in LES → work done by Geurts and Meyers (non-reacting).
    - Combustion/fire community: second order schemes in LES:
      - Combustion community: dynamic Smagorinsky, many cells.
      - Fire community: standard/dynamic Smagorinsky, fewer (too few?) cells.
    - RANS: second order schemes OK.
  - Convergence checks: in principle automatically OK.
  - Boundary conditions also extremely important (e.g. extended domains), but no time to talk about this today.



## Smoke modelling

- What is the question?
  - Binary question: is there smoke at a certain location (and at a certain moment) or not?
  - This is a relatively 'easy' question:
    - Smoke is 'passive' from a fluid mechanics point of view.
    - Smoke behaves like hot air.
    - The smoke production rate only has a secondary effect on the reply to the binary question.

## Smoke modelling

- What is the question?
  - Binary question: is there smoke at a certain location (and at a certain moment) or not?
  - Main difficulties to reply to this question:
    - The fire source (which drives the flow) needs to be quantified.
    - The geometry (and location of the fire) needs to be known.
    - The effect of forced/natural ventilation needs to be quantified.



## Smoke modelling

- What is the question? Binary question: is there smoke at a certain location (and at a certain moment) or not?
  - Can we use empirical correlations?
    - Yes, if fire is prescribed and if the geometry and conditions do not deviate too much from original set-up for which the correlations have been derived.
    - No, in all other situations.
    - Note: time information is problematic (correlations have not been developed to that purpose).

## Smoke modelling

- What is the question? Binary question: is there smoke at a certain location (and at a certain moment) or not?
  - Can we use zone modeling?
    - Yes, under the same conditions as empirical correlations.
    - No, in all other situations.
    - Note: some indication on time evolution is included in zone modeling.



## Smoke modelling

- What is the question? Binary question: is there smoke at a certain location (and at a certain moment) or not?
  - Can we use CFD?
    - Yes, but:
      - The fire needs to be prescribed.
      - The computational mesh must be adequate.
      - The boundary conditions must be well defined.
    - If the above is fulfilled: CFD is very reliable to reply to the binary question.

## Smoke modelling

- What is the question? More advanced question: how ‘thick’ is the smoke (‘visibility’)?
  - Can we use empirical smoke plume correlations? No.
  - Can we use zone models? No (at best, they give a reasonable value for the average).
  - Can we use CFD models? Yes, IF a reasonable estimate can be provided for the ‘source’ of smoke → bottleneck: soot model.
  - Fundamental issues:
    - Quality of soot models: reasonable (combustion community).
    - Under-ventilated vs. well-ventilated: problem.
    - What is the fuel? → Huge problem.



## Smoke modelling

- What is the question? More advanced question: how ‘thick’ is the smoke (‘visibility’)?
  - Conclusion for CFD: the answer is ‘yes, we can’, but only if the smoke production rate at the fire source is known.
  - Typical ‘solution’: make smoke production rate proportional to the fire heat release rate (or, more correctly, the burning rate), through a prescribed soot yield. Consequence: quality of results depends on this prescription (since the convection – diffusion equation with a source term is typically no problem).

## Smoke modelling

- What is the question? Still more advanced question: what is the composition of the smoke ('toxicity')?
  - Reasoning to previous question still holds, but now additional uncertainty since more detailed chemical reactions required.
  - Fundamental problem remains: what is the fuel?
  - Second fundamental issue: what to do in under-ventilated conditions?
  - Only 'solution' is to work with 'toxicity yield'. Care must always be taken in interpretation of toxicity calculations.



## Fire modelling

- Physics and chemistry involved.
- Focus on situation where physics is predominant.
- Situation:
  - Combustion in gas phase → generation of heat.
  - Heat transfer to surroundings and (solid or liquid) fuel, by radiation and convection (and conduction through the structure and in the fuel).
  - Pyrolysis phenomena inside the solid fuel and/or evaporation of liquid fuel → release of combustible pyrolysis gases (typically not very well known in terms of composition) → combustion in gas phase.

## Fire modelling

- Fundamental problem (in reality and in modelling): positive feedback loop with strong interaction → runaway if something in the models is not accurate.
- Reliability of sub-models (turbulence, combustion, radiation, convection, conduction, evaporation, pyrolysis, soot production): good.
- Fundamental problem: boundary conditions (e.g. fuel, material properties, ventilation situation) not well-known.
- Consequence: developing fires very hard to predict with coupled CFD – pyrolysis/evaporation calculations.



## Fire modelling

- ‘Solution’ in design calculations: work with prescribed fire (‘design fire’), be it in manual calculations, zone model calculations or CFD calculations.
- Consequence: everything strongly depends on the choice of the design fire, also in CFD. Indeed:
  - The fire size (geometry and HRR) is the driving force for the flows (including entrainment in e.g. smoke plumes).
  - Radiation is typically modeled as a fixed fraction of the HRR (see later).
  - Smoke production is typically modeled as proportional to the HRR (see above).

## Fire modelling

- Example: combustion model.
  - Mixture fraction based approach (non-premixed combustion), with (infinitely) fast chemistry: typically OK, since gas phase combustion time scales are much shorter than the other time scales.
  - Possible issues: ‘vitiated’ conditions (i.e. reduced oxygen, high temperatures) → chemical kinetics become important, as well as CO formation. Much activity in combustion community, with well-defined fuels.



## Fire modelling

- Example: radiation model.
  - Different solution methods for ‘difficult’ radiative heat transfer equation (e.g. DOM, FVM, 6-flux model, DRTM, P1, …).
  - Different advanced models for spectral dependence of emission/absorption coefficients of $H_2O$ and $CO_2$ (e.g. WSGGM, wide/narrow band, correlated k method, etc.), ignoring scattering.
  - Models for radiation from soot.
  - Fundamental problem again: how thick is the smoke and what is the fuel?
  - ‘Solution’ in design calculations: predefine radiative fraction (i.e. radiation is predefined as proportional to the fire HRR) → consequence: results depend on this value.

## Fire modelling

- Example: soot model.
  - Laminar calculations in combustion community: thousands of equations with very complex chemistry.
  - Other extreme ('solution' in design calculations): define fixed soot yield, so that soot production becomes proportional to the burning rate (HRR) → consequence: results depend on this value.
  - Engineering models: Moss model, Beji et al. model.
  - Fundamental issue: what is the fuel and the ventilation conditions?



## Fire modelling

- Example: pyrolysis model.
  - Very advanced: GPYRO (Lautenberger).
  - Very simple: integral model or moving pyrolysis front model (Wasan et al., Combustion and Flame 157, pp. 715-734, 2010).
  - Problems: what is the incident heat transfer and what is the fuel?
  - 'Solution': prescribe fire spreading rate → consequence: results depend on this.

## Fire modelling

- Recent evolution: fire forecasting, using video data.
  - PhD Wolfram Jahn (University of Edinburgh).
  - Further elaborated by Beji et al. and Verstockt et al. (Ghent University).
  - Idea:
    - Monitor present and recent past.
    - Predict the evolution (using zone models).
    - Correct if necessary and do a new forecast.
  - Still in research phase.



## Discussion

Questions?