Fire Simulations in OpenFOAM

RAS simulations

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Motivation

- Fire safety is an important issue for building engineers
- No experimental “fire test” of the building possible
- Simulations are only possible way to evaluate the behaviour of fires
- OpenFOAM offers solvers - e.g. fireFoam
- Possibility to test the accuracy by comparing to experimental data [1]

[1] K.D. Steckler, J.G. Quintiere, W.J. Rinkinen: Flow induced by a fire in a compartment

Theory

- compressible
- transient
- laminar and turbulent
- non-isothermal
- multi species incl. chemical reactions
- combustion model

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

Navier-Stokes equations:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (2S) + F_{buoyant} + F_T$$

Energy equation:

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) + \frac{\partial \rho \left(\frac{\mathbf{u}^2}{2}\right)}{\partial t} + \nabla \cdot \left(\frac{\mathbf{u}^2}{2}\right) =$$

$$-p \nabla \cdot \mathbf{u} + \nabla \cdot \frac{k}{c_v} \nabla h + \rho \mathbf{u} \cdot \mathbf{g} + H_T + \dot{Q}_{rad} + \dot{Q}_{HRR}$$

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Transport of species:

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_i) = \Delta \mu_{eff} Y_i + \dot{Y}_{reaction} + \dot{Y}_{source}$$

Theory

- compressible
- transient
- laminar and turbulent
- non-isothermal
- multi species incl. chemical reactions
- $\boxed{\text{combustion model}}$

Combustion - infinitelyFastChemistry:

fuel (*better: species*) consumption rate [kg/(m^{3}s)]:

$$wFuel = \frac{\rho}{\Delta t\, C} \cdot min(Y_{fuel}, Y_{O_2}/s)$$

s - Stoichiometric oxygen-fuel mass ratio; C - model constant

Species source term [kg/(m^{3}s)]:

$$\dot{Y}_{reaction} = c_{stoch}\, wFuel$$

Heat release rate [J/(m^{3}s);W/m^3]:

$$\dot{Q}_{HRR} = qFuel \cdot \dot{Y}_{reaction} \cdot Y_{fuel}$$

qFuel - heat of combustion [J/Kg]

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Combustion models

- Lots of combustion models exists
- Four most important implemented in OpenFOAM
  - infinitelyFastChemistry (mixed is burnt - perfectly stirred reactor)
  - EDM - Eddy Dissipation Method (mixed is burnt - perfectly stirred reactor)
  - EDC - Eddy Dissipation Concept (“well stirred” reactor)
  - PaSR - Partially Stirred Reactor

infinitelyFastChemistry

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EDM

fuel (*better: species*) consumption rate [kg/(m^{3}s)]:

$$wFuel = \rho \cdot min(Y_{fuel}, Y_{O_2}/s) \cdot max(\frac{1}{t_{turb}}, \frac{1}{t_{diff}})$$

$$\frac{1}{t_{diff}} = \frac{C_d}{\sqrt[3]{V_{cell}}^2} \cdot (\nu + \nu_t) \quad \frac{1}{t_{turb}} = \frac{C_{EDC} \cdot \epsilon}{k} = C_{EDC} \cdot \omega$$

s - Stoichiometric oxygen-fuel mass ratio; C_d, C_{EDC} - model constants

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$$\dot{Y}_{reaction} = c_{stoch}\, wFuel$$

Heat release rate [J/(m^{3}s);W/m^3]:

$$\dot{Q}_{HRR} = qFuel \cdot \dot{Y}_{reaction} \cdot Y_{fuel}$$

qFuel - heat of combustion [J/Kg]

EDC

- Most complicated model
- Conference papers by Magnussen and others
  - v1981: B. Magnussen: On the structure of turbulence and a generalized eddy dissipation concept for chemical reaction in turbulent flow, in 19th Aerospace Sciences Meeting (p. 42), January 1981
  - v1996: I. R. Gran, B. Magnussen: A numerical study of a bluff-body stabilized diffusion flame. Part 2. Influence of combustion modeling and finite-rate chemistry. Combustion Science and Technology, 119(1-6), p. 191-217. 1996
  - **v2005: B. Magnussen: The Eddy Dissipation Concept - A Bridge Between Science and Technology. In ECCOMAS thematic conference on computational combustion, p. 21-24, June 2005.**
  - v2016: A. Parente et al.: Extension of the Eddy Dissipation Concept for turbulence/chemistry interactions to MILD combustion. Fuel, 163, p. 98-111, 2016.
- Mostly change in model constants
- Infinitely fast limit is intinitelyFastChemistry models

EDC

Species source term [kg/(m^{3}s)]:

$$\dot{Y}_{reaction} = \kappa \cdot \dot{Y}_{reaction,laminar}$$

Heat release rate [J/(m^{3}s);W/m^3]:

$$\dot{Q}_{HRR} = \kappa \cdot \dot{Q}_{HRR,laminar}$$

between 0 and 1

$$\kappa = \frac{\gamma_l^2}{1 - \gamma_l^2}$$

v2005

$$\gamma_l = 2.1377 \cdot \left(\frac{\nu \cdot \epsilon}{k}\right)^{0.25}$$

PaSR

- Partially Stirred Reactor
- Each cell is divided into
  - perfectly stirred part (reacting)
  - unstirred part (non-reacting)
- Stirring limited by turbulence

PaSR

Species source term [kg/(m^{3}s)]:

$$\dot{Y}_{reaction} = \kappa \cdot \dot{Y}_{reaction,laminar}$$

Heat release rate [J/(m^{3}s);W/m^3]:

$$\dot{Q}_{HRR} = \kappa \cdot \dot{Q}_{HRR,laminar}$$

between 0 and 1

$$\kappa = \frac{t_c}{t_c + t_k}$$

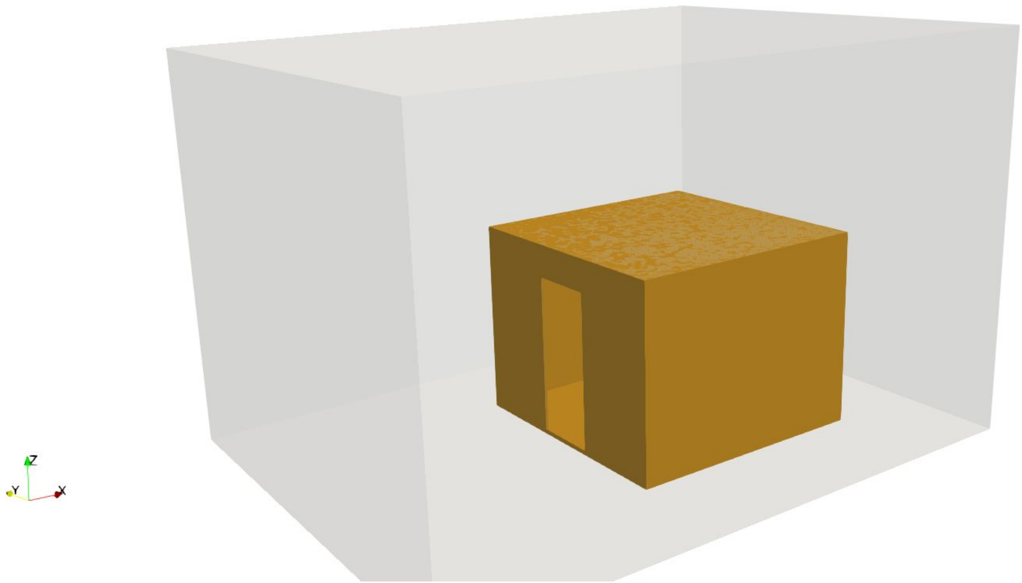
chemical time scale:
src/thermophysicalModels/chemistryModel/chemistryModel/StandardChemistryModel/StandardChemistryModel.C

turbulent time scale

$$t_k = c_{mix} \sqrt{\frac{\nu}{\epsilon}}$$

Steckler room

- Steckler room with opened door
  - small room
  - walls - open geometry
- Surroundings
  - bottom - wall
  - outlets



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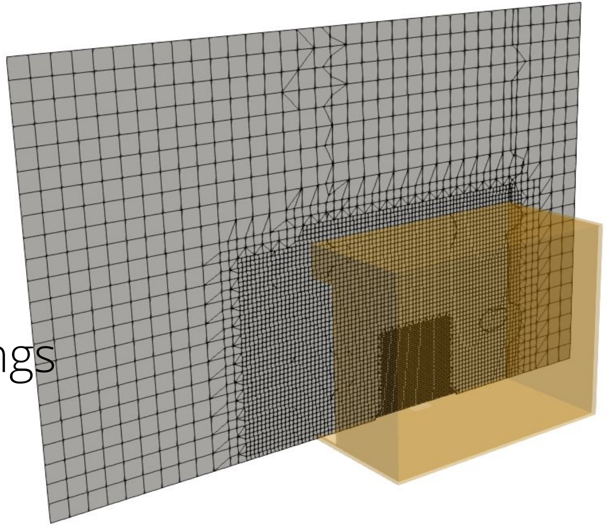
Steckler room

- Background mesh with blockMesh
  - cell size 0.2m
  - length 7 m
  - width 5.2 m
  - height 4.4 m
- Refinement region level 3 around fire
  - cell length 0.025 m (RAS simulations!)
- Refinement region level 2 in room
  - cell length 0.05 m
- Refinement region level 0 in surroundings
  - cell length 0.2 m
- 297144 cells



Steckler room

- Simulation time of 150 s
- 105.3 kW fire experiment [1]
    - measured temperature values in the door
    - comparison with simulations in “steady-state”
- P1 radiation model
- kEpsilon turbulence model
- Single equation reaction model
- GRI 3.0 thermophysical models
- Combustion models with standard set of model constants

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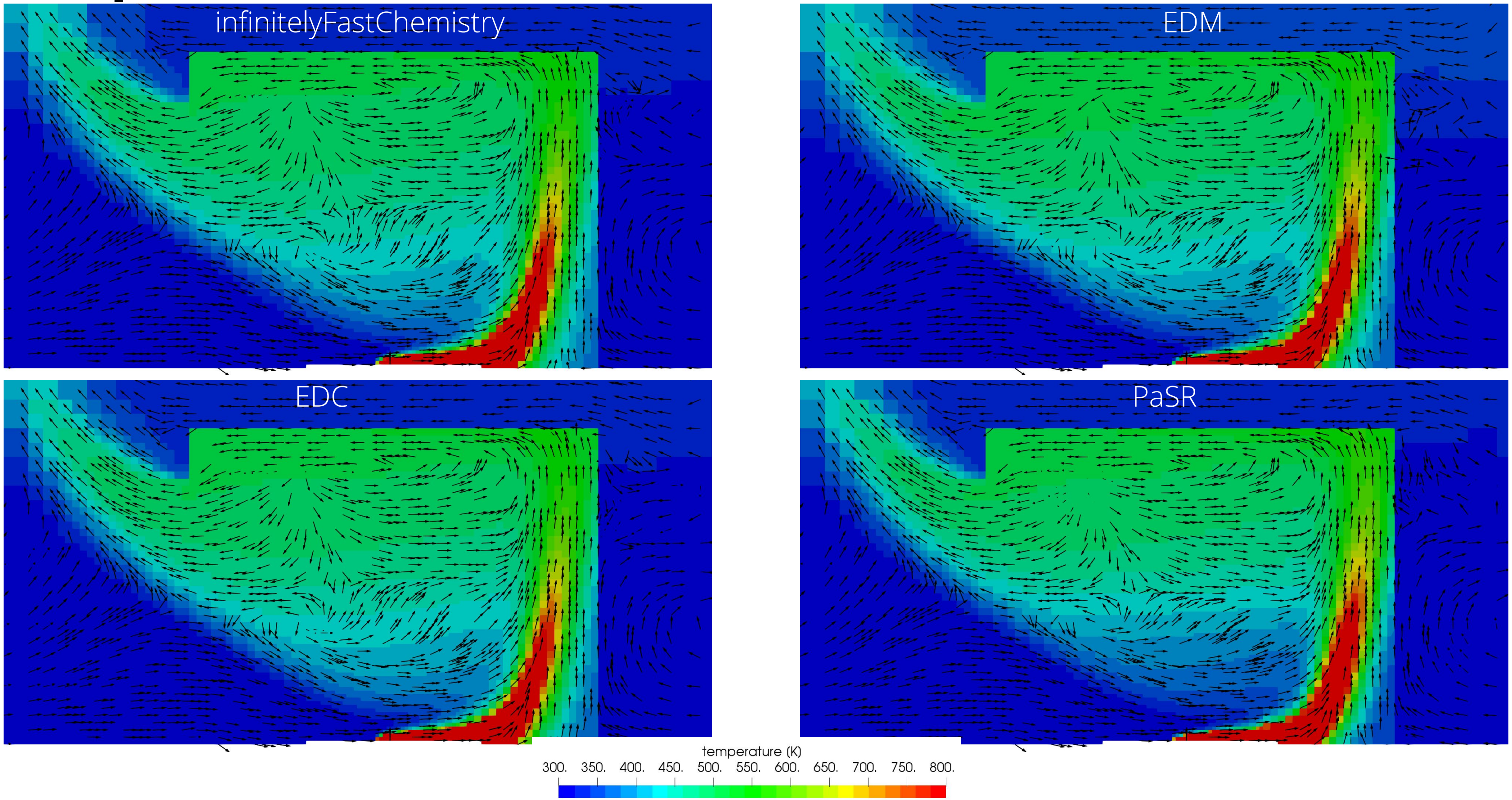
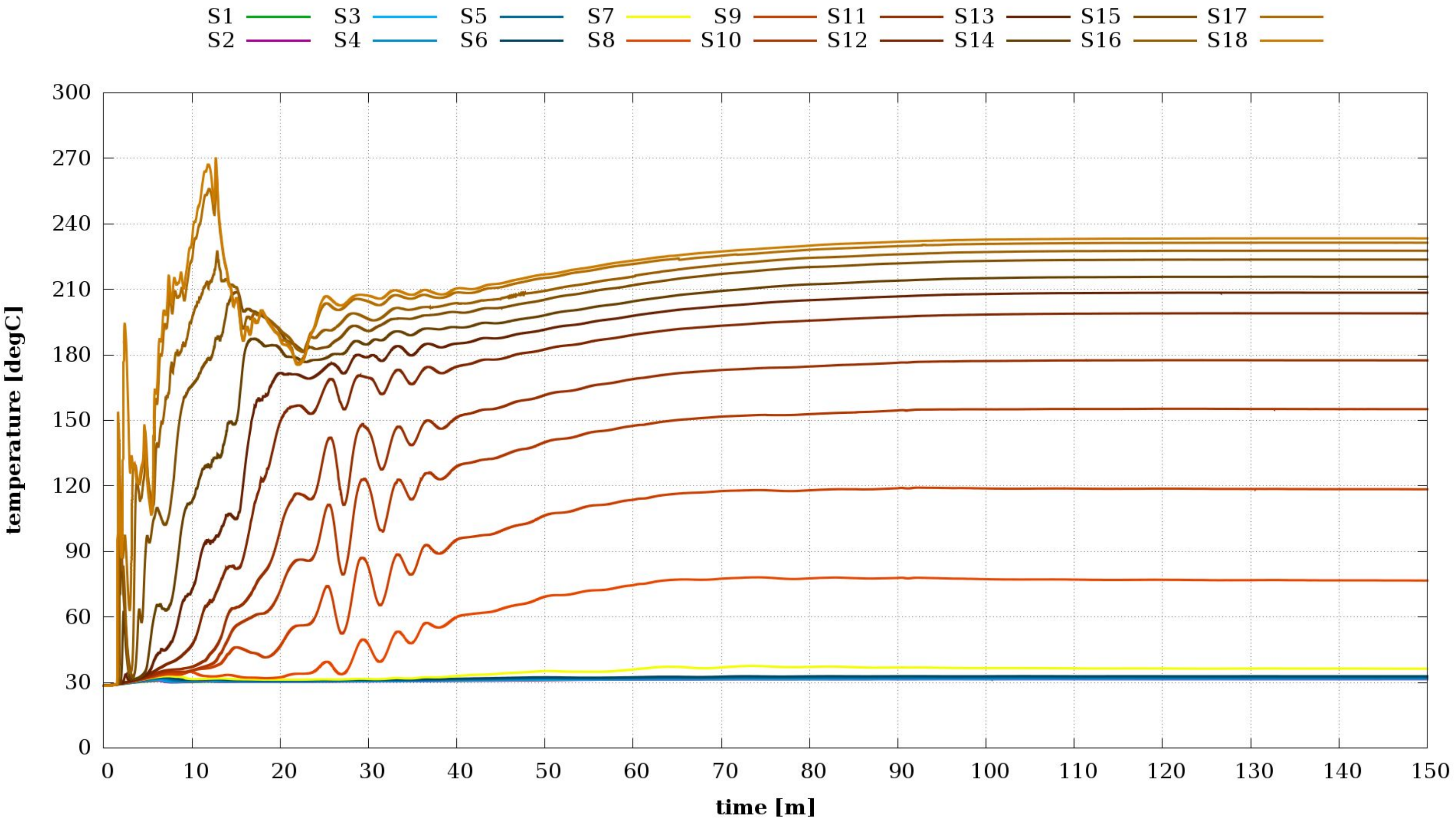
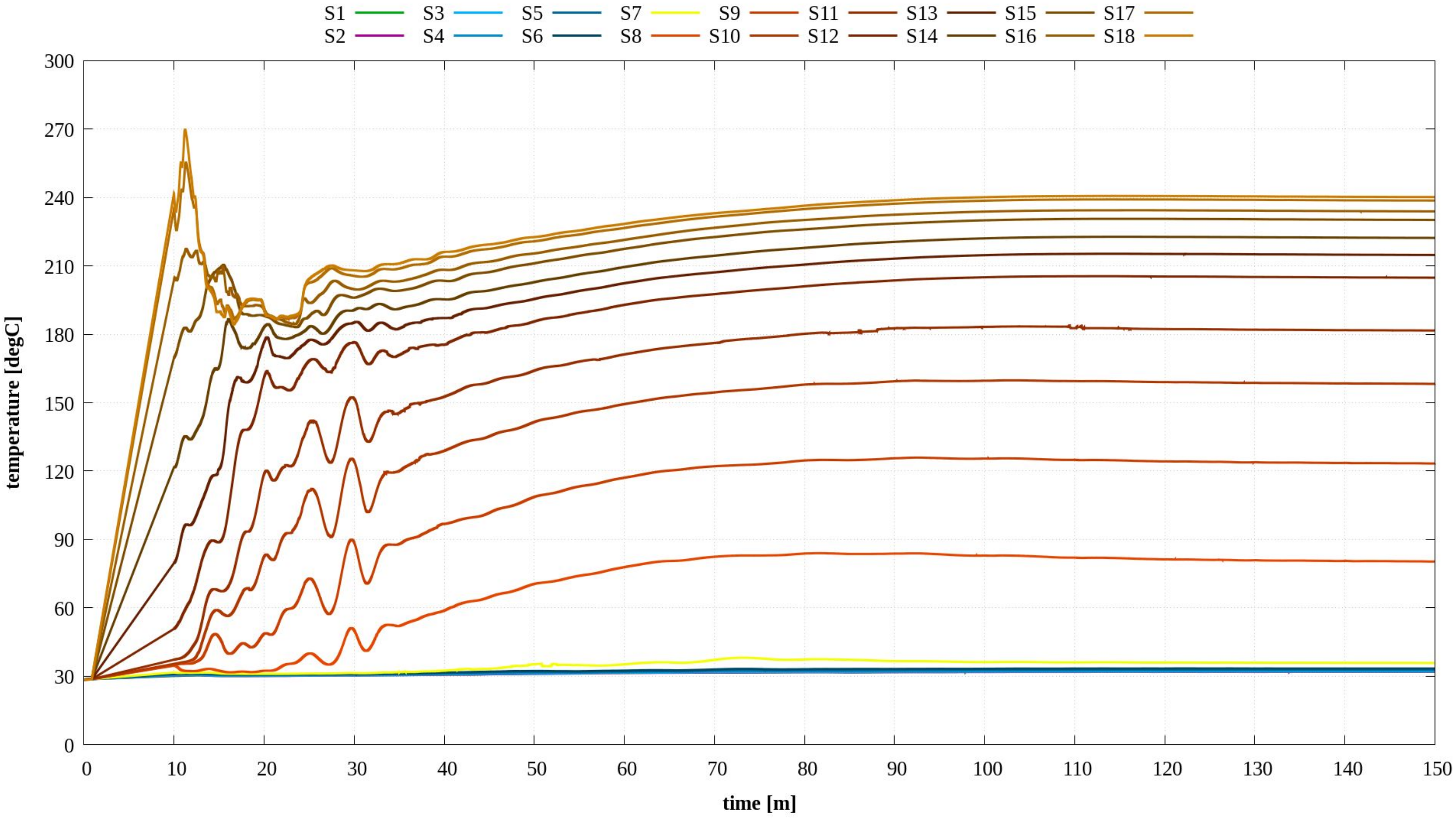
Temperature at t = 150s



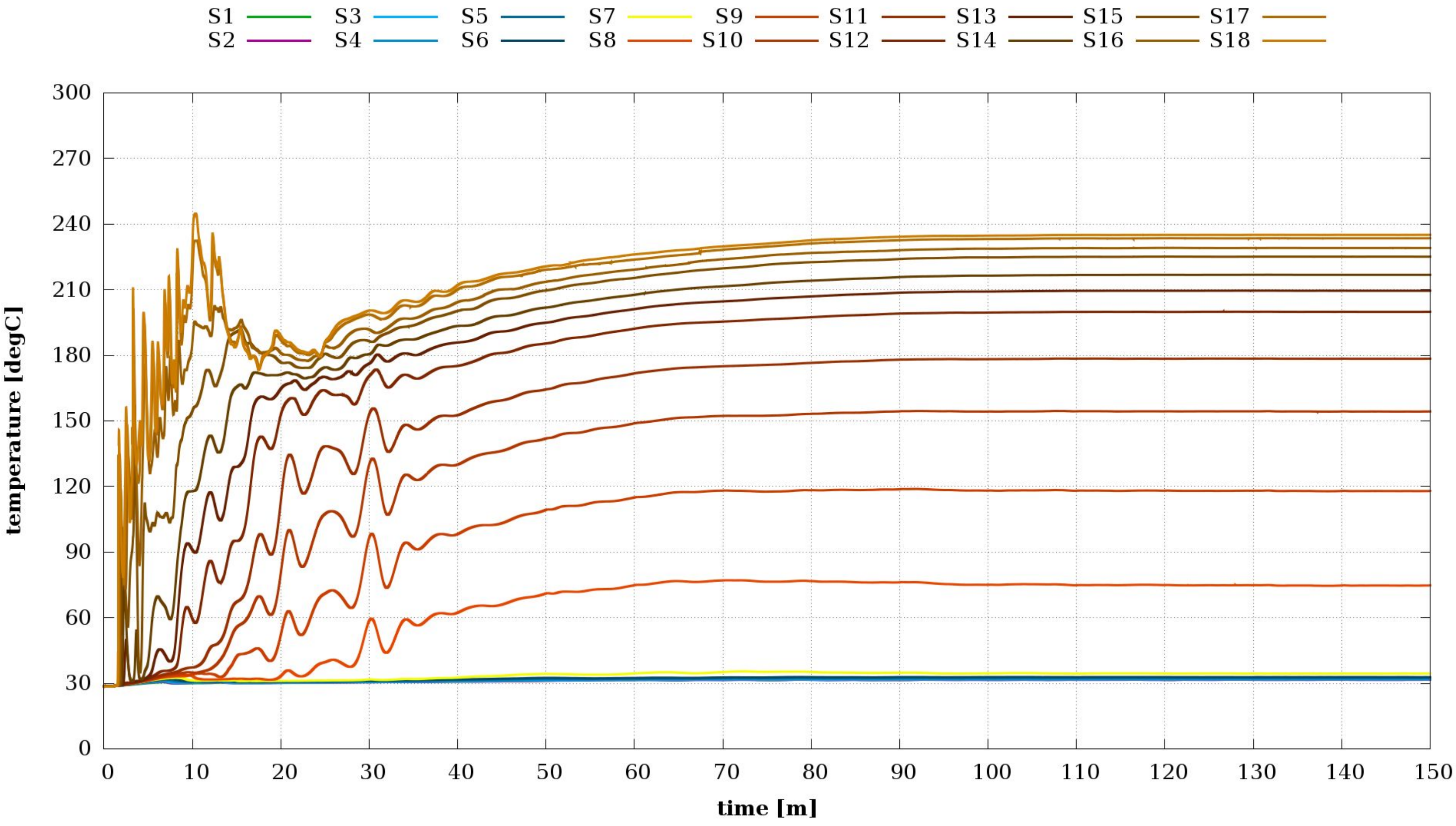
Temperature profile at door infinitelyFastCh.



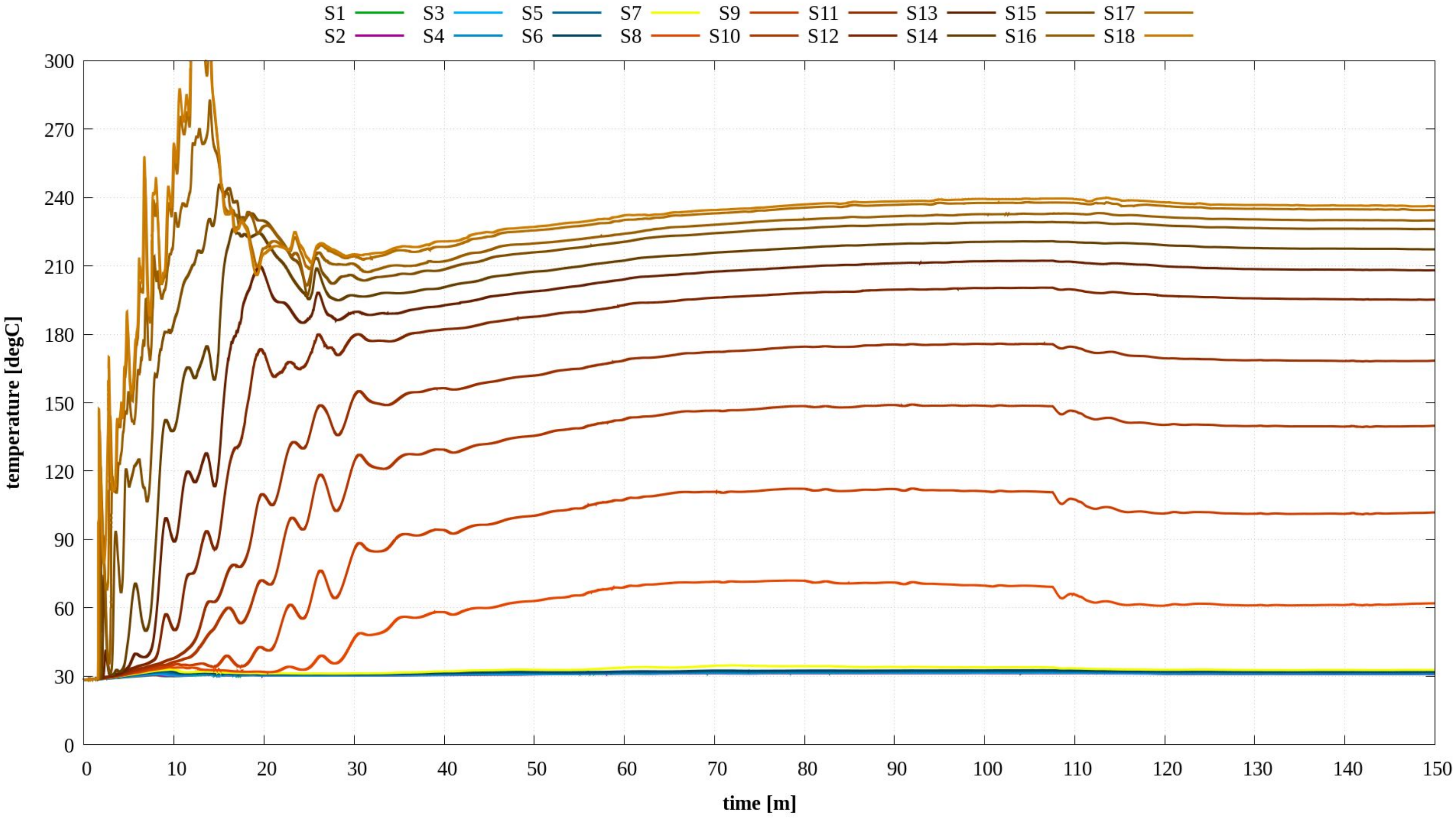
Temperature profile at door EDM



Temperature profile at door EDC



Temperature profile at door PaSR



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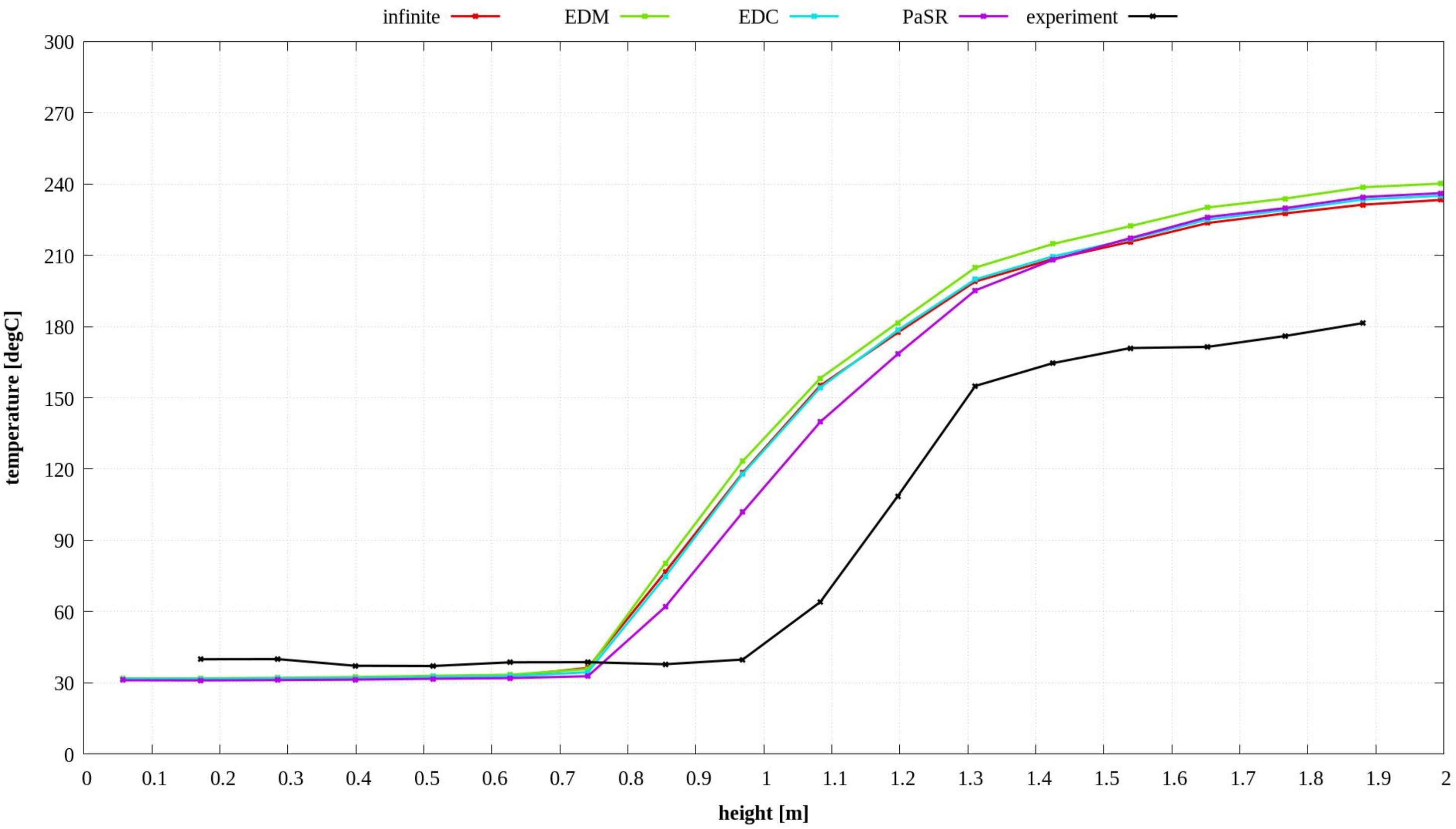
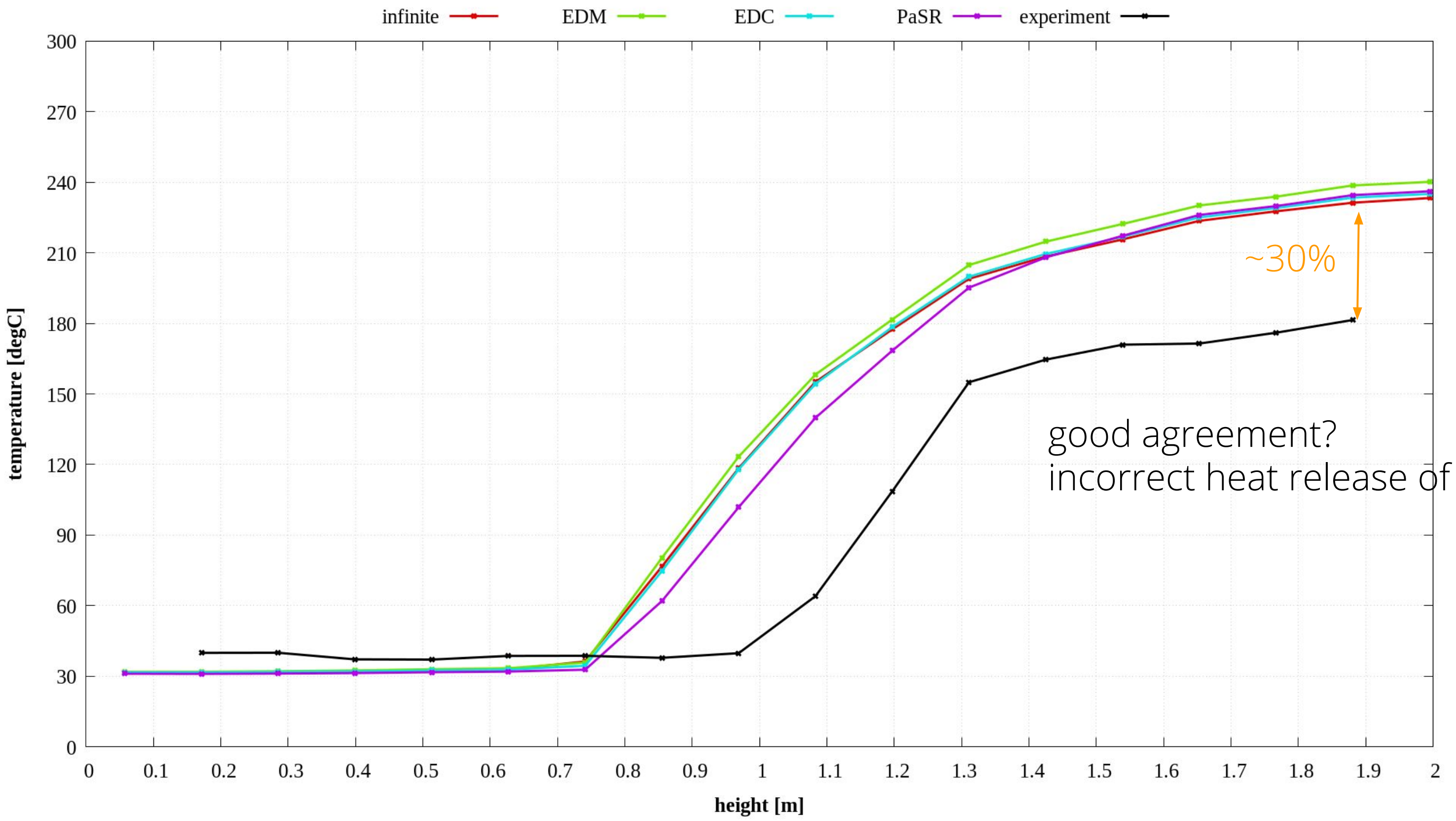


Temperature profile at door



good agreement?
incorrect heat release of 105.3 kW?

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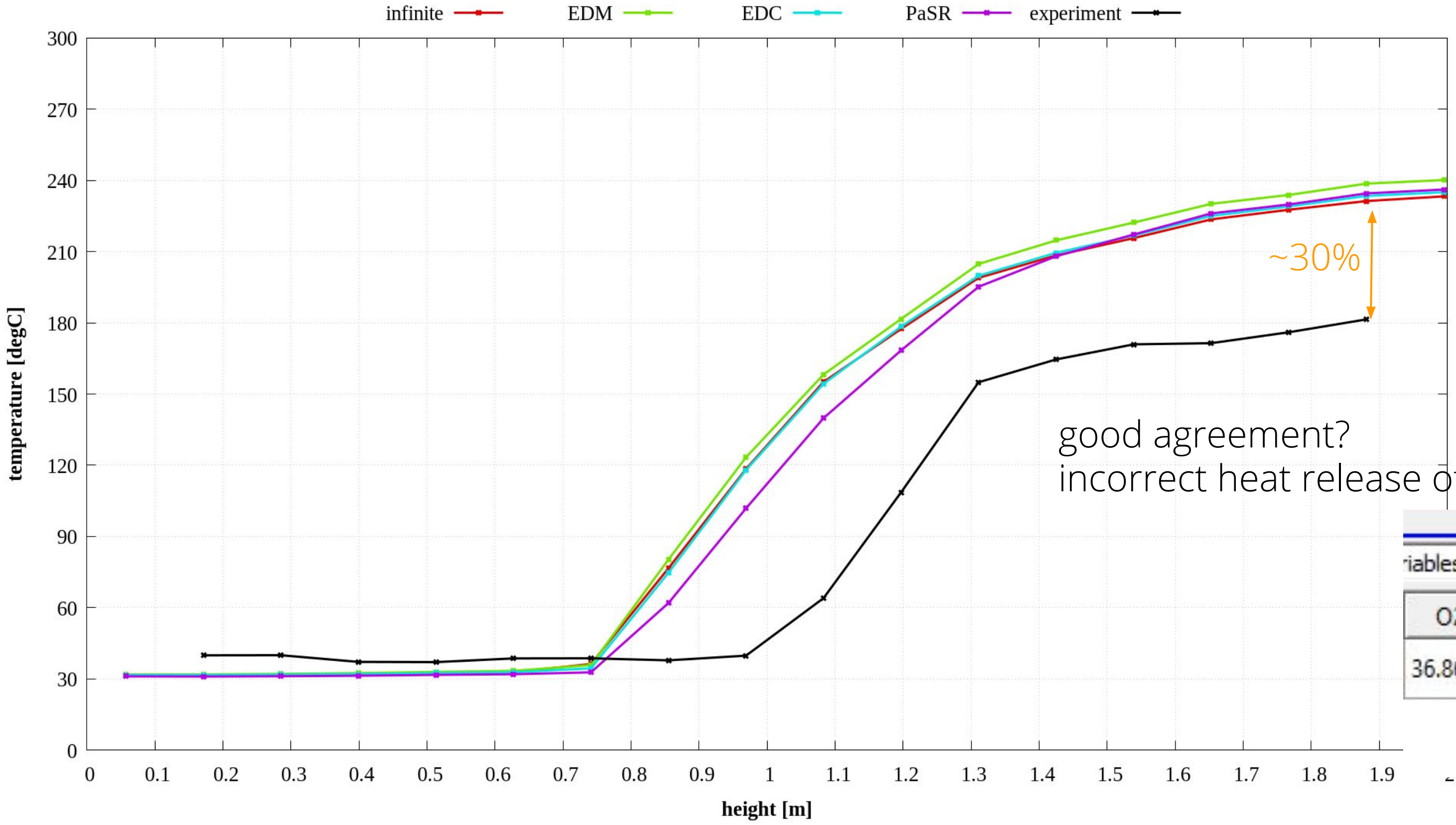

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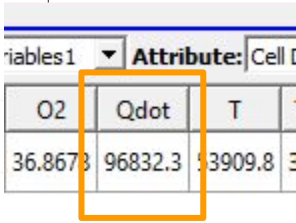

Summary

- Fire simulations in OpenFOAM
  - fireFoam
- fireFoam overpredicts temperatures
  - although heat release approximately correct
- Next step
  - test heat release via fvOptions
  - test heat release via fvOptions + conjugate heat transfer
  - conjugate heat transfer + combustion

Contact

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