CFD as an efficient design tool for wood stoves

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Expert workshop on Highly efficient and clean wood log stoves,

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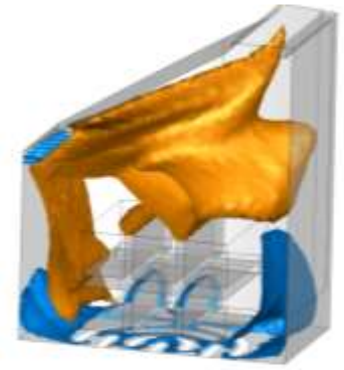
This presentation is connected to a competence building project financed by the Research Council of Norway and four wood stove producers

http://www.sintef.no/woodcfd

WoodCFD

Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches



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Outline

- Background
- Challenges
- Focus areas
- Solutions
- Results
- Recommendations
- The future

Increased sustainability

Building

Room

Stove

Fuel

Improved heat comfort
Increased wood log use

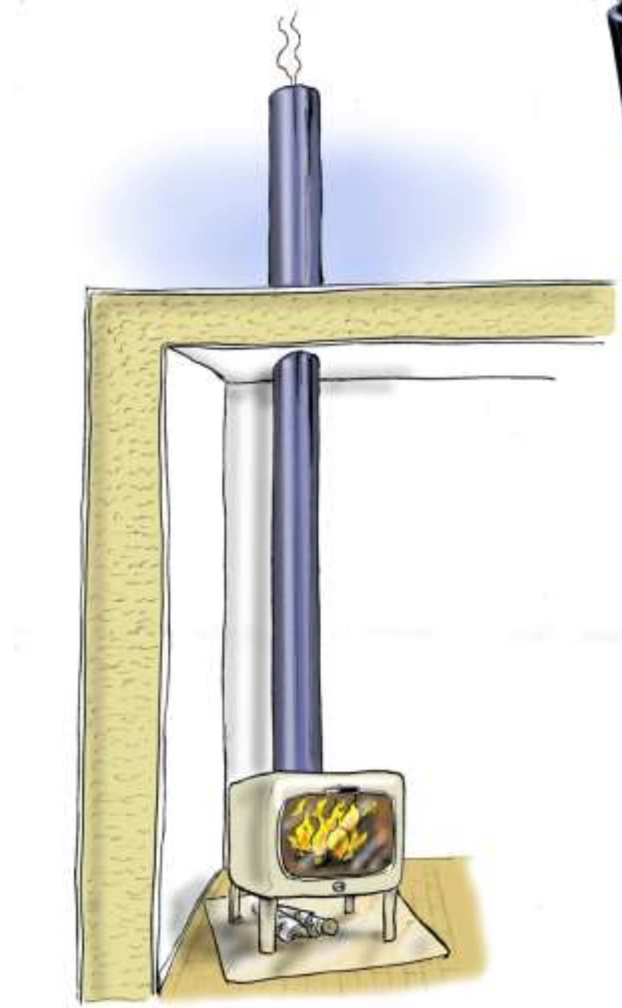
Background

- Wood log combustion in stoves is a very important domestic heat provider
- However, combustion of several large and anisotropic particles in a batch process in an appliance with limited control possibilities is indeed a challenge
- Still, emission levels from wood stoves are too high and efficiencies too low
- New energy effective houses demands less heat and are more sensitive for the typical effect peak from today's wood stoves
- Hence, the heat release must be decreased and the effect peak must be dampened, and both environmental and energetic performance must be at least maintained

Background

- Therefore, the next generation of wood stoves demands increased focus on optimum design, material use and control
- Trial and error in the lab then becomes increasingly costly, without the promise of ever finding and optimum
- The key to success will be to understand the fundamentals, apply this knowledge in a simulation based design tool, and combine it with the more traditional design process
- A Computational Fluid Dynamics CFD tool has the potential to become this simulation based design tool
- However, first a number of sub-models **with an appropriate detailing level** must be integrated in the CFD tool

Change in effect needed



WoodCFD – Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches

- **Main objective**:

  Development of clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches through:
  - **Model development**: improved transient wood log and gas release models, transient heat transfer and storage models, reduced kinetics models (NOx and soot), and transient models and approaches for heat distribution in the building; and verification of these
  - **Simulations**: transient and stationary CFD simulations of wood stoves, and room and building integration simulations; and verification of these

- Duration: 4 years (2015-18)

- Financing:
  - 4.4 MNOK/year, 17.5 MNOK total
  - Project type: NFR KPN
  - Research Council of Norway: 80%
  - Industry partners: 20% (cash)

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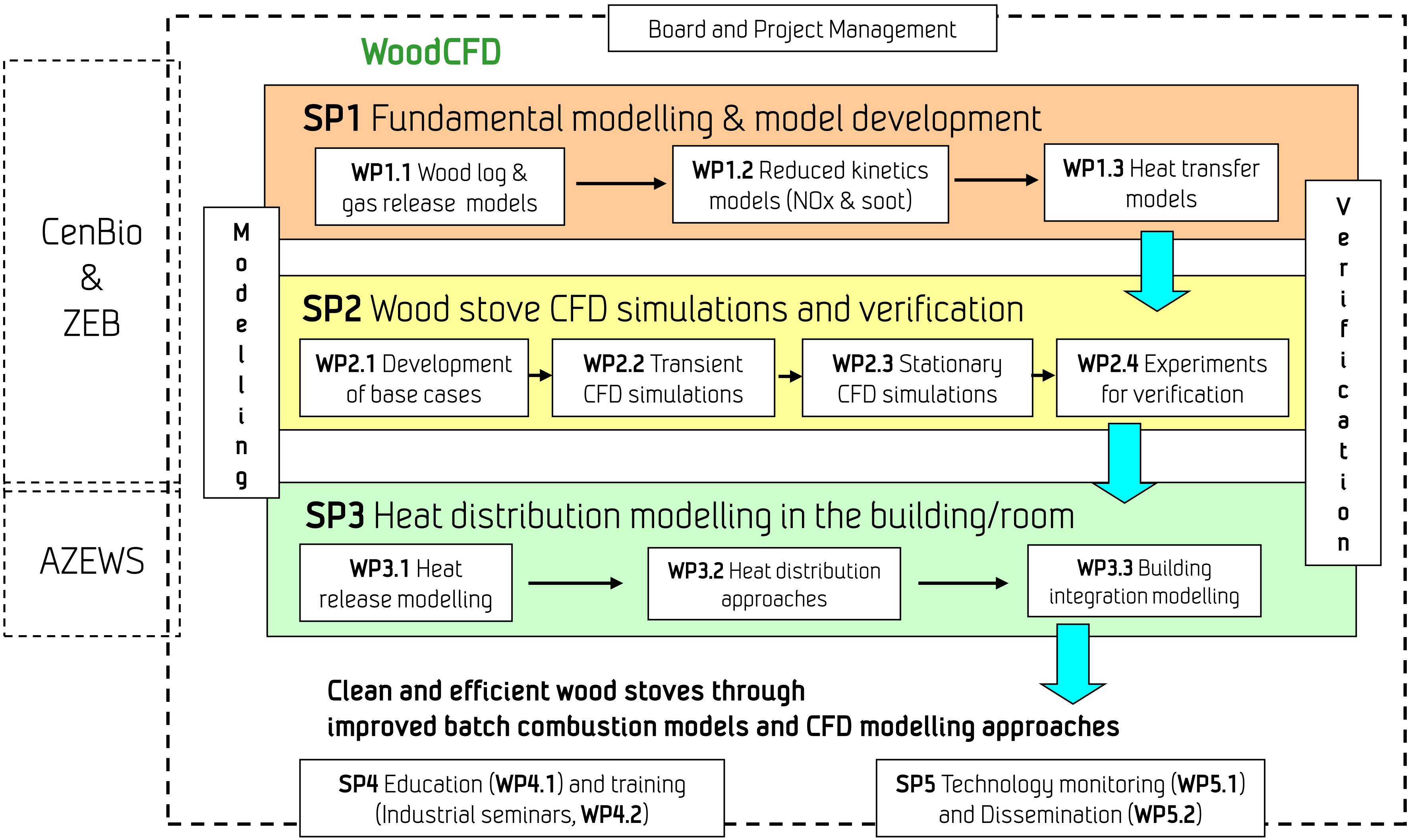
WoodCFD – Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches

Sub-objectives:

1. Develop improved sub models to be included in the CFD simulations
2. Develop a numerical tool that is suitable to study concept improvements for wood stoves and to recommend new improved concepts with respect to high energy efficiency and low emissions based on simulation results
3. Develop improved transient heat distribution models - giving reliable prediction of the effect of various heat transfer concepts in buildings and providing design guidelines for optimum wood stoves for tomorrows (energy efficient) buildings
4. Education of highly skilled candidates within this area and training of industry partners
5. Monitoring of activities and state-of-the-art within this area and dissemination of knowledge to the industry partners, and other interested parties when applicable

Project links and information flow



WoodCFD management and work break down structure and project links and information flow. (CenBio: The Norwegian Bioenergy Innovation Centre, http://www.cenbio.no, ZEB: The Research Centre on Zero Emission Buildings, http://www.zeb.no/, AZEWS: Almost Zero Emission Wood Stoves (2014-16), User-driven Innovation Project, with experimental focus on new combustion chamber concepts)

WoodCFD in perspective

New solutions and technologies for heating of buildings with low heating demand: Stable heat release and distribution from batch combustion of wood

Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches

StableWood# era (2011-14) – Broad knowledge building
- Unit sizes – typically 8 kW nominal effect
- Particulate emission levels – down to 2 g/kg dry wood
- NOx emission levels – no reduction
- Efficiency – up to 80 %
- Heating comfort – ok with 4 kW part load operation stoves with significant heat storage

Project achievements:
- Simple or initial fuel and kinetics models
- Simple fuel and walls integration into CFD model
- Phase change heat storage materials studied and tested
- Heat transfer/distribution concepts evaluated
- Simplified room/building models

Increased sustainability

Building

Room

Stove

Fuel

Improved heat comfort
Increased wood log use

WoodCFD era (2015-18) – Targeted knowledge building
- Unit sizes – typically 4 kW nominal effect
- Particulate emission levels – down to 1 g/kg dry wood
- NOx emission levels – 25% reduction by optimum air staging
- Efficiency – up to 85 %
- Heating comfort – very ok with 1-2 kW part load operation stoves with moderate heat storage

Expected project achievements:
- Advanced yet CPU effective fuel and kinetics models
- Detailed fuel and walls integration into CFD model
- Optimum heat storage concepts
- Optimum heat transfer/distribution concepts
- Advanced room/building models

www.sintef.no/stablewood

http://www.sintef.no/woodcfd

Challenges (not exhaustive)

- Transient process -"Everything" changes during the batch combustion cycle
- Often natural draft
- Wood logs are very big, inhomogeneous and anisotropic particles, of various size and shape
- Size and shape changes during the batch combustion cycle
- No standard way of loading the wood logs
- Relatively low temperature combustion process
- Cold zones/surfaces leading to flame extinction
- A fine balance between primary and secondary/window flushing air – far from stable flame conditions - rapid flame picture changes
- Varying stove thermal inertia
- Various designs, e.g. glass area
- Complex geometries and many small design details
- Emissions and indoor air quality
- ...
- **You and me, i.e. the "plant" operator**

Focus areas

- Detailed understanding of this batch combustion process
- Modelling of the fuel thermal decomposition throughout the process
- Modelling of the freeboard
- Coupling the fuel and the freeboard
- Sub-models with an appropriate detailing level
- Including the stove materials in the computational domain, including air preheating channels
- Geometry with an appropriate detailing level
- Coupling the stove with the room, thermally and physically
- Stationary CFD simulations for a certain moment in time
- Transient simulations for the complete batch combustion process
- Cost-effective simulation approaches
- Matching stoves with rooms/houses for optimum thermal comfort
- CFD simulations of the room

Solutions

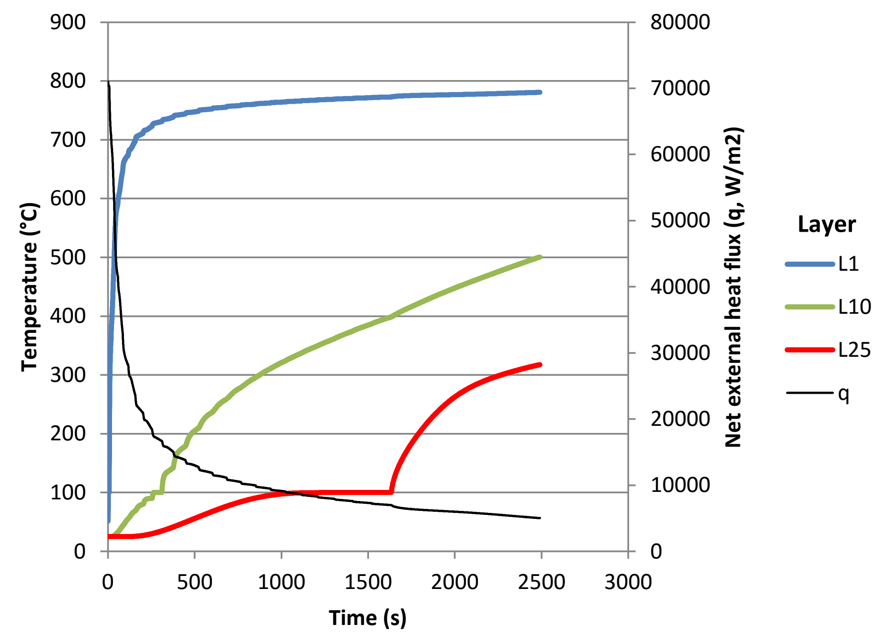
- Design simplifications needed – not possible to include all details - which design details can be left out without sacrificing too much accuracy?
- A fuel conversion model able to predict the transient and directional mass release and speciation into the gas phase computational domain
- Kinetics models able to describe the conversion of these species to final products/emissions, which is closely coupled with air addition, oxygen availability and local temperatures
- Applying appropriate models for soot formation and combustion, turbulence and turbulence-chemistry interaction and radiation
- Accounting for changing fuel geometry
- Appropriate boundary and initial conditions

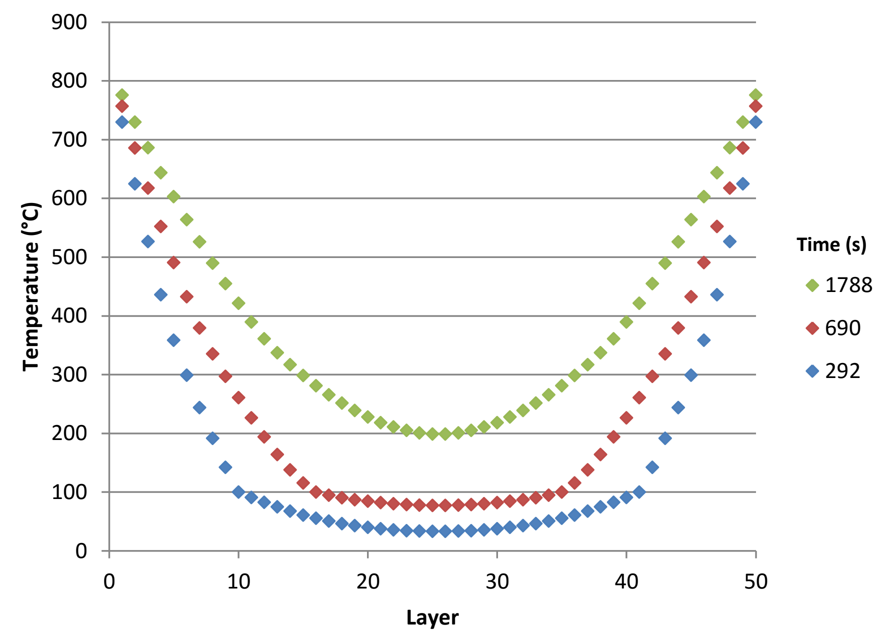
Solutions

- Fuel - "easy" approach
  - Drying, devolatilization and char gasification/combustion lumped into a black box model: Simple speciation (gas phase) and temperature based on elemental composition and experimental data, and satisfying an energy balance. Flow rate based on mass loss rate and "total" surface area
- Fuel - needed approach
  - Transient modelling (with verified models) of real wood logs of drying, devolatilization and char gasification/combustion: Expanded speciation (including tar) and temperature based on instantaneous elemental composition and kinetics, and satisfying an energy balance. Flow rate based on mass loss rate and "real" surface area

Solutions

Fuel





Example of temperature evolution as a function of time and position (layer) for a single wood log

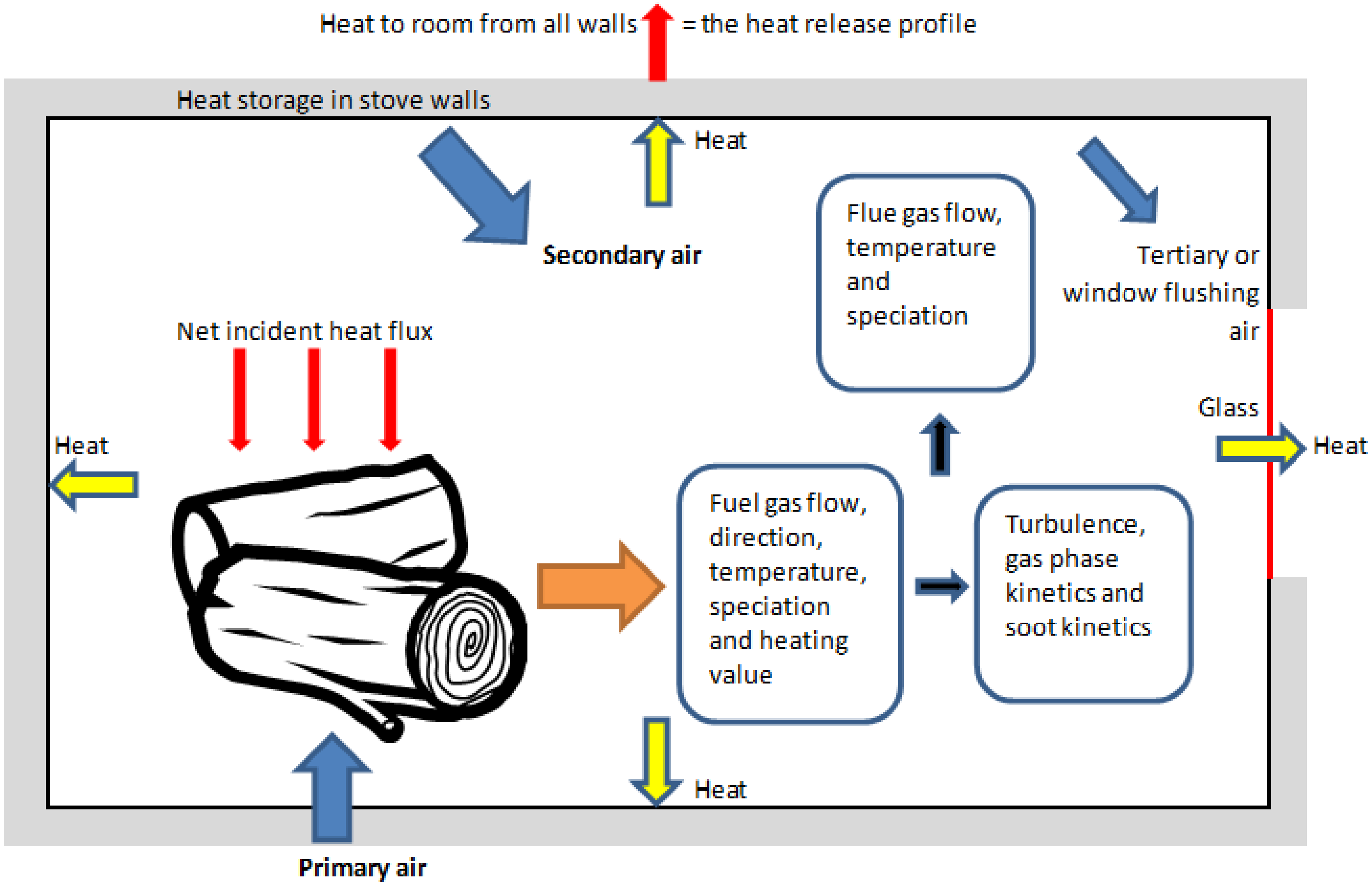
Several wood logs in a batch, with individual behavior

Solutions

- Freeboard - "easy" approach
  - Simple/standard turbulence model
  - Simple gas combustion modelling: mixed is burnt or global kinetics
  - Simple soot model
  - Simple radiation model
- Freeboard - needed approach
  - Improved turbulence model
  - Advanced gas combustion model: detailed chemical kinetics, including tar kinetics
  - Better soot model
  - Better radiation model

Solutions

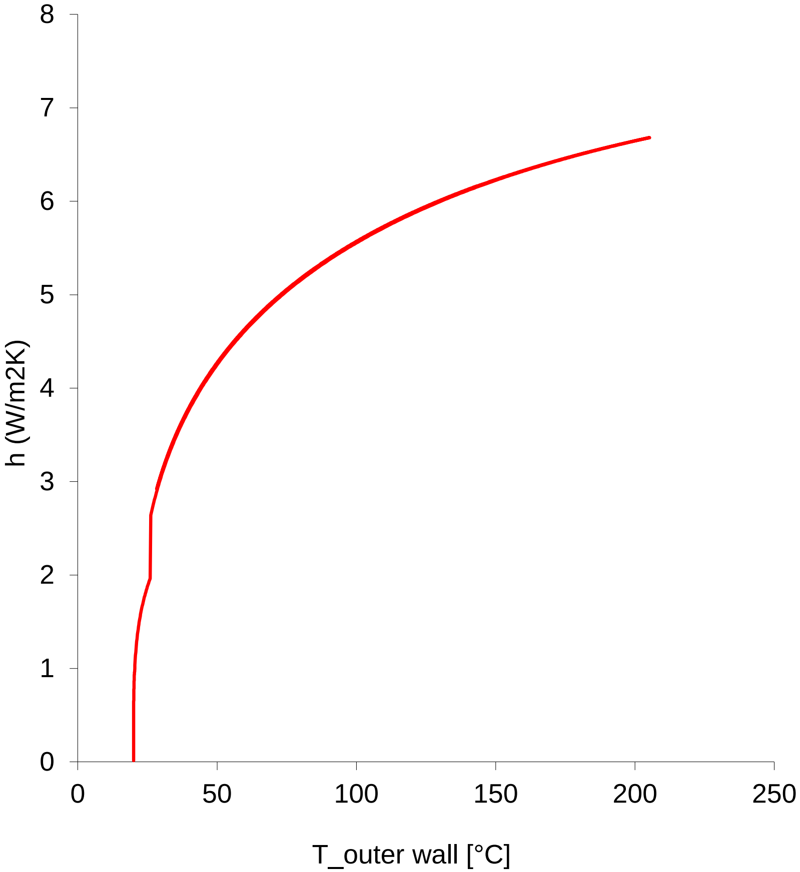
CFD + sub models

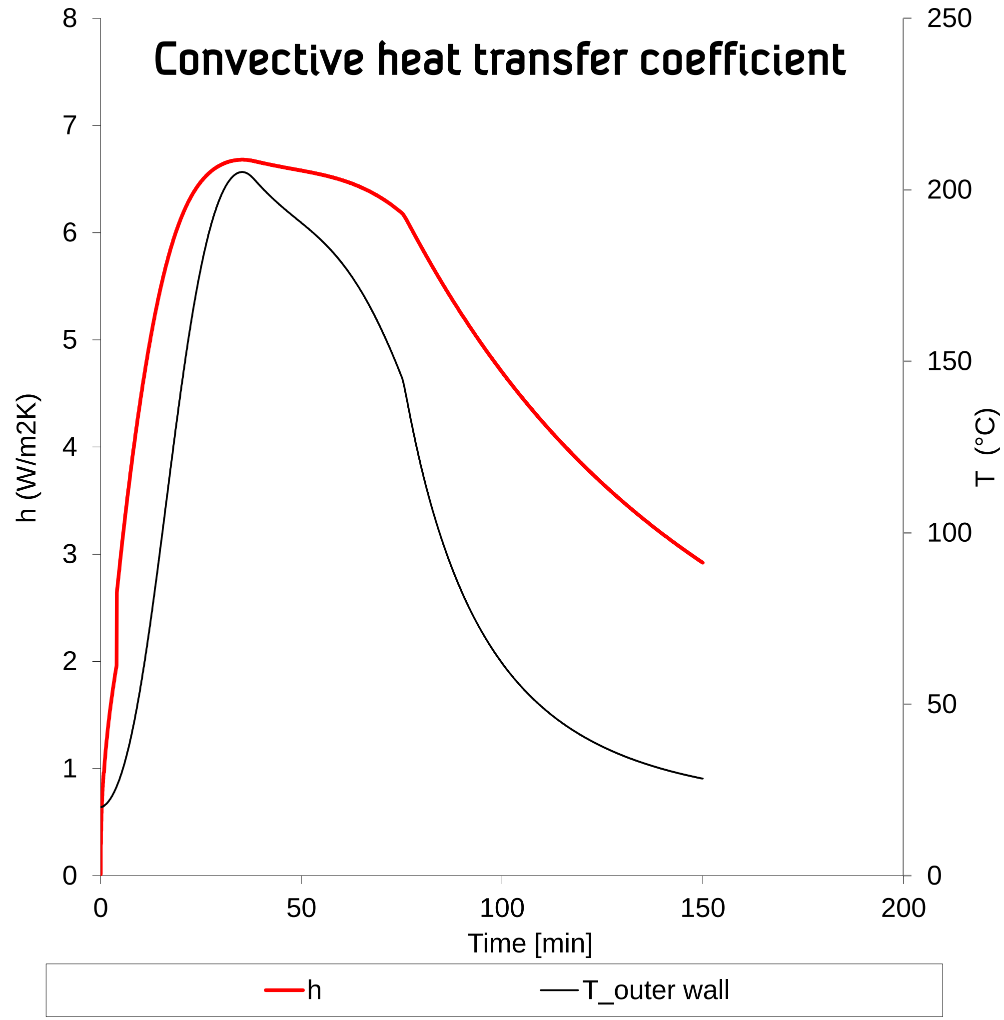


Øyvind Skreiberg, Morten Seljeskog, Laurent Georges (2015). The process of batch combustion of logs in wood stoves - Transient modelling for generation of input to CFD modelling of stoves and thermal comfort simulations. Chemical Engineering Transactions 43:433-438.

Solutions

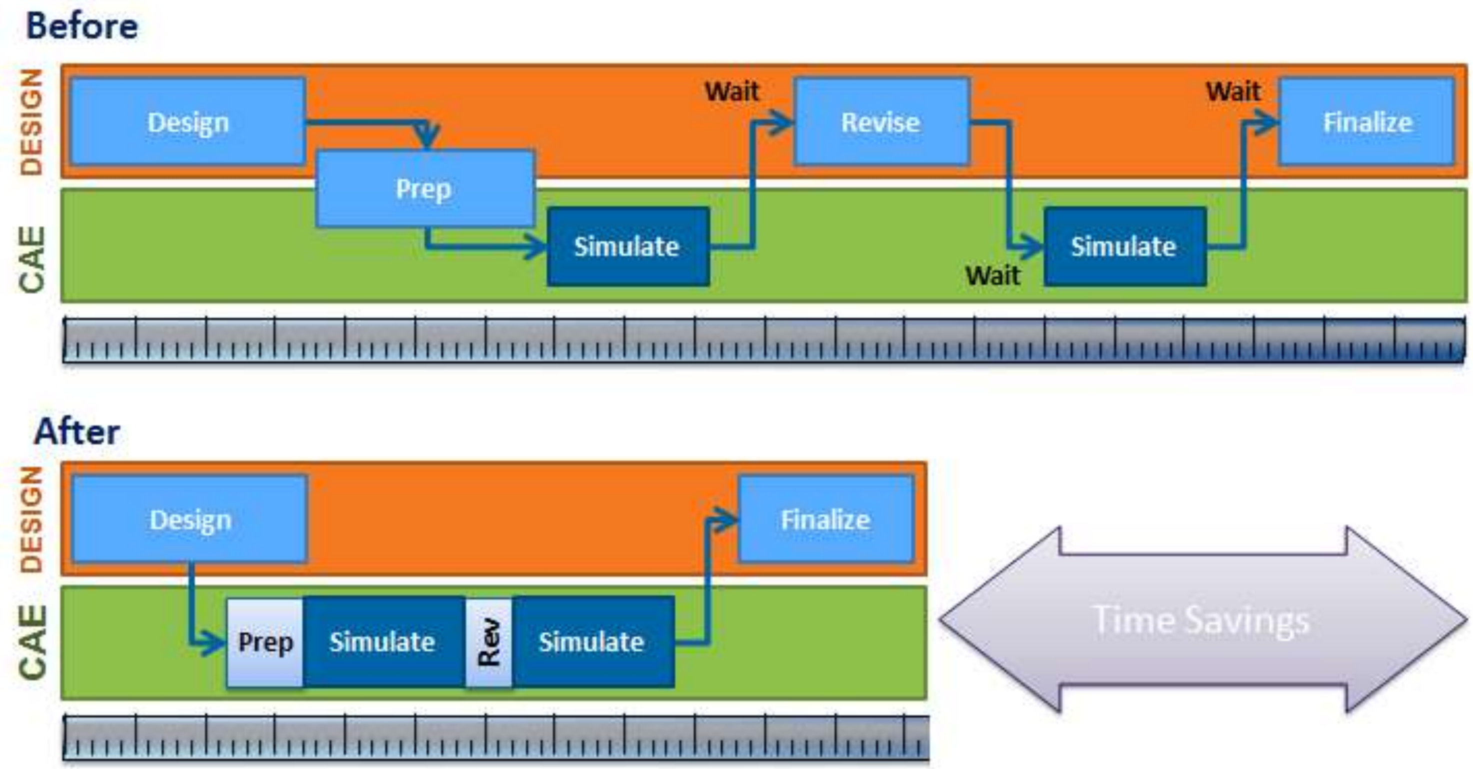
- Boundary conditions
- Initial conditions





Solutions

- Woodstove Computer-aided engineering (CAE)
- Stove and design simplifications
- Optimizing 3D model for CFD



Solutions

The Problem

- Production-level geometry can contain gaps, interferences, fasteners, and very small features. These features are often necessary for manufacturing, but can add unnecessary complexity for simulation.

The Solution

- To save time and computer resources, eliminate these features if they are too small to affect the results of the simulation.
- For large assemblies, consider analyzing only critical portions of the design. This can accelerate the analysis process.
- In some cases, it is faster to create a new, simpler version of your design to focus on the key areas of study.

Steps you should always take to prepare the geometry:

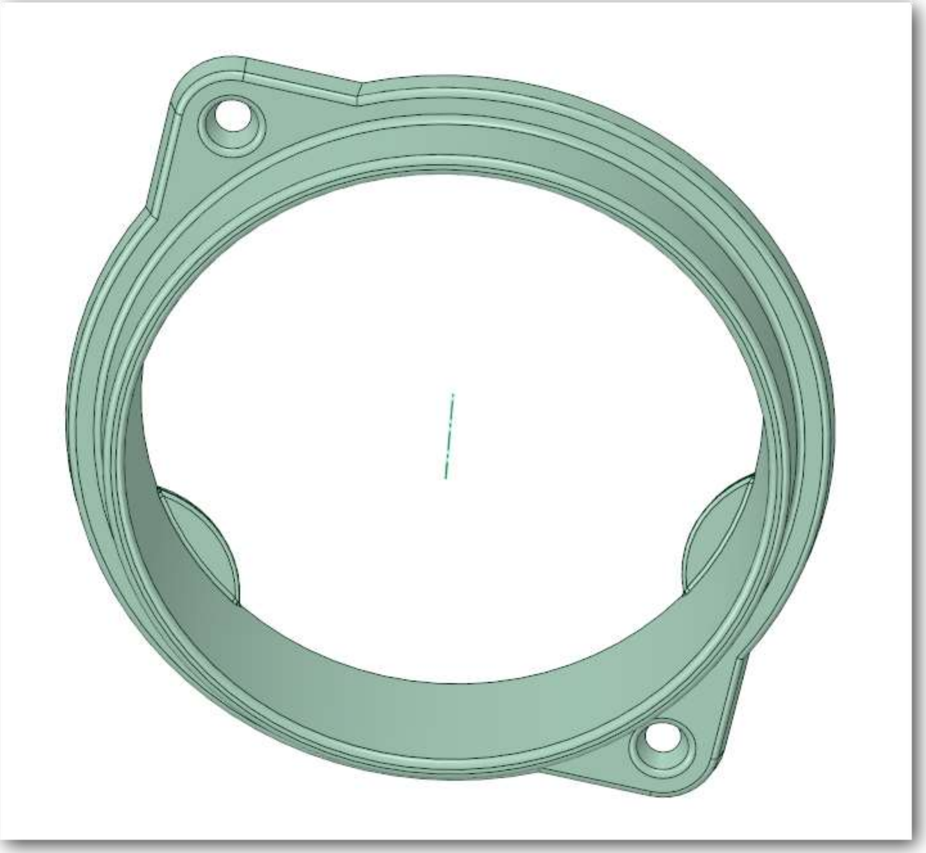
- Eliminate gaps that prevent void filling. These include clearances between parts, sheet metal reliefs, and fastener holes.
- Eliminate fasteners that do not impact flow or heat transfer.
- Reduce very large assemblies to include only vital components.
- Eliminate interferences. Examples include press-fits and improper mates.
- Ensure the void is watertight.

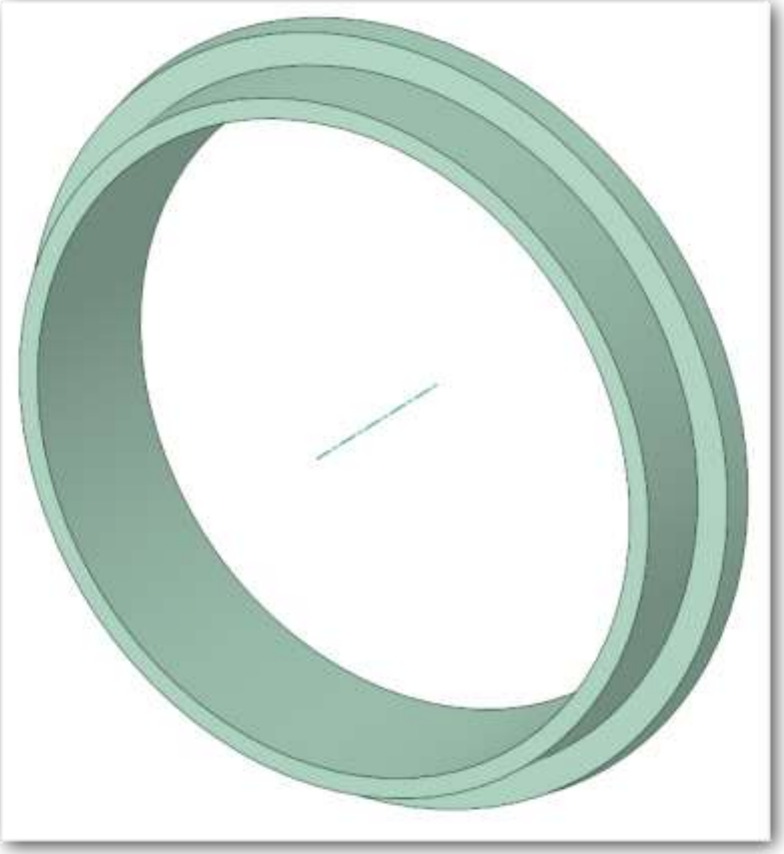
Steps to help reduce the analysis time:

- Eliminate very small features that do not affect the analysis results (Small fillets, chamfers and very small parts).
- Fill small gaps in the flow region that are not important.

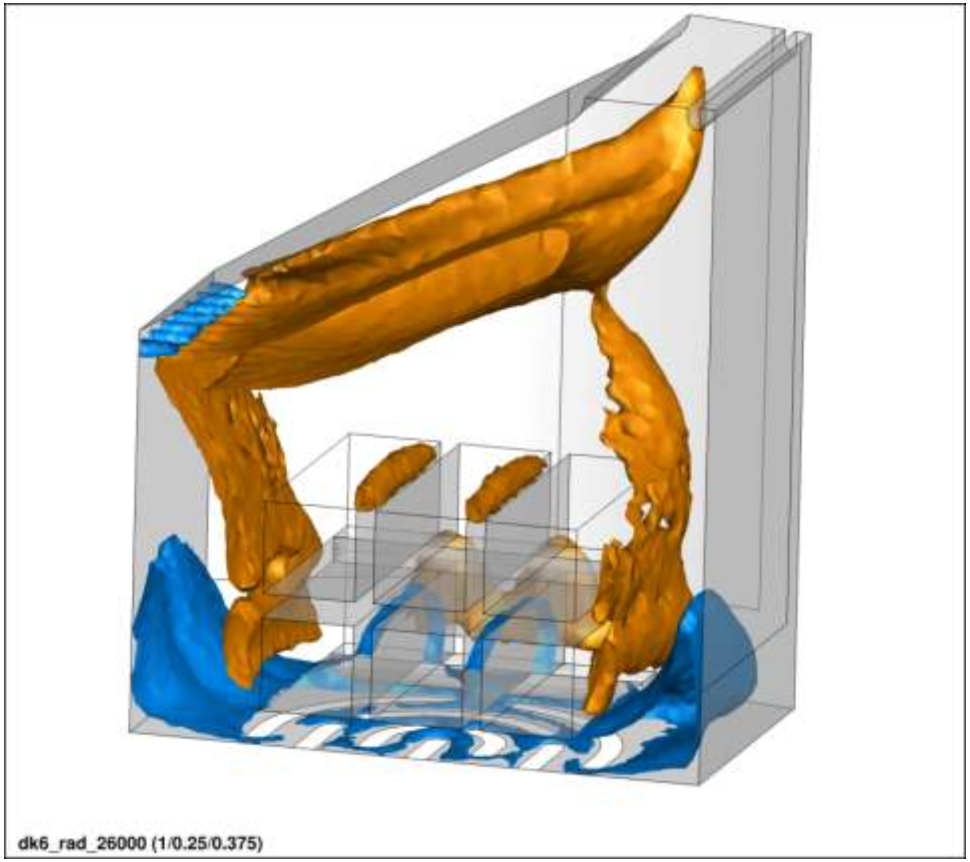
Solutions

Simplification - of design details not significantly influencing the phenomena to be simulated





Results

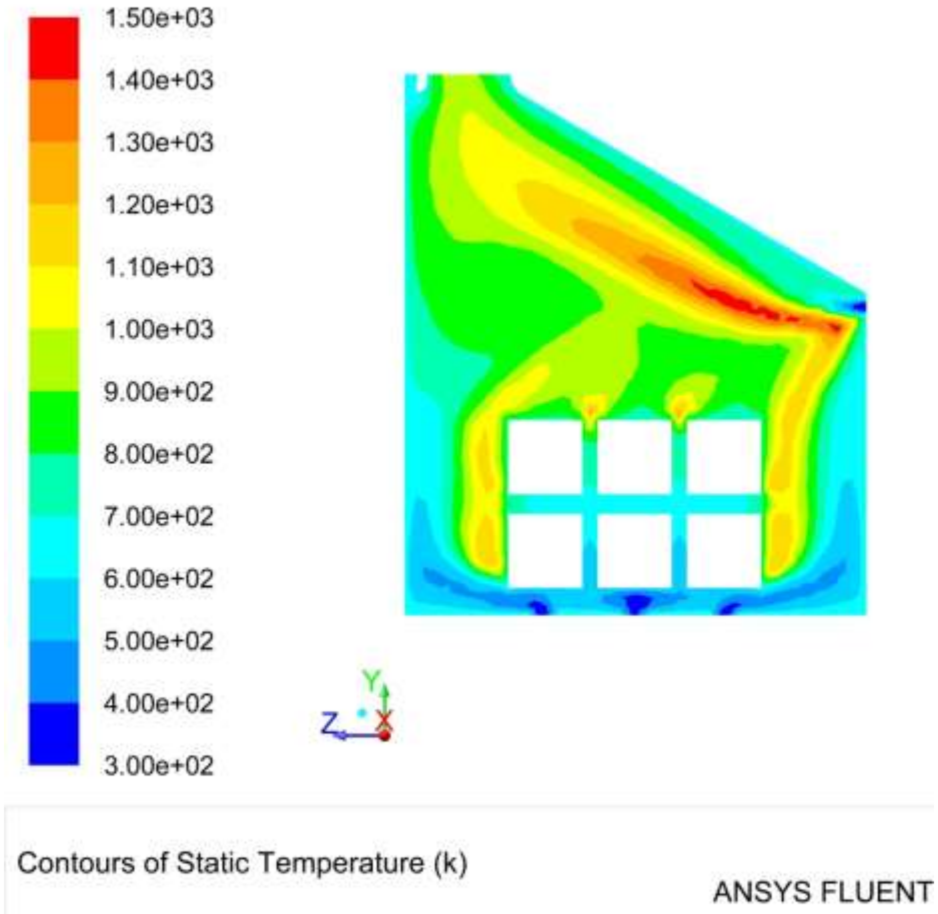


- Symmetry boundary
- kε - realizable turbulence model
- Radiation: Discrete ordinates method
- Soot: Moss & Brookes model
- EDC-model with finite rate chemistry
- 3 different chemical reaction mechanisms developed for biomass combustion (Løvås et al. 2013)
  - **81 species**
  - **49 species**
  - **36 species**

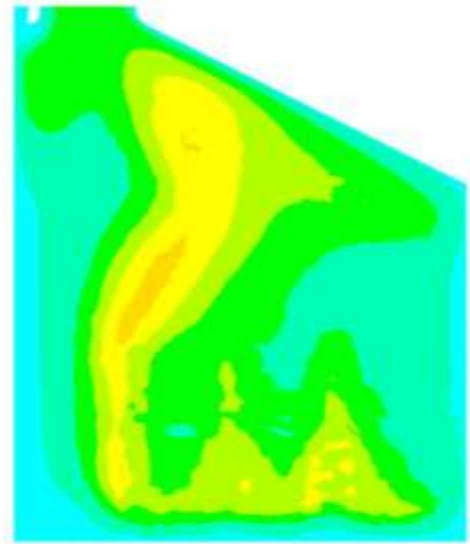
Mette Bugge, Øyvind Skreiberg, Nils E. L. Haugen, Per Carlsson, Morten Seljeskog. Predicting NOx emissions from wood stoves using detailed chemistry and computational fluid dynamics. Energy Procedia 75:1740-1745.

Results

Symmetry boundary T



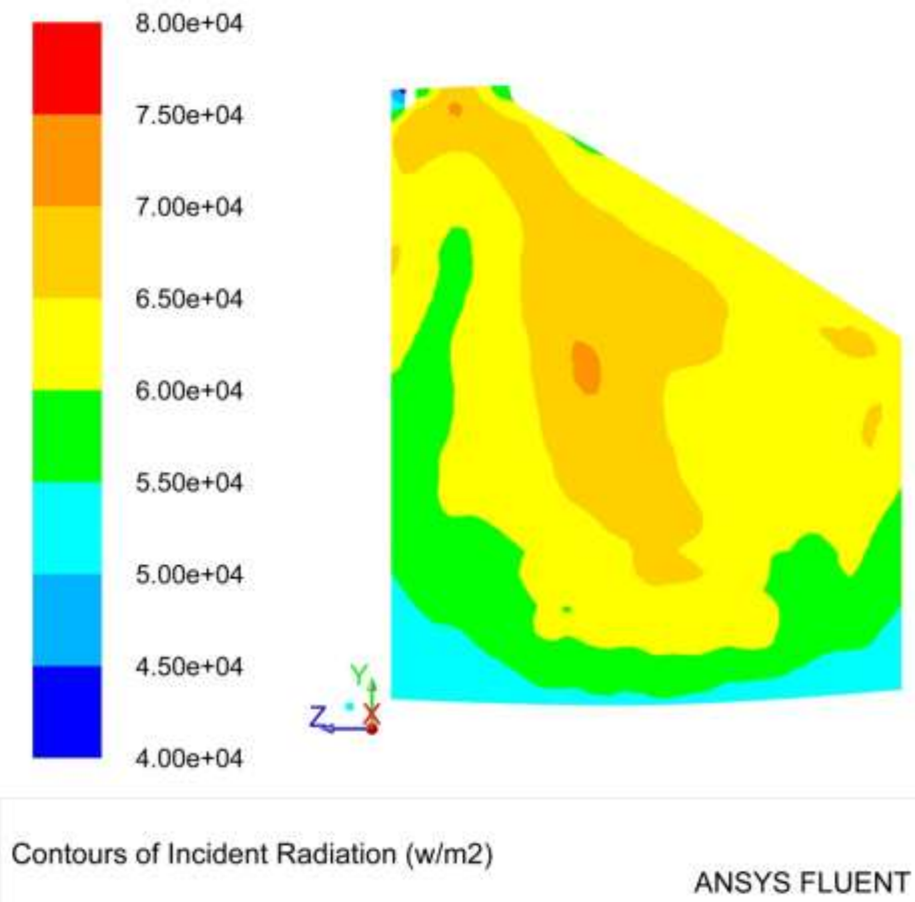
Close to side wall T



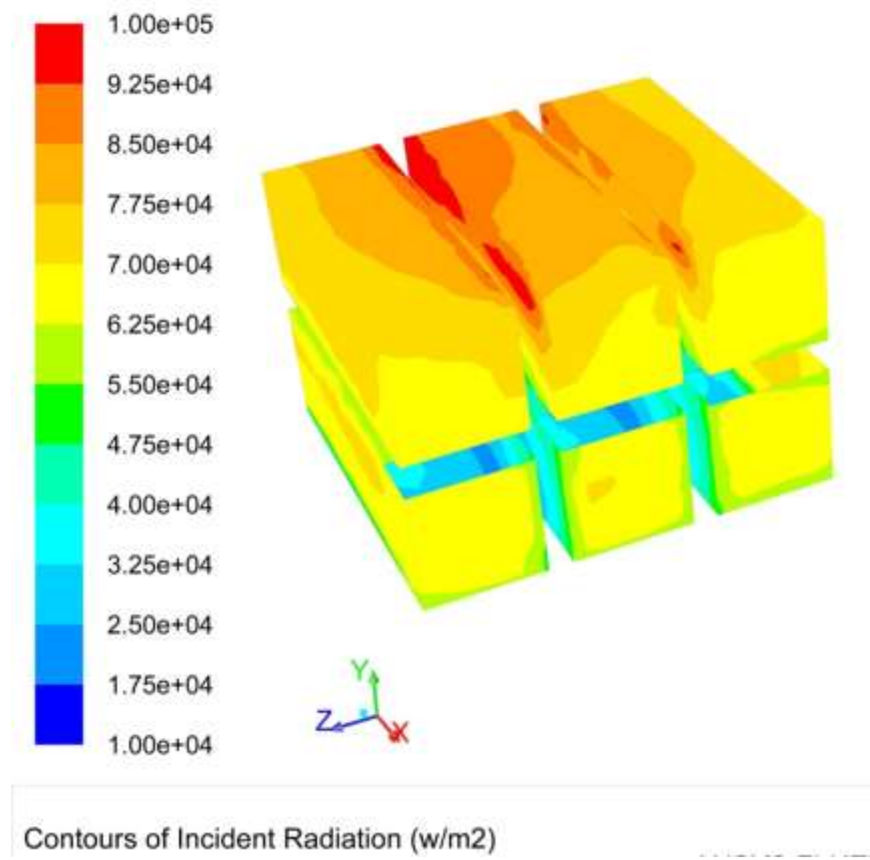
36 species mechanism

Results

Radiation flux on side wall



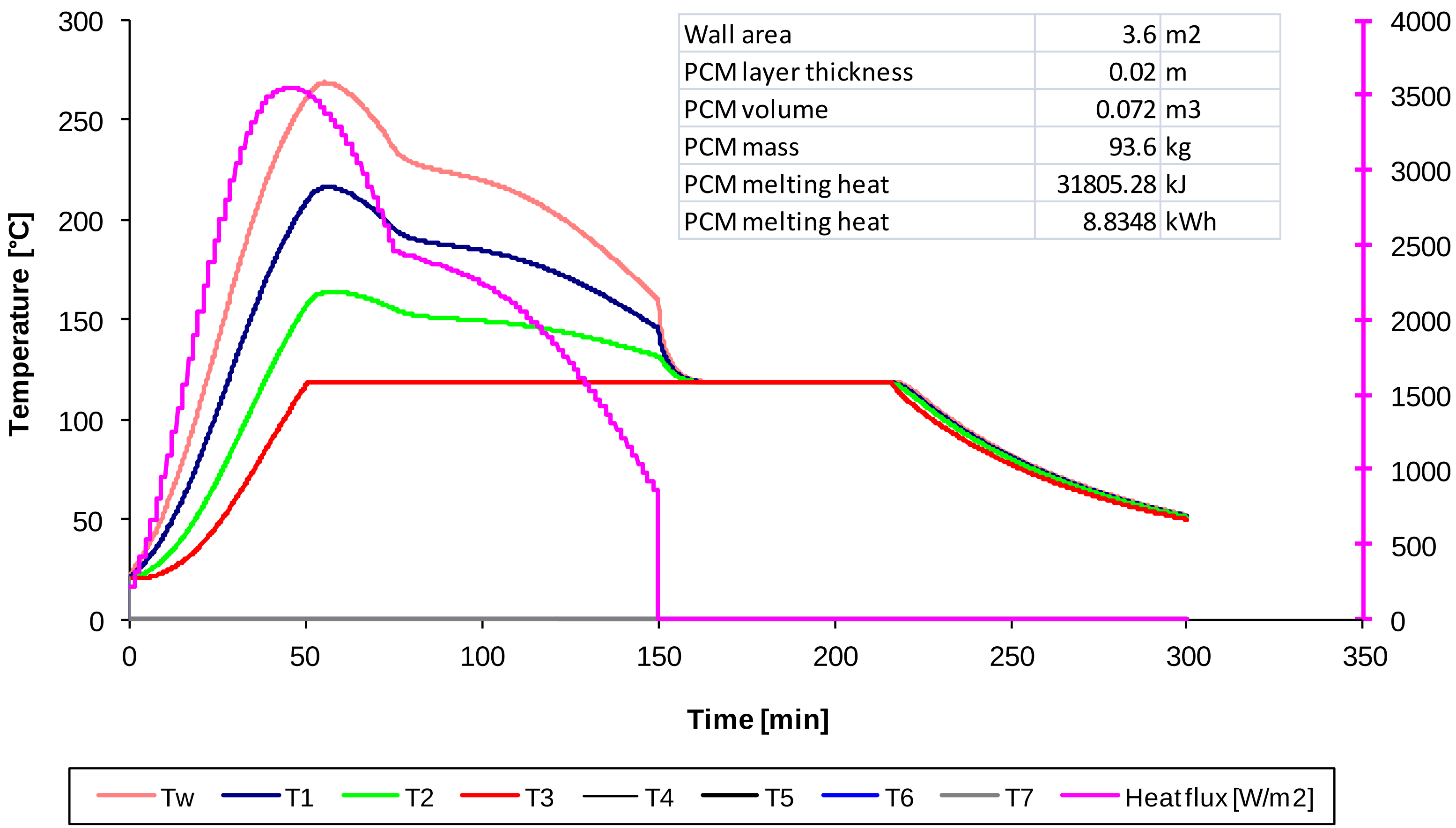
Radiation flux on fuel



Results

Use of heat storage materials (incl. phase change materials)

Phase change material - Erythritol, 20 kWh, 8 kW net effect, 85% efficiency



Wall area	3.6	m2
PCM layer thickness	0.02	m
PCM volume	0.072	m3
PCM mass	93.6	kg
PCM melting heat	31805.28	kJ
PCM melting heat	8.8348	kWh

Recommendations

- Computational time is valuable
- Put serious efforts into design simplifications and gridding
- A good enough devolatilisation model, and including the single wood logs in the CFD domain
- Good enough gas phase models
- Special focus on soot, which becomes increasingly important as the stoves get lower emissions
- Include the stove materials, also the glass, into the computational domain and make sure that the boundary conditions are well defined
- Use two sets of models, for transient and stationary simulations
- Remember that a wood stove is a heating device integrated in a room/building!

The future

- CFD as an efficient design tool for wood stoves
- Stoves with elegant, but effective design
- Downscaled stoves and stoves with increased thermal inertia
- Energy efficient buildings and warmer climate
- Standardized combustion chamber, with design variations around it
- More focus on proper air staging, even two chamber solutions
- More robust stoves with respect to user interference and malpractice
- Smarter solutions with respect to heat storage and transfer
- Tighter emission limits
- Tougher approval tests
- More focus on indoor air quality
- Tougher competition with hydronic systems, pellets, solar and heat pumps
- More comfort aware consumers

Acknowledgements

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Thank you for your attention!

The Research Council of Norway

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