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SINTEF

Simulation of the Indoor Thermal Environment of Passive Houses heated using Wood Stoves

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ZEB The Research Centre on Zero Emission Buildings

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

FME CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Space-heating in Norway

- Wood stoves:
  - Cover 20% of the space-heating needs of residential buildings stock
  - Half of the bioenergy use (decision to double bioenergy use in 2020)
  - The highest installed power after hydroelectricity
  - **Wood stoves have a role play in the future**

- Building concepts and regulation:
  - Currently the TEK10 building regulation is into force
  - The Norwegian Passive House (NS3700) standard seen as a basis for the next TEK15 building regulation
  - In 2020, all new building should be *nearly-zero energy* (nZEB)
  - R&D on *zero emission building* (ZEB) within the Norwegian ZEB FME center
  - **We can conclude that future buildings envelopes will be highly-insulated**

Integration of wood stoves in passive houses

- Challenge on **Indoor Air Quality** (IAQ):
  - Airtight building envelopes equipped with balanced mechanical ventilation
  - The stove envelope should be airtight (need a standard test method)
  - Independent air circuits for combustion air and flue gas removal
  - Lack of measurements on IAQ using wood stoves in highly insulated buildings (work of Ricardo Luis Carvalho from DBRI)

- Challenge on **Indoor Thermal Environment**:
  - Nominal Power wood stoves (Pn) is oversized for passive houses
  - 6-8 kW for pellet stoves and 4-8 kW for wood-log stoves
  - 160 m^2 detached passive house has ~3kW space-heating power for Oslo climate in design weather conditions (i.e. cold wave)
  - The wood stoves should operate on long combustion cycles (> 45 min) to get good efficiency and limited emission of pollutants
  - Risk of overheating in the room where the stove is placed
  - But potential to simplify space-heating distribution using wood stoves

Physical phenomena: many parameters

- **Building physical parameters**:
  - Building geometry and geographic location (e.g. climate)
  - Importance of internal and solar gains in passive houses
  - Thermal insulation of external walls as well as partition walls
  - Thermal mass as wood stoves are oversized (no steady-state regime)
  - Balanced mechanical ventilation with heat recovery
  - Buoyancy driven flow through open doors inside the building (bidirectional flow with airflow rates well higher than hygienic ventilation)
- **Stove physical parameters**:
  - Nominal combustion power (Pn) and efficiency
  - The combustion cycle length for pellet stoves
  - The amount of wood logs and the batch combustion dynamics
  - Power modulation capabilities and control
  - Thermal properties of the stove envelope:
    - Flatten the heat release profile to the room (stove thermal mass)
    - Ratio between power emitted by radiation and convection

- **Need for sensitivity analyses at acceptable computational cost**

Physical phenomena: many timescales

- A large spectrum of timescales (τ) are involved, a challenge for the time integration using numerical methods:
  - Natural convection with unsteady flow ($\tau < 1$min)
  - Stove combustion control such as power modulation ($\tau < 1$min)
  - Length of one batch combustion cycle ($\tau > 0.75$h to 3-4h)
  - Time constant of highly-insulated building envelopes ($\tau \sim$ days)
  - Boundary conditions of the building changing throughout the year:
    - Outdoor temperature
    - Solar irradiation
    - Internal gains and user behavior

- Need to perform simulation with small time steps
  - Ideally, all-year simulation at acceptable computational cost
  - Most critical operating conditions during the heating season but not well-established for Norwegian passive houses

Physical phenomena: thermal comfort

- Thermal comfort can be complex to assess: for instance
  - Local air temperature, vertical temperature stratification
  - Mean radiant temperature (Tmrt)
  - Local air velocity
  - Radiant asymmetry: need local thermal comfort assessment near the stove (on different body segments)
  - Direct radiation from the combustion chamber

- Recent study showed
  - From *Ghali et al., Building & Environment, 2008*
  - Far from the stove, a global thermal comfort assessment should be enough as regards the radiation asymmetry

- Propose to evaluate the thermal comfort based on ISO 7730 far from the stove and neglect direct radiation from combustion chamber (using the operative temperature, Top)

Modeling (1): Thermal Dynamic Simulations

- Example: TRNSYS, IDA-ICE, ESP-r or EnergyPlus
- Advantages:
  - Develop to solve **multi-physical** and **heterogeneous** problems
  - Acceptable computational time for all-year simulations and thus possibility of sensitivity analyses
  - Building modeled like a thermal network, usual approach in BPS

- Limitations:
  - Room air modeled using a single node (well-stirred tank approximation)
  - Vertical division possible if the airflow from convection between vertical layers known
  - Flow within a zone is not known
  - Flow between zones computed using a *ventilation network approach*
  - Bidirectional flow through door using a *large opening approximation* (introducing a discharge coefficient, Cd)
    - The IEA Annex 20, *Airflow in Buildings*, showed that the vertical stratification is important to get the right exchange of heat between rooms

Modeling (2): Computational Fluid Dynamics (CFD)

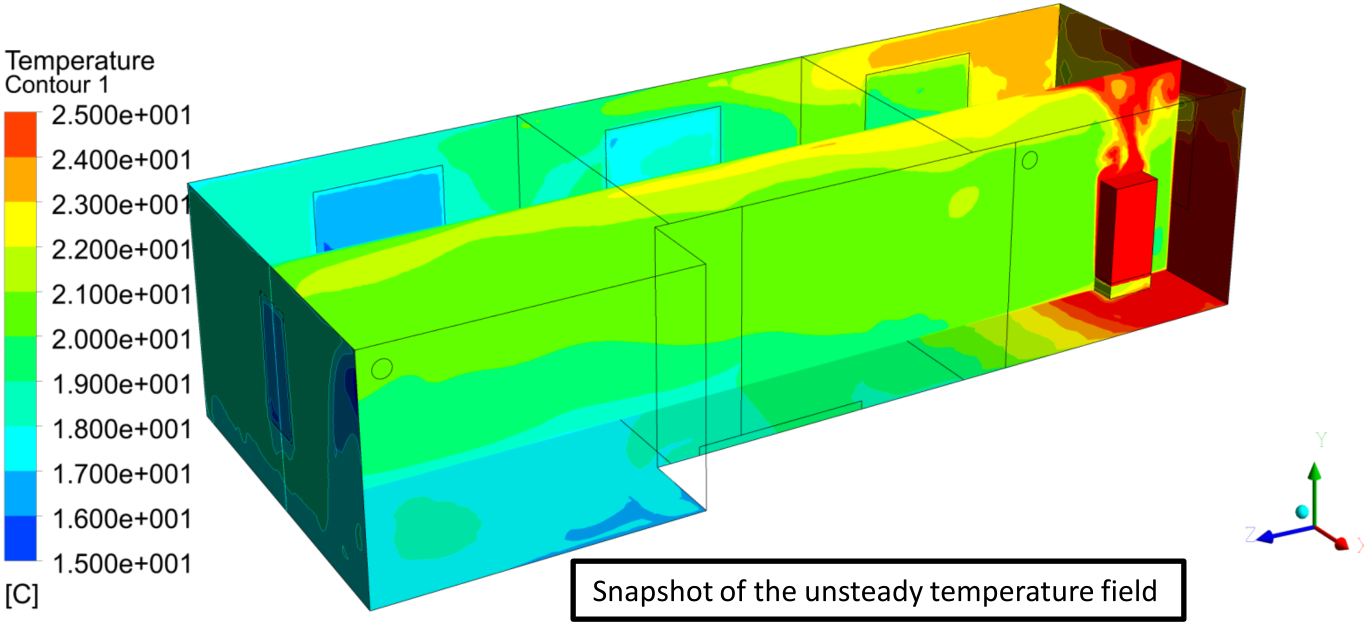
- Advantages:
  - Flow within a room can be known/approximated
  - Temperature stratification can be known/approximated
  - Bidirectional through open doors better computed than TDS
  - Detailed radiation between surfaces can be computed

- Main drawbacks:
  - Consistency of the boundary conditions around CFD domain
  - High computational cost
    - Need at least one stove cycle with an unsteady flow simulation

- Ideally, should couple CFD with TDS (next step)
  - Consistent boundary conditions for the CFD domain
  - Consistent convection coefficients for the TDS
  - Some tools exist but not always full satisfactory

Modeling (3): Computational Fluid Dynamics (CFD)

- Example CFD:
  - Steady-state simulation boundary conditions (stove not oversized)
  - Boundary conditions pre-computed using TDS (decoupled)
  - Unsteady flow due to high Rayleigh number
  - URANS using the k-ε RNG model on a 1.0 10^6 nodes tetrahedral mesh
  - *Georges et al., BSO 2012 conference, Loughborough*



Snapshot of the unsteady temperature field

Modeling (4): Summary

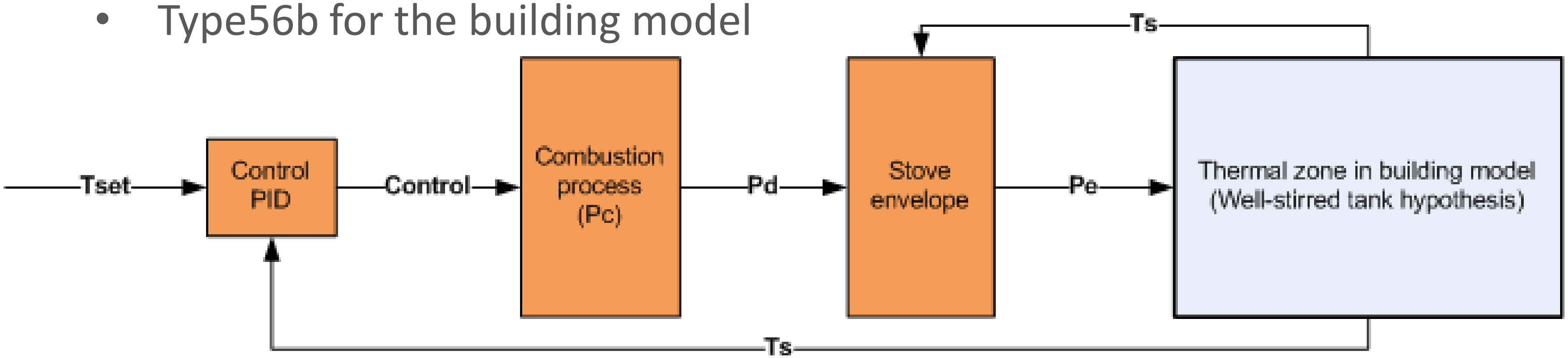
- Advantages and limitations of the three modeling approaches

Method	Δt imposed by	Tmin	Tmax	CPU time	Convection doors	Consistent BCS	Top	Stratifi-cation	Radiation asymmetry	Air velocity
TDS	Control/Flow	1-cycle	1-year	Low-Medium	Simple	Yes	Yes	No	Yes	No
CFD	Flow	1-cycle	Few cycles	High	Accurate	No	Yes	Yes	Yes	Yes
TDS+CFD	Flow	1-cycle	Few cycles	High	Accurate	Yes	Yes	Yes	Yes	Yes

Tmin = minimal simulation time; Tmax = maximal simulation time

Simplified wood stove model (1)

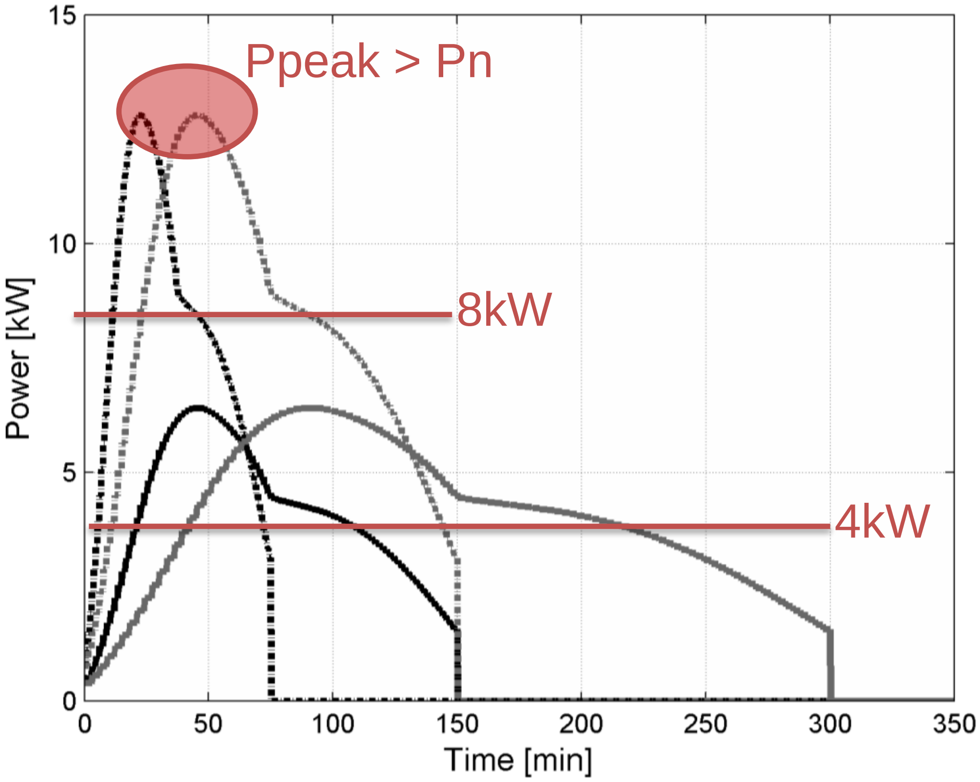
- Insight into all-year thermal comfort at acceptable CPU cost
- Implemented in TRNSYS/TRNFLOW
  - Type56b for the building model



  - PID control of power modulation for a pellet stove, manual for log stoves
  - Batch combustion model for wood logs
  - 1-D heat transfer in the stove envelope
  - Correlation for convection from the stove surface to the room
  - Detailed view factors evaluation from the stove to room surfaces and user
  - Stove emitted power as internal gain into building model (convection to air node and radiation to walls)

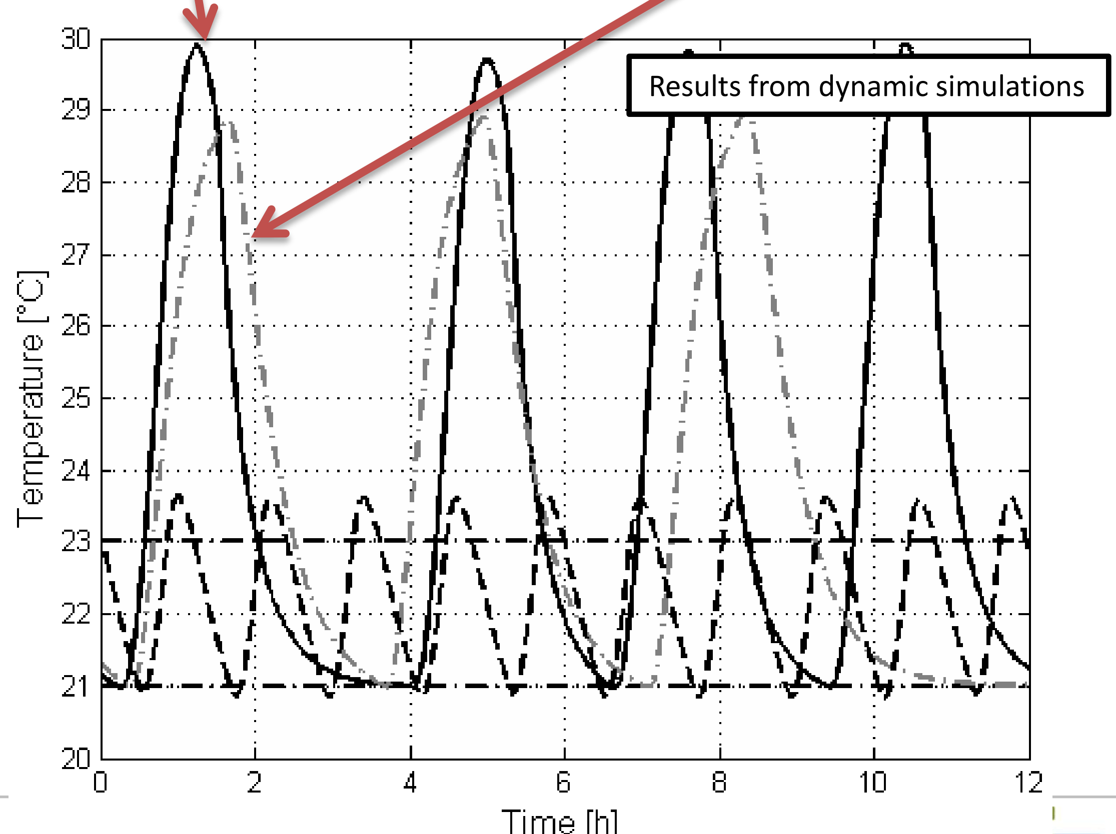
Simplified wood stove model (2)

- Batch combustion model for wood logs
  - Developed by Øyvind Skreiberg (SINTEF Energy Research)
  - Semi-empirical model with different phases:
    - Drying
    - Pyrolysis/devolatization
    - Char oxidation/gasification
  - Example of the 8 kW of Pn
    - No modulation (dashed)
    - 50% modulation (solid)
    - 20 kWh batch load (grey)
    - 10 kWh batch load (black)



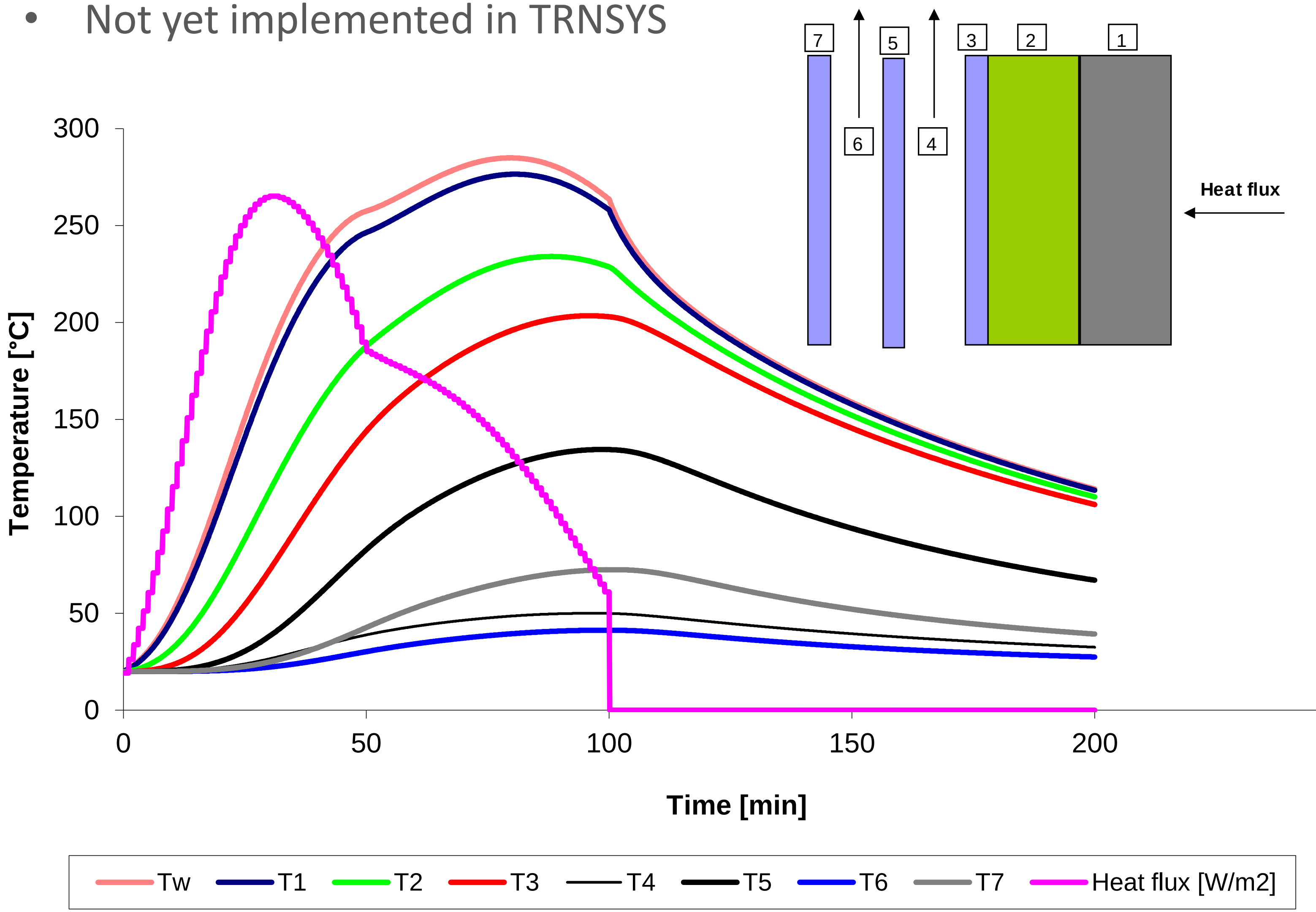
Simplified wood stove model (3)

- Batch combustion model for wood logs
  - Need to account for the real combustion profile and not average power
    - 8kW log stove and 1.25h cycle (black)
    - 8kW constant and 1.25h cycle (grey dashed-dot)



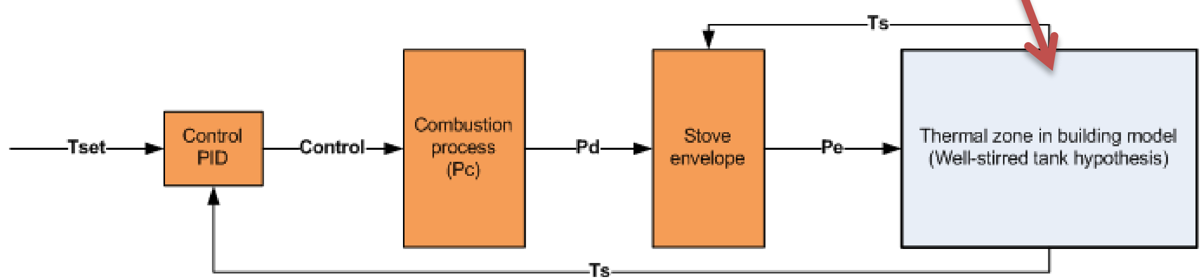
Simplified wood stove model (4)

- Multi-layer 1D heat transfer in walls
  - Developed by Øyvind Skreiberg (SINTEF Energy Research)
  - Not yet implemented in TRNSYS



Simplified wood stove model (5)

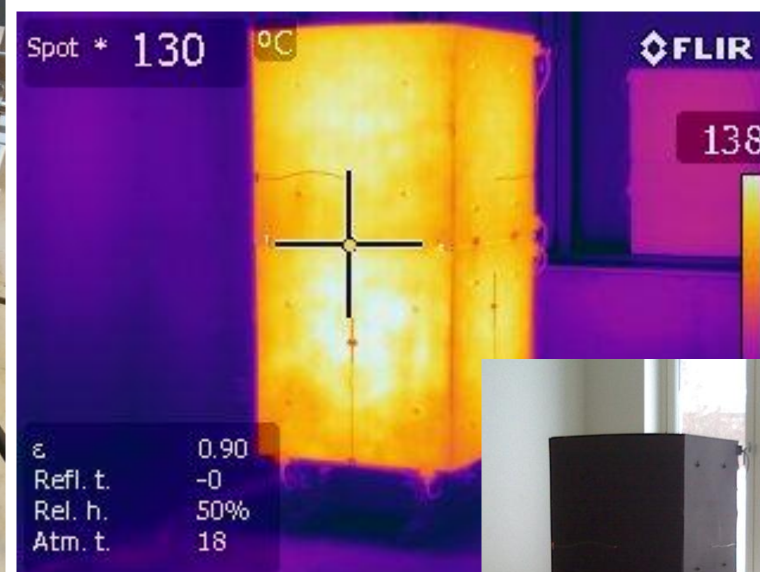
- Validation of the model for stove and building interaction
- Electric movable stove:
  - Surface temperature profiles imposed
  - Measure the resulting thermal environment in building



Movable electric stove (1)

- Advantages:
  - Does not need to be connected to a stack/chimney
  - Can be implemented temporarily and applied different heat release profiles
  - Electricity enables to control the heat release profile accurately
  - No risk for the IAQ

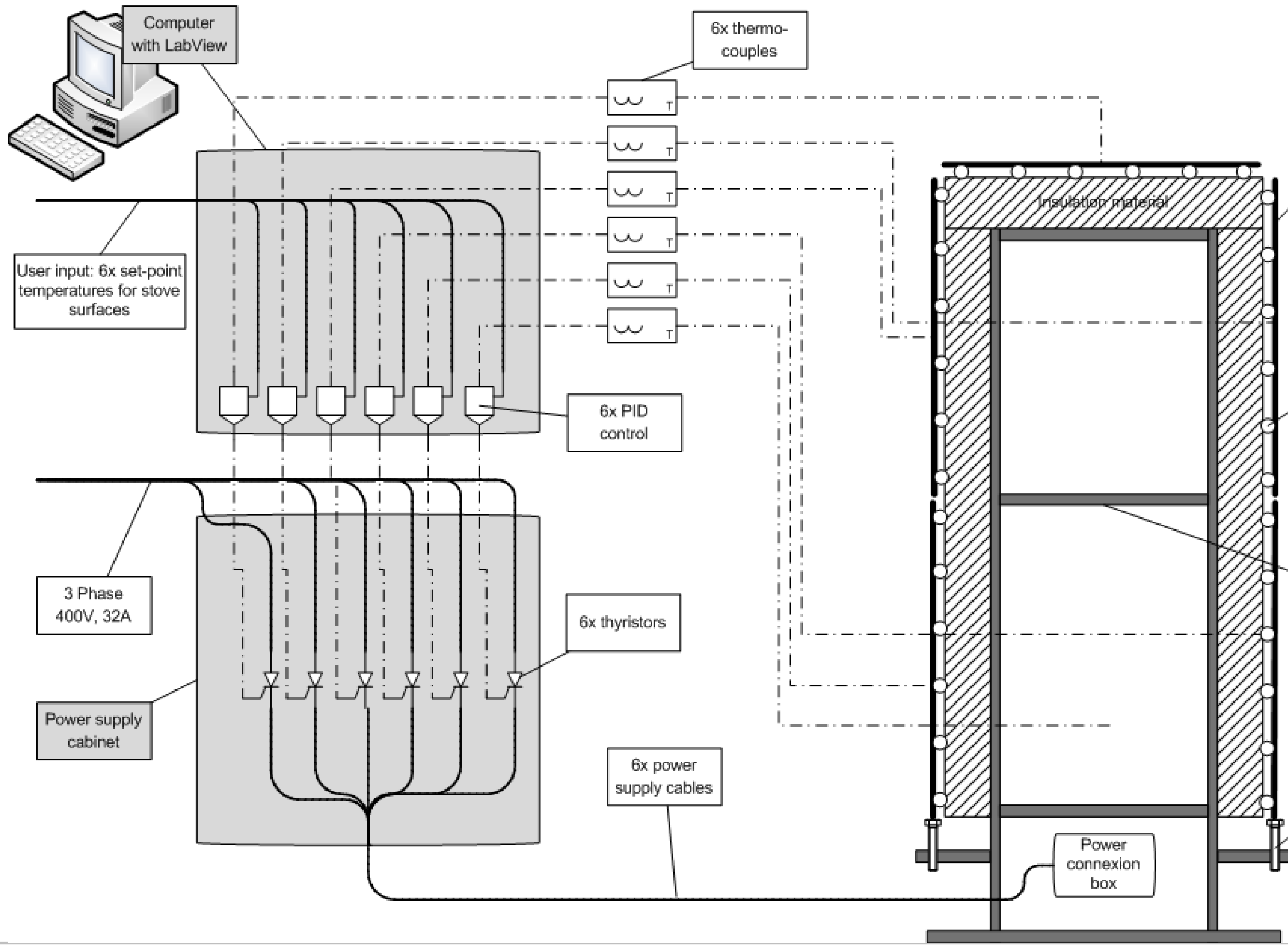
15.5 kWe and low thermal mass for quick reaction time



Good temperature distribution on stove surfaces

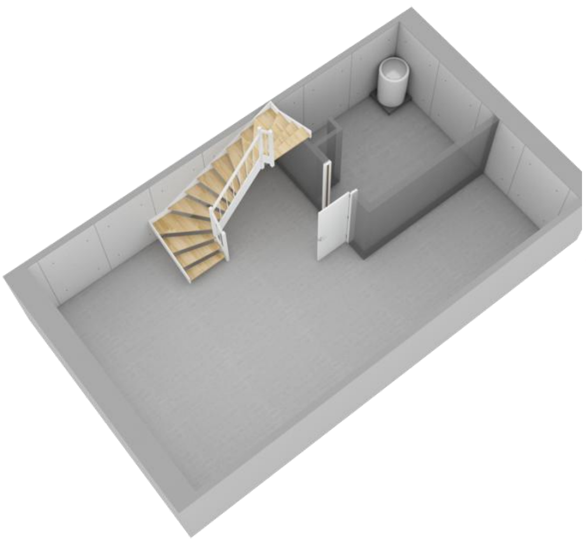
Movable electric stove (2)

- Principle:



Movable electric stove (3)

- Measurements in passive house
  - Miljø Granåsen project in Trondheim
  - Building of 142 m² heated area
  - Measurements Mars-April 2013
  - Lightweight wooden structure
  - Unoccupied without furniture



Basement

Ground floor

First floor

Movable electric stove (4)

- Measurements in passive house
  - Air temperature distribution in room
  - Wall temperature distribution in room
  - Flow through open door between ground and first floor

Type	Number	Location	Precision	Measure
PT-100	5	Ground floor	±0.1° C	Ts, stratification
	5	Staircase	±0.1° C	Ts, stratification
	1	Living-room	±0.1° C	Ts, 0.8 m height
	1	Kitchen	±0.1° C	Ts, 0.8 m height
	1	Kitchen	±0.1° C	Top, 0.8 m height
	7	Walls	±1° C	Twall
Radiant temperature transducer INNOVA MM0036	1	Living-room and kitchen	±0.5° C	Tmrt, 0.8 m height
Thermocouples Type T	10	Doorway or living-room	±1% ±0.5° C	Ts, profile or stratification
Anemometer TSI 8475	10	Doorway	±3% ±0.005 m/s	Air velocity profile
Temperature logger iButton Maxim Integrated DS1922L	11	Each room	±0.06° C	Ts, one by room
	1	Outdoor	±0.06° C	Ts, sheltered
	3	Air Handling Unit	±0.06° C	Ts fresh air

Movable electric stove (5)

- Test cases for measurements in passive house
  - Wood pellet stove (4 test cases)

Case	**P_n**	**Modulation**	**I_{th}**	**Cycle length**
N°	[kW]	[% of Pn]	[kJ/K]	[min]
1p	6	100	50	90
2p	6	100	150	90
3p	8	30	50	90
4p	8	100	150	90

  - Wood log stove (8 test cases)

Case	**P_n**	**Modulation**	**I_{th}**	**Batch load**
N°	[kW]	[% of Pn]	[kJ/K]	[kWh]
1w	4	50	50	5
2w	4	100	50	5
3w	4	50	50	10
4w	4	100	50	10
5w	8	50	50	10
6w	8	100	50	10
7w	8	50	150	10
8w	8	100	150	10

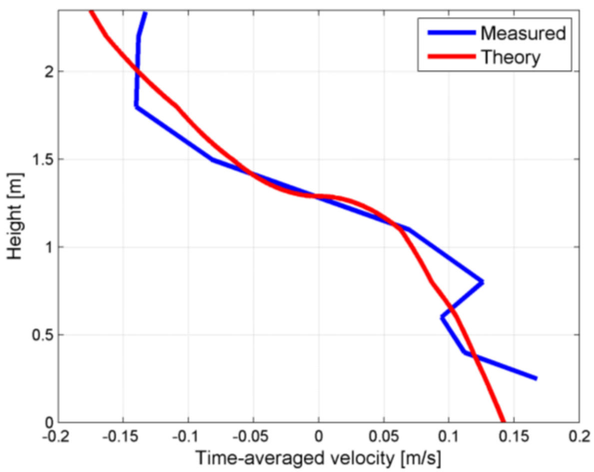
Movable electric stove (6)

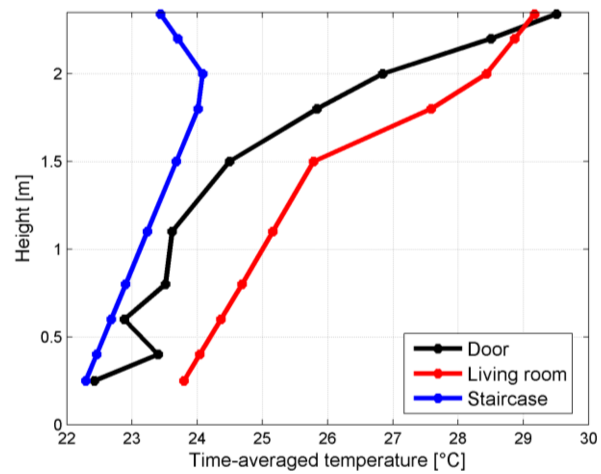
- Conclusion for temperature distribution in room
  - Significant vertical temperature gradient
  - Small horizontal temperature gradient (except with sun)
- Vertical stratification
  - Influence the thermal comfort
  - Enhance the heat transfer with the first floor (through ceiling)

Case	**Sun**	T_{ext}	$\Delta T_{op,max}$	$\Delta T_{s,hor,max}$	$\Delta T_{s,vert,z1,max}$	$\Delta T_{s,vert,z2,max}$
	Living room	Outside	Kitchen	Ground floor	Ground floor	Staircase
N°	[Yes-No]	[°C]	[°C]	[°C]	[°C]	[°C]
1p	No	-1	4.5	0.2	11	4.1
2p	No	+8	3.3	0.5	8.1	2.0
4p	No	+5	5.5	1.4	11	5.3
2w	No	+6	4.2	1.5	8.4	6.5
4w	No	+5	6.4	0.6	3.1	5.0
5w	No	+5	4.7	0.3	9.3	5.1
7w	No	+5	4.0	0.4	7.6	4.2
8w	No	+7	5.3	0.8	8.9	3.6
3p	Yes	+4	3.9	2.8	5.5	3.6
1w	Yes	+4	3.8	3.5	4.3	3.7
3w	Yes	+4	6.8	4.6	6.7	7.1
6w	Yes	+4	6.0	4.5	13	7.8

Movable electric stove (7)

- Conclusion for the bidirectional airflow through open door
  - *Large opening approximation* gives good approximation for the mass flow
  - The convective heat exchange is underestimated if the vertical temperature stratification is not accounted for





Case	C_{dv}	C_{dm}	C_{dms}	C_{des}	C_{desm}
N°	[-]	[-]	[-]	[-]	[-]
1p	0.36	0.35	0.32	0.58	0.40
3p	0.40	0.38	0.36	0.61	0.35
1w	0.39	0.37	0.35	0.54	0.33
2w	0.39	0.38	0.33	0.62	0.41
3w	0.41	0.40	0.39	0.62	0.43
5w	0.38	0.36	0.35	0.53	0.33

Conclusions

- A simplified wood stove model for detailed dynamic simulations was needed
  - Should provide insight into the all-year thermal comfort at an acceptable computational cost
  - An experimental setup has been created to validate the modeling of the stove surface temperature and building interaction (i.e. movable electric stove)

- The main modeling hypotheses seem realistic except for the **vertical stratification** in the room where the stove is placed
  - Influence the thermal comfort
  - Enhance the conductive heat transfer with the first floor
  - Enhance the convective heat exchange through the door (sensitivity analysis should be done with Cd taken as [0.4;0.8])

- The hypothesis of 1-D heat transfer in the stove envelope remains to be validated