NTNU – Trondheim
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WoodCFD

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

Wood Stoves for Future Energy Efficient Buildings

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Highly efficient and clean wood log stoves, Expert Workshop
IEA Bioenergy Task 32, 29 October 2015, Berlin, Germany

ZEB The Research Centre on Zero Emission Buildings

FME CENTRE FOR ENVIRONMENT FRIENDLY ENERGY RESEARCH

Towards highly-insulated buildings

- 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 (under development)
  - In 2020, all new buildings should be ***Nearly-Zero Energy*** (nZEB): *"A building with very high energy-efficiency where the reduced energy use is significantly covered by renewable energy sources onsite or nearby"*.
  - R&D on *zero emission buildings* (ZEB) within the Norwegian ZEB FME center

In Nordic countries, we can conclude that future buildings envelopes will be highly-insulated

Highly-insulated building envelope

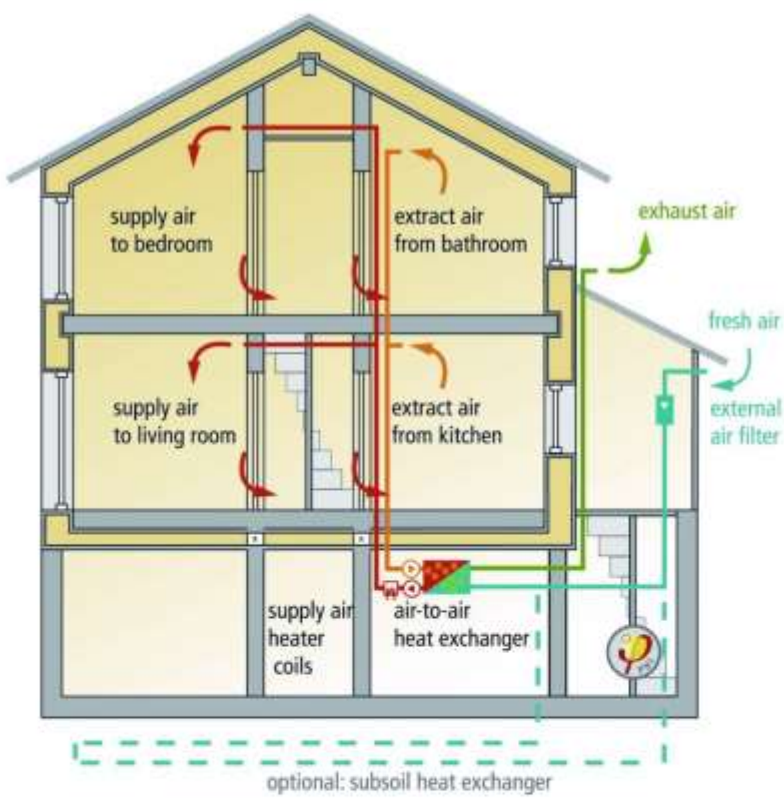
- Example of the Norwegian Passive House standard
  - Only requirements on the building envelope
  - Nothing is said about the energy efficiency of the space-heating system

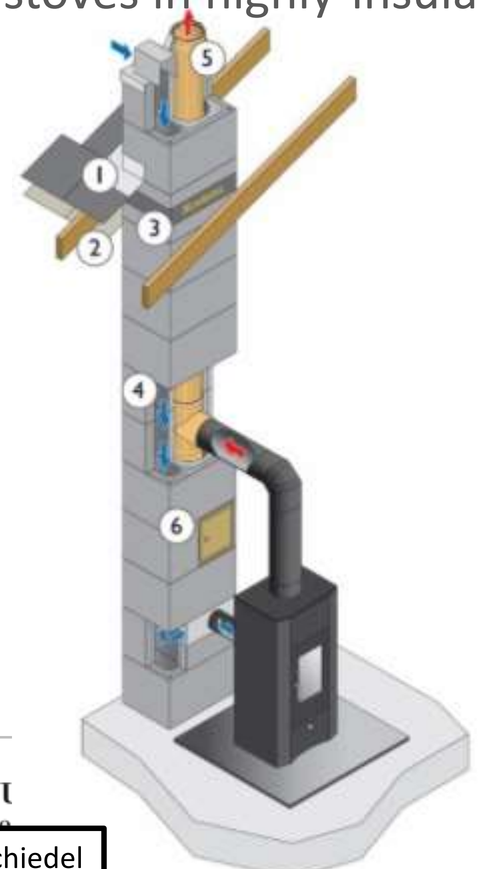
Minimal requirements	**TEK 10 (14.3)**	**NS 3700:2013**
U-value global	-	$\leq$ 0.48 W/m^2_{BRA}.K
U-value walls	$\leq$ 0.18 W/m^2.K	0.10-0.12*
U-value floor	$\leq$ 0.15 W/m^2.K	0.08-0.09*
U-value roof	$\leq$ 0.13 W/m^2.K	0.08*
U-value windows (total with frame)	$\leq$ 1.2 W/m^2.K	$\leq$ 0.8 W/m^2.K
U-value doors	$\leq$ 1.2 W/m^2.K	$\leq$ 0.8 W/m^2.K
Normalized thermal bridges, Ψ''	$\leq$ 0.03 W/m^2_{BRA}.K	$\leq$ 0.03 W/m^2_{BRA}.K
Yearly efficiency heat recovery, η_t	$\geq$ 70%	$\geq$ 80%
SFP ventilation	-	$\leq$ 1.5 kW/(m^3/s)
Air infiltration 50 Pa	$\leq$ 2.5 ach	$\leq$ 0.6 ach

(*) = typical value, not a requirement

Stove integration in highly-insulated houses (1)

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



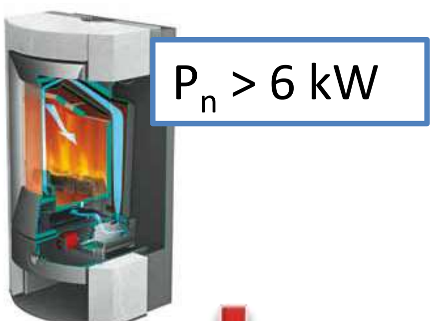


Pict. Schiedel

NTNU

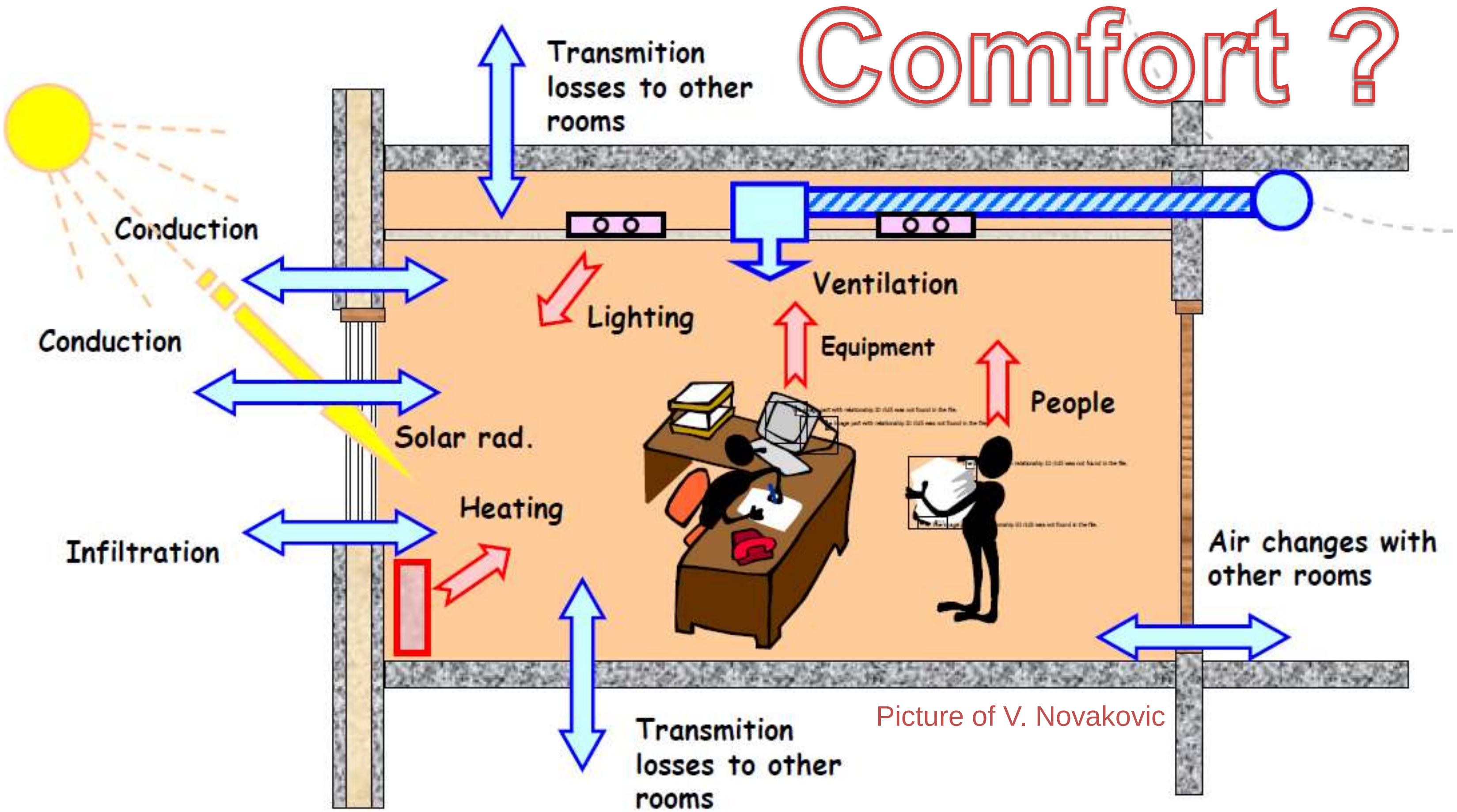
Stove integration in highly-insulated houses (2)

- Challenge for **Indoor Thermal Environment**:
  - Nominal Power (Pn) is oversized for passive houses
    - Ex. 6-8 kW for pellet stoves and 4-8 kW for wood-log stoves
    - Ex. 160 m² detached passive house has ~3kW space-heating power for Oslo climate in design weather conditions (i.e. cold wave)
  - Power modulation is limited and should operate on long combustion cycles
  - Risk of overheating in the room where the stove is placed
  - But potential to simplify space-heating distribution using wood stoves



Buildings are complex multi-physical systems

- Thermal dynamics of the building envelope



Picture of V. Novakovic

Thermal comfort assessment

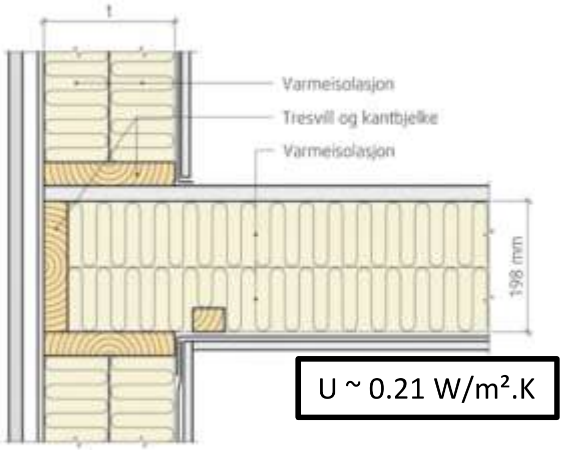
- Usually based on Fanger's approach (ISO 7730)
- **Global** thermal comfort
  - Operative temperature (main index here)
  - PMV and PPD (with Clo and MET)
  - Typical thermal comfort index in building performance simulation

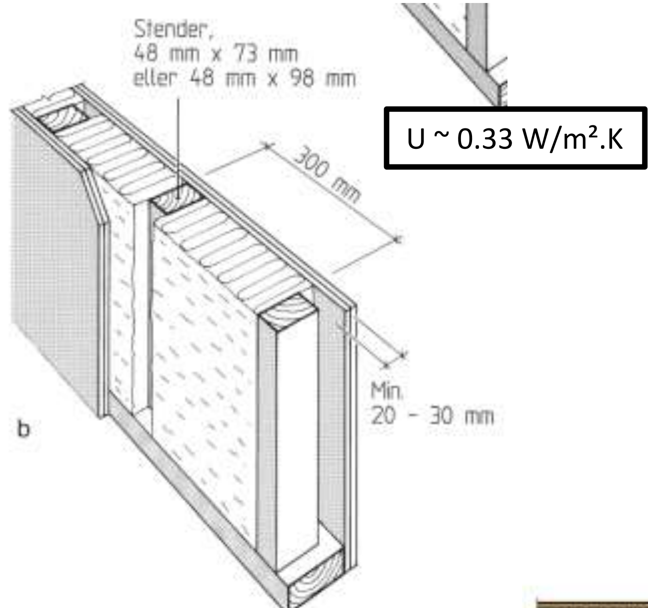
$$T_{op} = (h_c T_{air} + h_r T_{mrt})/(h_c + h_r) \approx 0.5\left(T_{air} + T_{mrt}\right)$$

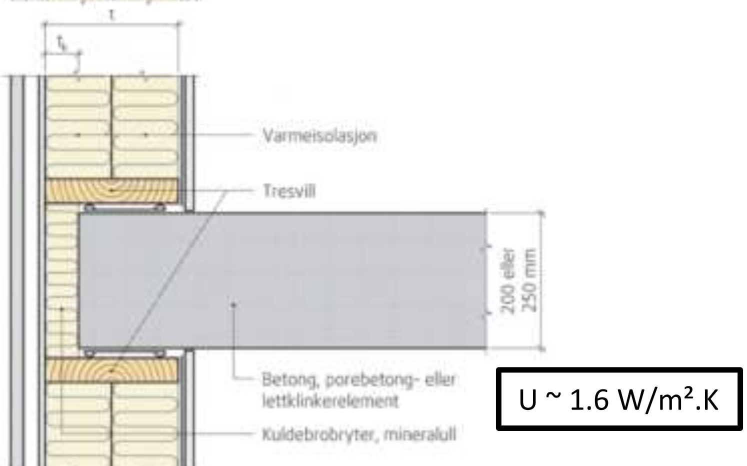
- **Local** thermal comfort
  - Based on wall temperatures
    - Radiant asymmetry
    - Cold/warm floor
  - Based on air and temperature fields
    - Draft
    - Vertical temperature stratification

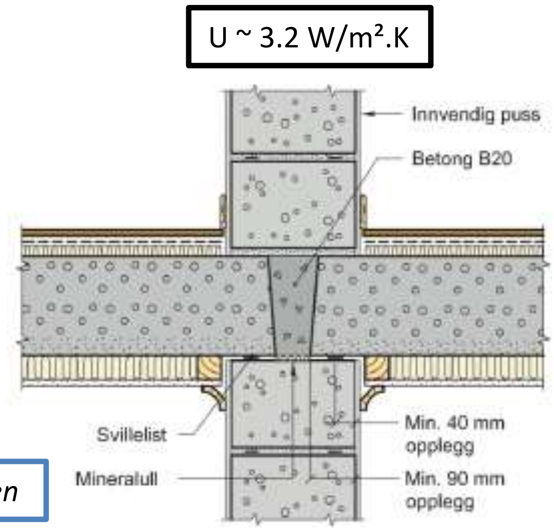
Heat conduction through internal walls (1)

- Construction of partition walls and ceilings
  - With wooden walls, insulation against noise propagation (mineral wool)





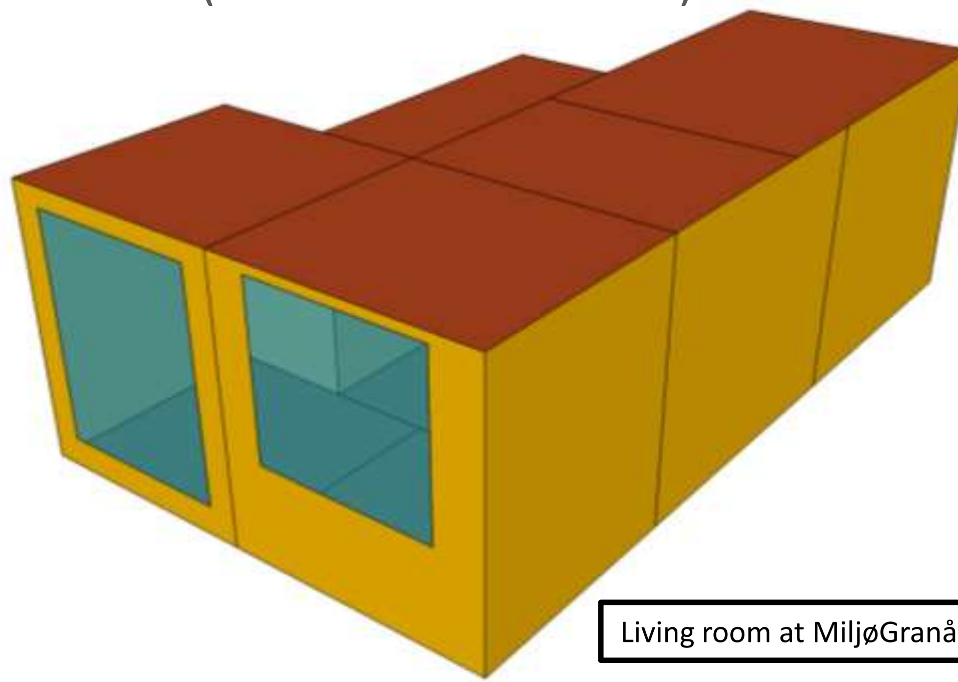




Pictures from Byggforskserien

Heat conduction through internal walls (2)

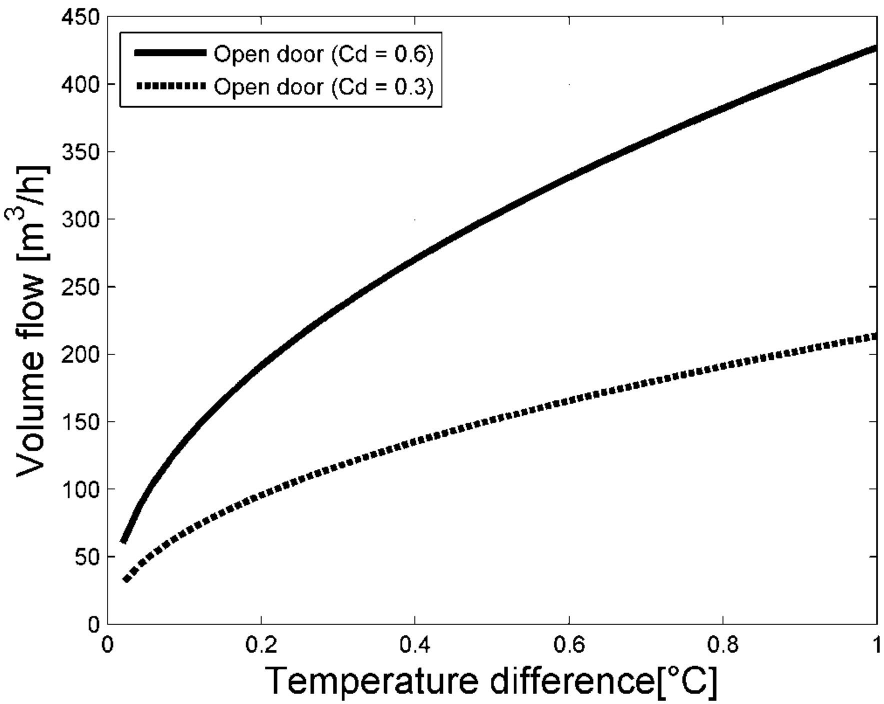
- Example
  - Partition ceiling of 32.5 m^2
  - Partition wall of 24.14 m^2
  - Concrete construction : U = 32.5*1.6 + 24.14*3.2 = 129 W/K
  - Wood construction: U = 32.5*0.21 + 24.14*0.33 = 15 W/K
  - Large temperature differences needed (for > 1 kW to transfer)
  - Risk of overheating

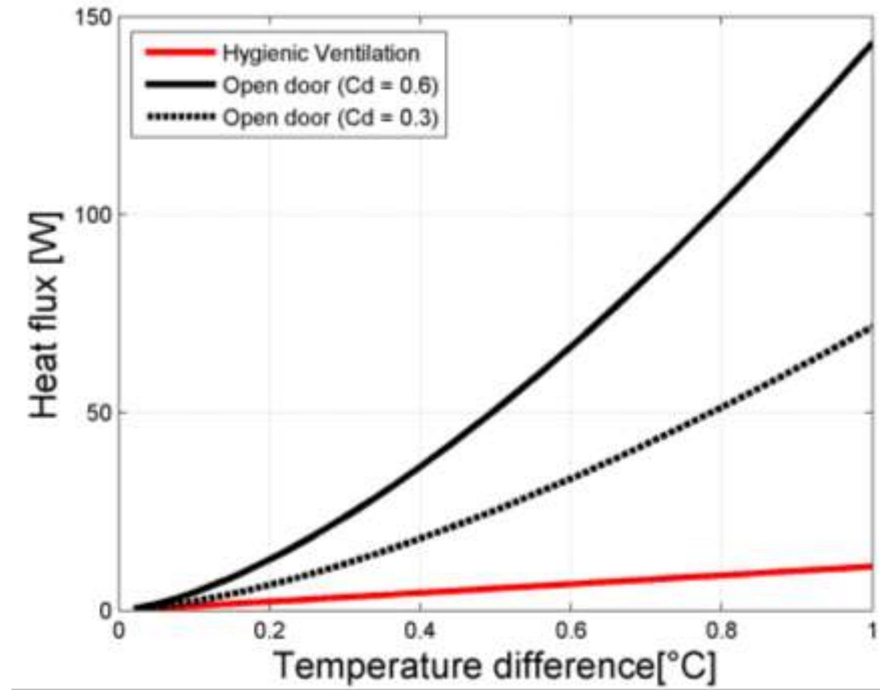


Living room at MiljøGranåsen

Heat flow through open doors (2)

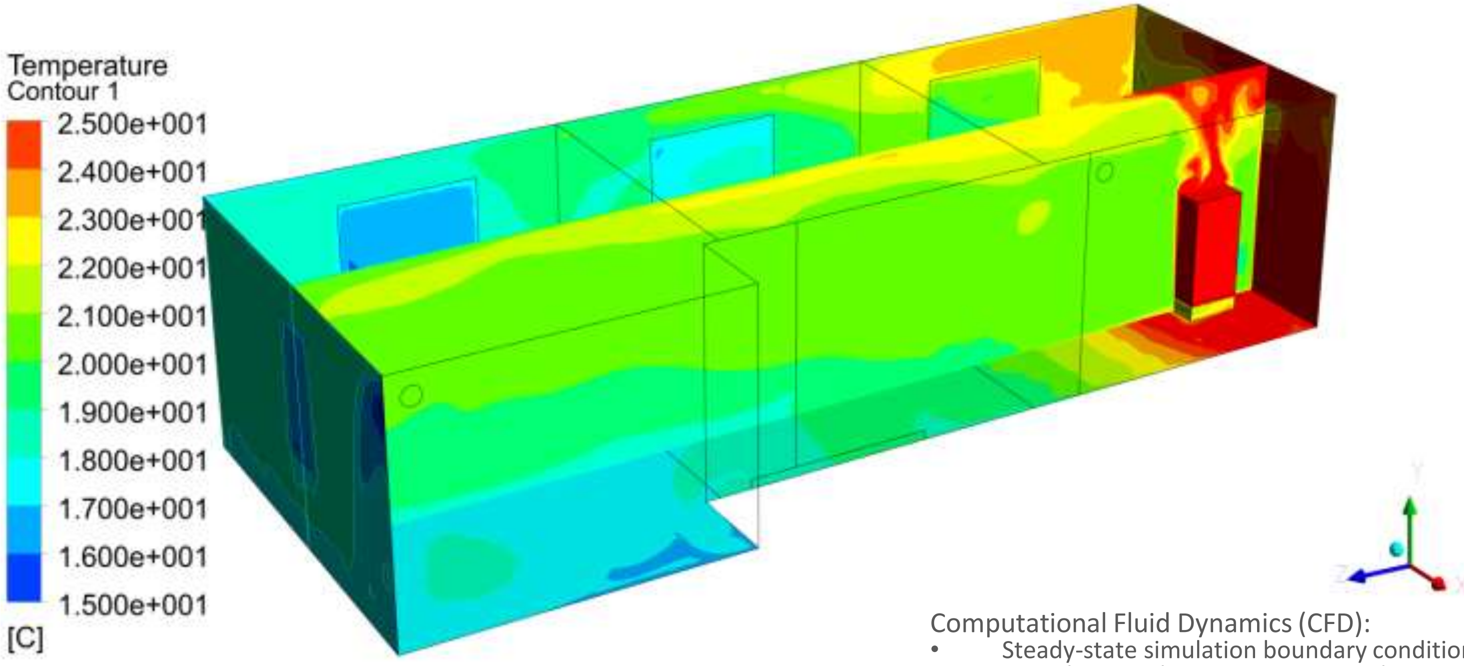
- Mass flow and convected energy
  - Door (0.9 x 2.35) m²
  - More power can be transferred but still not enough (for P > 1kW)





Temperature distribution inside room (1)

- Strong **gravity currents**: assuming no obstacle on the ceiling
  - The temperature difference in the horizontal direction is small
  - The temperature field is essentially 1D (in vertical direction)



Snapshot of the unsteady temperature field

Computational Fluid Dynamics (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*

Temperature distribution inside room (2)?

- Mass flow rates: flow controlled by the stove thermal plume
  - Hygienic ventilation (TEK 10): (**1.2m^3/h.m^2**)*32.5m^2 = 39 m^3/h
  - Bidirectional flow open door: 200-600 m^3/h
  - Thermal plume of the stove: 500-1000 m^3/h

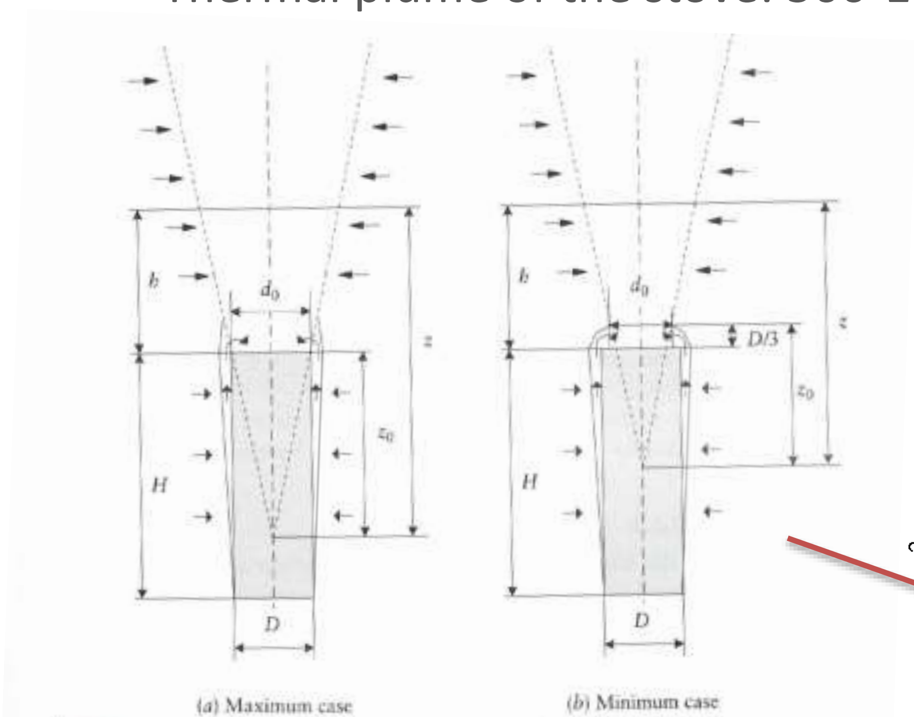
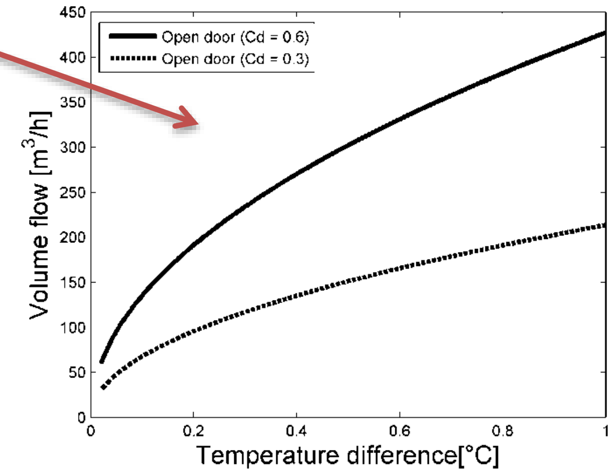
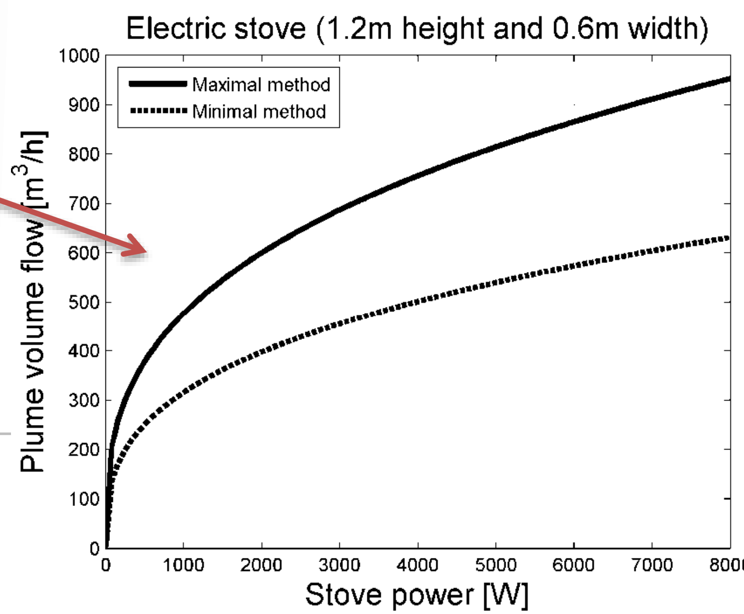


FIGURE 7.65 Convection flow above a vertical cylinder.

Industrial Ventilation: Design Guidebook (2001)





How to prevent overheating?

- Passively, the heat cannot be sufficiently transported
  - Through partition walls and ceilings
  - Through open internal doors

- Overheating can should avoided by
  1. Storing heat in the building walls (passive approach)
  2. Storing heat in the stove walls (cf. work Øyvind)
  3. Storing in water using a hydro-stove (active approach)
  4. Flatten the heat release from combustion

- (1) Storing heat in walls
  - Comfort based on **operative temperature** (T_{op})
  - Thermal mass to reduce wall temperature
  - Slow down the temperature increase of air
  - Transients should be analyzed by *thermal dynamic simulation* (i.e. no easy analytical solution)

$$T_{op} \approx \frac{T_{sens}^{air} + T_{mrt}^{wall}}{2}$$

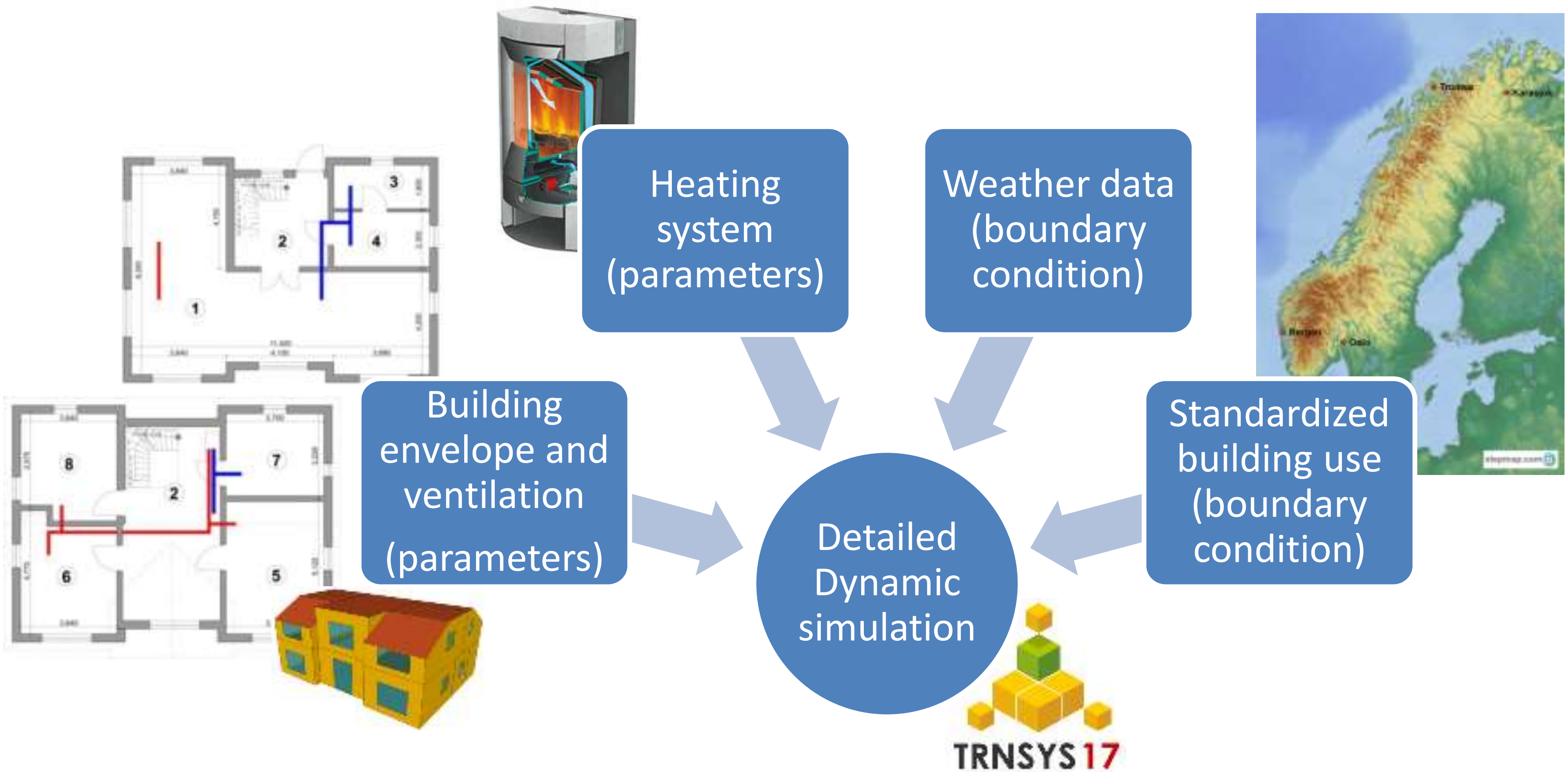
Modeling approaches

- Advantages and limitations of the main modeling approaches
  1. Thermal dynamic simulation (TDS)
  2. TDS + zonal model in rooms
  3. CFD
  4. CFD + TDS

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
Zonal TDS	Control/Flow	1-cycle	1-year	Low-Medium	Simple	Yes	Yes	*Maybe*	Yes	*Maybe*
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

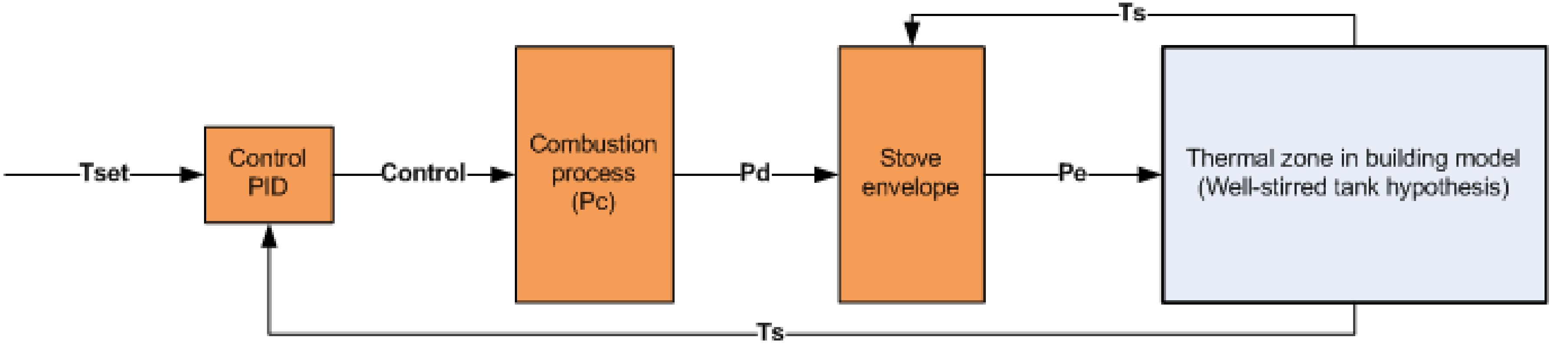
Thermal dynamic simulations (1)



- Coupled simulation of the building envelope, the ventilation and the stove during the entire heating period using TRNSYS

Thermal dynamic simulation (2)

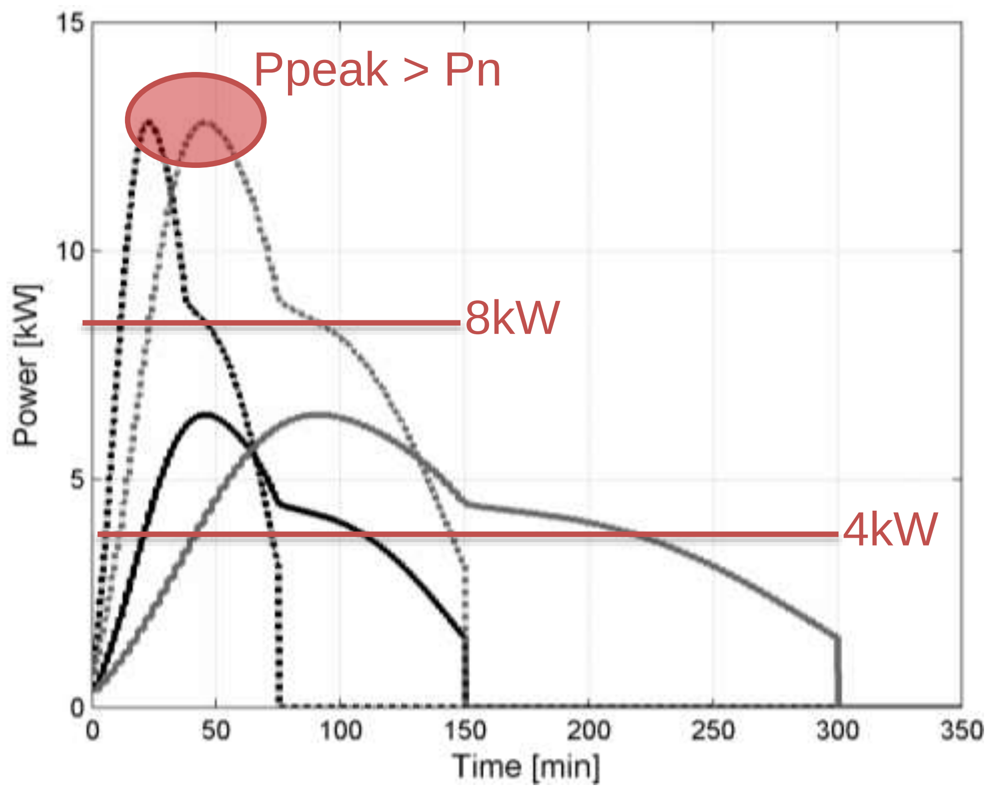
- Insight into all-year thermal comfort at acceptable CPU cost



- 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

Thermal dynamic simulation (3)

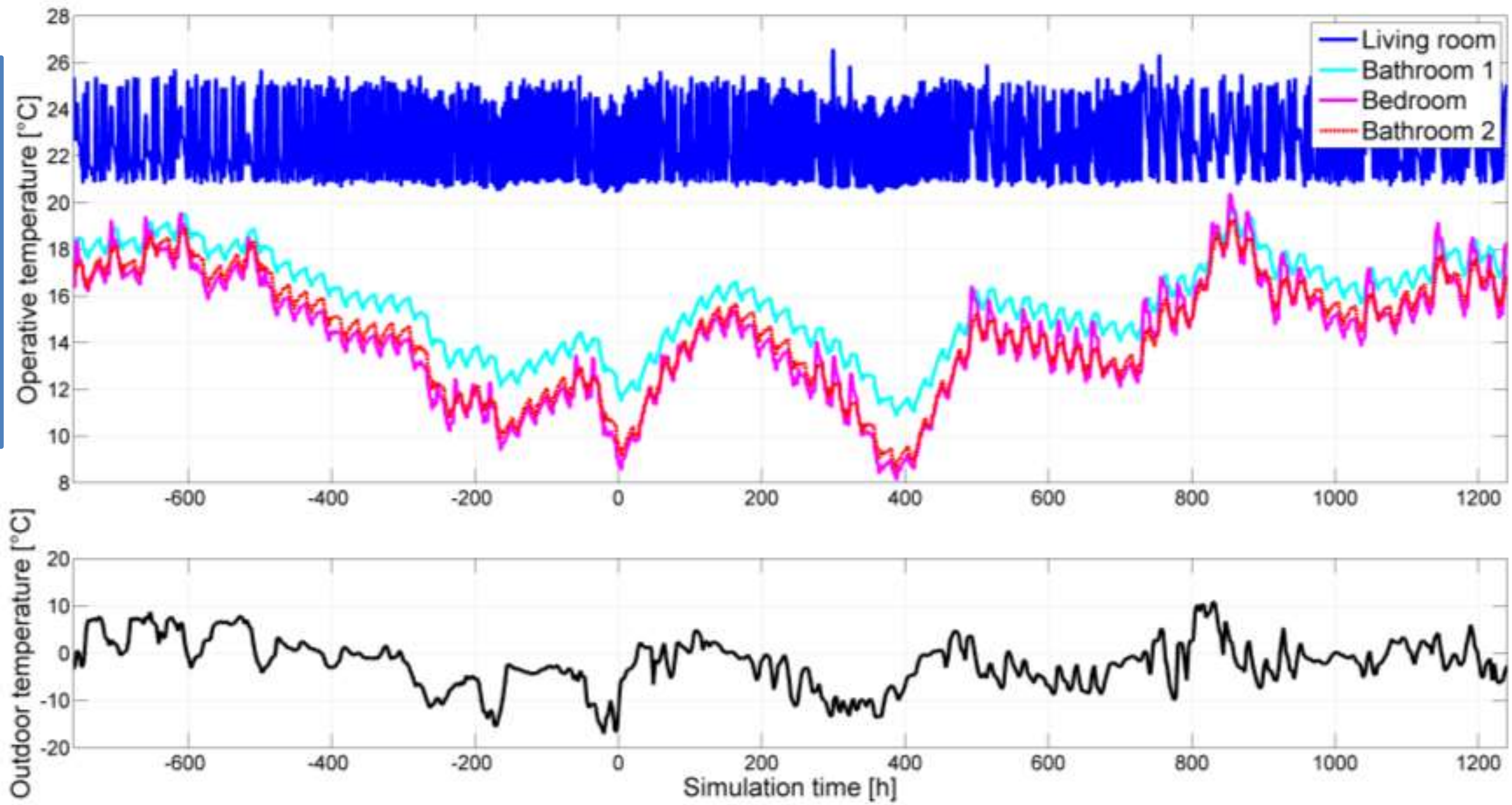
- Batch combustion model for wood logs
  - Developed by Øyvind Skreiberg (SINTEF Energy Research)
  - Semi-empirical model with different phases:
    - Drying
    - Pyrolysis/devolatilization
    - Char oxidation/gasification
  - Example of the 8 kW of Pn
    - No modulation (dashed)
    - 50% modulation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



Thermal dynamic simulations (4)

- Example result:
  - For the climate of Oslo, only heated by stove
  - Stove of 8kW with 30% power modulation
  - Wooden construction, closed internal doors

Performance index



Thermal dynamic simulations (5)

- Matrix risk overheating
  - Location
  - Stove thermal properties
  - Building architectonic properties
  - Period of the year

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On the proper integration of wood stoves in passive houses under cold climates

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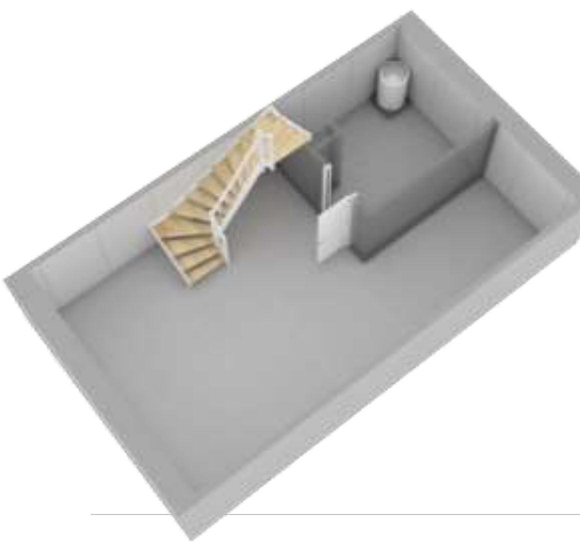
Table 7
Qualitative performance against overheating of log stoves equipped with 50 kJ/K thermal inertia: function of the stove nominal power, $P_{d,n}$ in [kW], power modulation [%] and batch load, Q_d in [kWh], computed for different locations and weather conditions.

Location	Oslo			Bergen			Karasjok		
Weather	TMY	CTMY	SDC	TMY	CTMY	SDC	TMY	CTMY	SDC
4 kW, 50%, 10 kWh	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊗
4 kW, 100%, 10 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙
4 kW, 50%, 5 kWh	⊙	⊙	⊕	⊙	⊙	⊕	⊙	⊙	⊕
4 kW, 100%, 5 kWh	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊕
8 kW, 50%, 20 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
8 kW, 100%, 20 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
8 kW, 50%, 10 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
8 kW, 100%, 10 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 50%, 30 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 100%, 30 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 50%, 15 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 100%, 15 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖

⊕: good control independent of the architectural measures.
⊙: control if one set of architectural measures is taken, ⊙⊙: control if complete set of architectural measures taken.
⊖: overheating whatever the architectural measures taken.
⊗: underheating because lack of emitted power.

Validation

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



Basement

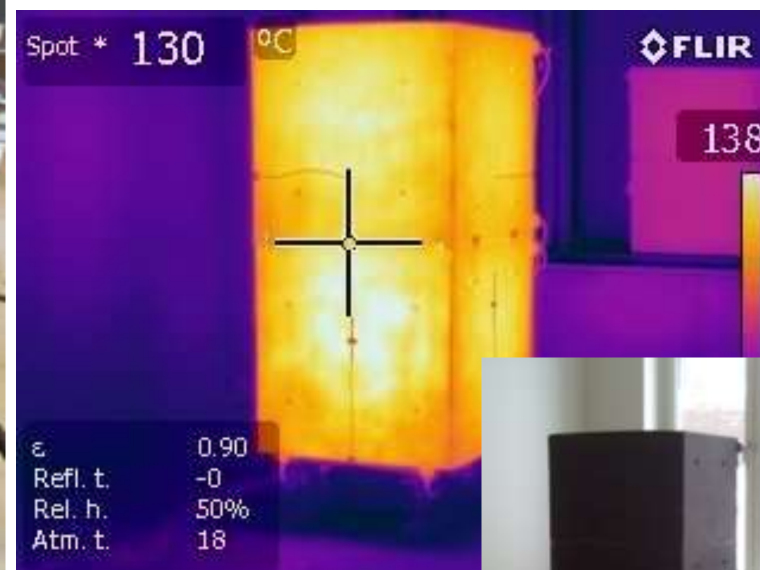
Ground floor

First floor

Movable electric stove (1)

- Electric stove heater, 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

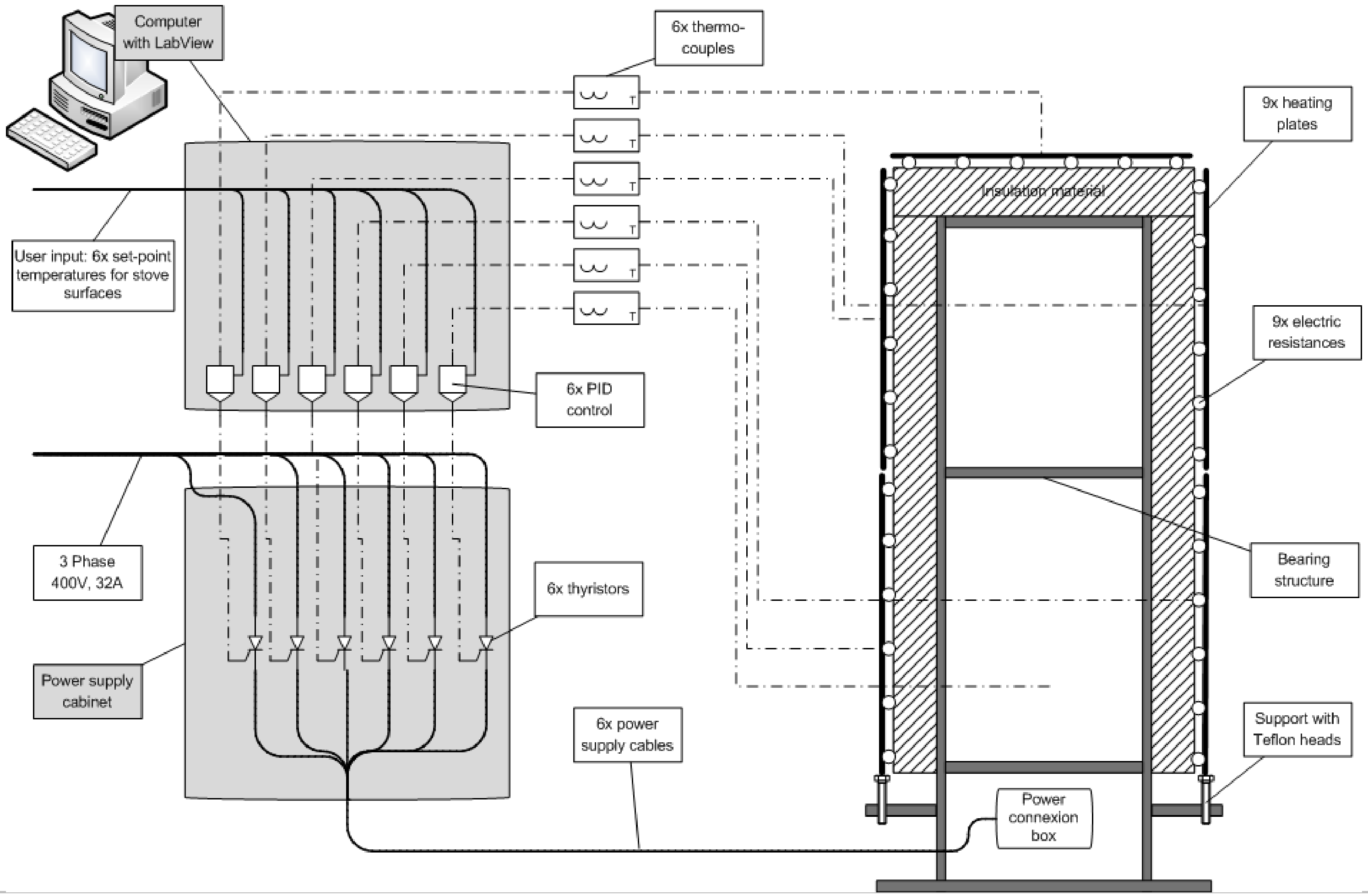
15.5 kWe and low thermal mass for quick reaction time



Good temperature distribution on stove surfaces

Movable electric stove (2)

- Principle:



Movable electric stove (3)

- Measurements in passive house
  - 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 (4)

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

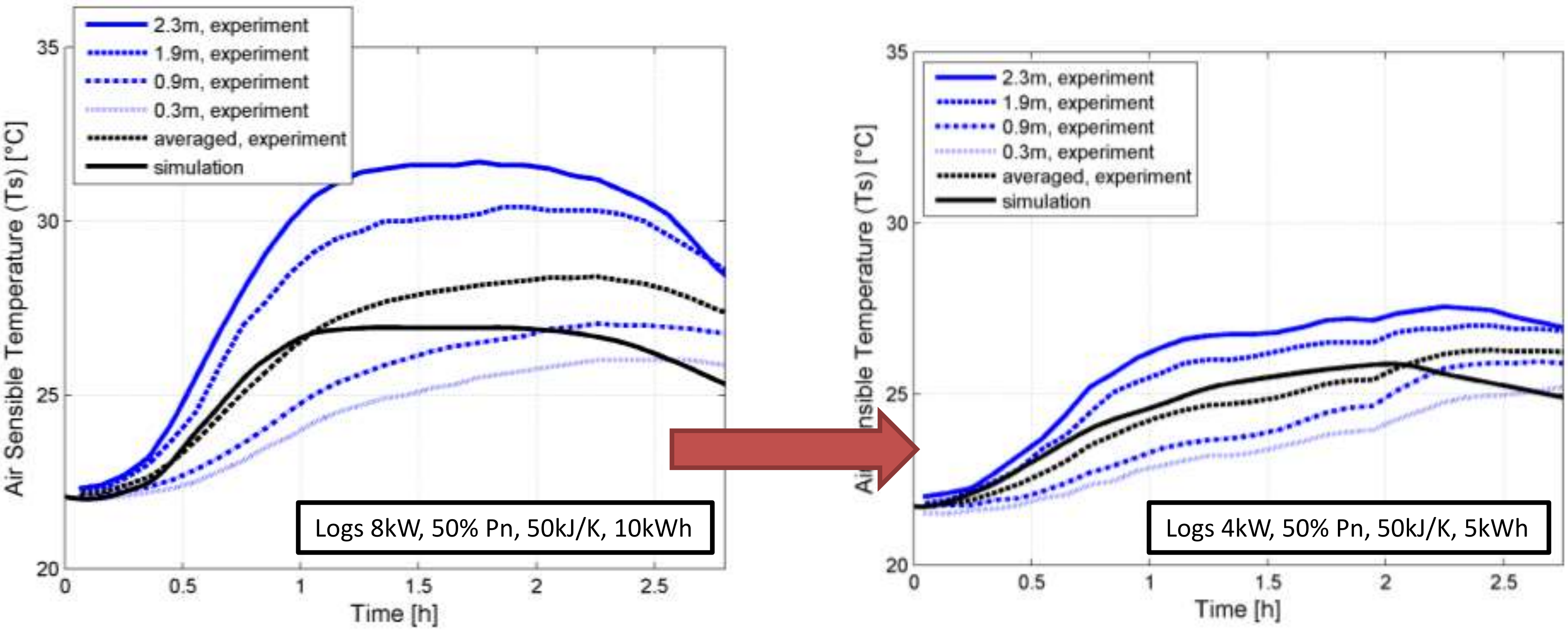
Case	P_n	Modulation	I_{th}	Cycle length
N°	[kW]	[% of Pn]	[kJ/K]	[min]
1p	6	100	50	90
2p	6	100	150	90
3p	8	30	50	90
4p	8	100	150	90

  - 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

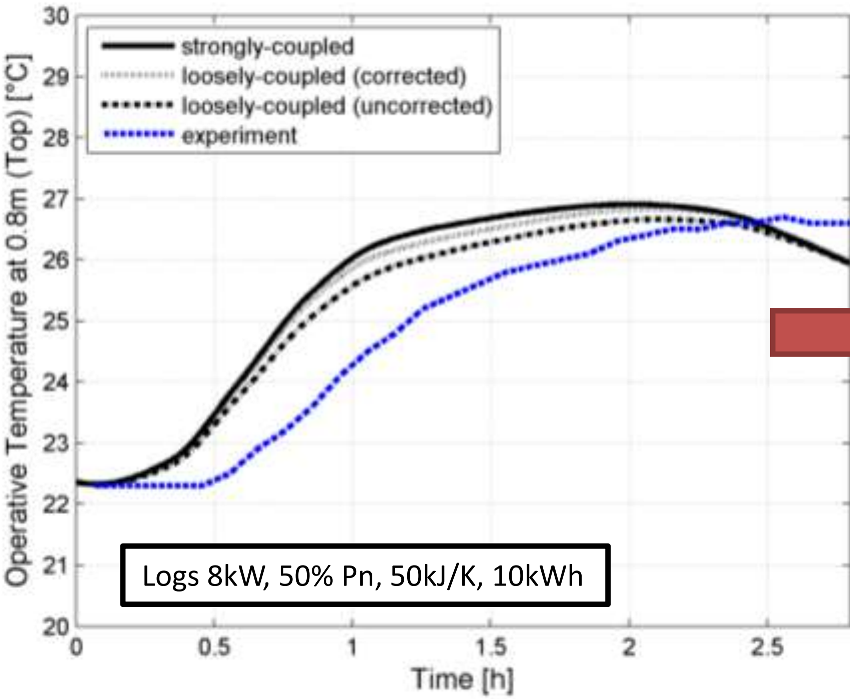
Movable electric stove (5)

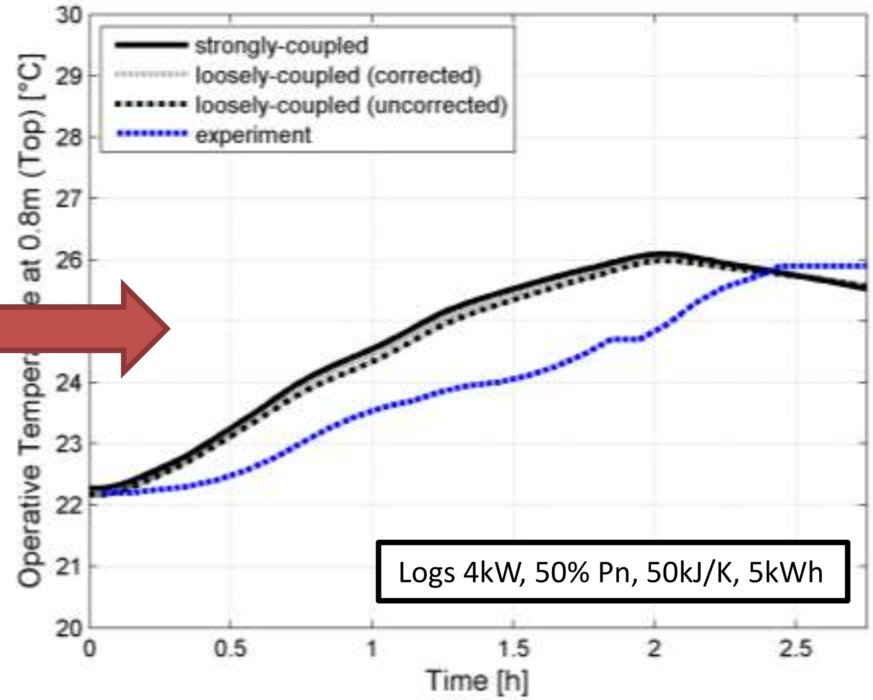
- Conclusion for temperature distribution in room
  - Significant vertical temperature gradient
  - Reduction from 8 to 4kW is efficient for wood-log stoves (with 50% Pn)
  - TRNSYS (TDS) don't capture stratification (here equal to temperate at 0.9m)



Movable electric stove (6)

- Comparison for operative temperature in room (at 0.8m kitchen)
  - TRNSYS and measurements in good agreement in magnitude
  - Shorter time response (to be investigated)





Movable electric stove (7)

- Conclusion for temperature distribution in room
  - Significant vertical temperature gradient
  - Small horizontal temperature gradient (except with sun)
- Vertical stratification
  - Influence the local thermal comfort (non negligible)
  - 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	4.6	0.2	11	4.1
2p	No	+8	3.3	0.5	8.1	2.0
4p	No	+5	4.5	1.4	11	5.3
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	4.8	0.8	8.9	3.6
1w	Yes	+4	3.8	3.5	4.3	3.7
3w	Yes	+4	6.6	4.6	6.7	7.1
6w	Yes	+4	6.0	4.5	13	7.8

Heat flow through open doors (1)

- Flow through **large openings** such as **open doors**
- Type of flow
  - *Bulk density flow*
  - *Boundary layer flow*

Isothermality factor: $\frac{\Delta T}{\Delta T_w} = \frac{T_h - T_c}{T_h' - T_c'}$

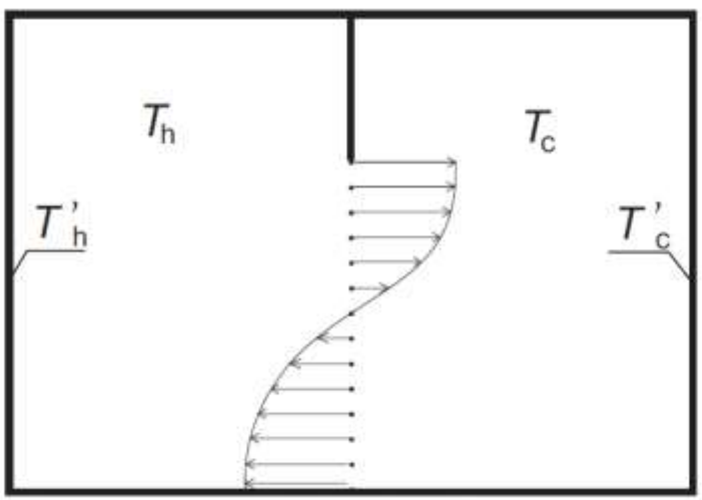


Figure 2.2 Bulk density flow
$\Delta T/\Delta T_W \approx 1$
Velocity profile nearly parabolic

From PhD Clæs Blomqvist

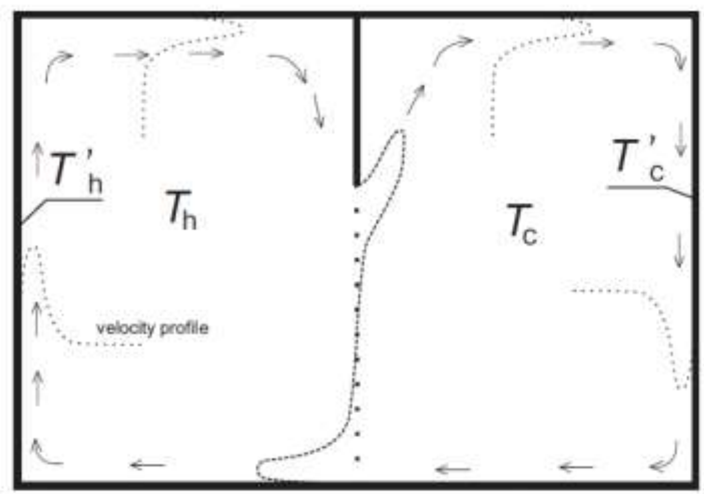
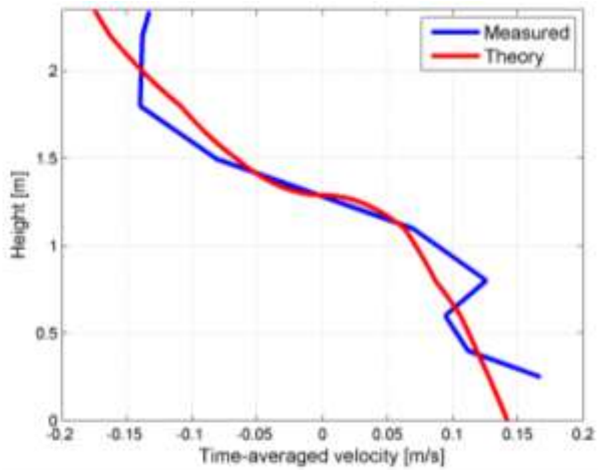


Figure 2.3 Boundary layer flow
$\Delta T/\Delta T_W \approx 0$
Flow if concentrated to top and bottom of the opening

Heat flow through open doors (3)

- Conclusion for the bidirectional airflow through open door
  - *Bulk flow and large opening approximation* correct for the mass flow
  - The convective heat exchange is underestimated if the vertical temperature stratification is not accounted for



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

Conclusions

- What have been done:
    1. Understand how the **heat propagates** (between rooms and inside room)
    2. Understand how the **airflow** is driven (in open doors and room with stove)
    3. Prove the importance of **open doorways** and **construction mode**
    4. **Measure thermal environment** in a same passive house with different stoves
    5. **Develop and validate a simple modeling procedure** to evaluate the all-year thermal comfort at an acceptable computational cost
    6. **Simulate integration of several different stoves** within a typical passive house (in Norway and Belgium)

- What remains to be bone:
    - Capture the **vertical stratification** in simulation (e.g. using CFD)
    - Model and investigate the influence of the stove **glazing**
    - A **quick-prototyping tool** is close to be ready
    - Influence of the addition of **phase-change material** (PCM) in the stove envelope

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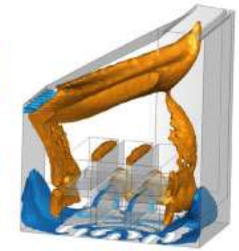
WoodCFD

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



Thank you for your attention!

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ZEB The Research Centre on
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