Integrated Modelling of a Dwelling and its Heating System

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I. Aim of the Research

**EPB Directive:**
- calculation of primary energy consumption

**The heating system is a heat pump:**
- heat delivered by a heat pump is more difficult to predict than the one delivered by an oil or gas burner
- Performance (COP) of the heat pump and primary energy consumption depend on the coupling between the building and the heat pump

**Study of the heat demand and of the performance of a heat pump installed in a single-family dwelling in Belgium:**
- simulation of the building and the heat pump
- comparison with experimental data (monitoring)
II. Heat Pumps

Heat sinks (H. S.):
- Floor heating
- Forced air Heating
- ...

Cold sources (C. S.):
- Outdoor air
- Backyard ground
- Underground water
- ...

Coefficient of Performance:
\[ \text{COP} = \frac{\Phi_H}{P_0} \]
P_0 is an electrical energy not a primary energy. Electricity is produced in power plants from primary energy (renewable or not)
II. Heat Pumps

\[ \text{COP} = \frac{\Phi_H}{P_o} \]

\[ \Phi_C \]

\[ \eta_{\text{plant}} = \frac{P_o}{E_{\text{primary}}} \]

\[ \Phi_{\text{losses}} \]

\[ \Phi_H \]

\[ \text{Heat Pump} \]

\[ \text{Boiler} \]

\[ \text{CO}_2 \]

\[ \text{E}_{\text{primary}} \]

\[ \eta_{\text{boiler}} = \frac{\Phi_H}{E_{\text{primary}}} \]
II. Heat Pumps

\[ E_{\text{primary}} = \frac{\Phi_H}{(\eta_{\text{plant}} \text{ COP})} \]

\[ E_{\text{primary}} = \frac{\Phi_H}{(\eta_{\text{boiler}})} \]

\[ \eta_{\text{plant}} \text{ COP} > \eta_{\text{boiler}} \]

- \( \eta_{\text{boiler}} = 0.9 \)
- \( \eta_{\text{plant}} = 0.4 \) (in Belgium)
- COP up to 3.0 (measurements)

- COP > 2.2 for energy savings
- COP > 1.8 for \( \text{CO}_2 \) emission reduction
- For costs, it depends on the peak and off-peak prices and the off-peak running rate
II. Heat Pumps

Performance \( (\Phi_H, P_o, \text{COP}) \) depends on \( T_{CS} \) and \( T_{HS} \)
II. Heat Pumps

Heat pump behavior curves

Heat flow (kW) vs. T evap (°C) for different temperatures:
- T cond 25 °C
- T cond 35 °C
- T cond 45 °C
- T cond 55 °C
- T cond 65 °C
II. Heat Pumps

Heat pump behavior curves

![Graph showing heat pump behavior curves with COP values and evaporation temperatures.](image)
III. Dwelling

Single-family detached house in a village: Leuze (centre of Belgium)

Data:  
- Insulation: rock wool: 14 cm (walls), 16 cm (roof)
- Windows: 23 m², $k_v=1.1$ W/m².K
- Walls and roof Area: 364 m²
- Heated volume: 439 m³
- Average heat loss coefficient: 0.38 W/ m²K
III. Dwelling

**Heating:** Air-to-water heat pump
- low temperature (35 °C) heating floor

**Cooling:** no mechanical cooling

**Domestic hot water:** solar panes (5 m²) and electric resistor

**Ventilation:** mechanical air extraction with counter-flow heat exchanger

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[Diagram of dwelling showing layout and equipment locations]

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Static air heat exchanger
III. Dwelling

Heat sink:
- Heating floor
- Water

Cold source:
- ‘static’ air heat exchanger (natural convection)
- glycol-water blend

![Diagram of dwelling heat sink and cold source system]
IV. Performance Monitoring

Monitoring of the heat pump during 2 years (November 2005 – May 2007):

Measurements: temperatures, pressures, volumetric flow rates (water, glycol-water, refrigerant (R404A)), electric consumption (compressor and pumps), various other measurements (climate)

Computation of:

- $\Phi_H = q_{M\text{R404A}} \cdot \Delta h_{\text{cond}}$ (R404A)
- $\Phi_H = q_{M\text{WATER}} \cdot c_p \cdot \Delta T$ (water)
- COP = $\Phi_H / P$
- Evaporation and Condensation temperatures

Diagram:

- $T$ and $q_{V\text{WATER}}$
- $T$ and $q_{V\text{R404A}}$
- $T_p$ and pump
- $T$ and $q_{V\text{WG}}$
- $T$ and $P_o$
- $T_{\text{indoor}}$, $T_{\text{outdoor}}$, RH, Wind speed, Solar Irradiance
IV. Performance Monitoring

COP
LEUZE - November 2005 - December 2006

COP (-)

T outdoor (°C)
## IV. Performance Monitoring

### Heat pump

<table>
<thead>
<tr>
<th></th>
<th>(kWh)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual heat</td>
<td>8744</td>
<td></td>
</tr>
<tr>
<td>COP</td>
<td>2.82</td>
<td></td>
</tr>
<tr>
<td>Annual electrical consumption</td>
<td>3103</td>
<td></td>
</tr>
</tbody>
</table>

### Costs

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Electricity (Peak rate)</td>
<td>Eur/kWh</td>
<td>0.180</td>
</tr>
<tr>
<td>Electricity (Off-peak rate)</td>
<td>Eur/kWh</td>
<td>0.090</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Eur/kWh</td>
<td>0.065</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>Eur/l</td>
<td>0.550</td>
</tr>
</tbody>
</table>

### CO₂ production (kg)

<table>
<thead>
<tr>
<th></th>
<th>kg/kWh</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (Belgium)</td>
<td></td>
<td>0.300</td>
</tr>
<tr>
<td>Natural gas</td>
<td>kg/kWh</td>
<td>0.251</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>kg/kWh</td>
<td>0.306</td>
</tr>
</tbody>
</table>

### Heating Costs (Eur/year)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Heat pump</td>
<td>414</td>
</tr>
<tr>
<td>Natural gas</td>
<td>632</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>575</td>
</tr>
<tr>
<td>Electricity</td>
<td>1163</td>
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</table>

### CO₂ production (kg)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Heat pump</td>
<td>930</td>
</tr>
<tr>
<td>Natural gas</td>
<td>2439</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>2973</td>
</tr>
<tr>
<td>Electricity</td>
<td>2623</td>
</tr>
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</table>
V. System Simulation

**Building Simulation**

- Heat transfer equations in MATLAB
- Monozone simulation
- Standard solar Irradiance for Belgium with shadowing factor (0.6)
- Standard internal gain
- Experimental outdoor temperature and RH
- Heating floor: model based on TRNSYS model
Heat Pump Simulation

- Software developed in our department (FRIPAC)
- Heat transfer equations for various heat exchangers: needs geometrical data of the exchangers
- Model for scroll and reciprocating compressors from: parameters determined from fit of experimental or manufacturer data
V. System Simulation

Coupling

- Building model, heating floor model and heat pump model are coupled in MATLAB
- Static Air Heat Exchanger not modelled yet

Simulation conditions

- Differential equations solved every 6 minutes for one year
- Heat pump set on at the same time as measured experimentally: allows the computation of the indoor temperature and of the heat delivered to the dwelling as well as the electrical consumption
V. System Simulation

Mass flow rate

![Mass flow rate graph](image)

- **Exp**
- **Simulation**

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Mass flow rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1344,00</td>
<td>0,000</td>
</tr>
<tr>
<td>1349,00</td>
<td>0,005</td>
</tr>
<tr>
<td>1354,00</td>
<td>0,010</td>
</tr>
<tr>
<td>1359,00</td>
<td>0,015</td>
</tr>
<tr>
<td>1364,00</td>
<td>0,020</td>
</tr>
<tr>
<td></td>
<td>0,025</td>
</tr>
<tr>
<td></td>
<td>0,030</td>
</tr>
<tr>
<td></td>
<td>0,035</td>
</tr>
<tr>
<td></td>
<td>0,040</td>
</tr>
<tr>
<td></td>
<td>0,045</td>
</tr>
<tr>
<td></td>
<td>0,050</td>
</tr>
</tbody>
</table>

0,000 1344,00 1349,00 1354,00 1359,00 1364,00

0,050 0,045 0,040 0,035 0,030 0,025 0,020 0,015 0,010 0,005 0,000

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V. System Simulation

Heat flow rate

- Exp
- Simulation

Time (h) vs. Heat flow rate (kW) graph showing data points for both experimental (Exp) and simulation (Simulation) results.
V. System Simulation

Evolution of Month Heat Demand

Heat (kWh)

Simulation
Exp
Evolution of Month COP

- Simulation
- Exp

COP (-)

dec 05  jan 06  feb 06  mar 06  apr 06  may 06  jun 06  jul 06  aug 06  sep 06  oct 06  nov 06
## V. System Simulation

### Heat pump

<table>
<thead>
<tr>
<th></th>
<th>Heat (kWh)</th>
<th>Electricity (kWh)</th>
<th>COP (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp (dec 05 - nov 06)</td>
<td>8743</td>
<td>3103</td>
<td>2.82</td>
</tr>
<tr>
<td>Sim (dec 05 - nov 06)</td>
<td>9312</td>
<td>3185</td>
<td>2.92</td>
</tr>
<tr>
<td>NBN 62-002</td>
<td>9778</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EPB Belgium</td>
<td>14201</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Primary Energy (EPB Belgium)

<table>
<thead>
<tr>
<th></th>
<th>Heat (kWh)</th>
<th>E primary (kWh)</th>
<th>E ref (kWh)</th>
<th>E level (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flemish Region</td>
<td>14201</td>
<td>20471</td>
<td>28721</td>
<td>0.71</td>
</tr>
<tr>
<td>Walloon Region</td>
<td>14201</td>
<td>20471</td>
<td>34209</td>
<td>0.60</td>
</tr>
</tbody>
</table>
VI. Conclusions

**Simulation:**
- Improvement of the calculated heat flow rate (heat pump parameters)
- Multizone building model

**Heat pump:**
- Add model for the static air heat exchanger

**Primary Energy Consumption:**
- Try better heat pumps (variable speed compressor)
- Try other heat pumps (ground-coupled, …)