Thermal Storage in a Heat Pump Heated Living Room Floor for Urban District Power Balancing

Effects on Thermal Comfort, Energy Loss and Costs for Residents

R. P. van Leeuwen[1,2], J. B. de Wit[1], J. Fink[2,3] and G. J. M. Smit[2]

[1]*Sustainable Energy Group, Saxion University of Applied Sciences, P.O. Box 70.000, 7500 KB Enschede, The Netherlands*

[2]*Department of Computer Science, Mathematics and Electrical Engineering, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*

[3]*Supported by STW, Project iCare (11854)*

Keywords: Thermal Activated Building Systems (TABS), Thermal Storage, Demand Side Management, Power Balancing, Peak Shaving, Smart Grid, Optimal Control, Renewable Energy System, Thermal Network Model, Thermal Comfort, Floor Heating System.

Abstract: For the Dutch smart grid demonstration project Meppelenergie, the effects of controlled thermal energy storage within the floor heating structure of a living room by a heat pump are investigated. Storage possibilities are constrained by room operative and floor temperatures. Simulations indicate limitations for floor heating storage due to absorption of solar energy within the house. To balance power for district renewable energy supply, substantial energy can be stored into the floor without violating comfort limits. Heat loss to the outside due to floor heating storage is small in case of low energy houses and can be financially compensated. This may result in a proposition for residents which is equivalent to heating without thermal storage for power balancing purposes.

1 INTRODUCTION

For the smart grid demonstration project Meppelenergie, funded by the Dutch program Switch2Smartgrids, we develop smart grid control for the energy system of the new Meppel district Nieuwveense landen (AgentschapNL, N.D.).

The Meppel energy concept consists of a biogas CHP (Combined Heat and Power engine), heat pumps and underground thermal storage. The CHP is the main electric and thermal heat generator. The heat is used for a district heating system, supplying part of the houses in the district with domestic hot water and space heating. The electricity is used to drive heat pumps placed at houses with no connection to the district heating. The heat pumps supply these houses with domestic hot water and space heating. The heat source for the heat pumps is an underground aquifer which consists of a warm and cold well. During the heating season, the warm well provides heat for the heat pumps, during the cooling season, the cold well provides cooling energy for the houses.

Using heat pumps together with underground aquifers is increasingly applied in the Netherlands for commercial buildings, e.g. hospitals, office parks and malls (Rijkswaterstaat, 2013). Within housing projects, underground aquifers are mainly used for apartment buildings. Houses often use closed systems such as underground heat exchangers (CBS, 2011) and as an example (Witte et al., 2006).

For the Meppel district heating, there are large water stores to store thermal energy from the CHP, which is beneficial for the heat grid control. The houses with a heat pump have a domestic hot water storage but not for space heating. However, some storage capacity can be provided by thermal storage within the inert concrete floor heating system, which we will name Floor Heating Thermal Energy Storage (FHTES) throughout the paper. The application and economics of such a storage system within smart grid electricity control is investigated in (Toersche et al., 2012) and (Nykamp et al., 2012) which demonstrates that investments for strengthening the electricity grid can be avoided by applying FHTES for demand side control. However, FHTES has immediate effects on thermal comfort of

van Leeuwen R., de Wit J., Fink J. and Smit G..
Thermal Storage in a Heat Pump Heated Living Room Floor for Urban District Power Balancing - Effects on Thermal Comfort, Energy Loss and Costs for Residents.
DOI: 10.5220/0004916300430050
In *Proceedings of the 3rd International Conference on Smart Grids and Green IT Systems* (SMARTGREENS-2014), pages 43-50
ISBN: 978-989-758-025-3
Copyright © 2014 SCITEPRESS (Science and Technology Publications, Lda.)

residents and also on energy loss of the building and therefore costs for the residents, which are not investigated yet. The problem statement for this paper is therefore: what are the effects on thermal comfort if energy is stored in the floor heating system, what is the energy loss and what are the related financial consequences?

Contribution of this paper is to develop mathematical relations and to demonstrate the relation between FHTES, thermal comfort, energy loss and energy costs. These insights and relations are to be used for developing algorithms to control district heating and heat pumps.

Outline of this paper: Chapter 2 describes related works on Thermal Activated Building Systems (TABS), control and performance. Chapter 3 gives theoretical backgrounds on modelling and thermal comfort. Chapter 4 describes a case study, followed by results and discussion in chapter 5. Conclusions are drawn in chapter 6. The appendix contains a list of abbreviations and the applied thermal network model.

2 RELATED WORK

In this section we discuss related work on TABS and power balancing by FHTES.

FHTES is investigated for different applications. One of the applications is cooling offices by thermal activation of floors during night hours (Fellin and Sommer, 2003), (Lehmann et al., 2007), (Pavlov and Olesen, 2011), (Rijksen et al., 2010) and (Saelens et al., 2011). Another application is lowering peak heating power for residential buildings (Airaksinen and Vuolle, 2013). More close to our application is a study on measured performance of heating and cooling systems using TABS in apartments (Alvi and Qureshi).

Besides effects on thermal comfort, FHTES also influences energy loss of the building and therefore energy costs paid by the residents. In (Scheepens, 2013) the ecocost approach was applied to investigate a novel house heating/cooling system with individual room temperature control for the Meppel project. In (Tahersima et al., 2011) the contribution of a control strategy for power balancing and FHTES is investigated. Thermal tolerance is introduced as a measure for effects on thermal comfort due to FHTES. In (Verhelst et al., 2012) optimal heat pump control in case of floor heating in relation with varying electricity prices is investigated. Thermal discomfort is introduced as a measure for effects on thermal comfort. Instead of using thermal tolerance or thermal discomfort, we propose in this paper to develop measures from governing standards on thermal comfort, as outlined in section 3.2.

Most of the mathematical work within the cited papers is applicable for general use. However, effects on thermal comfort, energy loss and energy costs are not investigated yet in a way corresponding with thermal comfort standards. Therefore we investigate how thermal comfort is influenced by FHTES and from this we deduce constraints and guidelines for control algorithms.

3 MODELLING APPROACH

In this section we define a simulation model and constraints from theory on thermal comfort.

3.1 Thermal Network Model

The thermal network approach is a convenient way to demonstrate the relation between FHTES, energy demand and effects on thermal comfort. Another reason to adopt this approach is to use the model equations for model predictive control within the TRIANA smart grid control method (Molderink, 2011), which is a part of future work. Accuracy of thermal networks is demonstrated in (Liu et al., 2011) and (Bacher and Madsen, 2011).

The applied thermal network for the living room of typical Dutch low energy house as defined by (AgentschapNL, 2013) and model equations are shown in the appendix. The concrete floor, the zone including internal separation walls, inner and outer parts of envelope walls and ceiling are modelled as temperature nodes with a thermal capacitance. Solar gains are defined at the outer wall node and the zone node by window transmittance. Heat loss due to ventilation and infiltration is defined at the zone node, as well as appliances and people gains. Heating input is defined at the floor node.

Weather data from Hoogeveen (close to Meppel) of ambient temperature and global transmittance, i.e. total solar radiation on the horizontal plane is used as input data within the model. Solar radiation on building planes is calculated using correlations by (Erbs, 1982) and equations by (Duffie, 1980). Transmitted radiation through the windows is for 25% absorbed by the floor and 75% by the zone structure. The house orientation is ideal for passive solar gains and there are no obstacles which could cast shadows on the house surfaces. In practise, this may not always be the case, especially not in midwinter when the sun is quite low above the horizon.

The simulation model includes Proportional Integral (PI) control of the heating/cooling input to the floor with the error between the zone temperature and its set point as controlled variable.

3.2 Theory on Thermal Comfort

The thermal network model of the living room is defined in such a way that it is possible to calculate the operative temperature of the zone. The operative temperature is defined in (ISO, 2005) and (ASHRAE, 2010) and is the most important comfort parameter to evaluate the influence of radiation from surfaces and air convection on experienced human thermal comfort. For relatively low air velocities applicable for home situations, the operative temperature of a zone is calculated from (ASHRAE, 2010):

$$T_{op} = \frac{T_{air} + T_{rad}}{2} \quad (1)$$

In which T_{air} is the zone air temperature and T_{rad} is the mean radiation temperature of all surfaces surrounding a person. It is impractical to calculate T_{rad} for each person as this also depends on the place where the person is situated in a room. Hence an average for a zone is proposed based on (ASHRAE, 2009).

$$T_{rad}^{\ 4} \cdot \sum_{i=1}^{6} A_i = \sum_{i=1}^{6} A_i \cdot T_i^{\ 4} \quad (2)$$

The living room zone is surrounded by 6 surface areas A_i with surface temperature T_i. Guidelines for the operative temperatures are defined in ISO 7730 and are related to the outdoor temperature in case adaptivity to outdoor conditions is taken into account:

- If $T_{outdoor} < 10°C$ then $20°C < T_{op} < 24°C$
- If $T_{outdoor} > 15°C$ then $22°C < T_{op} < 26°C$

A heated or cooled floor has an effect on the mean radiant temperature and on the operative temperature. But according to ISO 7730, a warm or cold floor also directly influences the thermal comfort of people. Limits can be calculated from the percentage dissatisfied equation given in ISO 7730 which yields: $19{,}2°C < T_f < 28°C$.

According to ISO 7730, another constraint is on dynamic changes of the operative temperature. Periodic peak-to-bottom variations should be limited to 1°C which is combined with a maximum rate of change of less than 2°C/hour.

Limits on radiant asymmetry pointed out in ISO 7730 are quite large and therefore not relevant for floor heating systems.

For home applications, it is worth to note the following:

1. ISO standard 7730 is developed and validated mainly for people working in offices and schools. People may evaluate thermal comfort different in a home situation, while people are more at rest while being at home. Besides that older aged people tend for higher operative temperatures than younger people. This causes differences in energy demand between households, which is important to take into account for the energy system configuration.
2. The minimum allowable floor temperature may not be reached during the heating season, as the floor heating will have to compromise heat loss of the house. So the minimum floor temperature is the floor temperature which is necessary to maintain a comfortable operative temperature of the zone.
3. The minimum allowable floor temperature limits cooling capacity of the floor cooling system during the summer season.

4 CASE DESCRIPTION

In this section we describe relevant details for the living room model and define scenarios for the case study.

Model parameters, i.e. specific mass of the concrete floor, ceiling and walls are derived from Dutch building details (Bouwformatie, 2013), (BUVA, 2013) and (VIEGA, 2009), which are currently applied for low energy houses in the Netherlands. The floor is a hollow channel concrete type. On top of the floor, the floor heating tubes are laid on a grid mat filled up with a concrete casting. Specific density of the total floor is typically 514 kg/m^2. The ceiling has the same structure as the floor. The envelope wall consists of a concrete inner wall, insulation material, air gap and brick outer wall.

To calculate electricity demand for the heat pump, a constant COP of 4,5 is assumed at all times.

Weather data of February 2012 from station Hoogeveen is used. Simulation results are shown for the 2^{nd} week which runs from hour 168 to 336, i.e. midnight of the 1^{st} until the 7^{th} day.

The following control scenarios are investigated:

1. Control 1: Constant temperature set point of 20°C.

2. Control 2: Varying temperature set point: 19,5°C at night, 20,5°C at day. Control 2 is scheduled in such a way that operative temperatures are within thermal comfort limits during daytime hours and total energy demand is comparable to control 1.
3. Control 3: Same as scenario 2 but with additional short term storage for district power balancing.

Besides these control scenarios, the following energy price schemes are investigated:

1. Conventional: conventional power grid with lower night time energy rates.
2. Alternative: district power grid based on renewable PV-generation. Lower rates apply during hours with sunshine and higher rates during hours without sunshine.

5 DISCUSSION OF RESULTS

Simulated heating input for control 1 is shown in Figure 1 together with the global transmission, $G_{t,h}$ and the operative temperature of the living room. The influence of solar absorption by the interior of the living room can be observed as hours of less or even no required heating input. Besides this positive effect, this however reduces the possibilities for FHTES by the heat pump, as is deduced from the operative temperature. As explained in section 3.2, operative temperature variation should be less than 1°C, so the allowable range for this case is 20-21°C. On the 1st day, 21,3°C is reached due to solar absorption. As this is just outside the allowable range and energy can be saved by using the absorbed solar energy, possibilities to store energy by the heat pump are limited. It is also observed that as solar energy decreases the remainder of the week, longer periods of heating energy are required and operative temperatures are more stable, enabling more possibilities for FHTES by a heat pump.

To study heat loss, control 3 is introduced, which is basically the same as control 2 but with small additional two hour storage periods taking place at the indicated circles in Figure 3. As is observed from Figure 2, the heating input of control 3 is shifted in time compared to control 2. A simple way to accomplish this in a smart grid is that the central controller asks the home controller to temporarily raise the temperature set point. The total stored energy in the floor during each shift is 1600 Wh. Observe from Figure 2 that the total energy demand for the whole week is almost not influenced by these storage periods. The additional energy loss is calculated at 479 Wh, i.e. 6% of the total charged energy (8.000 Wh). This is rather small because of (a) good insulation of the house and (b) stored heat is consumed by the interior and results in a period of less heating input, observe the larger drop in the heating input of control 3 after each storage period, compared to control 2.

The effects of the storage periods on the operative temperature are shown in Figure 3 (compare control 3 with 2). The last four peaks almost reach to 21°C, which is just within the allowable range. The operative temperature seems to increase quite fast, but still less than 0,5°C/h, well below the requirements set out in section 3.2.

The short term storage period which was just calculated is significant for district power balancing. For the living room, the average heating requirement during the investigated week is calculated at 475 W.

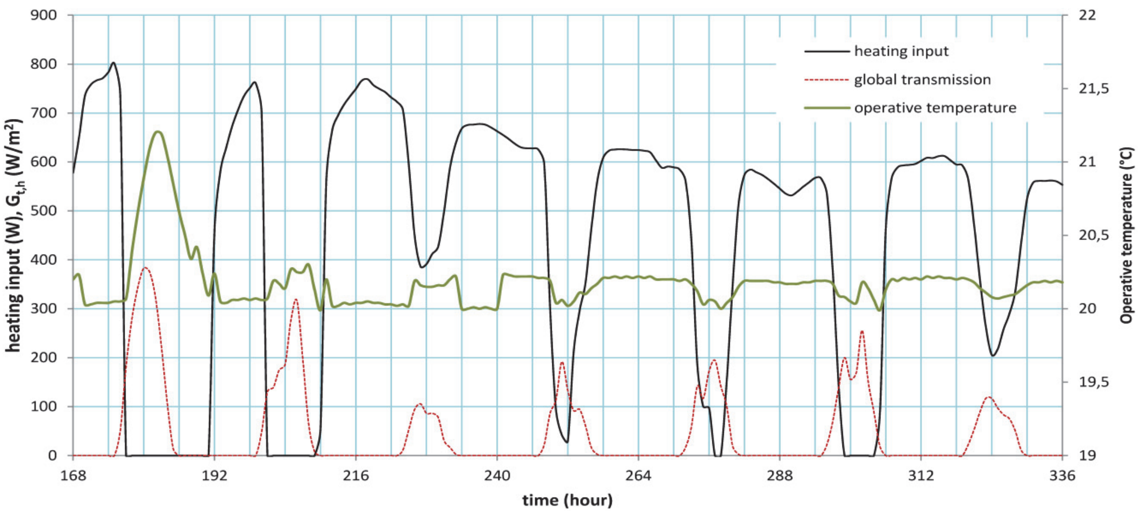

Figure 1: Floor heating input and operative temperature for control 1.

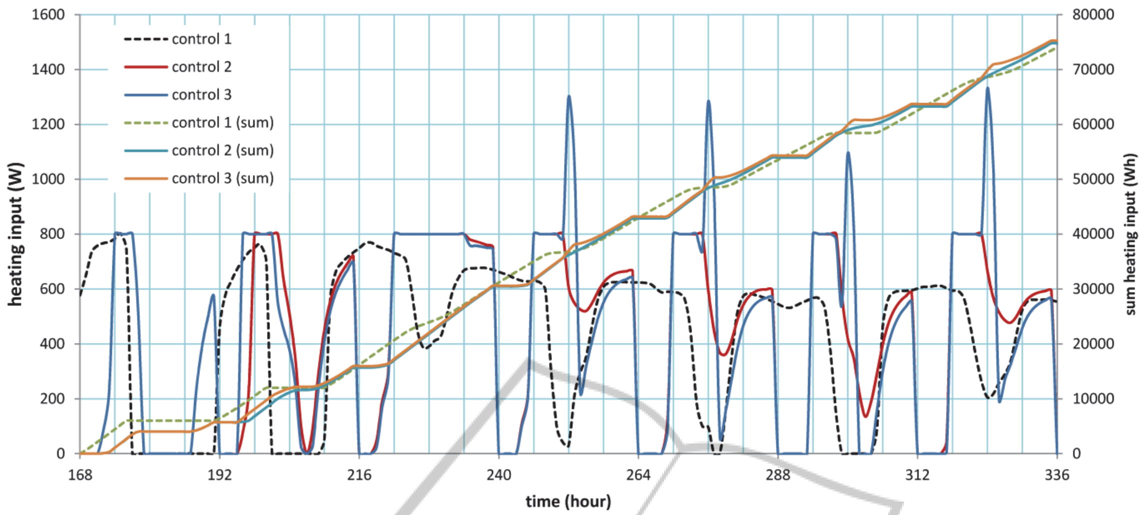

Figure 2: Heating input and sum of heating input to floor heating system.

SCITEPRESS
SCIENCE AND TECHNOLOGY PUBLICATIONS

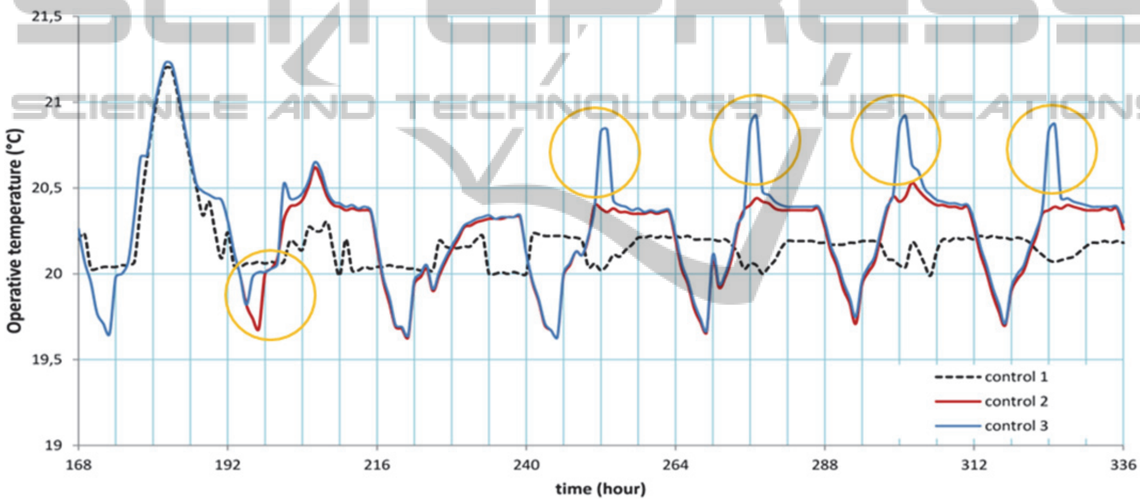

Figure 3: Operative temperatures.

With the heat pump COP assumed at 4,5 the CHP has to deliver on average 106 W electric energy to the living room. The short term storage period just investigated involved 800 W, i.e. 178 W electric energy. This is 168% of the average electric energy demand. Hence we conclude that floor heating systems can be used very well for short term periods of storage for district power balancing.

To study energy costs for the residents, the simulated energy input for the three control methods is translated into total required electric energy which is multiplied by energy price rates. A high rate of €0,30/kWh and low rate of €0,20/kWh including taxes and network costs are defined, i.e. close to actual Dutch consumer electricity rates.

Energy costs for the investigated week are referred to the reference case on the first line (i.e. 100%) in Table 1. As observed from Table 1 costs are higher for control 2 than for control 1 in case of a conventional power grid (compare both grey marked lines), because energy demand for control 2 is shifted towards daytime hours.

In case of PV-generation, control 1 has higher costs and control 2 has lower costs, as is observed from the 2nd and 4th line of Table 1.

Control 3 (5th line, Table 1) has the same basic temperature control as control 2 (lower night time temperature) but with some additional heat storage periods during day hours, typical for district power balancing in case of PV-generation. If on average the heat storage is offered for €0,21/kWh then the costs are comparable to the reference.

As a general rule for the storage rate, the standard rate for the applicable hour should be reduced with the percentage energy loss (i.e. 6% in this case) caused by storage to offer a cost neutral proposition for the residents.

Table 1: Results energy cost comparison.

control	peak rate hours	energy costs (%)
1	07.00-23.00	100
1	18.00-24.00 0.00-09.00	112
2	07.00-23.00	119
2	18.00-24.00 0.00-09.00	100
3	18.00-24.00 0.00-09.00	100

6 CONCLUSIONS

By simulation the amount of Floor Heating Thermal Energy Storage (FHTES) by a renewable energy supply system, energy loss and cost strategies associated with FHTES is investigated. Resulting values are case specific, but the observed effects on energy demand and operative temperatures due to FHTES are valid for any building equipped with floor heating.

Our simulations show that the amount of energy that can be stored in a floor heating system depends on the house and floor heating structure, degree of insulation, weather and temperature settings by the residents.

From theory on thermal comfort, we find the following constraints for FHTES:

- allowable room operative temperature range: 20 to 24°C.
- periodic operative temperature variation: less than 1°C peak to bottom.
- operative temperature rate of change: less than 2°C/hour.
- allowable floor surface temperature range: 19 to 28°C.

In our simulations we compare three types of temperature control. A constant day/night temperature set point (control 1) shows that heating demand mostly occurs at night hours. A lower set point during night hours (control 2) shifts heating demand towards day hours. For district power balancing, control 2 has the advantage that the heat pump can be used more flexible during the night for generating domestic hot water. If additional to control 2, short storage periods during daytime hours are introduced (control 3), we find that operative temperatures remain within allowable comfort limits. We conclude from this that a house with a floor heating system provides substantial storage capacity which can be used to maintain power balance within a district energy supply system.

Energy loss due to FHTES appears to be small, at least for low energy houses. However, a fair energy cost policy should take this loss into account, e.g. by offering a discount energy storage rate to residents. In this way FHTES can facilitate district power balancing while maintaining acceptable levels of thermal comfort and energy costs for residents.

Our future work will be dedicated to further research on district power balancing and algorithms for smart grid control in which we apply knowledge presented in this paper.

REFERENCES

Agentschapnl. N. D., *Meppel heats new housing development with biogas*. Available: http://www.agentschapnl.nl/sites/default/files/Meppel heats new housing development with biogas.pdf, retrieved: 18-10-2013.

Agentschapnl. 2013. Referentiewoningen nieuwbouw 2013. Available: http://www.agentschapnl.nl/sites/default/files/2013/09/Referentiewoningen.pdf, retrieved: 18-10-2013.

Airaksinen, M. & Vuolle, M. 2013. Heating Energy and Peak-Power Demand in a Standard and Low Energy Building. *Energies,* 6**,** 235-250.

Alvi, A. & Qureshi, 2011, H. F. Evaluation of Building Integrated Heating System in Terms of Thermal Comfort & Energy Efficiency, Mälardalen University, Sweden.

ASHRAE 2009. *ASHRAE Handbook-Fundamentals,* Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

ASHRAE 2010. ASHRAE standard 55-2010 Thermal environmental conditions for human occupancy. Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Bacher, P. & Madsen, H. 2011. Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings,* 43**,** 1511-1522.

Bouwformatie 2013. Available: http://bouwdetails.bouwformatie.nl., retrieved: 18-10-2013.

BUVA 2013. *BUVA bouwdetails* [Online]. Available: buva.archidat.nl., retrieved: 18-10-2013.

CBS 2011, Hernieuwbare energie in Nederland 2011. Heerlen: CBS.

Duffie, J. A., Beckman, W. A. 1980. *Solar engineering of thermal processes,* New York, Wiley.

Erbs, D. G., Klein, S. A., Duffie, J. A. 1982. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy,* 28**,** 293-302.

Fellin, F. & Sommer, K. 2003. Study of a low energy office building with thermal slabs and ground coupled heat pump. *Dipartimento di Fisica Tecnica, Università di Padova (Italia)*.

ISO 2005. NEN-EN-ISO 7730 Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005,IDT). Delft: NEN.

Lehmann, B., Dorer, V. & Koschenz, M. 2007. Application range of thermally activated building systems tabs. *Energy and Buildings,* 39**,** 593-598.

Liu, K., Tian, Z., Zhang, C., Ding, Y. & Wang, W. 2011. Establishment and validation of modified star-type RC-network model for concrete core cooling slab. *Energy and Buildings,* 43**,** 2378-2384.

Molderink, A. 2011. *On the tree step methodology for smart grids.* University of Twente.

Nykamp, S., Molderink, A., Bakker, V., Toersche, H., Hurink, J. & Smit, G. 2012. Integration of heat pumps in distribution grids: Economic motivation for grid control. *3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*, IEEE, 1-8.

Pavlov, G. K. & Olesen, B. W. 2011. Building thermal energy storage-concepts and applications, Technical University of Denmark.

Rijksen, D. O., Wisse, C. J. & Van Schijndel, A. W. M. 2010. Reducing peak requirements for cooling by using thermally activated building systems. *Energy and Buildings,* 42**,** 298-304.

Rijkswaterstaat. 2013. *WKO tool*. Available: www.wkotool.nl, retrieved: 21-10-2013.

Saelens, D., Parys, W. & Baetens, R. 2011. Energy and comfort performance of thermally activated building systems including resident behavior. *Building and Environment,* 46**,** 835-848.

Scheepens, A. E., Flipsen S.F.J., Vogiatzakis, P., Brezet, J.C. 2013. An Ecocost-Value Ratio (EVR) approach to the design of a Product-Service System for environmentally sustainable residential heating energy use. *Energy and Environment Knowledge Week - E2KW2013.* Toledo, Spain.

Tahersima, F., Stoustrup, J., Meybodi, S. A. & Rasmussen, H. 2011. Contribution of domestic heating systems to smart grid control. *50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC)*, IEEE, 3677-3681.

Toersche, H., Bakker, V., Molderink, A., Nykamp, S., Hurink, J. & Smit, G. Controlling the heating mode of heat pumps with the TRIANA three step methodology. *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, IEEE, 1-7.

Verhelst, C., Logist, F., Van Impe, J. & Helsen, L. 2012. Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system. *Energy and Buildings,* 45**,** 43-53.

VIEGA 2009. Technische handleiding Fonterra vloer- en wandverwarming, Available: http://www.viega.nl/cps/rde/xbcr/nl-nl/Technische_handleiding_Fonterra_vloer_en_wandverwarming.pdf, retrieved: 18-10-2013.

Witte, H., Van Gelder, A., Klep, P. & Groenholland, B. 2006. A very large distributed ground source heat pump project for domestic heating: Schoenmakershoek, Etten-Leur (the Netherlands). *Proceedings Ecostock, the Tenth International Conference on Thermal Energy Storage.* New Jersey, 2006.

APPENDIX

This appendix contains the applied thermal network model and state equations for the temperature nodes. The used symbols and subscripts are listed in Table 2.

Table 2: Symbols and subscripts.

Nomenclature	
T	Temperature
R	thermal resistance
E	electric energy
q	thermal energy
HP	heat pump
Subscripts	
z	zone
f	floor
c	ceiling
z2	zone on first floor above living room
cs	creeping space
wi	interior wall of envelope wall
wo	exterior wall of envelope wall
rad	radiation
cv	convection
a	ambient or outdoor

Thermal network model equations

$$C_z \frac{dT_z}{dt} = \frac{T_c - T_z}{R_{zc}} + \frac{T_a - T_z}{R_{win}} + \frac{T_{wi} - T_z}{R_{zw}} + \frac{T_f - T_z}{R_{zf}} + q_{gain,z}$$

$$C_f \frac{dT_f}{dt} = \frac{T_z - T_f}{R_{zf}} + \frac{T_{cs} - T_f}{R_{fcs}} + \frac{T_c - T_f}{R_{fc}} + q_{gain,f}$$

$$C_{wi} \frac{dT_{wi}}{dt} = \frac{T_z - T_{wi}}{R_{zwi}} + \frac{T_{wo} - T_{wi}}{R_{wi\text{-}wo}} \quad (3)$$

$$C_c \frac{dT_c}{dt} = \frac{T_z - T_c}{R_{zc}} + \frac{T_{z2} - T_c}{R_{cz2}} + \frac{T_f - T_c}{R_{fc}}$$

$$C_{wo} \frac{dT_{wo}}{dt} = \frac{T_{wi} - T_{wo}}{R_{wi\text{-}wo}} + \frac{T_a - T_{wo}}{R_{wo\text{-}cv}} + \frac{T_{sky} - T_{wo}}{R_{wo\text{-}rad}} + q_{gain,wo}$$

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS

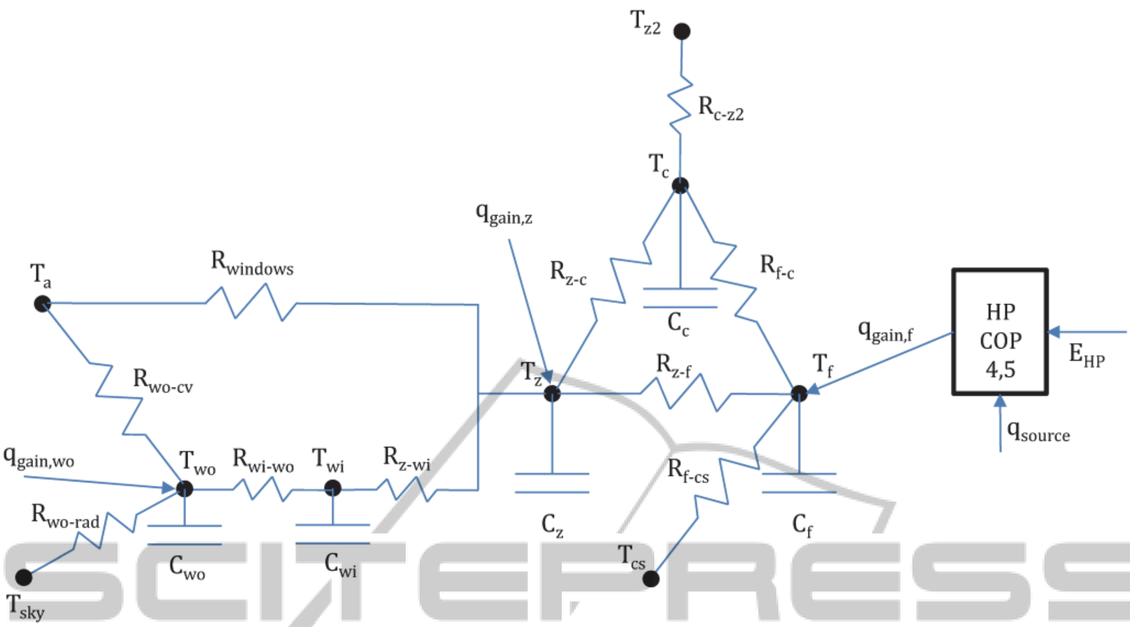

Figure 4: Thermal network model of low energy house living room.

SCITEPRESS
SCIENCE AND TECHNOLOGY PUBLICATIONS