



Studies of Heat Dynamics in an Arctic Low-energy House

Andersen, Philip Hvidthøft Delff; Rode, Carsten; Madsen, Henrik

Published in:
Proceedings of the 5th International Building Physics Conference

Publication date:
2012

[Link back to DTU Orbit](#)

Citation (APA):
Andersen, P. H. D., Rode, C., & Madsen, H. (2012). Studies of Heat Dynamics in an Arctic Low-energy House. In Proceedings of the 5th International Building Physics Conference

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Studies of Heat Dynamics in an Arctic Low-energy House

Philip Delff¹, Carsten Rode², and Henrik Madsen¹

¹*Department of Informatics and Information Modelling, Technical University of Denmark, Kgs. Lyngby, Denmark*

²*Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark*

Keywords: Low-energy houses, Heat dynamics, Arctic climate, statistical modelling, greybox modelling.

ABSTRACT

A low energy house situated in Sisimiut, Greenland is used as study object for analysis of dynamic thermal properties of energy efficient buildings. The building is instrumented with a number of energy meters and thermal sensors, and these thermal data are logged with fine time intervals. Statistical methods are being developed in a PhD project to derive the properties to be used in a dynamic thermal model of the whole building. Characteristic of the building is its exposure to the extreme Arctic climate, which is both very cold and where the sun in some periods may shine constantly, or not at all. The house is equipped with a weather station measuring temperature, solar radiation, wind speed and direction. The building is highly energy efficient and its performance has been followed since its inception in 2005. The energy efficiency of the building is due to good thermal insulation, large energy-efficient windows, and heat recovery. The house is divided into two symmetric apartments, of which one is inhabited by a family, and the other is used for experiments and demonstration. The situation provides unique options for measuring and analysis with large signal to noise ratios facilitating observation of thermal response to external temperatures, solar radiation, wind, user behaviour, and heating.

1. Introduction

In 2005, a low-energy house was inaugurated in Sisimiut, Greenland. The objective of the house was to build a house with very low energy consumption for heating, which should inspire the development of energy efficient housing in Greenland and demonstrate the potentials for energy efficiency that can be achieved in a house which should also be a leading example of good indoor thermal environment.

The house and its objective were presented by Norling et al. (2006). Therefore the current paper will only briefly introduce the house and then focus on how well the house has lived up its performance targets, and which challenges it has incurred. Some preliminary performance results were presented also by Rode et al. 2009, but significant improvements have occurred since then.

2. Description of the house

It was set as a target for the house that the energy consumption for heating and ventilation should be only half of that permitted by the 2006 edition of the Greenlandic Building Regulations: 230 kWh/(m²·yr) (Government of Greenland, 2006). Furthermore, considering that the house was planned to have a ventilation system with heat recovery, something that was not assumed for residential dwellings in the building regulations, the target value 80 kWh/(m²·yr) was chosen. Building energy simulations were executed to substantiate that this level of annual energy consumption was possible.

The means to reduce the energy consumption in comparison with common Greenlandic houses has been to use extra insulation in floors, exterior walls and the roof. Advanced windows have been used with low energy glazing using normally 3 layers of glass. A solar collector is installed on the roof for domestic hot water heating. The house has been orientated to exploit the light and it has a geometry which optimizes the daylight. The ventilation system is supplied

with a counter-flow heat exchanger that uses the warm exhaust air to preheat the cold inlet air.

Sisimiut is the second largest city of Greenland (5,500 inhabitants) located on the west coast just 42 km north of the Polar Circle. The mean average temperature is around 6 °C in summer and around -13°C in the winter months. The number of heating degree days is around 8,000 K·days (base 19°C).

The house is approximately 200 m² and is made as a semi-detached house, where the two living areas are built on each side of the boiler room and an entrance hall. Fig. 1 shows a picture of the house, and Fig. 2 shows the cross section and floor plan of the house. One of the two dwellings serves as home for a family, while the other is used as a guest house for visitors.



Fig. 1. Photo of the low energy house in Sisimiut as seen from the west.

Table 2. Heat transmission coefficient (U_g , U_w), solar energy transmission (g_g , g_w) and net annual energy gain (Q_g , Q_w). Index g for glazing and w for window.

Type	U_g W/(m ² ·K)	g_g -	Q_g kWh/m ²	U_w W/(m ² ·K)	g_w -	Q_w kWh/m ²
1: 1+2	0.7	0.45	172	1.0	0.30	-17.3
2: 2+Vac.glaz	0.7	0.40	136	1.1	0.27	-59.3
3: 2+1	0.8	0.56	228	1.1	0.47	67.1

The three types of glazing units are shown in Fig. 4. Data for the glazing units are shown in Table 2. The net energy gain is calculated as a mean value of windows orientated north, east, west and south for a reference house.

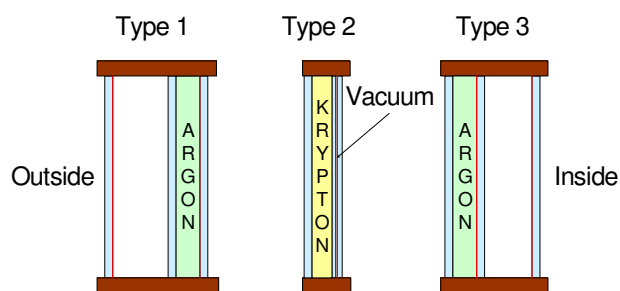


Fig. 4. The three glazing units used in the low-energy house

2.3 Heating system

The low-energy house is constructed with a hydronic floor heating system based on PEX-tubes installed in aluminium plates just below the wooden floor boards. The floor heating system in the toilets is based on PEX-tubes cast in the concrete. The ventilation system is equipped with a heating coil which is positioned in the supply air duct after the heat exchanger. The heating coil is meant to ensure that the supply air is delivered at a minimal temperature of 18°C. The ventilation system's heating coil is based on the same hydronic system as the floor heating.

Hot water for the floor heating and heating coil is supplied from an oil furnace, which is located in the boiler room of the house. Heat for the domestic hot water comes from a solar collector which has a size of 8.1 m² and faces southeast. The oil furnace supplies back up heat in periods when the solar heating is insufficient. Finally, a radiator in the entrance hall is meant to be heated with excess heat from the solar collector system when available.

2.4 The ventilation system

Mechanical ventilation with heat recovery in cold climates can present problems with ice formation in the heat exchanger. That is, when warm humid room air is brought in contact with the cold surfaces of the exchanger (cooled by the outside air), the moisture in the exhaust air condenses in the heat exchanger. If the outside air is below freezing, the water vapour will freeze, resulting in a larger air flow resistance on the exhaust side of the exchanger, which in turn decreases the air flow. The decrease in the amount of warm air through the exchanger will result in the exchanger being cooled further, and eventually the system will become fully blocked by ice and stop.

This problem can be prevented by preheating the inlet air before it reaches the exchanger. This will however result in extra energy consumption and higher installation costs, and is therefore not an optimal solution.

Therefore a new design of a heat recovery unit was developed for the low-energy house in Sisimiut in cooperation between EXHAUSTO A/S and the Technical University of Denmark. The dimensions of the unit are: Length 1,760 mm, width 930 mm and height 660 mm. The unit consists of two highly efficient aluminium counter flow heat exchangers coupled in a serial connection. A damper is able to switch the air flow direction through the units. When ice formation starts to reduce the air flow in the coldest exchanger, the air flow direction is switched. The exchangers, damper and filters are mounted in a cabinet with 50 mm insulation, although the unit is recommended to be placed in a heated place to minimize risks of frost damages from the condensing water. A diagram of the system is shown in Fig. 5. The theoretical temperature efficiency of the heat recovery unit is approximately 90 %.

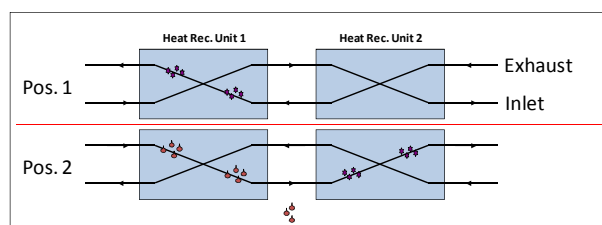


Fig. 5. Diagram of the heat recovery unit with two heat exchangers. A valve and a timer switch the flow direction when ice formation reduces the air flow.

2.5 The solar collector

Solar hot water panels installed on the low-energy house constitute a flat plate collector. It has a total surface area of 8 m² and the system is able to produce 1,700 kWh/year. This covers approximately 57 % of the hot water consumption of the house. The house and its inhabitants use around 150 litres of hot water per day. The solar collector faces south-east and is tilted 70° from horizontal to have the optimal position in relation to the sun.

3. Linear modelling of existing data

Since the inauguration of the house, consumption recordings have been stored together with measurements of indoor climate variables. The consumption recordings consist of oil and electricity consumption recordings for each apartment and for common areas. For the ventilation and heating systems all inlet and outlet flows and temperatures have been measured. Moreover, measurements have been taken of temperatures and relative humidity both indoors and in some construction parts.

The measurement recordings have been interrupted so only limited periods can be used for modelling. Two periods of approximately 2.5 months each have been chosen for analysis. The first period starts on September 1st 2009 while the second starts on February 1st 2010. Quite some mending had been carried out between these two periods so the house is expected to perform better – namely be tighter and have a better control of the heating – in the second period. A first comparison of the energy consumption for the two periods can be seen in Fig. 6. It is seen that the largest energy consumption is in floor heating which has been reduced by more than 90 MJ/day or more than 29%. The ventilation heating is in general only 10-20% of the contribution from floor heating but it has increased with about 12 MJ/day or

36%. Energy consumption for water has dropped dramatically with 69%. While for a household this consumption is equally interesting as the others, in the modelling of the performance of the building envelope it will be left out. This is because the hot water consumed is largely assumed to be drained while still warm. The three electricity consumptions have all increased with 30-52% or 5.5—15 MJ/day. Omitting heating of domestic water, the daily consumption is 54 MJ lower in the second period than in the first, which corresponds to a reduction of 13%.

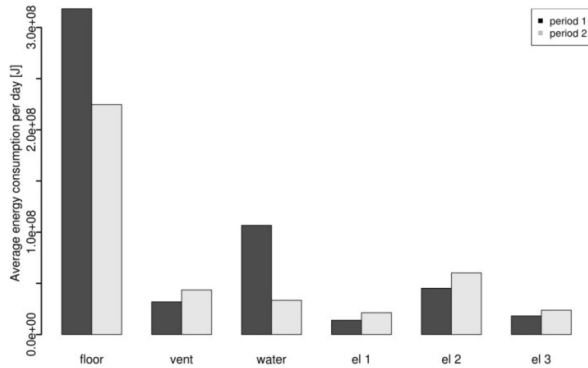


Fig. 6 Comparison of the energy consumption in the house for the two chosen periods.

However, such periods are hard to compare because of the different weather conditions, possibly differences in the use of the house etc. For this reason, a model is needed to describe the influences from the different variables. The

variables that will be used here are indoor and outdoor temperatures, solar radiation, and wind speed. In Nielsen, 2008 the following model is used to estimate both UA and gA values:

$$Q = b_0 - UA \cdot T_a - gA \cdot \Phi_s + b_1 \cdot W_s + e \quad (1)$$

See Table 3 for nomenclature. The work in Nielsen, 2008 is based on measurements where only the outdoor temperature was measured. In the data from Sisimiut indoor temperature measurements are however available and so instead of using only the outdoor temperature, the difference between the indoor and outdoor temperature can be used.

Table 3 Nomenclature

Symbol	Explanation
T_i	Indoor temperature
T_a	Outdoor temperature
T_d	$T_i - T_a$
Φ_s	Solar radiation (from the house)
W_s	Wind speed
e	Gaussian error term

A re-sampling has been performed on the data to obtain daily values. Temperatures and wind speeds have been averaged whereas energy measures (consumptions and solar radiation) have been summed. The re-sampled data for the two periods is plotted in Fig. 7 and Fig. 8 respectively.

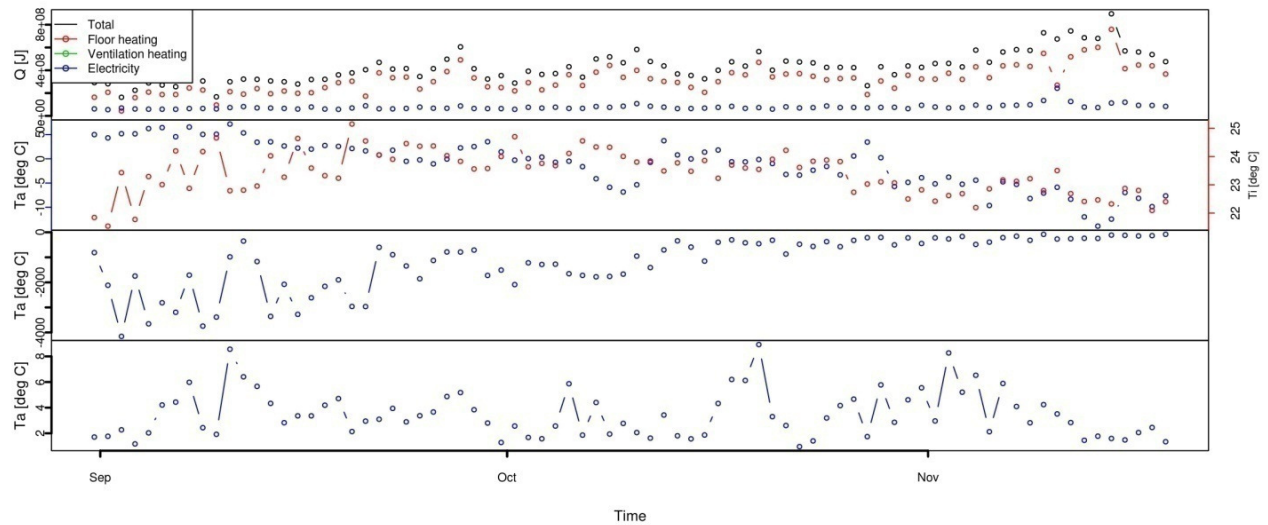


Fig. 7 Data for the first period used for linear regression.

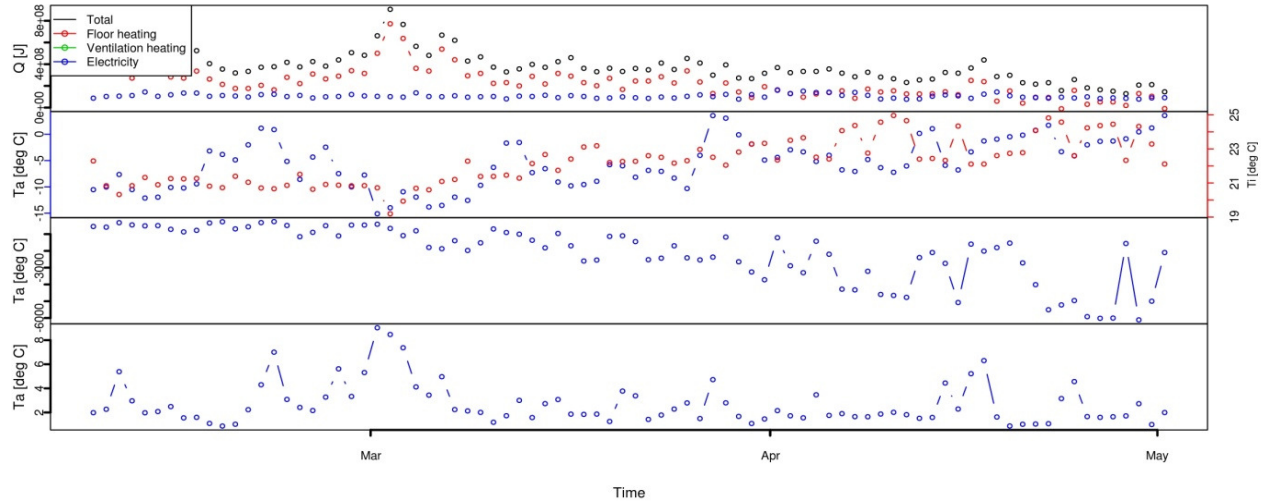


Fig. 8 Data used for the second period used for linear regression.

As argued in Nielsen, 2008 the term related to conduction can be better estimated by also using data from the day before. This was also found significant in this dataset. Moreover, the convection part is multiplied with $T_{d,N-1}$. The physical relation in convection suggests this relation, and it was found to describe data slightly better. The model becomes

$$Q_N = b_0 + UA_1 T_{d,N} + UA_2 T_{d,N-1} - gA\Phi_s + b_1 T_d W_{s,N} + e_N \quad (2)$$

Where N refers to data from day N. The UA value will be estimated as

$$UA = \frac{UA_1 + UA_2}{2} \quad (3)$$

Table 4 Estimates of parameters in the linear model fitted to the two periods of existing data.

Parameter	Period 1	Period 2
$b_0(kJ)$	-118568	-13476
$UA(kJ/K)$	10851	6840
gA	16×10^3	35×10^3
$b_1(kJ s/K m)$	432	1079
$\sigma(kJ)$	68930	61940

The obtained parameter estimates are listed in Table 4. The intercept can be interpreted as “Daily energy consumption when there is no indoor/outdoor temperature difference, no temperature difference the day before, and no solar radiation”. It seen that it increases significantly from period 1 to period 2. This could be explained by the increased electricity consumption which will normally be independent of the indoor climate. The negative sign of the parameters is surprising and the lack of physical explanation suggests that the values estimated here should only be used as a first look into the performance of the house.

For both parameters directly related to temperature differences, there is a significant drop from period 1 to 2, and the sensitivity to solar radiation is more than doubled. The

only parameter change that indicates a decreased performance of the building is b_5 , the parameter related to the product of wind speed and temperature difference between inside and outside. Whether this is because of a decrease in the tightness of the house or it is caused by aspects of the used data will have to be analysed further. In general, it has to be kept in mind that this model has been justified on the data used but if the purpose was to find a “best model” by some statistical measure this is not the model that one would end up with for both data sets. Therefore, correlation structures can have an important influence on the estimates. I.e. the estimates of UA and b_1 will most likely be correlated because of the use of the temperature difference in both of the related terms.

By the estimates of the variances of the noise terms, it is seen that the model fits the energy consumption with a standard error of less than 70 MJ or 20 kWh per day. This corresponds to multiple values of 0.734 and 0.797, respectively.

Comparing with results in Nielsen, 2008 is not straightforward. In that work, care is taken to estimate the firing season and base the estimate on a whole firing season. Also, outlier removals have been performed in a certain way that is not followed here, and last but not least the data sets are very different and the assumption that the model can be extrapolated between the two has not been justified. But at least to get an idea of the order of magnitude of the estimated UA value, it still serves some purpose to compare. The two UA values found correspond to 125.6 W/K and 79.1 W/K, respectively. The values estimated in Nielsen, 2008 are between 88.5 W/K and 243.45 so the values are of the same order of magnitude and the results even suggest that the house in Sisimiut performs well and after the improvements even very well.

4. Improved measurement and control equipment

In the spring 2011, new measurement equipment and a programmable logic controller (PLC) system was installed in the house. This facilitates online and centralized scheduling and surveillance of experiments. Air temperatures in all rooms, heating and ventilation inlet and outlet temperatures and flows are measured. Moreover open/closed sensors are installed on all exterior doors and windows, and CO2 concentration is measured in the apartment not rented out.

A weather station taking meteorological measurements is installed on-site. Ambient temperature and horizontal solar radiation as well as wind speed and direction are measured. See an overview of the measurements most relevant to modelling of the heat dynamics in Table 5. Meteorological data is also available from a governmental weather station nearby.

Table 5 Overview of some of the measurements taken in the new experimental setup.

Measurement	Common areas	Rental apartment	Experimental apartment
Indoor Temperature	-	All rooms	All rooms
Full standard indoor temperature measurement in living room			
<i>Heating</i>			
Floor heating	1/2	0/5	5/5
Floor heating		All measured together	
Ventilation after heating		All measured together	
<i>Ventilation flow</i>			
Central ventilation		All measured together	
Outer doors open/closed	2/2	3/3	3/3
Windows open/closed	0/0	2/2	2/2
Cooker hood	0/0	0/1	1/1
<i>Occupancy</i>			
PIR sensors	0	0	Living room/kitchen, corridor
CO2 concentration	0	1 (deactivated)	1
<i>Consumption</i>			
Oil		All measured together	
Electricity	1/1	1/1	1/1
<i>Meteorology</i>			
Ambient temperature	All at one common weather station		
Solar radiation	Yes		
Wind speed	Yes		
Wind direction	Yes		

Control of heating and ventilation systems can be based on all measurements, functions hereof, or even exogenous inputs. An overview of the state of the system can be reached on-line, and a screen dump of this is seen in

. The overview intuitively shows how the different systems are connected and interact. There are two circulation systems, illustrated by different colours of the pipes. Follow the one leaving from the boiler; it goes to the domestic hot water tank (if the return valve is open), to ventilation after heating, and/or to floor heating. Before it comes back to the furnace, it passes through a heat exchanger. Follow the other pipe system from after (left of) the solar panel. It goes to

either heating the domestic water tank or to the radiator and buffer tank when a surplus of heat from the solar panel is present. The storage tank is both loaded and unloaded from the top so that a vertical temperature gradient can be maintained in the tank.

5. Greybox modelling

Statistical model building is an iterative process, and when modelling systems of high complexity it

is often most fruitful to start from a simple description and then step-by-step include new terms if they significantly improve the description of the system.

A first description of the heat loss was given in the preceding section. In order to describe the heat dynamics in more detail, grey-box models can be applied. Grey-box modelling combines the advantages of using physical knowledge about the system with statistical methods to obtain precise descriptions of the dynamics behind measurements on a physical system. Grey-box modelling typically uses stochastic differential equations and since these are based on the well-known differential equations of heat dynamics, they are by nature dynamic.

A dynamical linear model is formulated in (Bacher and Madsen, 2011):

$$dT_i = \frac{1}{RC}(T_a - T_i)dt + \frac{1}{C}A_w\Phi_s dt + \frac{1}{C}\Phi_h dt + \sigma_1 d\omega \quad (4)$$

$$\tau_k = T_{i,k} + e_k \quad (5)$$

where T_i is the indoor temperature, R is the thermal resistance of the building envelope, C is the heat capacity of the building, A_w is the effective area of the windows, Φ_h is the heat supply from the heating system. ω is a Wiener process (a white noise process in continuous time), and e_k is a constant. The first of the two equations is the model equation which describes the dynamics of the system. The last of the equations is the measurement equation and expresses in this case that the discrete-time measurements of the indoor temperature are encumbered with a measurement noise, $\{e_k\}$. Here, the short-hand notation $t \sim t_k$ is used.

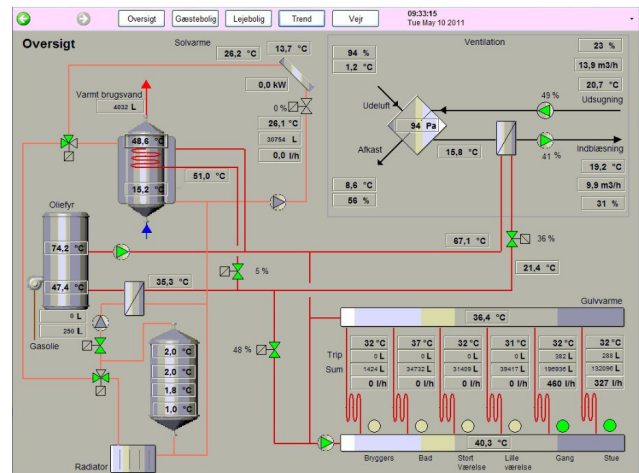


Fig. 9 Overview of the most important flow and temperature measurements in the house.

The test facilities available for the project are expected to enable observation of non-linear phenomena in the heat dynamics better. Hence a general heat balance in a house is considered. Let Φ in general denote a heat flux, and the

subscripts h, v, c, s, and i denote the heating system, ventilation, conduction, solar radiation, and infiltration. Then

$$dT_i = \frac{1}{c} (\Phi_h + \Phi_v + \Phi_a + \Phi_s + \Phi_i) \quad (6)$$

expresses the interior temperature development. σ_2 is a constant and ω_2 is a Wiener process.

The conduction Φ_a through walls, roof, doors and windows is expected to be of major importance. It leads to heating of the envelope which is again cooled by convection and long-wave radiation. The energy balance in a state on the outer surface of the building envelope is that the thermal energy accumulated in this state equals what is conducted from the inside surface plus the convection and radiation. The convection term is linear for a given convection heat transfer coefficient, h . But h is expected to be a non-linear function of wind speed and wind direction. The radiation term is non-linear in both T_o and T_{surr} . With this knowledge the energy balance can be written as

$$dT_o = k_1(T_i - T_o)dt + f_h(W_s, W_d)(T_a - T_o)dt + k_2(T_{surr}^4 - T_o^4)dt + d\omega \quad (7)$$

The challenge is now to estimate the constants, k_1 and k_2 , and the function f_h . In Jimenez et al., 2008 f_h is modelled for a PV-module with an allometric function. In the present case the independence of the wind direction may be insufficient. In addition a way of modelling T_{surr} must be found. This could be as a function of T_a and the exterior relative humidity.

This non-linear extension of the linear dynamic model is only one of many possible extensions. It has been justified from physical considerations but the main criterion is the ability to describe the behaviour of the system. Experiments will be carried out in the test house in the winter 2011-2012, and then different models will be evaluated on the results.

6. Conclusions

Statistical modelling of heat dynamics is a strong tool for characterization of and improving energy performance of buildings. Promising results have already been obtained by applying linear dynamic models on heat dynamics in buildings. Test facilities in arctic area have been described and the advantages of these in relation to non-linear modelling have been discussed. Finally, some examples on modelling, non-dynamic and dynamic, linear and non-linear, have been given.

7. References

- Andersen K. K., Madsen H., Hansen L. H.. 2000. Modelling the heat dynamics of a building using stochastic differential equations. *Energy and Buildings*, 31(1):13-24. ISSN 03787788.
- Bacher P., Madsen H.. 2011. Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings*, In Press, Corrected Proof. ISSN 0378-7788. doi: DOI: 10.1016/j.enbuild.2011.02.005. URL <http://www.sciencedirect.com/science/article/B6V2V-5281SNX-1/2/b2eae0acc59b94e358cc3e7816bd94ae>.
- Enfor. Analysis of energy consumption in single family houses. Technical Report 03EKS0009A002, Enfor, 2010.

Government of Greenland. 2006. Building Regulations 2006.

Jimenez M.J., Madsen H., Bloem J.J., Dammann B. 2008. Estimation of non-linear continuous time models for the heat exchange dynamics of building integrated photovoltaic modules. *Energy and Buildings*, 40(2):157-167, ISSN 03787788.

Kristensen N.R., Madsen H., Jørgensen S.B. 2004. Parameter estimation in stochastic grey-box models. *Automatica*, 40(2):225-237. ISSN 00051098. URL <http://www.imm.dtu.dk/pubdb/p.php?3084>.

Madsen H. Holst J. 1995. Estimation of continuous-time models for the heat dynamics of a building. *Energy and Buildings*, 22(1):67-79. ISSN 03787788.

Nielsen H. Aa. 2008. Estimation of {UA}-values for single-family houses, ENFOR..

Norling C.R., Rode C., Svendsen S., Kragh, J., Reimann, G. 2006. A low-energy building under arctic conditions – a case study. In: *Research in Building Physics and Building Engineering – Fazio, Ge, Rao & Desmarais (eds)*.

Rode, C., Kragh, J., Borchersen, E., Vladykova, P., Furbo, S. Dragsted, J. 2009. Performance of the Low-energy House in Sisimiut. Cold Climate HVAC Conference, Sisimiut, 16-19 March 2009.

Vladykova P., Rode C., Borchersen E., Furbo S. 2009. Low-energy house in Sisimiut. Annual report of Low-energy house performance July 2008 to June 2009. Rapport SR 09-06. Technical University of Denmark.