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ECOBUILD RESEARCH: FULL-SCALE TESTING OF INNOVATIVE TECHNOLOGIES FOR ENERGY EFFICIENT HOUSES

E.J. Bakker

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E.J. BAKKER

Energy research Centre of the Netherlands (ECN),
unit Renewable Energy in the Built Environment (DEGO)
P.O. Box 1, NL-1755 ZG Petten, The Netherlands
Tel: +31 224 56 4974, Fax: +31 224 56 8966
E-mail: e.bakker@ecn.nl

SUMMARY

In one of the four test houses built on the ECN premises, a validation experiment has been carried out, comparing real-life energy performance of the total house with the predicted performance using a simulation model. Compared to the traditional housing market, a clear change in variable relevance for this energy efficient house was found. Valuable knowledge has been gathered on the energy balance for this house and on how to further reduce the uncertainty in experimentally obtained variables and in prediction of energy performance by numerical modeling.

THE ECN TEST HOUSES

Recently, Energy research Centre of the Netherlands (ECN) has built four test houses on its premises in Petten, The Netherlands. One of these terraced houses (the house on the right in Figure 1) is used to test ICT applications to save energy and to improve comfort (e.g. personal safety and indoor air quality). One of these applications is a demand controlled hybrid ventilation system [1]. This system is a combination of mechanical and natural ventilation, including heat recovery, controlled by e.g. CO_2 concentration and presence of occupants.

Figure 1: Block of four terraced test houses (A, B, C, D from left to right), built on the ECN premises in Petten, The Netherlands

The other three houses are built and used by the Ecobuild Consortium (consisting of building constructors, suppliers, researchers and housing associations) to test innovative energy concepts for the Dutch housing market. These innovations concern both construction and HVAC equipment. The consortium chose to build full-scale houses to be able to test under real-life conditions and to take into account the fact that the integration of house and systems is more than the sum of the components.

THE ECOBUILD RESEARCH PROJECT

The Ecobuild Research project consists of two phases. In the first, recently completed phase, energy concepts to reduce energy consumption by 50% (compared to the current Dutch building energy performance code, see Figure 2) were tested. In the second phase the consortium will test concepts that will lead to "zero-energy", i.e. an annual (local) energy production equal to the annual energy demand. Besides energy, the project also focuses on other relevant aspects that can be seen as boundary conditions for a successful large-scale introduction of the concepts:

- thermal comfort, determined by e.g. indoor air temperatures and ventilation,
- economic feasibility, determined by investments and reduction of energy consumption,
- environmental impact, determined through Life Cycle Analysis,
- living comfort, determined by e.g. noise levels, daylight levels and indoor air quality.

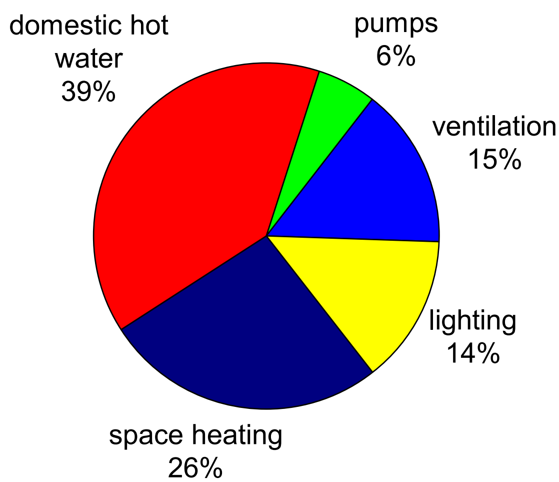

Figure 2: Building related primary energy demand, according to current Dutch building energy performance code (EPC = 1)

The houses have different constructions, varying from a concrete body, a semi-concrete body to a timber frame body. The façade cladding varies from standard bricks to Western Red Cedar wood. The result is that, going from house A to D in Figure 1, the thermal mass decreases per house. This allows investigation of the effect of thermal mass on energy performance and thermal comfort. The level of insulation however is equal, about 5 m^2.K/W for the roof and façade and about 8 m^2.K/W for the floor. Examples of technologies used in the first phase of the project are:

- double-pane Argon-filled and triple-pane Krypton-filled glass,
- compression heat pump with ground heat exchangers,
- low temperature floor and wall heating systems,
- modulating HE gas-fired boiler,
- heat storage in flexible 5.6 m^3 bag tank placed in crawlspace,
- solar thermal collector (from 4.5 up to 12 m^2) with hot water storage tank,

- PV-air collector supplying heat to a heat pump boiler,
- heat recovery from ventilation air and from domestic hot water,
- passive cooling using vertical and horizontal ground heat exchangers,
- preheating of ventilation air with ground heat.

MEASURING ENERGY PERFORMANCE

In the Ecobuild Research project the energy performance of the different houses has to be determined. Because it is not practical to make a single experiment last one year and because the weather during an experiment cannot be controlled, a numerical simulation model is used to "translate" the experiment results to the desired "annual energy performance under standard conditions".

This paper focuses on a validation experiment carried out during the first phase of the Ecobuild Research project in “house B” (the second house from the left in Figure 1). This house with semi-concrete body is among other things equipped with a balanced ventilation system with heat recovery, a modulating HE gas-fired boiler, low temperature radiators and solar thermal collectors (6 m^2) with a heat storage tank. Some technical details about this house, valid for phase 1 of the project, are given in Table 1.

Table 1: Technical details for Ecobuild house B (phase 1 of the project)

Technical details Ecobuild house B		
Net volume	279 m^3	measured value
Rc façade and roof	5.7 m^2.K/W	calculated value
Rc ground floor	8.7 m^2.K/W	calculated value
Glazing	double-pane Argon-filled	-
U glass (center of glass)	0.84 W/m^2.K	calculated value
ZTA glass	0.39	calculated value
LTA glass	0.61	calculated value
Infiltration air ($q_{v,10}$)	91 dm^3/s	measured value
Ventilation air (face value)	150 m^3/hr	measured value

The purpose of this experiment was to determine the actual energy performance of the house over a limited period of time and to compare this with the predicted performance. By doing this, the method to predict energy performance could be validated and the performance of the construction and installation could be determined under real-life conditions, providing valuable information to the concerning designers, suppliers and/or manufacturers. The latter will not be discussed in this article.

During the experiment, which took about one month, over 50 different variables were registered in the house, the most relevant ones being consumption of water and natural gas, electricity use for different (groups of) installations and devices, energy flows at relevant points in the installations and air temperatures and humidity in every room. On-site climate data, such as wind speed, wind direction, solar irradiation and ambient temperature, is also available. Occupation of the house is simulated by computer-activated schedules for domestic hot water, room temperature settings, ventilation and internal gains (electrical heaters). These schedules are based on values used in the Dutch building code for calculating energy performance. Every time step (standard setting is 10 minutes) the values of all variables are registered in a central database, together with climate data and set points for the occupant simulation. The central computer in the house allows remote access to set points and experiment data to prevent unwanted disturbance of ongoing experiments by entering the house.

PREDICTING ENERGY PERFORMANCE

To predict the energy performance of the house, a dynamic numerical simulation model was set up, using TRNSYS [2]. This simulation model is based on the technical documentation of the house and detailed information from suppliers/manufacturers, which was (as far as possible) verified in the house itself, and on several measurements, such as a blower door test (to determine the air tightness of the building envelope) and a check of ventilation airflows. The windows (glass, coating, gas filling, spacers and frame) were modeled in great detail in the program Window, using detailed material data from manufacturers. In the building model, three thermal zones are defined, corresponding to ground, first and second floor.

The first focus of the model is to predict the energy demand for space heating, as a result of on one hand ventilation and infiltration losses and on the other hand solar and internal gains. Because it concerns net energy demand over a period of about one month, the dynamic behavior of the heating installation is not taken into account. In the simulation, experiment data such as climate data, total electricity consumption (internal gains) and thermostat settings are imported into the building model. The simulation time step is therefore equal to the time step used in the experiments. The heat losses from the domestic hot water boiler are determined from the experiment and used as an internal gain in the model. For the ventilation system, the model assumes heat recovery efficiency as given by the manufacturer and airflows as measured. Special attention was given to air infiltration, as this was expected to have a significant impact on the total energy balance. Through a blower door test, the infiltration rate $q_{v,10}$ was determined, i.e. the infiltration of air in liters per second at 10 Pa pressure difference (inside-outside). Considering the dynamics of infiltration, the constant $q_{v,10}$ value is replaced in the model by a function taking into account wind speed, temperature difference inside-outside (assumed to be a constant 15°C), turbulence, the height and location of the building and the distribution of infiltration over the building envelope [3]. This distribution was determined by measuring air tightness per zone using CO_2 injections (the reduction of CO_2 concentration in the air is used as an indicator for air change rate).

VALIDATION OF SIMULATION MODEL

Using the model described above, the thermal behavior of the house is simulated for the conditions registered during the experiment. The output of the model is compared with the output of the experiment. By comparing the indoor temperatures and energy demand, the simulation model can be validated. The first simulation showed significant difference between measured and calculated total energy demand of the house. The prediction of the model was about 20% lower than the measured value. For the second simulation the assumption that the adjacent houses have equal indoor temperatures ("identical boundaries") was replaced by measured temperatures in theses houses during the experiment in house B. This improvement of the model led to a satisfying agreement between experiment and simulation results.

The predicted total net energy demand for space heating differs only 6% from the actual energy input. Indoor air temperatures show an even better agreement, as can be seen in Figure 3. The difference in mean temperature between experiment and simulation is for the ground floor 0.0°C, for the first floor 0.3°C and for the second floor 0.2°C. The model seems to be less suitable for calculating the energy demand per thermal zone (a zone is equal to a floor in this case), since the simulated energy demand is lower than the measured value for the ground floor and higher for the first floor.

There are different possible reasons for the difference in energy demand between experiment and simulation:

1. the simulation model is not correct,
2. there are more heat losses than accounted for in the model,
3. there are less heat gains than assumed in the model.

To check if the model is correct, the measured energy input for space heating is imported into the model as an internal gain. With the heating turned off, the model now calculates the resulting indoor temperatures. Comparison of these temperatures with the experiment data seems to prove that the model is basically correct. To explain the differences between simulation and experiment, attention is therefore directed towards the assumptions for heat losses and heat gains in the model.

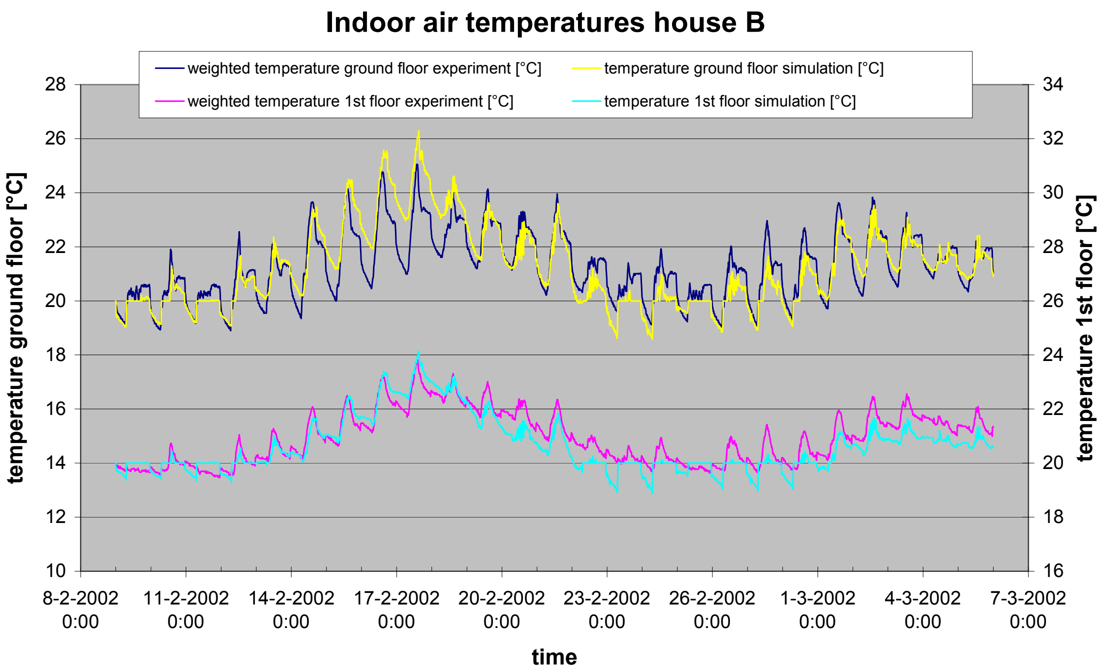

Figure 3: Comparison of measured and simulated indoor air temperatures in house B

SENSITIVITY ANALYSIS

To investigate the effect of the assumptions for heat losses and heat gains on the output of the model, a sensitivity analysis is carried out, given a realistic variation in the variables of the model. Variables with an expected significant impact on model output and with uncertainties as to the exact values are selected for this analysis:

- Solar irradiation:
  uncertainty due to possible measuring errors (±3%) and due to transforming irradiation data measured on a horizontal plane to a vertical plane (±5%).
- Outside temperature:
  uncertainty (±2°C) due to possible measuring errors and influence of surrounding buildings.
- Outside humidity:
  error due to assumed constant humidity (50%), estimated minimum 50% and maximum 70%.
- Thermal resistance of building envelope:
  effect of thermal bridges, estimated to reduce heat resistance of non-transparent building envelope by 1.0 m^2.K/W.
- Ground reflectance of irradiation:
  error due to assumed constant reflectance (20%), estimated minimum 20% and maximum 40%.
- Glazing:
  effect of overestimating (U = 1.1 W/m^2.K, ZTA = 0.43) or underestimating (U = 0.7 W/m^2.K, ZTA = 0.40) the thermal resistance of the glass.
- Efficiency of heat recovery from ventilation air:
  error due to assumed constant efficiency (90%), estimated minimum 75% and maximum 90%.
- Infiltration:

uncertainty in the dynamics of air infiltration, assumed maximum 91 dm^3/s (constant) and assumed minimum 18.6 dm^3/s (constant).

- Internal gains:
  uncertainty (+11%, -12%) in utilization of internal gains for heating, e.g. electricity use exhaust fan, boiler pump and domestic hot water use.

Figure 4 shows the result of this analysis: the effect of realistic variations in variables on net space heating demand. The horizontal dash at 426 MJ is the reference point, i.e. the net energy demand according to the validated simulation model as described above.

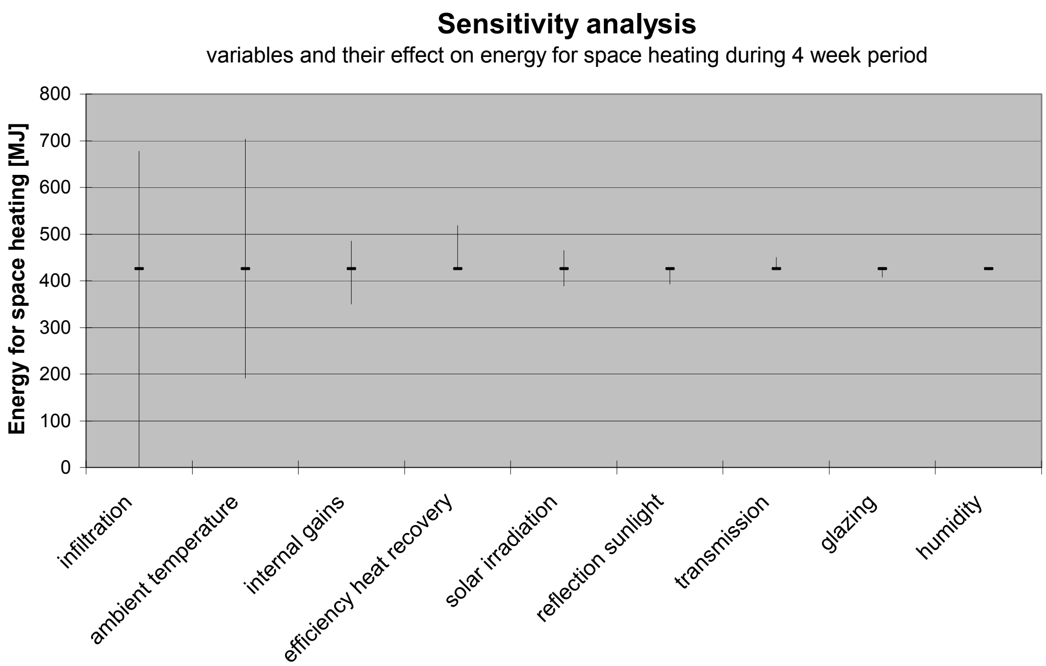

Figure 4: Effects of realistic variations in variables on space heating demand for the validated model of Ecobuild test house B

Infiltration and ambient temperature turn out to be the most influential variables for this energy efficient house; the resulting variation on space heating demand is more than 50%. This implies that there is a need for

- good modeling of air infiltration through the building envelope, given the measured air tightness, relevant climate data and location details,
- reliable measurement of the ambient temperature, wind speed and wind direction.

Next, with an effect on space heating demand between 10 and 50%, are the variables internal gain and efficiency of ventilation air heat recovery. And less than 10% variation is found for the variables solar irradiation, ground reflectance of sunlight, transmission through the non-transparent part of the building envelope, glazing and humidity.

Although the above-mentioned results strictly speaking only apply to the considered Ecobuild test house B, the following more general conclusions can be drawn for energy efficient houses:

- For an accurate prediction of energy performance, it is crucial to measure air tightness, wind speed and ambient temperature as exactly as possible. Furthermore, there should be a detailed model of air infiltration describing the dynamic relation between air tightness and resulting air flows. Exact measuring of climate data appears to be something obvious, but turns out to be rather complicated, as it concerns both the sensors involved and the location of these sensors.

- It is important to determine the exact efficiency of heat recovery from ventilation air and the amount of energy that can be seen as an internal gain. The latter refers to the use of electricity and domestic hot water.
- For this energy efficient house, a theoretical determination of the thermal resistance for the building envelope seems to suffice. Small deviations due to e.g. thermal bridges fall well within the margin of the simulation.

Taking into consideration the number of variables, the uncertainties and resulting sensitivity, the conclusion can be drawn that the validated simulation model can be used for a reasonably accurate prediction of the energy performance of this house.

IMPROVEMENT OF THE SIMULATION MODEL

In previous paragraphs the relevant variables for an accurate prediction of energy performance were identified. Clearly, reducing any uncertainty regarding these variables leads to an improvement of the simulation model. However, there are also several other possible improvements, identified in the validation process:

- Ventilation air flows
  On the ground floor, the exhaust capacity exceeds the air inlet capacity. The assumption of the designers is that this exhaust is powerful enough to draw in air from the first floor, where the inlet exceeds the exhaust. Verification of this assumption is necessary to get an accurate model of heat recovery.
- "Communication" between floors
  Because of open stairwells, air and therefore heat can move freely between the floors. For this energy efficient house the effect on the total energy balance is probably negligible, but it seems to be relevant when investigating the energy performance per floor. This "communication" could explain why the simulated energy demand is lower than the measured value for the ground floor and higher for the first floor.
- Balanced ventilation system
  The temperature of the exhaust air is calculated as a weighted average of air temperatures in the ventilated zones, using the surface area of the zones as weighting factor. The model could be improved by using actual exhaust air volumes as weighting factor, thus including the above-mentioned "communication" effect.
- Infiltration as a function of indoor temperature
  In the current model, a constant temperature difference between inside and outside is used in the calculation of air infiltration. This temperature difference could however also be calculated using real-time temperatures. To determine the "average indoor air temperature" a weighting factor for the zone temperatures is needed.

CONCLUSIONS

As part of the Ecobuild Research project a numerical model of a test house has been set up and validated. A sensitivity analysis of the model was carried out, resulting in the conclusion that infiltration and ambient temperature are the most critical variables for this model. This means there is a need for good modeling of air infiltration through the building envelope, given the measured air tightness, relevant climate data and location details, and for reliable measurement of the ambient temperature, wind speed and wind direction. Considering the uncertainties in infiltration and climate data, the validated model gives a very acceptable prediction of the energy performance of the test house: the predicted heat demand turned out to be merely 6% lower than the actual value, whereas the average air temperatures did not differ more than 0.3°C. With this validated simulation model it is now possible to:

- “translate” results from short experiments to longer periods, e.g. a year,
- “translate” results from experiments to other climate conditions,
- analyze the effect of a single measure on the total energy efficient concept.

Furthermore valuable knowledge has been gathered on how to further reduce the uncertainty in experimentally obtained variables and in prediction of energy performance by numerical modeling. This knowledge will be used in future research.

Compared to the traditional housing market, there is a clear change in relevance of variables for this energy efficient house. The sensitivity analysis showed that infiltration has become a much more critical topic than ventilation and transmission in this test house. Considering the house as a whole (the total of construction and installation) has led to this insight.

The validation process has turned out to be a rather complex undertaking, but it has taught the involved researchers and designers a lot, especially about the house as an integral concept.

FUTURE WORK

Until now, the energy performance experiment focused on the winter situation. In the second phase of the Ecobuild Research project, special attention will be given to energy performance in summer. With the increase of energy efficiency, the thermal comfort in summer gains importance. Topics like cooling loads, peak temperatures and the performance of sun shading will be investigated. The impact of infiltration on the energy performance has led to several building improvements prior to the start of phase 2, reducing the air infiltration ($q_{v,10}$) by about 60%.

The knowledge gathered in this project will be used in the recently built test facility “the rotating test house”. This facility has 4 test cells fully equipped to test so-called “active façades” (façade reacting actively to changing ambient conditions such as temperature, irradiation and sound) and can be directed towards any desired orientation by rotation around its center axis.

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