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Air tightness and energy performance of an Arctic Low-Energy House

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ABSTRACT

A low-energy house has been built in Sisimiut, Greenland, five years ago. An ambitious target was set for its low energy consumption for heating: 80 kWh/(m^2·a). But unfortunately, the house has used more energy than planned, approximately 140 kWh/(m^2·a). Although higher than anticipated, this is still for Greenland a very low energy consumption. The purpose of the work presented in the paper has been to analyze the energy consumption of the house and to understand why it was different than anticipated. One significant lesson learned is that the house was not built with sufficient air-tightness and that it was one of the main reasons for its higher energy consumption.

KEYWORDS

Low-energy house, building envelope, heat exchanger, air tightness, blower-door test

INTRODUCTION

Purpose of the work

A low-energy house has been built in Sisimiut, Greenland, and was inaugurated in April 2005. The purpose of the house has been to test and visualize the application of low-energy building technology in an arctic climate and thereby start the development of sustainable buildings in Greenland.

An ambitious target was set for a low energy consumption for heating of the house: 80 kWh/(m^2·a). But unfortunately, the house has used more energy than planned: approximately 140 kWh/(m^2·a). The purpose of the work reported here has been to analyze the energy consumption of the house and to understand why it was different than anticipated.

An important contribution to the explanation for the high energy consumption lies in the fact that the building is not as airtight as it should have been if it were to perform as effectively as anticipated. The article will therefore put emphasis on conditions regarding air tightness of the building and the air handling system.

LOW-ENERGY HOUSE IN SISIMIUT

Sisimiut is the second largest city in Greenland, and is located just north of the Arctic Circle. The location is at the sea, which means that Sisimiut has a coastal climate with relatively mild winters and the summers are rather cool. Typical mean temperatures are around –10℃ to –15℃ in the winte r months and 5℃ to 6℃ in summer. It is very common for the Greenlandic climate that sudden changes in weather occur. Strong winds often pass along the coastline and most of the west coast is exposed to unsteady weather caused by these winds.

These weather conditions constitute a challenge for the building envelope and the building services systems, which must be able to endure both large temperature differences and high wind gusts. However, the amount of precipitation is not very high, around 360 mm/a.

As a low-energy house, it was intended that it should use less than half of the permissible energy for heating according to the building regulations. However, the house was inaugurated just the year before a revision of the Greenland Building Code was to be instigated, and so the target was set according to the then expected energy targets: 230 kWh/(m^2·a). In addition, the house was planned to be made with a ventilation system with heat recovery, and such a possibility was not considered in the Building Code. Analyses showed that savings around 70 kWh/(m^2·a) could be expected if houses were required to have a heat recovery system, and thus, it was regarded realistic that it could have been required of normal buildings that their heating consumption should be not more than 160 kWh/(m^2·a) if they were equipped with a heat recovery unit. As a low energy house, it was decided that the current building should consume only half of that: 80 kWh/(m^2·a). Simulations with the energy design tool *BSim* (Danish Building Research Institute, 2010) also showed that it was a realistic target if certain other energy efficient building technologies were applied in the building.

An architectural competition was held, and the winning design was a semi-detached (double) house with common entrance hall and service room. The building was erected in 2004-05 by local craftsmen.

Figure 1: Picture of the low-energy house in Sisimiut.

The total floor area of the resulting building is around 200 m^2. The building is all in one floor but with split levels between the front north-western facing part and the rear south-eastern part of the building. Over the inhabited part of the building is a cold attic, where the ducts for the ventilation system and the heat recovery unit were placed. The roof is sloped with a main inclination towards south-east, but the roof is split such that the middle section slopes toward north-west. The north-western facade is not vertical but made as a very steeply sloping wall (18° reclining) in which four roof windows are inserted. The building has an open basement between concrete strip foundations, such that the underside of the floor is exposed to the outdoor climate.

The building envelope of the low-energy house is characterized by well insulated constructions with only minimal thermal bridges and the use of good windows.

All constructions in the house are wood frame constructions. The constructions are made such there are several layers of wooden frame and insulation where the wooden members are staggered from layer to layer so the solid parts do not penetrate all the way through the constructions, see Figure 4. The insulation thickness in the walls is 300 mm, while the thickness in floors and ceiling is 350 mm. The U-values of the constructions are between 0.13 and 0.15 W/(m^2·K).

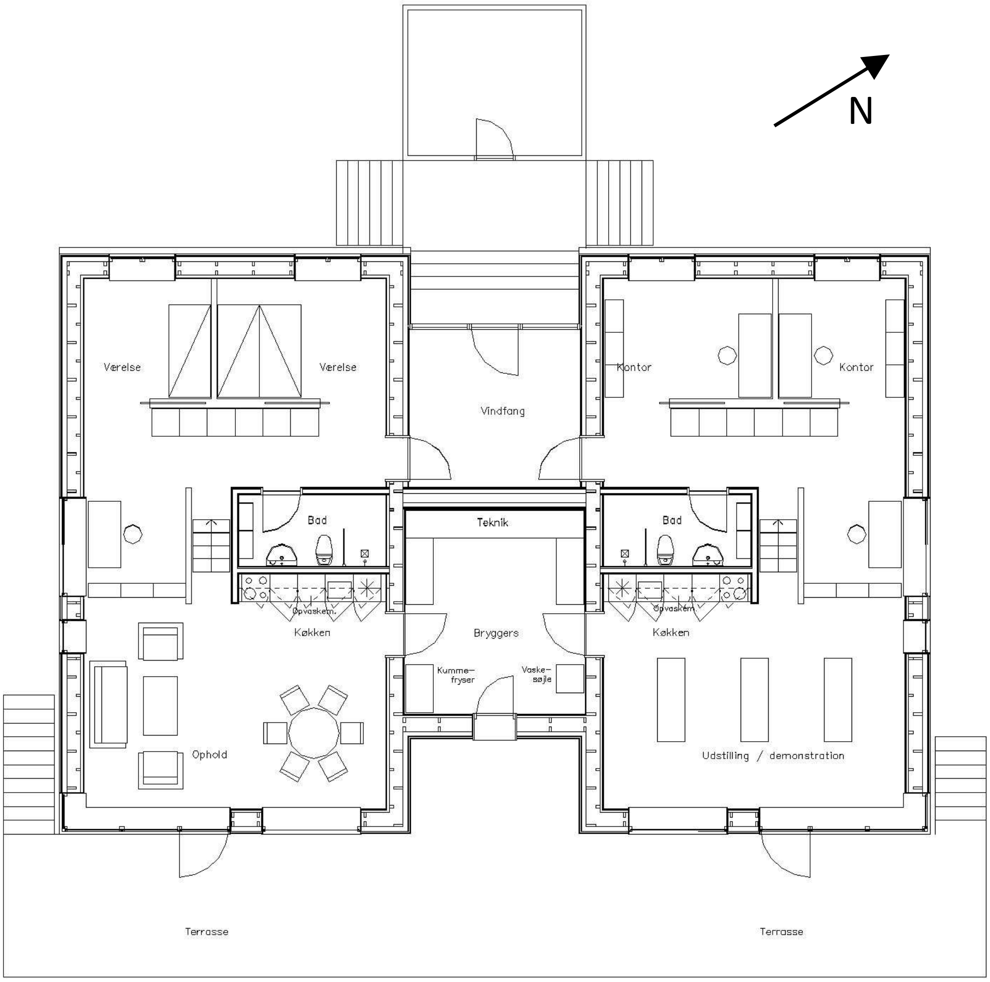


Figure 2: Floor plan of the low-energy house

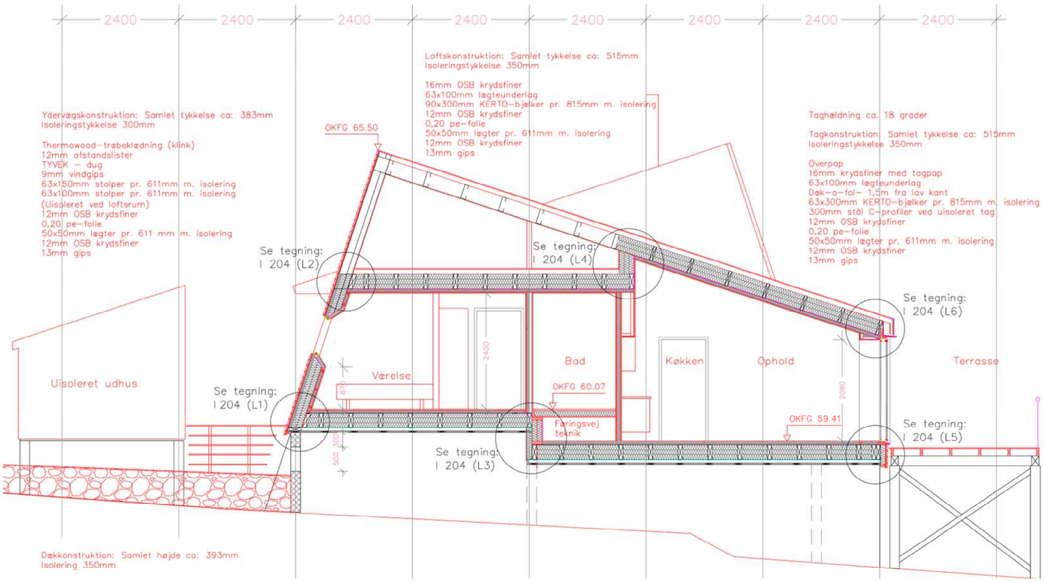


Figure 3: Cross section of the low-energy house.

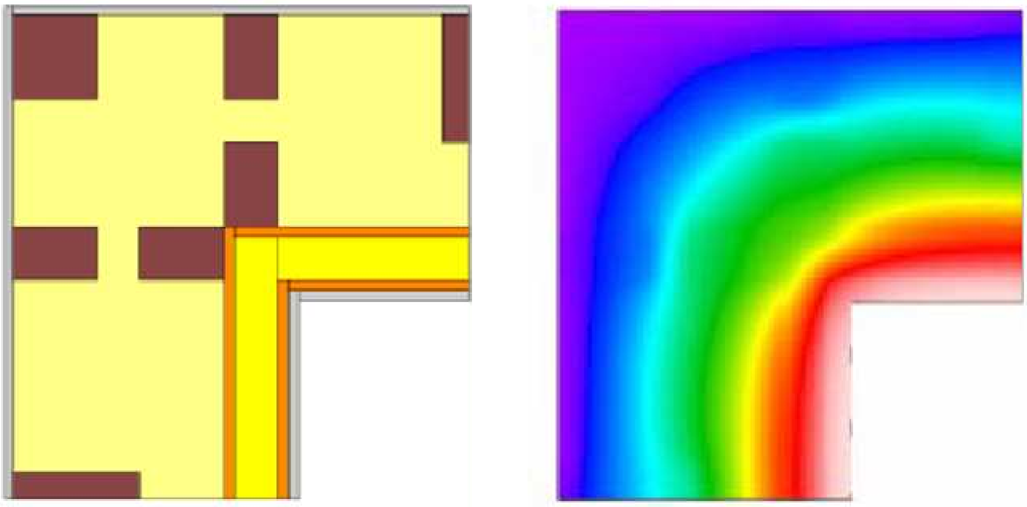


Figure 4: Model of the outer wall corner showing that no wooden members penetrate the whole construction. To the right a calculated temperature profile.

Three different types of windows were used in the house. Most windows are of the Type 3, as can be seen in Figure 5 with a sealed double glazing unit with argon filling at the outside and an extra single window pane on the inside. The windows which are used in the almost vertical roof windows on the north-western façade are either Type 1 or Type 2 (two of each). Type 1 has a single window pane on the outside and a sealed double glazed unit with argon filling on the inside. Type 2 is possibly the most advanced window. It is also a triple layer composition, but this type has a sealed double layered unit with krypton filling on the outside, which is only separated by vacuum from the inside single layer glass pane. Small glass pillars keep the glass panes from each other where there is only an evacuated space between them. All window types had U-values in the range 1.0 - 1.1 W/(m^2·K). The U-values for the glazing alone ranged between 0.7 and 0.8 W/(m^2·K).

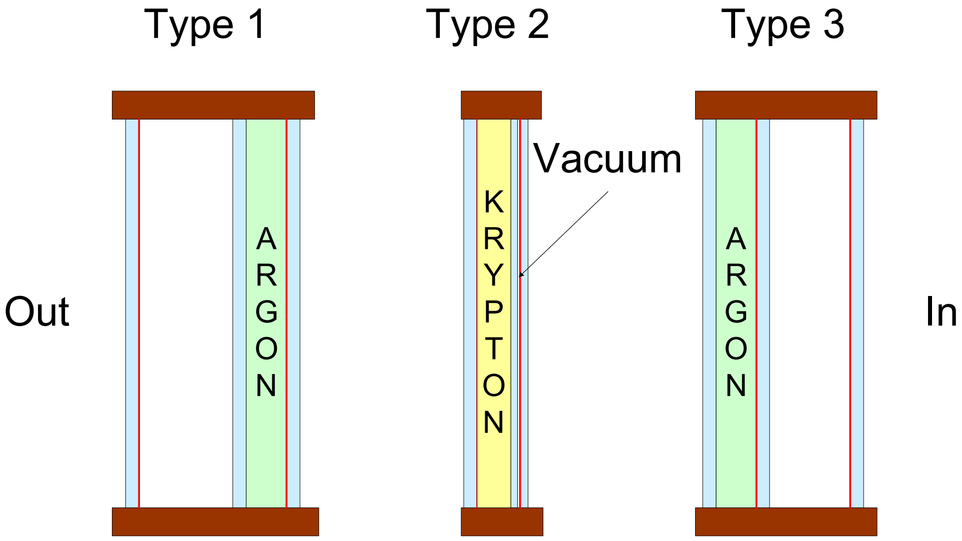
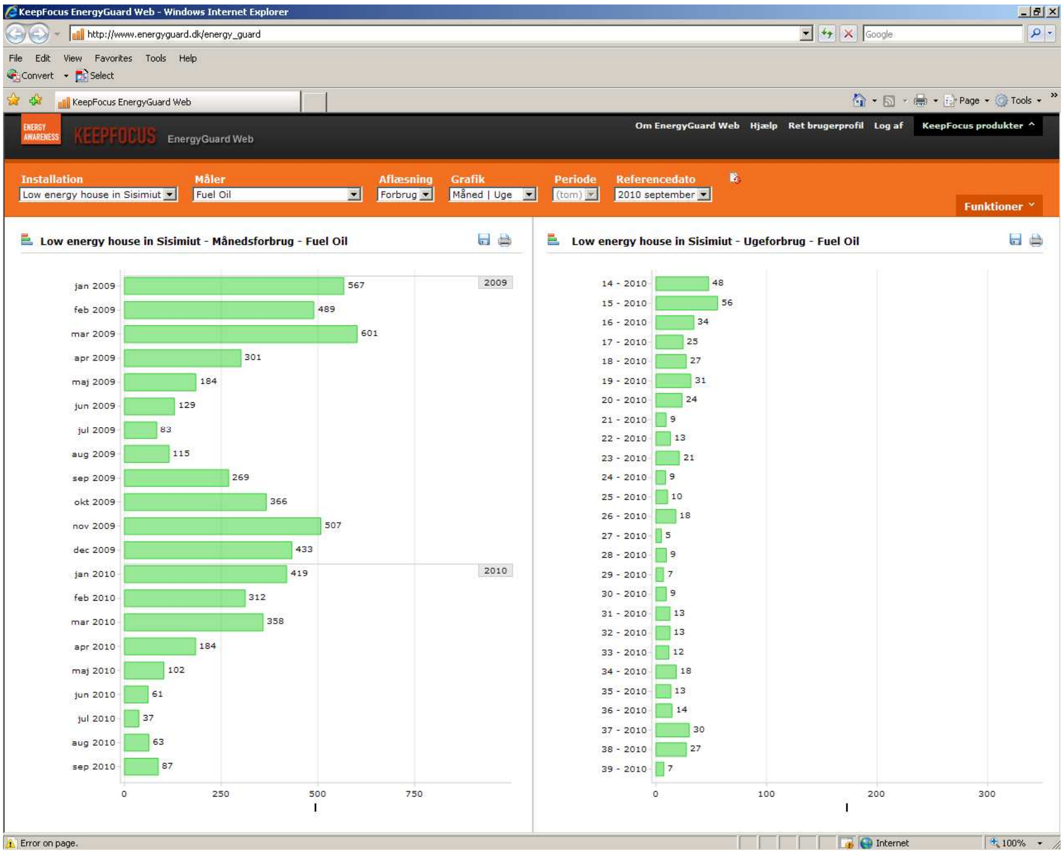


Figure 5: The three types of glazing units used in the low-energy house

The building services are a ventilation system with a counter flow heat recovery system, and a solar collector for domestic hot water with provision for delivering excess heat to a radiator in one of the rooms in the house. The house is heated primarily by a hydronic floor heating system, while an after-heater in the ventilation system ensures that supply air is always heated to around 18°C before injection into the rooms. Hot water is produced by an oil furnace.

Several of the technologies used in the house have not previously been commonly used in arctic buildings, and thus it has been the ambition to learn how well such low-energy technologies perform in reality in an arctic environment.

The performance of the house has been followed through an extensive measuring programme, and many of the measuring results have continuously been accessible on-line. Measurements from the house can be seen on the web-address www.keepfocus.dk, login: *DTU4*, password: *sisimiut*.



Installation: Low energy house in Sisimiut
Måler: Fuel Oil
Aflæsning: Forbrug
Grafik: Måned | Uge
Periode: (tom)
Referencedato: 2010 september

Figure 6: Fuel consumption as registered on the “Keepfocus” logging system

RESULTS

Energy consumption

During the first four-five years of operation of the house, the annual energy consumption for heating has been around 28.000 kWh, which corresponds to approximately 140 kWh/(m^2·a). This is low energy consumption for a house in

Greenland, i.e. it is considerably below the permissible consumption according to the Greenlandic building code. However, it is significantly more than the 80 kWh/(m^2·a) the house was designed for.

Several possible explanations have been sought to explain the deviation. Among the possible explanations are:

- The indoor temperature was higher (around 23°C) than assumed during the design process of the house (21°C).
- The house has not been sufficiently airtight.
- An after-heater unit in the ventilation system has malfunctioned so it heated the supply air to an unnecessarily warm temperature (sometimes up to 40°C whereas it should be around 18°C).
- The heat exchanger has in some periods suffered from ice formation.
- Ventilation ducts in the cold attic were insufficiently insulated (originally with 50 mm of insulation).
- The entrance hall was planned to be unheated. However, that room has in reality always been heated like the other rooms of the building.
- Since the living rooms have in periods been quite warm because of solar gains, the users of the building have opened the terrace door. However, since the outdoor air has been significantly colder than the desired indoor temperature, this cold air has cooled the floor heating system undesirably.
- In order to avoid dew formation on the inside of the sealed glazing unit of window type 3 caused by imperfect tightness of the gasket for the innermost glass pane, some relatively large holes were drilled through the outer frame to vent the window cavity with outside air. An in-situ measurement of the U-value of the glazing with heat flux transducers and thermocouples revealed that the realized U-value was 1.2 W/(m^2·K), and not 0.8 W/(m^2·K) as anticipated.

However, a few reasons exist also why the energy consumption could have been smaller than designed:

- The winters have been warmer than usual according to the test reference year that was used to predict the energy consumption for heating of the house.
- Presumably, the air flow rate of the ventilation system has been smaller than it was designed for.

The following sections will elaborate further on the analyses carried out on the issues which are pertaining to the air flow conditions in several places of the building and its systems.

Blower-door test

Requirements regarding air tightness of buildings will be implemented in the Greenlandic Building Regulation 2010/11 as a demand that air leakage rate shall be below 1.5 l/s per m^2 of heated floor area measured by blower-door test @ 50 Pa ($q_{50} < 1.5$ l/s per m^2). This condition will need to be fulfilled for a certain percentage of newly built buildings. The result from the blower-door test can be also compared to the value for permissible air change rate according to the Passive house specifications $n_{50} < 0.6$ h^{-1} (calculated with A_{TFA}).

The air tightness of the low-energy house was investigated in two blower-door tests (February 2009 and March 2010). The house was measured in accordance with the European Standard 13829, method B, where all the vents have been sealed and taped, and the house was considered as one zone with all the doors open. The blower-door test measures the airflow V_{50} at 50 Pa in units (l/s) or (m^3/h). The air change rate (l/s per m^2) is calculated according to Eqn., where V_{50} is the corrected airflow at 50 Pa (l/s) and A_{TFA} is the internal floor area (m^2). The air change, n_{50} (h^{-1}) can be calculated in accordance with Eqn.2, where V_{50} is the corrected airflow at 50 Pa (m^3/h) and V_{net} is the internal building volume (m^3). The infiltration q_{50} (l/s per m^2) is calculated using Eqn.3 where V_{50} (l/s per m^2) is the measured air change from the blower-door test and A_{gross} is the external heated area (m^2).

$$w_{50} = \frac{V_{50}}{A_{TFA}} \qquad \text{(Eqn.1)}$$

$$n_{50} = \frac{V_{50}}{V_{net}} \qquad \text{(Eqn.2)}$$

$$q_{50} = \frac{V_{50}}{A_{gross}} \qquad \text{(Eqn.3)}$$

TABLE 1: Blower-door test results at 50 Pa and under normalized pressure

Method / Date	Pressure at 50 Pa			
	Airflow V_{50} [l/s]	Air change rate w_{50} [l/s m^2 @ 50 Pa]	Air change rate n_{50} [h^{-1} @ 50 Pa]	Leakage rate q_{50} [l/s m^2] of A_{gross}
Blower-door, Feb 2009	474	2.55	3.35	2.28
Blower-door, Mar 2010	436	2.35	3.07	2.10

Internal building volume V_{net} = 450 m^3, net floor area A_{TFA} = 186 m^2, heated floor area A_{gross} = 208 m^2.

The calculated results at 50 Pa have to be converted to air change at normalized pressure state using following methods: The method of the Danish Building Research Institute, SBi (Aggerholm 2008) with q_{inf}, Princeton method (Sherman, 1987) using factor “20”, Sherman method with different effects and EN method. The Princeton and Sherman methods are developed and usually apply for U.S. conditions; the EN and SBi method apply for European conditions respectively.

The SBi method calculates the airflow q (l/s per m^2 of heated floor area) with the following Eqn.4 where q_{50} (l/s per m^2 of heated floor area) is a leakage rate calculated from the blower-door test. After that the infiltration air change is calculated in Eqn.5 where the airflow q (m^3/h) is divided by internal volume of the building V_{net} (m^3).

$$q = 0.04 + 0.06 \cdot q_{50} \tag{Eqn.4}$$

$$q_{\inf} = \frac{q \cdot A_{groos} \cdot 3.6}{V_{net}} \tag{Eqn.5}$$

The Princeton method uses simple factor “20” to convert the blower-door results to normalized pressure state Eqn.6 where n_{50} (h^{-1}) is divided by 20. The result gives the infiltration air change in a building. The Princeton equation was derived from several experiments and neglects many factors which have the effect on the infiltration.

$$N = \frac{n_{50}}{20} \tag{Eqn.6}$$

The Sherman method includes the effects on infiltration as windiness, climate, stack effect, and construction quality. The following equation (Eqn.7) includes those factors such as the climate correction factor C ($17<C<20$), height factor H (H=1 for one storey building), shielding factor S (0.9, no shielding) and leakiness factor L (1.4 as tight).

$$n = \frac{n_{50}}{C \cdot H \cdot S \cdot L} \tag{Eqn.7}$$

The EN method is determined according to EN 13790 for balanced ventilation systems with heat recovery and is calculated using Eqn.8, where n_{50} (h^{-1}) is fan pressurization test results, e is wind screening coefficient according to EN 832 (0.1 several sides exposed and no screening) and V_{n50} is net air volume (m^3) and V_{RAX} is net air volume for pressurization test (m^3).

$$n_{V,\mathrm{Res}} = n_{50} \cdot e \cdot \frac{V_{n50}}{V_{RAX}} \tag{Eqn.8}$$

TABLE 2: Infiltration air change results at normalized pressure

Method / Date	SBi q_{inf} [h^{-1}]	Princeton N [h^{-1}]	Sherman n [h^{-1}]	EN $n_{V,Res}$ [h^{-1}]
Blower-door, Feb 2009	0.30	0.17	0.14	0.34
Blower-door, Mar 2010	0.28	0.15	0.13	0.31

Tracer gas

During July 2005, as part of a student project, the tracer gas method was used to measure the air tightness of the low-energy house. The Concentration-decay method and sulfur hexafluoride (SF6) as tracer gas were used.

Infiltration air changes were obtained from three different days, and the results varied from 0.27 h^{-1} to 0.39 h^{-1}, with an average of 0.32 h^{-1}.

Thermography

The thermographic pictures were taken during the blower-door test to examine the cold places and air leakages. Investigation with thermal camera shows problems with air leaking. The three dimensional cold bridges were identified at floor/wall joints and ceiling/wall joints and around windows. Significant thermal bridges were also indentified at the door threshold at terraced doors which was made from aluminum. Also the air leakages between tiles in entrance hall and between kitchen and horizontal ventilation shaft were identified.

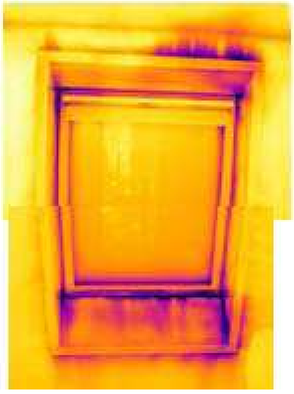


Figure 7: Thermo image of a window in an inclined wall and leakage of air tight barrier (Blower-door test by Lars Due, 2009)

Annual infiltration heat loss

As infiltration losses constitute a large part of the total losses, the annual infiltration heat loss through the building envelope is calculated using the values from the blower-door test (average value from two tests) and the following equations. The total infiltration (EN 13790, 2004) throughout the year Q_{inf} (kWh/a) is expressed in Eqn.9 where V is internal insulated volume of the house (m^3), q_{inf} is the calculated infiltration air change (h^{-1}), c_P is the thermal capacity of the air (1,005 J/(kg·K)), ρ is air density (1.2 kg/m^3), and *HDD* is heating degree days from design reference year for Sisimiut (208 kKh/a)..

$$Q_{\text{inf}} = V \cdot q_{\text{inf}} \cdot \frac{c_P \cdot \rho}{3{,}600} \cdot HDD \tag{Eqn.9}$$

The annual infiltration heat loss is calculated based on the average result from two blower-door tests and for the required value of q_{50} = 1.5 l/s per m^2 of gross heated area from the future Greenlandic Building Regulations, GBR (see TABLE 3). Those results are calculated for the net-volume (V_{net}) of the whole low-energy house, which includes the two apartments, the entrance hall, the technical room and the installation shafts.

TABLE 3: Infiltration heat loss through the whole building envelope

	Leakage rate q_{50} [l/s m^2] of heated floor area **	Infiltration q_{inf} [l/s m^2] of heated floor area**	Infiltration q_{inf} [h^{-1}]	Q_{inf} [kWh/a]
Designed infiltration *	-	-	0.10	2,900
Air tightness (GBR 2010/11) **	1.50	0.13	0.22	6,800
Real infiltration based on SBi	2.19	0.17	0.29	9,100
Based on Princeton			0.16	5,100
Based on Sherman			0.14	4,400
Based on EN			0.33	10,400
Real infiltration based on Tracer gas			0.32	10,100

* Designed infiltration heat loss from BSim model for the whole house (not including entrance) with V = 410 m^3 was 2.900 kWh/a with as designed infiltration 0.1 h^{-1},

** Heated gross area A_{gross} = 208 m^2, internal building volume of the whole house V_{net} = 450 m^3.

Ventilation system

As it was mentioned before, the ventilation system is placed in the unheated attic. But it was originally meant to have been a heated attic. Therefore any heat losses through the ducts weren't considered. But the real situation is that there is a significant heat loss from the entire ventilation system.

During the first four years the ducts were only insulated with 50 mm of insulation from mineral wool which led to transmission heat losses of the supply ducts calculated from the equations Eqn.10 and Eqn.11 where U (W/(m·K)) is the heat transfer coefficient, d is the outer diameter of the non insulated pipe (d = 201 mm), λ_{is} is the thermal conductivity of the insulation (λ_{is} = 0.035 W/(m·K)), Ø is the diameter of the insulated pipe (Ø = 301 mm and 501 mm respectively) and α_e is the heat transfer coefficient on the outer surface (α_e = 10 W/(m^2·K)), H (W/K) is the specific heat loss coefficient of the ducts and l is the total length of the supply ducts (l = 23 m). Eqn.10 neglects the effect of metal parts of the ducts.

$$U = \frac{\pi}{\frac{1}{2 \cdot \lambda_{is}} \cdot ln\frac{\text{Ø}}{d} + \frac{1}{\alpha_e \cdot D}} \qquad \text{(Eqn.10)}$$

$$H = U \cdot l \qquad \text{(Eqn.11)}$$

H_{50}=12.5 W/K which when multiplied by the heating degree hours 208 kKh/a, and divided by a floor area of 200 m^2 results in 13 kWh/(m^2·a). In the autumn 2009 the ducts were insulated with another 100 mm of insulation which decreased the extra heat losses to H_{150}=5.5 W/K which is about 5.8 kWh/(m^2·a).

Another reason for increased energy consumption compared to what was designed is the lower thermal efficiency of the prototype heat exchanger. It consists of two flat plate counter flow heat exchangers connected in series and its efficiency was expected to be at least 90%. But the measurements showed that it is only about 68%. This fact means that there is more auxiliary energy needed for after heating of the air in the heating coil in order to make it sufficiently warm and thus avoid draught problems.

DISCUSSION

Results and assessment of their significance

One significant lesson that has been learned is that the house was not built with sufficient air tightness to achieve the desired low heat loss. The house has been blower-door tested at several occasions.

The air change rate measured in a blower-door test has been found to be 2.4 l/(s·m^2) (at 50 Pa pressure difference). This is a value which is clearly above the permitted air change rate set in the Danish Building Code since 2006: 1.5 l/(s·m^2). However, the house was built before such rules came into force in Denmark, and even today there are no quantitative rules for permissible air exchange rates in Greenlandic buildings.

Air tightness problems have been identified particularly to window flashings, and penetrations for electric and liquid tubing.

The extra heat loss due to the building envelope not being sufficiently airtight can be estimated to correspond to some extra approximately 20% of the anticipated total energy consumption of the house.

There is no simple way how to accurately convert a single blower-door test result into an infiltration air change rate as the effects of various climate-dependent factors and quality of the building construction may have a large impact on true infiltration. The climate-dependent factors are the local conditions such as wind, high temperature difference and stack effect with height of the building will have great impact on the calculated infiltration. Nevertheless, there is a need for a straightforward translation of a pressurize test to an infiltration rate.

The comparison of the results indicates that the designed infiltration rate (which should be 0.1 h^{-1} at normal pressure) differs from the calculated average infiltration 0.29 h^{-1} from the blower-door tests (after conversion to neutral pressure), and thus gives around twice the expected infiltration loss. The calculated infiltration is only under steady conditions, meaning that the effects of wind, stack effect, and other effects of weather have not been considered.

The poorly insulated ducts placed in the cold unheated attic in combination with lower efficiency of the heat exchanger than anticipated have meant that the ventilation heat loss has had a significant share of the reason for the extra energy consumption of the low-energy house. The heat loss of the ducts could have been avoided by just putting the ductwork inside the insulated envelope of the house. The lower efficiency of the heat exchanger was investigated and some suggestions how to improve it were done.

CONCLUSION

An advanced low-energy house has been built and now tested under real in-use conditions in a Greenlandic city. Among other lessons learned from the first 5 years of its operation it is quite clear how important it is to ensure proper air-tightening of the building envelope, including the conduits for building services.

Also the placement of ventilation ducts plays a significant role and might unnecessarily increase the heat losses when done improperly.

ACKNOWLEDGMENT

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