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Publication date:
2012

Prospective future introduction of reduction of energy use in buildings in the Arctic regions – How might it affect the indoor climate?

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SUMMARY
Existing residential buildings in Arctic Greenland often have problems with draughts, uncomfortably low temperatures indoors, and inadequate ventilation. The standard wooden house 18D provides low thermal comfort and poor indoor air quality and has high energy consumption. On the other hand, the new Low-energy house in Sisimiut, Greenland, provides good indoor air, thermal quality and reduced energy consumption. Using measurement data from both buildings, this paper discusses the impact of various issues, such as low indoor relative humidity, temperature variations, and high indoor humidity production, the use of buildings in the extreme Arctic climate with high density of inhabitants, problems with air leakages and overheating creating by solar radiation and heating system, and other issues affecting health of inhabitants. Looking at these issues leads to interesting findings in terms of the relationship between reducing energy consumption and indoor air quality (IAQ), which result from the need for sufficient airflow and sufficient relative humidity levels in buildings situated in the Arctic.

KEYWORDS
Energy performance; IAQ; Residential; Thermal comfort; Energy retrofits; Arctic climate

1 INTRODUCTION
There are many good reasons for saving energy, but thermal comfort and good indoor climate are important parameters in the search for energy savings in buildings. The research for this paper focused on the comparison and evaluation of indoor climate parameters affected by the design of homes, building use and living standards, along with the effect of outdoor temperature on energy consumption and potential poisons built into structures. The aim was to link low energy consumption and good indoor environment to the temperature and humidity levels indoors in the extremely cold climate of the Arctic regions.

Sisimiut, Greenland (coordinates: 66.6ºN, 53.4ºE), experiences extremely low temperatures during the winter, storms with high-speed winds, and periods without sun or the sun at low angles. The mean annual temperature is -3.9ºC (the coldest monthly average is -14.0ºC), and mean daily temperatures range from -32.4ºC to +23.6ºC during the year (HDH 208 kKh/a with T_{base} = 20.0°C). Outdoor relative humidity is high, but the water content in the air is low. Global solar radiation on a horizontal surface is 945 kWh/(m^2.a) (Meteonorm, 2010). Out of 22,075 buildings across Greenland, there are approximately 11,632 detached and semi-detached wooden houses with an average floor area of 65 m^2 and a documented consumption of 381 kWh/(m^2.a) (Bjarløv and Vladykova, 2011).

2 METHODOLOGY AND TWO CASE STUDIES

The methodology is based on the evaluation of two case studies: an older traditional house and a newer Low-energy house, both located in Sisimiut, Greenland. The approach considers parameters related to building design, indoor climate and energy consumption (Table 1). The building construction of each home is described by building characteristics, including gross heated area, measurements of air tightness evaluated in accordance with (EN 13829, 2011), and infiltration at normalized pressure calculated using the Princeton method (Sherman, 1987; Rode et al., 2010). The temperature and relative humidity were measured hourly using special data loggers located in the kitchens / living rooms and bedrooms (sensors placed in no direct sunlight, on internal walls, 1.6 m from the floor). Actual energy consumption is based on the collection of oil supplies to the house (18D) in litres and designated energy for heating (LEH).

Table 1. Parameters related to the building structure, indoor climate and energy consumption in18D and LEH.

Parameter	Symbol and unit	Standard house 18D		Low-energy house	
Gross heated floor area	A_{gross} [m^2]	63		208	
Energy consumption	[kWh/(m^2.a)]	381		90	
Internal volume of a building	V [m^3]	157		450	
Thickness of insulation and U_{wall}	[mm]; [W/(m^2.K)]	100	0.497 (1)	300	0.150 (2)
Thickness of insulation and U_{floor}	[mm]; [W/(m^2.K)]	100	0.439 (1)	350	0.140 (2)
Thickness of insulation and U_{roof}	[mm]; [W/(m^2.K)]	100	0.434 (1)	350	0.130 (2)
U_{window} for glazing and window	[W/(m^2.K)]	2.0	3.0	0.8	1.1
Leakage air change	n_{50}; n[h^{-1}]	18.5	0.78	3.1	0.15

(1) Lambda value of Rockwool in 1962 was ≈ 0.049 W/(m.K) (2) compared to 0.035 W/(m.K) today.

The following parameters are considered in the article: indoor climate, energy consumption, lifestyle, outdoor climate, and possible toxins from the building construction. Moreover, thermal comfort and draught problems related to infiltration of the building envelope and indoor temperature variations are discussed. The design and use of the buildings are taken into account along with the high density of inhabitants, problems with overheating, high indoor temperatures, and the production of moisture indoors. These aspects are linked to a ventilation system with sufficient airflow and good indoor air climate. The measurement data in both buildings is limited in terms of collection period, i.e. the energy data is from the years 2005–2011 and the indoor climate data is from November 2010 – October 2011 inclusive.

Figure 1. Standard house 18D (left) and the Low-energy house (right) in Sisimiut, Greenland

Type houses 18D

The standard wooden house type 18D (standard house 18D) was built in 1962 and is a pair of two-storey semi-detached houses each with a floor area of 63 m^2 (Figure 1). Single-frame constructions of external walls, floor and roof were completed with 100 mm of mineral wool insulation. Air, water and wind tightness was ensured by ventilated external cladding with a windshield of tarred paper and an interior vapour barrier of aluminium-covered paper. The windows are mainly orientated to the north and west, and consist of a wooden casing with one outer and one inner single layer of glazing. The heating system is an oil-fired boiler ($\eta = 0.9$) with radiators. Each room in the building is naturally ventilated through a vent (150 x 150 mm) with a manually operated grill. The documented heating consumption is 2,200 litres of oil per year (excluding hot water consumption). The monitoring system in the house is part of the renovation project for standard wooden houses in Greenland (Bjarløv and Vladykova, 2011).

The Low-energy house

The Low-energy house (LEH), built in 2005, is a pair of single-storey semi-detached houses with a shared utility room and hall with a floor area of 208 m^2 (Figure 1). External walls are made of mineral wool insulation and wooden frames separated into an external and an internal part to achieve lower thermal bridging effect. The wall construction has a ventilated façade with a wind-tight barrier on the outside and an air-vapour barrier located in the inner third of the total thermally resistant insulation. The roof and floor have single-beam system with mineral wool insulation. The windows are mainly orientated to the east, south and west, and have 2 layers of glass with a vacuum plus an additional layer of glass. The house is equipped with a balanced mechanical ventilation system with an experimental cross-flow heat exchanger to use the warm exhaust air to heat up the cold inlet air, and it has a special damper valve and options for after-heating. The documented efficiency of the heat exchanger is between 55% and 80%. The oil-fired boiler ($\eta = 0.9$) supplies floor-heating and hot water. The house has a heating consumption of 1,500 litres of oil for the whole building and it is equipped with an extensive monitoring system (Vladykova et al., 2011).

3 RESULTS

Indoor temperature and relative humidity

To maintain a satisfactory indoor temperature in the old standard family house in cold climates, the air temperature must be kept higher to maintain a given operative temperature because of the colder radiant temperatures of surfaces which are insufficiently insulated and not tightly sealed. This also leads to uneven temperature zoning in 18D, so the average indoor temperature in the bedroom and living room is 23.6°C, but 17.2°C in the bathroom. Figure 2 shows that there is a higher temperature in the bedroom (windows orientated towards north) than in the living room (windows towards north and west). In the Low-energy house, Figure 2 shows that the average temperature is 21.4° and there is less fluctuation in temperature during the winter. The overheating in the LEH during the summer is shown by higher temperatures in the apartment orientated toward SE than in the apartment orientated towards SW. The overheating is created by solar radiation through the window and heating overproduction in the house.

Relative humidity indoors should be between 30% and 50%, ideally around 45%, to maintain a proper moisture level in houses. Low humidity is more common in colder climates, because cold air is less able to retain water vapour. In 18D, the average relative humidity throughout the year is between 25.8% and 29.2%, but it varies from the coldest period, March and April, with an average of 18.7%, to 28.8% in June and July (Figure 3). The Low-energy house uses a mechanical ventilation system with two cross-flow heat exchangers connected in series and by taking in the dry cold air and adding heat, the relative humidity of the air is further reduced. The average indoor relative humidity is between 28.4% and 28.7%. The humidity in March and April is 21.4% on average and in June and July it is 28.2% on average.

The profiles for relative humidity (Figure 3) in the two houses are almost identical; but relative humidity in 18D is higher than in LEH due to higher air change through the building envelope and natural ventilation in 18D, and better air tightness and a mechanical ventilation system in LEH.

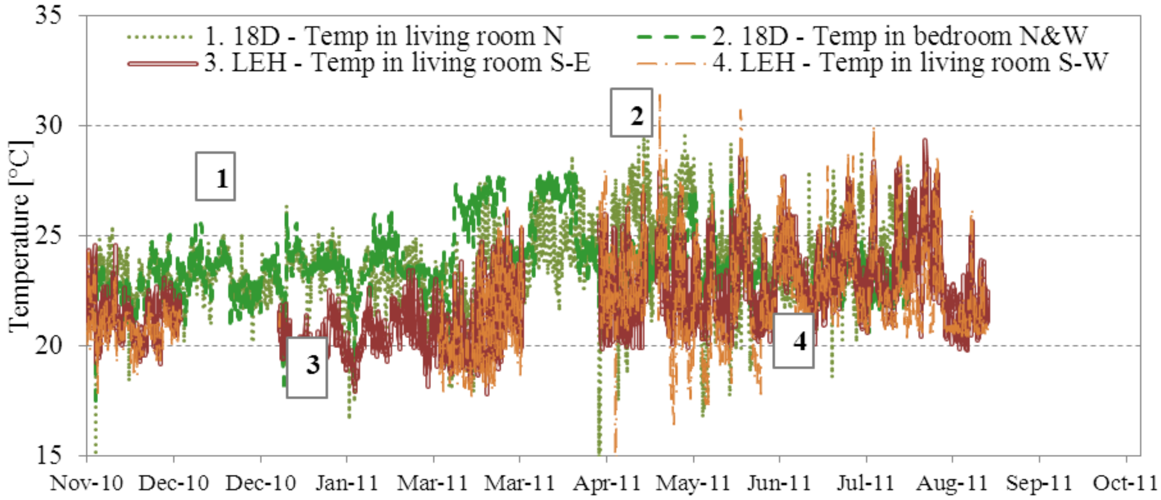

Figure 2. Hourly measurements of indoor temperature (Temp) in 18D and LEH in 2010/2011

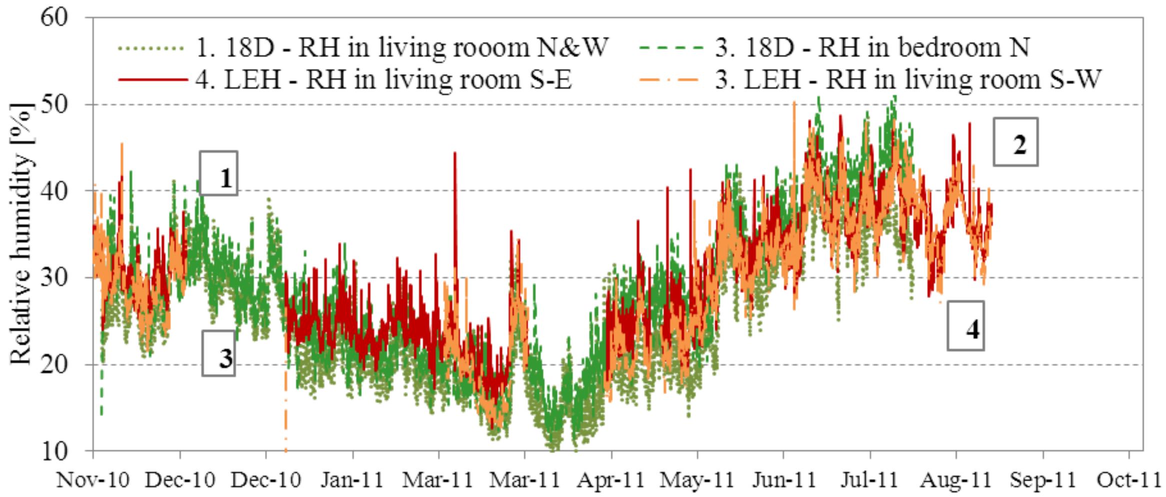

Figure 3. Hourly measurements of relative humidity (RH) in 18D and LEH in 2010/2011

The LEH is located in a climate with low content of water in the outdoor air. The high humidity production in kitchens and bathrooms leads to the ventilation unit being unable to recover the humidity and often it also decreases the efficiency of the cross-flow heat exchanger in the ventilation system. Since the ventilation system is not able to add recovered moisture back into the house, the interior humidity is still relatively low, both in winter and summer (Figure 3).

Building envelope: air tightness and thermal comfort

Buildings in cold climates must be able to withstand and respond to changing temperatures, including very low temperatures, strong winds and moisture conditions through controlled humidity and increased pressure applied into the façades. The thermal qualities of standard house 18D are limited due to the building construction, where the wooden frames have roughly 3 times the heat flow of the insulation materials. The house only has 100 mm of insulation, which has proved to be inadequate and in combination with insufficient air tightness ($n_{50} \approx 18.5\ h^{-1}$) leads to unsatisfactory thermal comfort. This has been confirmed by questionnaire-survey conducted among inhabitants in 18D, which indicated problems with cold floors, uncomfortable draughts, cold walls and various types of leakage issues. In contrast, the Low-energy house has good thermal properties due to its special double-frame construction in combination with 300 mm of insulation and relatively good air tightness ($n_{50} \approx 3.1\ h^{-1}$). All these features contribute to a good energy balance and thermal comfort in the house as confirmed by investigations and a questionnaire-survey.

Health damaging materials in the houses

Other things that affect health include the health-damaging materials that can be found in buildings in Greenland in such high concentrations, e.g. lead (found in paint), PCB (polychlorinated biphenyl used in rubber seals, etc.), formaldehyde (used in glue in chipboard, etc.), asbestos (in rubber seals, cement asbestos plates, etc.), radon (from the ground), and fungus (mould). The 18D houses have remains of lead paint, which should be taken care of when they are retrofitted; but there is no PCB, formaldehyde and asbestos. These materials are no longer used in buildings and were not used in the construction of the LEH. Radon and mould are common in Greenland. Ventilated crawl space and thermally sound building construction along with ventilation strategies are used against radon and mould problems in the LEH. In 18D, the proper ventilation of the basement and improvement of the building construction should be carried out to prevent entry of radon and mould growth.

Energy consumption and use of buildings

In the LEH, the energy used for heating is registered directly in the monitoring system, and it comprises of the energy for floor-heating and after-heating (source: www.energyguard.dk, login: DTU4, password: sisimiut). In the years 2005–2009, the consumption in LEH was constant, but in subsequent years, consumption has been reduced by approximately 30% due to repairs and improvements made in the house (Figure 4). Energy for heating in 18D is based on oil supplies to the oil tank documented by paper bills verified by calculated consumption. From 2006 to 2008, there is a consistent pattern, where 200 litres of oil were delivered every month. In following years, there is no more consistency, because the owner has not supplied all bills for registration.

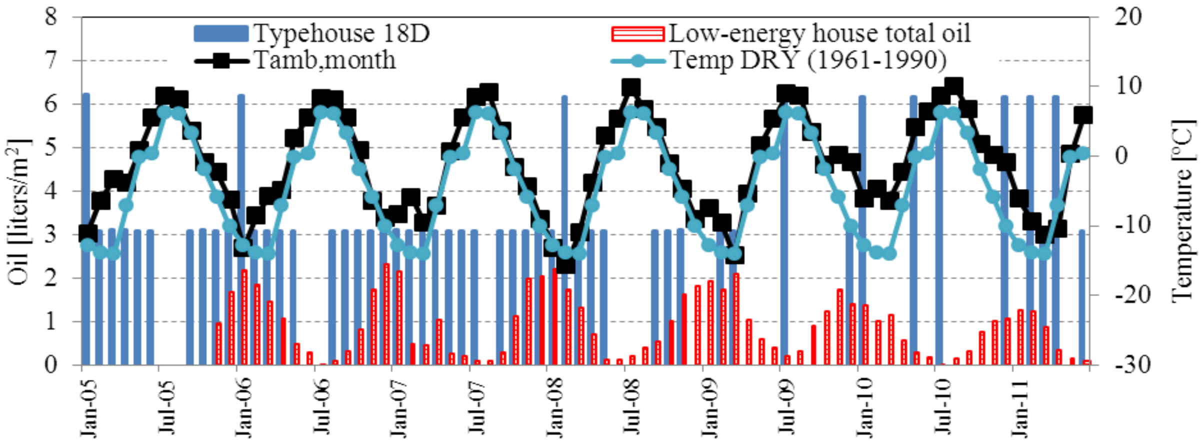

Figure 5. Comparison of monthly values for oil consumption / deliveries in 18D and LEH with measured mean outdoor temperature $T_{amb,monthly}$ and temperature from the design reference year

Building use depends on the design conditions, living preferences and the influence of the weather. Usually, design conditions for relative humidity are defined as 30-60% and indoor temperature is defined as 20.0-24.0°C in winter and 23.0-26.0°C in summer (ISO EN 7730, 2005). The design temperature for houses in Greenland is usually 20°C and this temperature was used for the design of 18D. But LEH was designed with a temperature of 21°C to allow higher indoor temperatures based on observed lifestyle preferences in Greenland and a higher internal load of 5.0 W/m^2. Other lifestyle preferences related to cultural heritage, such as cooking traditional dishes. The low content of water in the air may cause some problems. Inhabitants in both 18D and LEH have encountered these problems, which also resulted in various problems in the houses, such as high energy consumption due to unnecessary ventilation, inadequate shading causing overheating, high moisture accumulation in the ventilation system, or large temperature variations (Vladykova, 2011).

4 DISCUSSION AND CONCLUSION

In Greenland, the standard house 18D consumes large amounts of energy and provides an unsatisfactory indoor climate and poor thermal comfort due to its badly insulated and leaky building structure combined with uncontrolled air change by natural ventilation. The Low-energy house is energy-efficient, thermally controlled and airtight with mechanical ventilation providing a good indoor environment. Our investigations show that the focus in the future energy renovation of wooden standard houses like 18D should be based on the following data about the buildings: energy, indoor and outdoor climate, lifestyle and building materials. In order to properly register these elements, advanced monitoring systems will be applied in 18D houses, and the monitoring system in LEH is in the process of improvement at this moment. The data registration will help with energy optimization in the renovation project of 18D houses, just as it has supported energy and indoor climate improvements in LEH. Comparison of the older standard house 18D with the newer LEH shows tremendous differences in energy consumption, but a similar pattern in temperature variations, generally low indoor humidity levels, with remarkably low indoor relative humidity in the cold period in March-April albeit for different reasons, and problems with overheating. Potential future reductions in energy use in buildings in the Arctic regions will be directly connected to the environment, effectiveness of ventilation strategies, building materials and their properties, the lifestyle of inhabitants, and the design of buildings.

ACKNOWLEDGEMENT

The article is based on research performed at the Technical University of Denmark, Denmark, and time to work on this article was donated by Swegon AB, Sweden.

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