Can collected hygrothermal data illustrate observed thermal problems of the façade? – A case study from Greenland

N K Friis¹, E B Møller¹ and T Lading¹

¹Technical University of Denmark, Department of Civil Engineering, Brovej, Building 118, 2800 Kgs. Lyngby

Corresponding author: nfri@byg.dtu.dk

Abstract. Buildings are more vulnerable to faults in design and construction, when exposed to the extreme Greenlandic climate, however, most new materials and designs have not been tested for Arctic conditions. Thus even minor errors can result in failures like mould growth, discomfort, and unnecessary heat loss. Recognising the source of the error can be difficult, yet valuable. But how can it be identified whether the error lies in the design or quality of workmanship? This paper describes a case study from Nuuk, Greenland, where a new mineral wool insulation system was implemented. Residents were complaining about draft and cold areas. An investigation revealed that inaccurate use of the system caused several problems. Simulations of the exterior wall performance were conducted and compared to measurements. This paper discusses whether these measurements and simulations support the identified issues, and therefore if this kind of general surveillance of exterior walls can be used to determine the total performance of an exterior wall. The paper concludes that the collected data can support the issues of the complaints, and that the fundamental reasons for the problems are the design, the precision of the casted concrete and the lack of a wind barrier protecting the insulation.

1. Introduction

The arctic climate is harsh due to a combination of cold temperatures, precipitation, and strong winds. In the case study, located in Nuuk, Greenland, temperatures within a year span from -18.9 °C to 18.4 °C with mean -0.4 °C and median 0.8 °C. 12 % of the year (42 days), the temperatures are below -10 °C. In 27 % of that time the wind speeds were 8 m/s or more. The weather conditions are therefore more challenging than the typical climate in Europe for which many constructions are developed originally.

Before introducing new building materials and methods to the marked, these are usually tested under controlled conditions, but the practical aspects are difficult to test or assess before introducing it to reality, where the conditions are no longer controlled. Sometimes, this results in inexpedient situations, where mistakes or unforeseen challenges result in a product or design, which does not comply with the expectations. This scenario occurred in a multi storey building in Nuuk, where a new insulation material of mineral wool was introduced to the construction sector in Greenland. The residents of the buildings started complaining about draft, cold floors and walls and general discomfort in the apartments. Often complaints like these are treated by measuring the indoor temperature over some time to determine if the residents’ complaints are justified. In this case, the owner chose a more thorough investigation to pinpoint the problems and determine the cause. The investigation was performed in February 2019, almost 2 years after the building was finished. Because the insulation system was new, the building had been chosen as a case study in another project and the façade was therefore already equipped with...
sensors. As the sensors were placed before the first winter, the location was chosen randomly and was therefore not necessarily placed in one of the apartments with most complaints.

This paper aims to investigate if the observations from the inspection and the collected data tells the same story. Will the data from the sensors reveal the observed thermal issue and can this kind of surveillance be used to determine how a wall performs? The scope considers only the thermal quality of the insulation system and how it is installed. General issues of the building, such as thermal bridges, leaks and ventilation humidity content or risk of mould were relevant [2] but not reported here.

2. The investigated structure
The case study encompassed four identical three-storey buildings, each with 12 apartments, placed in a weather exposed area in Nuuk, Greenland. Usually, exterior walls in Greenlandic multi storey buildings consist of a wooden structure with insulation and a vapour barrier on the internal side and a wind barrier on the external side, which is finished with a ventilated cavity and external cladding. The insulation is thereby protected against precipitation and wind penetration, ensuring high performance. In this case, the vapour barrier also acts as an air barrier, ensuring a tight construction with limited air leaks. The term “wind barrier” describes a membrane, with the purpose of protecting the construction from cold winds [3].

In this specific case, the wall was a heavy structure of in-situ casted concrete with an external layer of very firm mineral wool (\(\lambda=0.033\) and \(\rho=80\) kg/m\(^3\)). The insulation was followed by an air cavity and an external cladding of a composite material. In theory, the design concept of insulation being applied tightly to the concrete makes a wind barrier redundant, as the wind needs space to create convection and the concrete acts as an air barrier. The insulation mats had two flexible zones (two adjacent sides of the mat) so the mats could be pressed tightly together without gaps between them. Figure 1 illustrates the construction along with green dots indicating the placement of the installed sensors.

![Figure 1](image)

**Figure 1.** Detail of the new wall insulations system in Greenland. Composition of the investigated wall and green dots indicating the sensor locations. All dimensions are given in mm.

3. Methods and materials
This section will introduce the construction of the exterior wall, and the three methods applied in the investigation of the building: An inspection, data collection including assessment of data and finally, simulations conducted in Delphin.

3.1. Inspection and photos
The inspection was performed February 27\(^{th}\) 2019, a sunny day with outdoor temperature of -4°C and no wind. It included measurements of indoor temperature and relative humidity, thermography to identify cold areas, smoke sticks to identify air flows and visual observations. Four apartments were inspected from the inside. The exterior wall of all four buildings was visually inspected from the outside. Furthermore, the evaluation also included photos from prior visits at the construction site and interviews with residents and managers.
3.2. Data from sensors.

The hygrothermal performance of a south facing façade of one of the apartments has been monitored since September 2018, by four sensors (see Figure 1) measuring temperature and relative humidity every hour. Sensor S0 measured the conditions in the apartment. S1 measured the conditions between the concrete wall and the insulation, while S2 was placed in the air cavity and S3 measured the conditions outside the building. S3 was placed in a box, sheltered from direct sunlight and precipitation. The sensors are of type “HYT 221” from Innovative Sensor Technology [4], and can measure relative humidity and temperature digitally with an accuracy of ±1.8% RH at +23°C (in the range 0% RH to +90% RH) and ±0.2K (in the range 0°C to +60°C).

3.3. Weather data

Asiaq and DMI, governmental meteorological institutions located in Greenland and Denmark respectively, provided weather data for Nuuk. The weather station of Asiaq is located at 64.183333 N and 51.730833 V. The data included date, time, relative humidity, precipitation, wind direction, wind speed, air pressure, air temperature, and incoming short-wave radiation. The latter is also called “global radiation” and includes all short-wave radiation measured on a horizontal plane placed in 2 m height.

3.4. Simulations

Dynamic 1D simulations with DELPHIN 6.1.0, developed by Baumklimatik-Dresden [5], were conducted to get an indication of the theoretical expectations. The chosen materials and the relevant properties are presented in Table 1. The materials were chosen from the Delphin database, as no material properties were measured in this study. The insulation material, however, is defined for the specific product applied. The exact air flow in the cavity could not be defined due to insufficient data. Instead the air flow is considered constant, with a value of 250 h⁻¹ based on literature [6].

| Material                  | Density ρ [kg/m³] | Heat capacity cp [J/kgK] | Thermal conductivity λ [W/mK] | Water vapour resistance factor μ [-] | Air change rate ACH [h⁻¹] |
|---------------------------|-------------------|--------------------------|-------------------------------|-----------------------------------|--------------------------|
| Concrete                  | 2400              | 900                      | 2.100                         | 110                               | -                        | 56                       |
| Insulation                | 80                | 840                      | 0.033                         | 1                                 | -                        | 645                      |
| Ventilated air cavity     | 1.3               | 1.050                    | 0.067                         | 1                                 | 250                      | 15                       |
| Cladding                  | 1158.7            | 1.188                    | 0.313                         | 26                                | -                        | 654                      |

The internal boundary conditions for the Delphin model included relative humidity and temperature, which were obtained from the sensor S0 as hourly values. The external boundary conditions included 7 parameters: Temperature, relative humidity, horizontal rain, wind direction, wind velocity, diffuse radiation, and direct radiation. These were obtained from the weather data from Asiaq (see Section 3.3. However, the files only provided global radiation; sum of direct, diffuse, and reflected short-wave radiation, while Delphin uses direct and diffuse radiation. Reflected short-wave radiation is neglected.

The fractions of direct and diffuse radiation can be estimated from the Global radiation. It is an extensive method based on time and location, which is used to define the extra-terrestrial radiation. From this and the global radiation, the hourly clearness index, Kd, is calculated indicating the clearness of the atmosphere. Finally Kd is used in the “Orgill & Hollands” method resulting in the diffuse radiation, leaving only a simple calculation for defining the direct radiation too [7].

The output files were defined as points in the model. S1 and S2 were placed according to the sensors in reality (presented in Figure 1). The initial conditions in the model were defined to be 15°C and 80% relative humidity. The simulation was performed for 1 year, equal to 8,760 measure points, which was chosen based on the intention of having as few missing values as possible, while complying with Delphin’s default settings of managing maximum a year. The chosen period begins 2019-10-02 at 1 pm.
Despite the careful choice of the presented period, there are lacking some values in the included data. Especially, wind direction and wind speed have some holes. Delphin demands input for every hour, why the holes must be filled with suitable values.

The missing values for air pressure were replaced with the mean value, while temperature and relative humidity were defined as a mean of the two values prior and the following values. For precipitation 0 was chosen to fill the gaps. Filling the gaps of radiation was more circumstantial. In cases missing single data, the surrounding values of the specific day were interpolated, and when a whole day was missing it was filled by a mean of the previous day and the following day, respecting the respective hours. The issue of wind direction and wind speed was challenging as these values come and go within hours, there is no way to estimate the missing values, however, the missing values were filled in with mean values unless, it was a only few in a row, which could be solved by interpolation.

4. Results and analysis
This section presents the results and analysis of the described methods.

4.1. Inspection and photos
The inspection revealed different issues, of which most could be logically explained by visiting the building and performing simple measurements. The main issues considered at the inspection were draft, cold floors, air flow between the apartments, and cold walls, of which the latter is of highest interest in this paper. The thermography revealed thermal bridges and cold floors, but no specific cold wall surfaces. Fortunately, a look on the pictures from the construction period, could reveal that the new type of insulation was not installed according to the instructions from the manufacturer. This has led to gaps between the insulation pieces. Furthermore, the product sheet demands a very smooth surface, leaving a tolerance of the concrete surface of only ±2 mm, which is basically unrealistic for in-situ casted concrete with the technology and facilities available in Greenland.

As there is no wind barrier between the insulation and the free space of the air cavity, there is risk of cold air blowing through the gaps between the batts to the concrete wall where the risk of another unintentional air cavity was identified (Figure 2), caused by the irregularities of the concrete. When the air has entered the cavity, it can flow along the concrete walls and potentially cool it down depending on the season. This phenomenon compromises the insulating properties of the insulation. In short, the tolerances are not kept, and thus the design works different than intended. If a wind barrier had been implemented in the design, the consequences might have been reduced considerably.

![Figure 2](image-url). Illustrations of how wind can penetrate the insulation layer due to gaps between insulation mats and uneven concrete surfaces. Left: Photo taken during construction. Right: graphic illustration, which may exaggerate the situation.
4.2. Data from sensors and simulations

According to the data from the sensors, the temperatures at S2 and S3 follow each other closely despite the big instabilities. This is no surprise, as S2 is placed in fresh air as S3, with the only difference, that the air flow is usually reduced in an air cavity like this. This means that direct solar radiation might heat up the air in the cavity to be slightly warmer than outside. However, in practice, S3 is placed in a box as well, meaning that the conditions are quite similar for the two sensors. Furthermore, S0 is the foundation of the input data to the indoor climate, which leaves S1 as the main point of interest for this section.

Figure 3 illustrates the measured (black line) and simulated temperatures at S1. The orange line is based on the simulation with original λ-value of the insulation (0.033 W/mK). Apparently, the insulation is reduced due to convection. To illustrate the size of the reduction, simulation-scenarios with higher lambda values were performed although this represents conductivity, a different transport mechanism than convection. The average deviation of the annual mean of the sensor data for S1 and the simulated data for the original value of $\lambda=0.033$ W/mK is -4.1°C, calculated by formula (1). The deviation decreases to -3.0°C at $\lambda=0.1$ W/mK and -0.6°C at $\lambda=0.3$ W/mK. The simulated scenarios are chosen in an attempt to approach the measured data.

\[
\text{deviance} = \frac{\sum T_{\text{sensor}}}{8760} - \frac{\sum T_{\text{simulation}}}{8760}
\]  

Figure 3. The difference between measured and simulated data, including two variants of insulation, in a 1-year period from 02-10-2019. The box marks the area shown in Figure 4.

The January peak towards 10°C, marked with the dash line box in Figure 3, became of interest. Therefore, it was investigated how the weather conditions were at that time, especially if the wind conditions were of importance as suspected. The peak is appearing at 1 PM, and there is some solar radiation, however it should be considered as very cloudy to no sun (global radiation of 25 W/m²).

In Figure 4, a short period of time, surrounding the event, is presented. The black line indicates the temperature measured by the sensor and the grey shadow indicates the wind speed, which is high at this point. However, it is not higher than at other times, where the temperature is affected less. The air temperature might be the reason, being low at the time. One last aspect is the orientation of the wind, which is presented as a factor of how critical it is. Due to the orientation of the wall, the most critical wind directions are from south, spanning from SW to SE, while the least critical directions are between E and W. However, there is a potential risk from wind coming from the last two spans, as the wind in these directions might hit the corners. The factors given are 8 for risky, 4 for potential risk and 0 for no risk, meaning that there is a potential risk to the wind direction in this case.
The tendency in Figure 5 is that the temperature deviance increases with higher wind speed, while there is a general deviance of 3-4 °C, even with low wind speeds. However, the coefficient of determination ($R^2$) is very small, and contrary to what was expected, the tendency is similar for wind from north and south. It might be caused by wind entering at the corners creating turbulence, where the local wind speed and direction is different from what was observed at the weather station. The gap between the insulation mats is permanent and will probably contribute more to the cooling of the concrete wall than if it was only forced convection through mineral wool.

5. Discussion
This study is based on measurements as well as simulations. Both parts contain uncertainties that must be addressed. Furthermore, the implications and the general relevance of the study must be discussed.

5.1. Uncertainties for inspection and measurements
The inspection was performed during wind still and relatively warm conditions, which was not ideal conditions to look for issues expected to be more significant under cold windy conditions. Therefore, the inspection itself was less useful compared to photos from the construction phase and interviews. The investigation showed that the complaints were not caused by unrealistic expectations from the residents.

Although the sensors were calibrated prior to installation, there is always a risk of them losing the calibration. As the measured temperatures in general were lower than in the simulations, this could be a part of an explanation. Additionally, the installation of the sensors is done by cutting out pieces of the
wall to insert the sensors in the respective layers. If the pieces are not put back properly, this might cause uncertainties – especially in relation to cold winds. There was extra focus on this during installation.

5.2. Uncertainty in simulations

Many elements are included in simulations. The inputs are based on measurements from the sensors, which are already at risk of uncertainties, and from weather data, for which the same counts. In general, there were some missing data – especially in the weather data. It was attempted restored, but it is impossible to predict weather into this level of detail. Additionally, the properties of the materials used in the construction are estimated not measured. The simulation was simplified; as a 1D simulation although the construction included a ventilated air gap, and the ventilation was estimated as a constant air change rate. A sensitivity analysis of the air flow has been performed and shows that increasing the airflow by 100% (to 500 h⁻¹) leads to a maximum temperature change of 0.07 °C. Thus, the simplification is acceptable. It was tested how different ways to interpret the global radiance of the weather files would influence the differences between measured and simulated temperature. This is shown in Figure 6. In the same figure it is shown how the wind speed has an effect on the temperature difference.

The simplifications cannot alone account for the differences in measured and simulated temperature, the wind speed also seems to have an effect. If the measurements are correct, there must be a fault in the construction.

5.3. Reduced insulation effect

The inspection, the photos from the construction process, the dialogues with the residents and the measurements all indicate reduced effect of the insulation, possibly by faulty use of a new insulation product. It is not surprising, that faulty installation reduces the insulation effect and that was not the main goal of this analysis. The aim was to investigate if general measurements could reveal this kind of faults where it was expected to be a patchy issue, scattered around the external walls rather than an even distribution of cold air entering the construction. Thus, the probability that the sensors were placed exactly in one of these areas was considered very limited. Still, the results of the analysis suggest that the sensors detected this issue. Whether this is luck or due to the issue being widespread could probably be defined by a new inspection at a time with suitable weather conditions. But it seemed that the insulation effect was reduced by a factor 10, as the temperatures resembled simulated temperatures with a material of a $\lambda$-value 10 times higher than the expected. This might have been reduced considerably if there had been a wind barrier. Enhancing airtightness of the insulation layer itself seems less realistic.

![Figure 6](image_url)
In principle, the issue is caused by faulty application of the material, but it can be argued that the dissatisfactory workmanship is rooted in bad design decisions. It must be expected that state of the art technologies for the location of any construction are respected in a design phase. If the general tolerances of in-situ casted concrete in Greenland had been considered, the choice might have been different, resulting in buildings of higher quality.

5.4. General perspective
If it is pure luck that the sensor was placed in an area with the problem, it does not necessarily reduce the potentials of measuring the conditions through a wall, though the measurements might not be able to stand alone. This counts in two ways. First, if the sensors provide data, with no unexpected twists, it might not mean that the building is designed and or constructed optimally. Second, collecting the measurements from different houses might tell more about the construction sector in Arctic climate and about the individual houses, than stand-alone examples as the one presented here. Therefore, several other buildings with the same construction are monitored over several years.

6. Conclusion and future work
In four buildings in Nuuk there had been complaints about thermal comfort. The insulation system used in these buildings was new to the Arctic and did not contain a wind barrier. The buildings were investigated through an inspection with simple measurements and interviews, photos taken during the construction phase and long-time measurements of temperature behind the insulation. The most likely reason for the cold walls were discovered to be convection through gaps in the insulation due to no wind barrier. This was mainly discovered through the photographs from the construction phase but supported by the other findings. Although the problem was expected only to occur as isolated incidents at the exterior wall it could be detected by long-time measurements as well. It could be a coincidence that the sensor was placed in an area with this problem, however, in this case the collected data could support the observed problems. The reason for the issues seems to build on insufficient design decisions, making it challenging for the workers to apply the product correctly. This case proves the combination of the unforgiving arctic climate, uneven concrete surfaces, and lack of wind barriers to be bad.

It is the intention to work more with this topic in the nearest future, why more data is currently being collected for further analysis and investigation. Hopefully, it can lead to general recommendations for how to build in Arctic climate.

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