Introduction

The present high temperature water born central heating system at Nidaros cathedral was designed by professor Watzinger at the Norwegian Institute for Science and Technology around 1930 (Watzinger 1935). It is now in relatively poor condition and great need of repair. Due to demands from users, the indoor climate of the cathedral is warm and dry in the heating season, but according to various studies, not adversely affecting other objects than the two organs and a few painted sculptures. It is also possible that heat transfer through masonry leads to more frequent freeze-thaw events at outside stonework, but this phenomenon has not been confirmed scientifically.

Thus, the main problem at the moment is that the heating system is too old and inflexible, implying that it is not possible to control the indoor climate in directions that are desirable now or might become desirable in the future, as more knowledge about the effect of heating on the fabric of cathedral is produced.

As a result of corroding and leaky radiators, recent studies about the indoor climate and history of the heating system began in 1995 (Storemyr 1995) and reached a peak through the Master's Thesis of Nørsett in 1996. Through the work of Storemyr (1997) comprehensive indoor climate recording began and in the restoration plan for the cathedral (Storemyr & Lunde 1998) it was firmly stated that the cathedral needed a new heating system. The EC
Raphaël programme has provided the necessary means for starting the process of designing a new system, a task that was given to the company Scandiaconsult AS in Trondheim in 1999. This paper aims at briefly summarising and discussing the report of the project, which was undertaken by Nørsett & Larsen (2000). Their investigation and subsequent, supplementary studies by the German company Mahr GmbH will form the basis for choosing a new heating system.

**Characteristics of the present heating system and indoor climate**

The cathedral has since c. 1930 been heated by a high temperature central heating system which replaced former systems introduced already by 1870. The system is based on radiators at floor level in the whole church, as well as in the triforia (in order to avoid draught generated from cold stained glass windows (not insulated) and masonry). The nave is in addition equipped with electrical floor heating and there are a few electrical panel ovens at specific places in the church. The heating plant is situated in the cellar below the chapter house.

Originally, the system was designed for a background temperature of 10ºC, which could be increased to 16ºC when necessary. This means a total effect requirement of c. 500 kW (14 kW/ºC, minimum outside temperature -20ºC). However, over the 70 years that have passed since the system was designed, users of the cathedral have steadily demanded higher temperatures. At present the temperature in the heating season (October-May) is on average more than 18ºC, which implies a total effect requirement of some 630 kW (17 kW/ºC, minimum outside temperature -19ºC). Since many radiators are destroyed or removed, and that the remaining ones are partly blocked by dirt, giving the system a total capacity of only c. 360 kW, it may appear somewhat astonishing that the old system is able to deliver such high

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**Figure 2: Characteristics of the heating system and the indoor climate in the cathedral during the heating season (October-May). Note the uniform temperature distribution. After Nørsett (1996) and Storemyr (1997)**

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Heated areas: 
- <18 C
- 18-20 C
- >20 C

Air movements: 
- Cold
- Warm

Location of radiators

SEN 1996/PS 2000
temperatures. However, this is because the heating system works quite good in draught-free areas (see below). Moreover, in the coldest periods it becomes rather cool in the church and extra heaters often have to be used before concerts and other events.

People often complain about the low temperature in the church. However, measurements have shown that the congregation and public are in fact more affected by draughts than by low temperatures in the heating season. It has been confirmed that the west wall with its large rose window generate draughts with mean air velocity of some 0.4 m/s, which is a very high value. A few years ago new radiators were installed below the rose window, but due to complex architecture in the area, it is not possible to effectively reduce the draught by radiators.

Because of the generally high temperature in the heating season, the relative humidity is low, at times extremely low (15-20%). It should, however, be noted that extremely low RH only occurs when the outside temperature is lower than, say, -10°C or when there is high-pressure dry winter weather. The cold maritime climate in Trondheim is in fact generally dry because of the low absolute humidity. Also precipitation is quite low, only 900-1000 mm/year.

The indoor climate can thus be summarised as follows:

- **Heated parts:** Warm (15-22°C) and dry (15-45% RH) in the heating season (October-May). Relatively cool (17-21°C) and humid (50-75% RH) in the summer. Infrequent summer condensation events in cold corners.
- **Unheated parts:** In principle completely dependent on the exterior climate. Very frequent condensation events inside turrets and towers, especially in late autumn and spring.
- **Draughts:** Due to large-scale thermal movements (cold air from the west front and from openings and windows,) the nave is severely affected by draughts in the heating season.
The absolute humidity during the heating season is about 4 g/kg air, which is 1 g/kg higher than on the outside. This means that there is a net supply of moisture to the interior; probably from a combination of water leaks and moist masonry, the cellar and ground, wet cleaning, people and humidifiers. Around the Steinmeyer organ in the western part of the nave, as well as in the southern chancel triforium, there are six humidifiers, but these do not seem to alter the climate significantly.

As mentioned in the introduction, cracking and flaking of painted wooden objects are the most significant adverse effects of a warm and dry indoor climate. In the cathedral there are few such objects and instead the organs suffer the most. Generally, the problems are that wooden parts of the organs dry out and get cracks. In effect they become untuned and have to be repaired and tuned in quite frequently.

Another adverse effect of the warm indoor climate in the cold season is related to thawing of snow and ice on heated building parts. The lower parapets of the chancel and nave are probably affected because of radiators located in the nearby triforia. Also snow on stringcourses and sills at the transept and chapter house seem to melt more rapidly than on unheated building parts. The effect may be more frequent freeze-thaw cycles and more problems with leaks.

A positive effect of heating (compared to unheated areas) is that it effectively reduces the number of condensation events inside the church, as well as on outside walls of the heated areas. Condensation and white frost are far more frequent on exterior walls of unheated areas, probably contributing significantly to the weathering of these parts.

**Design criteria for a new heating system**

Since there are relatively few adverse effects of the current heating in the cathedral, there is no need to fundamentally alter the existing system. In addition to slightly lowering the room temperature and increasing the relative humidity, the most important objectives should be to:

- Design a flexible system, in which the indoor climate in different sections of the building can be controlled independently.
- Increase the *operative* ("felt") temperature for people. In practice this means to avoid draughts, as well as to "heat people instead of the building". It does *not* mean increasing the general room temperature.

On this background the following criteria were used as a basis for the proposed system solution:
• Mean general room temperature: 16°C
• Operative temperature during events: c.18ºC (max. c. 20ºC) (NB! Felt temperature)
• Relative humidity in the room: Min. 35-40%, or as high as possible in the winter

It has been calculated that an average room temperature of 16ºC reduces the number of days with relative humidity of less than 40% from 203 to 125, when compared to the present situation (1999). Thus, there is still a need to increase the relative humidity on cold winter days. One solution is to lower the temperature to, say, 12-13ºC; another is to install effective and controllable, new humidifiers. It has been calculated that when adding up to 0.5-0.7 g/kg moisture on the coldest days, there is still very little risk of condensation/white frost on the coldest areas of the cathedral’s heated parts (windows). If choosing the latter solution, the number of days with relative humidity between 20 and 30% will be about 10 annually.

Since the outside absolute humidity is lower than in the church (winter), it is also a good idea to insulate selected doors and openings better than today (especially at the west wall). Moreover, installing air-tight entrances (“locks”) should be considered. No decision with regard to these matters has yet been taken.

Another issue is whether the relative humidity is too high in the summer season. At times it may reach 75% in the coldest corners in the church (e.g. chapter house), but it is rarely above 65% in other parts. On average the relative humidity in the summer season lies between, say 50 and 60%. We believe that this is not causing any significant problems, and consequently that there is no need at the moment to try to reduce the relative humidity.

There is much salt on interior walls, but salt types are mainly sodium sulphates and carbonates with equilibrium relative humidities above 80%. Consequently, the salts are in crystalline form most of the time, except in the coldest corners (e.g. the west wall of the chapter house). If one wants to do something here, a possibility is simply to turn on slight heating for a few days.

With regard to future use of the cathedral, it has been assumed that the present pattern will continue. At present there are c. 2500 larger and smaller events in the cathedral every year. It should be noted that there are plans to move the large Steinmeyer organ from its present place close to the west wall to a place somewhat further east. This might be favourable with regard to dealing with the cold draught from the west wall (see below).

Proposed system solution for the heating system

It has already been decided that the heating system is to be connected to the water born district-heating system in Trondheim. The plan is to use the cellar of the cathedral’s coming (probably 2002) information building beside the west front square as the heating central. From there it is suggested to distribute the water via pipes to two small sub-centrals; one for the eastern part of the church in the cellar below the chapter house, and one for the western part in the cellar below the north aisle of the nave.

From these sub-centrals the water may be independently distributed to four sections of the church: 1) the chapter house, 2) the chancel and the octagon, 3) the transept and 4) the nave. This means that each major building part easily can be controlled independently from the others.

With a background temperature in the heating season of 16ºC, an operative temperature of 18ºC and in order to be flexible enough, the system should have a total capacity of about 630 kW (17 kW/ºC). It is suggested to distribute this capacity on the following heating methods:
• Floor heating (100 kW)
• Water born radiators (470 kW)
• Direct heating of people (electrical radiation heaters - 60 kW)
• In addition: effect required for preventing cold draughts in the nave.

Floor heating in the nave, transept, chancel and chapter house is suggested to secure the background temperature and, perhaps more importantly, to increase the operative temperature for people (by radiation). There is already electrical floor heating in the nave, but due to the fact that the system is more than 60 years old and in need of repair, it should be renewed, which in turn means that the floor has to be taken up. For the other parts of the church floor heating is much more controversial because it implies taking up marble floors from 1871 (chapter house), 1890 (chancel) and 1905 (transept). Whether such operations are justifiable from a preservation point of view have to be discussed. Otherwise, there are two possibilities for the heating medium; either warm water or warm air. Air is the most secure as seen from a potential water leak perspective, but this solution demands much space (more than available?) and may give a potential noise problem. Thus, as modern water-born floor heating systems seem secure enough, such a solution should perhaps be preferred.

The suggested main heating method is radiators as today - and with the radiators also placed more or less like today. The possible controversial question is whether it is justifiable to replace the cast iron radiators from c. 1930. These are in much better condition than the wrought iron radiators from the same period, which are strongly corroded and leaky. From a flexible heating perspective the best would have been to replace all radiators, but a compromise might be to keep the cast iron radiators in, for instance, the octagon and the chancel. However, in case such a solution is chosen, these radiators would have to be investigated more closely with regard to corrosion and expected remaining lifetime.

Instead of water born radiators (and perhaps also floor heating), warm air heating might be an alternative, as in most German churches. However, the discussion of such a solution is beyond the remit of this paper. It will be investigated by the German company Mahr GmbH.

Direct heating of people instead of heating the fabric of the cathedral has been discussed for a while. However, the original alternative - to place electrical radiation heaters in the triforia of the nave and chancel - seems difficult due to the distance from the congregation/public. Since the cathedral does not have - and cannot have - fixed chairs with radiation heaters underneath, the only possible solution is to utilise the lighting system for obtaining an operative (felt) temperature of more than 18ºC. In this connection it should be noted that there are plans for replacing the existing illumination in the cathedral. In order to obtain satisfactory aesthetic results, a design process would have to be carried out if choosing this alternative.

Reducing the background temperature to 16ºC will also somewhat reduce the worst draughts. However, in order to obtain a "draught-free cathedral", the only solution is to reduce the cold air movements from higher parts, especially from the west wall. It is difficult to do this by radiators, and the suggested solution is to apply high velocity air, turning the draught upwards, from small nozzles placed strategically. There should be no problem with noise (max. 20 dB) or aesthetics with such a solution, since the nozzles can be placed in the triforia and behind the westernmost pillars (if the Steinmeyer organ is moved - see above).

A solution including heating centrals and a distribution system based on floor heating, new water born radiators and electrical radiation heaters, as well as draught prevention is estimated at c. 9 million NOK (incl. VAT). This estimate also includes expenses for new pipelines inside the cathedral, taking up the floors and design/production of radiation heaters, but not for eventual archaeological excavations related to establishing necessary pipelines outside. It neither includes expenses for eventual humidifiers and clearance of asbestos around the old pipes in the cellar.
Concluding remarks and further work

It should be strongly underlined that the project that has been discussed and summarised in this paper is a proposal for a new heating system in Nidaros cathedral. The proposal has to be submitted for comments to other experts on heating systems in historic buildings as well as to the parish and the Norwegian Ministry of Church, Education and Research, which is ultimately responsible for the cathedral. Moreover, it is strongly recommended that other system solutions are worked out, for instance related to extensive use of warm air heating. Another recommendation is to simulate the effect of various solutions using computers, for instance by involving the Norwegian University of Science and Technology.

However, one of the main objectives of the project; to design a flexible and controllable heating system has been attended to in the proposed solution. A flexible and controllable system is of utmost importance because it will enable those responsible for the cathedral to manage the indoor climate in desired directions as new knowledge about the interaction between the fabric of the cathedral, the people using it and natural laws become available. Heating Nidaros cathedral should from now on be regarded a large-scale experiment.

References


