Heat pumps for conservation heating

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SUMMARY:

Conservation heating is used to control relative humidity in order to better preserve historic buildings and their interiors. The heating load for conservation heating when applied in a Nordic climate was characterized in order to investigate if and how air-to-air heat pumps can be used for conservation heating. Heating for conservation results in indoor temperatures that follow the seasonal variation of the outdoor temperature. Depending on the season and moisture load on the building, the indoor temperature will be 0-10 °C higher than the ambient temperature. The heating load is much smaller and more stable over the year as compared to heating for comfort. In the south of Sweden conservation heating is motivated mainly by preservation aspects, whereas in northern Sweden the potential for energy saving is considerable. Heat pumps in general and air-to-air heat pumps in particular, have properties that match the requirements of conservation heating and can provide a cost effective solution. Heat pumps specially designed for conservation heating could improve the performance radically in relation to standard heat pumps.

1. Introduction

1.1 Background

Climate induced degradation is one of the major threats to historic buildings and their interiors. The best conservation strategy is to act in order to prevent damages. Climate control, when properly used, is an efficient and cost-effective method for preventive conservation. The present paper deals with historic buildings, such as churches, castles and manor buildings where preservation is a primary consideration in determining the proper indoor climate. Climate control in this type of buildings should ideally be a combination of passive control and active measures such as heating, ventilation, humidification, and dehumidification. In practice, heating is often the only kind of active climate control available.

Heating used to control relative humidity (RH) for preservation purposes is called *conservation heating* . Conservation heating is used mostly in temperate climates in buildings that are heated for comfort intermittently or not at all. The effects of conservation heating on the preservation of buildings, interiors and objects has been the subject of a number of investigations, (Staniforth et al 1994, Padfield 2007, Maekawa 2003 and Neuhaus et al 2006)

In Scandinavia a limited number of churches use conservation heating in combination with intermittent heating for services. Background heating, i.e. heating the building to a constant temperature, is used in a wide range of building types even though the objective is seldom clear. Many historic buildings are unheated, but would require some kind of climate control to reduce relative humidity. Other old buildings, for example churches, can no longer be heated due to increasing energy costs. Global warming may increase the need for conservation heating in some regions. A number of warm and humid summers and autumns during the last ten years have caused mould in buildings that have been without problems for hundreds of years.

Conservation heating is becoming more common in Scandinavia and national policies for conservation heating have been discussed. There is a growing pressure from building owners to use relatively cheap air-to-air heat pumps for conservation or background heating. It has become clear that the consequences of and requirements for conservation heating in a Nordic climate are not well understood. Engineers, conservators and policy makers need scientific facts, methods and verified solutions in order to use conservation heating in a responsible manner.

1.2 Objectives

The primary objective of this paper is to investigate, from an engineering point of view, if and how air-to-air heat pumps can be used for conservation heating. In order to do this, the heating load for conservation heating when applied in a Nordic climate must be characterized in a general way, not only for individual objects. This analysis will also add new and relevant information about conservation heating in general when applied in a Nordic climate.

2. Indoor climate criteria for preservation

One major problem in controlling the indoor climate in historic buildings is to specify the appropriate climate. For museums, the research and development on climate specifications is summarised in ASHRAE handbook (2007). There is a continuous development and discussion about climate specifications which is well reflected by the contributions to the conference on Museum Microclimate in Copenhagen 2007. Often the museum requirements are too strict for historic buildings; this is due to the use of the building or to economic limitations. The present paper does not intend to extend the knowledge or discussion about climate requirements. The following is a description of the general requirements for conservation heating.

An upper limit for RH is needed in order to prevent biodeterioration; mould, insects etc. Mould and other fungi depend on a combination of relative humidity and temperature (Krus et el 2007). At normal room temperatures the limiting RH is around 80%, the colder it gets, the higher RH can be allowed without any risk for mould growth. In Scandinavian historic buildings mould growth occurs mostly in late summer and early autumn when it is both warm and humid. Insects have optimal conditions between 20 and 35°C and RH above 70% (Child 2007). In defining the upper limit for RH one should take into account microclimates that may occur in parts of the building; in corners behind furniture etc.

The moisture content in wood and other hygroscopic materials depends on the surrounding relative humidity. As the moisture content varies, the materials will shrink and swell. In order to avoid damages, such as cracking, flaking and peeling, variations in relative humidity must be limited.

Salt damages are due to the crystallization of salt on the surface or inside porous materials. Repeated cycles of varying RH can be detrimental if crystals are formed and dissolved. The critical levels depend on the types of salt involved.

All organic materials degrade with time, the rate of degradation increases with temperature and RH. This means that, if we have a choice, cool and dry is generally better than warm and humid. Conservation heating increases temperature and reduces RH. The effects on degradation would tend to offset each other, but in some cases conservation heating could accelerate degradation (Padfield 2007).

In the following calculations, a set value for relative humidity of 70% has been used. This represents a minimum requirement for conservation heating that would give a stable indoor climate and a margin with respect to biodeterioration.

3. Conservation heating

The basic principle of conservation heating is to control the temperature in a building in order to keep relative humidity within given limits. Hygrostats are used to control the heat input, this is a reliable solution based on commercially available technology. The result is that the indoor temperature will follow the seasonal variations of the outdoor temperature throughout the year as shown in fig 1.

There are some limitations to the use of conservation heating. When the RH is too low, the temperature can only be reduced to the level set by the ambient temperature and/or the temperature of the interior surfaces. In the winter, conservation heating may result in uncomfortably low temperatures, even below 0°C. In the summer time conservation heating may result in uncomfortably high temperatures.

Assuming that the humidity by volume inside the building is the same as on the outside, the temperature required to maintain a specified relative humidity can easily be determined. In most buildings however, the humidity by volume is higher inside than outside. For buildings in general this can be related to the use of the building, but in many historic masonry constructions moisture is continuously added from the walls, (Broström 1996, Klenz Larsen 2007). The evaporation from the walls increases with indoor temperature.

$$v_i = v_a + \Delta v \tag{1}$$

v_i Indoor humidity by volume (g/m^3)

v_a Ambient humidity by volume (g/m^3)

Δv Humidity added from the building structure (g/m^3)

The indoor temperature required to maintain a given relative humidity depends on the specified relative humidity, the ambient humidity by volume and the vapour added from the building

$$T_i = f(\phi_{is}, v_a, \Delta v) \tag{2}$$

T_i Indoor temperature (°C)

ϕ_{is} Set value for the indoor relative humidity

A set value or range for RH should be defined by a conservation specialist, in this case 70% is used. The ambient vapour concentration depends on time and location. The humidity added to the indoor air depends on the building construction and the weather. A typical range of Δv from 0 to 2 g/m^3 was used in the following calculations.

4. The heat load for conservation heating

The indoor temperature resulting from conservation heating was calculated based on climate data for two different locations in Sweden. Malmö in the south of Sweden has a mild coastal climate with a high RH most of the year. Östersund, located in the middle of Sweden has an inland climate, colder and drier than Malmö. Weather data for 2007 were used, provided by the Swedish Meteorological and Hydrological Institute.

4.1 Temperatures resulting from conservation heating

The indoor temperature required to maintain 70% relative humidity was calculated for a range of Δv based on monthly average values for the ambient climate in Malmö and Östersund, fig 1.

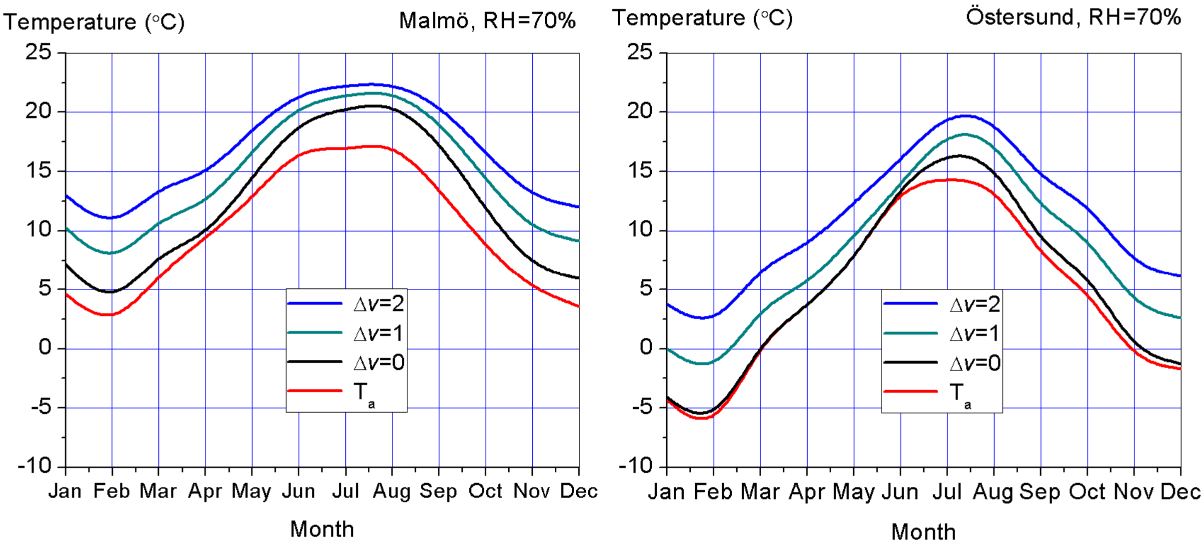

FIG. 1: Indoor temperatures resulting from conservation heating at 70% RH for Malmö (left) and Östersund (right) at varying values of Δv. The outdoor temperature is included for reference.

The calculated indoor temperature follows the variation of the outdoor temperature. In Malmö the indoor temperature is in the range of 3- 23°C and in Östersund -6 – 20°C. Sub zero temperatures indoors are not necessarily a problem from preservation point of view, many castles and churches are left unheated in the winter without any problems.

Comfort in the buildings using conservation heating would be low in the winter, limiting the use of the building and increasing demands on intermittent heating systems for comfort. In the summer time the monthly average for the preservation temperature in Malmö reaches 22°C, which indicates that at times it will be too warm for comfort. In Östersund, summer heating would generally not be a comfort problem.

The amount of moisture added from the building has a significant influence on the temperature levels required.

4.2 Energy demand

To design heating systems in general, we need to determine energy demand and heating load variation over the year. For heat pumps in particular, this is crucial both for technical and economic reasons which will be explained in the following chapter. Rules of thumb and know how related to heating for comfort are not applicable, other design criteria must be used.

The heating power for conservation is indicated by the difference between the indoor temperature and the ambient temperature. By multiplying the temperature difference with the heat loss coefficient for a building, we get the heating power. Thus the monthly averages would give a relative indication of the monthly energy demand of a building.

The temperature difference, $(T_i - T_a)$ required to maintain 70% RH was calculated for a range of Δv and compared to the temperature difference resulting from background heating with a constant indoor temperature10 °C, fig 2.

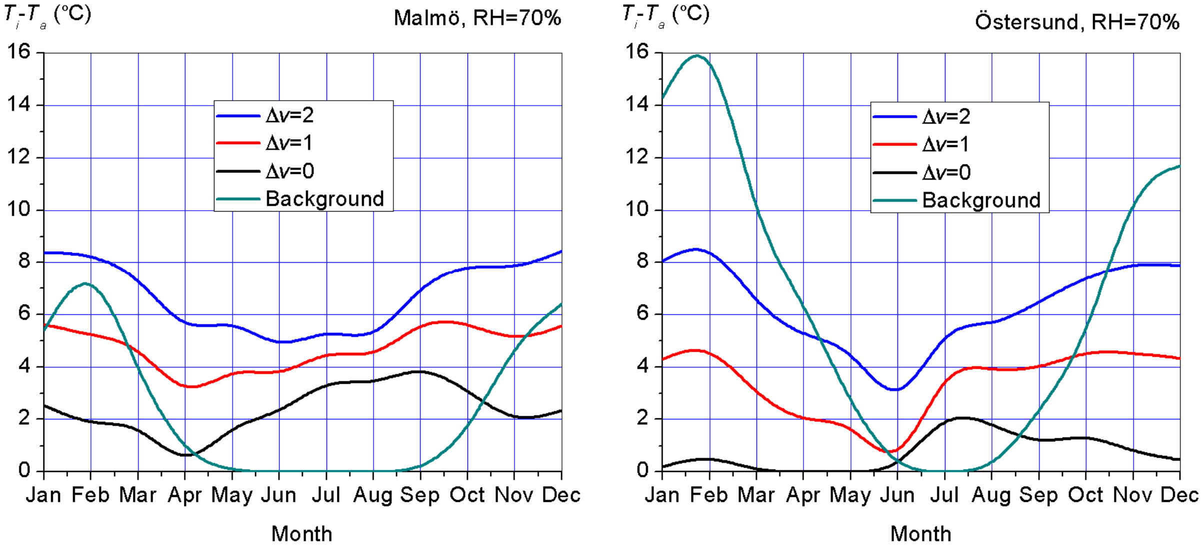

FIG. 2: The temperature difference $(T_i - T_a)$ *for conservation heating compared to background heating with a constant indoor temperature 10 °C.*

It can be seen that the heating load for conservation heating is much more stable over the year as compared to low temperature background heating. The winter heating loads for both locations are remarkably similar. In Malmö, conservation heating would be needed throughout the year for all ranges of Δv. In Östersund, a dry building with Δv =0 would need conservation heating only a few months.

Table 1 shows the annual energy consumption, expressed as an annual average temperature difference, for conservation heating and background heating. It can be seen that conservation heating in southern Sweden does not necessarily lower the energy consumption as compared to background heating. In northern Sweden, conservation heating can give significant energy savings as compared to background heating. The moisture added to the indoor air from the walls is a very important parameter from an energy point of view.

TABLE. 1: The average annual temperature difference $\overline{(T_i - T_a)}$ *for conservation heating and background heating. The annual energy demand is proportional to this temperature difference.*

	$\overline{(T_i - T_a)}$ for conservation heating			$\overline{(T_i - T_a)}$ for background heating		
	Δv=0	Δv =1	Δv =2	T_i=8	T_i=10	T_i=12
Malmö	2.4	4,7	6,8	1,6	2,6	3,7
Östersund	0,73	3,4	6,4	5,2	6,7	8,2

4.3 Heating power

To determine the optimal heating power of the system in relation to the heating load, a higher resolution than monthly averages is required. Since most historic building have a relatively high inertia with regard to temperature and humidity variations it was assumed that daily averages would be relevant in this case. The preservation temperature was calculated in the same way as in the previous cases, but based on daily average climate data. For design purposes the results are presented as load duration graphs, fig 3.

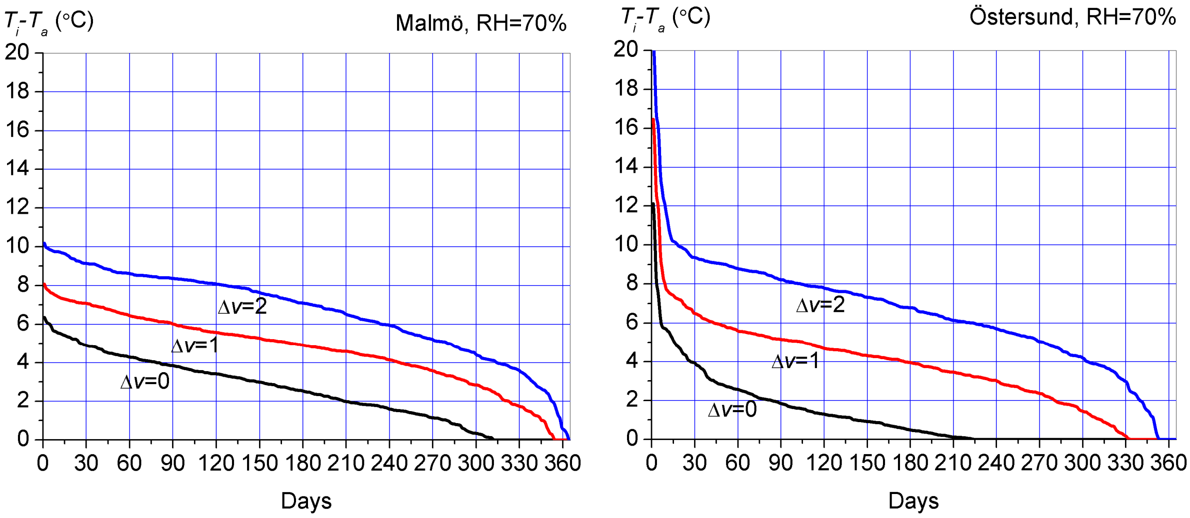

FIG. 3: Load duration graphs based on the temperature difference $(T_i - T_a)$ *required to maintain RH at 70%.*

The load duration graph shows the maximum heating load, the time variation of the load and the energy demand over the year (as the surface under the curve).The load duration graph is a tool to find the optimal design of a heat pump, which will be explained in the next section.

The extreme values on the high end for Östersund are associated with a few very cold days. Since risk for mould is nonexistent, they could be disregarded in determining the maximum heating power.

The utilization factor is the ratio between actual energy produced over the year and the amount of energy produced if the system was running at full power the whole year. For Malmö and Östersund, the utilization factor would be 20-25% for comfort heating. For conservation heating it is in the range of 40-60%.

5. Air-to-air heat pumps for conservation heating

In the last years, air-to-air heat pumps have increased their performance to cost ratio dramatically. In combination with a relatively simple and unobtrusive installation, this makes them an interesting option for conservation heating. An additional benefit is that some air-to-air heat pumps can be used for dehumidification in the summer.

As shown above, the heating load for conservation heating is quite stable over the whole year. The ideal working conditions for a heat pump is a continuous and stable heat load. From a technical point of view this will enhance efficiency and makes the heat pump last longer. From an economic point of view, the heat pumps need a stable load to pay off a relatively high investment. For this reason, heat pumps in Scandinavia are generally not designed to cover the maximum load, as this leads to high investment costs and low utilization. The heat pump is designed for a base load, the top load is provided by an auxiliary heat source with lower cost per kW, typically direct electric heating. Consider the top curve in the left graph of fig 3. If a heat pump is designed to cover 80% the maximum load, it would cover around 95% of the energy demand.

The optimal combination of heat pump and auxiliary heating is determined by comparing the power cost and the energy cost for both heat sources:

$$C = C_F + C_E \tau \tag{3}$$

C	Annual cost per kW
C_F	Annual fixed cost per kW
C_E	Cost per kWh
τ	Utilization time

The intersection of the cost lines for the heat pump and the auxiliary heat source define the optimal relation between the two heat sources, fig 4. By superimposing the lines on the load duration graph, we can determine the right heating power for the heat pump and the electric heaters to minimise the total heating cost.

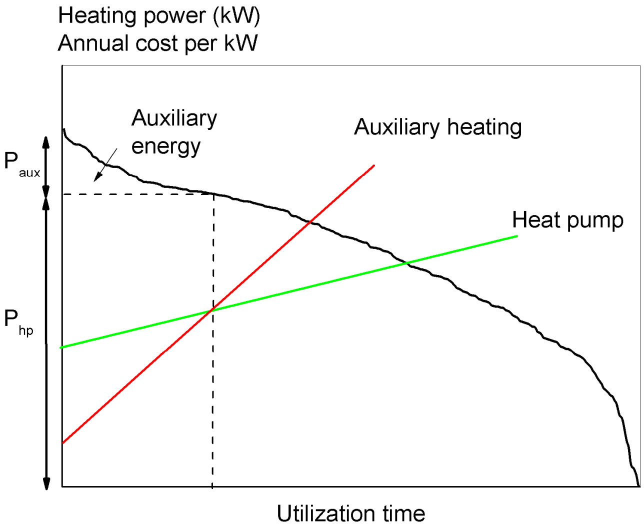

FIG. 4: By superimposing the cost lines for a heat pump and direct electric heating on a load duration graph, the optimal heating power for the heat pump P_{hp} and auxiliary power P_{aux} can be determined.

Thermodynamically conservation heating is a good match for heat pumps because their efficiency increases as the indoor temperature decreases. The coefficient of performance (COP) for a heat pump is defined as

$$COP = \frac{Q}{W} \tag{4}$$

Where

Q is heat produced (J)

W is work added (J)

For the ideal Carnot process the COP depends only on the temperature levels on the hot and cold side of the heat pump:

$$COP = \frac{T_1}{T_1 - T_2} \tag{5}$$

T_1 temperature of the heat sink (indoor air) (K)

T_2 temperature of the heat source (outdoor air) (K)

The performance of the ideal heat pump will improve radically as the difference between the heat source and the heat sink decreases. Even though this is an ideal process, the Carnot process sets the ultimate limit and potential for heat pumps. In practice COP may reach 60-70% of the Carnot value. Theoretically a heat pump designed and optimised for conservation heating could reach COP values around 10; this is yet to be investigated in practice.

Commercially available air-to-air heat pumps typically have COP-values in the range of 1,5 – 4,0 depending on the outdoor temperature and the load. These heat pumps are optimised for normal room temperatures, and can be operated at room temperatures down to 8-10°C. At lower indoor temperatures, defrosting becomes a problem.

Two pilot studies have been started with the objective to investigate if and how commercially available air-to-air heat pumps can be used for conservation heating. The objects are the church in Ludgo south of Stockholm and a vernacular 18th century dwelling house on Gotland. In the church, the main incentive was to save energy. The second building has severe moisture problems; mainly algae and insects. The results so far can be summarised as follows:

- The heat pumps provide a cost effective alternative to other heat sources. They are reliable and there have been no technical complications.
- The heat pumps are controlled by thermostats with a lowest temperature of 10 C. This is because defrosting cannot be guaranteed at lower temperatures. One company has introduced a hygrostatic control module which will be added on one of the heat pumps.
- It is not possible to see if the COP is higher due to lower indoor temperatures. Laboratory testing is on the way.
- Dehumidification was used in the dwelling house. Technically it works fine, but the control algorithms are not adjusted to conservation heating.
- With air-to-air heat pumps the heat is supplied by convection from a limited number of point sources. Investigations of resulting temperature distribution and air movements will be presented in the near future.

6. Conclusions

The present paper has related the heating load for conservation heating in a Nordic climate to the properties of heat pumps. The heating load is characterised by a low temperature difference (T_i-T_a) and a relatively stable heating load over the whole year. The results provide rudimentary tools for engineers to design conservation heating systems. This is a first step, further studies should take into account transient effects, dynamic indoor climate requirements, more representative data for the ambient climate and a wider geographical distribution. Simulations and detailed field studies are needed to better understand conservation heating.

Depending on the use of the building, conservation heating may have to be limited for comfort reasons. It gets cold in the winter and warm in the summer. In southern Sweden, conservation heating would mainly be motivated by preservation, whereas in the northern part energy conservation would also be a factor.

Heat pumps in general, and air-to-air heat pumps in particular, have properties that match the requirements of conservation heating. They can provide a cost effective solution for conservation heating. Heat pumps designed and optimised for conservation heating could significantly increase the performance in relation to standard heat pumps. Air-to-air heat pumps may not be the ideal long term solutions for historic buildings, but in many cases, they could enable the use and preservation of the buildings until more appropriate solutions have been developed.

The results also show that there is an economic potential in controlling the moisture transport into the building by improving the structure and controlling ventilation and/or infiltration. Clearly there is a need for integrated solutions based on a combination of passive and active measures for climate control

Another application for conservation heating, which is becoming more common, is winter heating of summer houses. There is a huge potential for energy saving by using heat pumps and replacing thermostats by hygrostats.

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