Characterizing and comparing monumental churches and their heating performance

Characterizing and comparing monumental churches and their heating performance

D. Neilen, H.L. Schellen, M.A.P. van Aarle
Eindhoven University of Technology, The Netherlands

ABSTRACT: In this paper a research on monumental church heating is described. The main focus was preservation of the interior and the monumental building itself and human thermal comfort. The characteristic parameters are described and a comparative study for 8 different monumental churches was performed. Furthermore one particular case study was examined more in depth. For this case a validating measurement program was carried out.

1 INTRODUCTION

In a previous study on church heating, measurements and simulations on 8 monumental churches were involved (Schellen, 2002). Because of the differences in approach it was not possible to compare all of these case studies in a similar way. First additional research on these 8 churches was performed to define characterizing quantified features and performance values for these churches. The second goal was to create a clear overview of required constructional and installation data. Furthermore the required indoor climate for human thermal comfort, preservation of the building and it's interior should be defined for simulation purposes.

2 SIMULATIONS

2.1 *Hygrothermal simulation model; WaVo*

The computer simulations in this research were performed by means of the hygrothermal simulation model WaVo (Wit, 2000)

The thermal room model basically consists of 2 nodes: an air temperature node for the description of the ventilation heat losses and an environmental temperature node for the transmission heat losses.

The heat sources consist of heat supply, casual gains and solar heat gain. The solar gain is corrected for the short-wave radiation falling from the interior side on the windows.

One external temperature is the 'environmental temperature' of the adjacent room, or in case of an external wall, the equivalent temperature as an outdoor reference temperature.

The hygric room model is quite analogues to the thermal wall model.

The moisture storage in the air volume is far more important than the heat storage in the air in the thermal case. Also the moisture storage in furniture cannot be neglected, as wood and other interior furniture are very hygroscopic.

The total transmission heat flow is calculated with the heat diffusion equations of the multilayer walls. In the WaVo church model the diffusion equations for heat and moisture transfer in the walls are modeled with a finite difference scheme and solved with an implicit method (degree of implicitness close to 0.75). The time step is one hour and the place step of each layer for the heat transfer calculations is determined by the Fourier number of the layer (Fo~1).

The total moisture flow from walls is calculated with the vapor diffusion equation of the multilayer walls. By linearization of the hygroscopic curve (ξ is constant) and by considering the vapor flow only, this wall model is not very accurate for high and very low humidities (RH < 30%, RH > 80%). The advantage, however, is that less sophisticated material properties are needed. The effect of this inaccuracy on the indoor climate is expected to be very small as the hygric storage of the air volume is more important (large volume to church ratio in churches).

For isothermal transport the moisture diffusion equation is analogous to the heat diffusion equation, with the thermal diffusivity replaced by the hygric diffusivity and temperature replaced by vapor pressure.

The effective penetration depth for vapor transfer is much smaller than for heat transfer.

The effective thickness indicates how far a cyclic disturbance at the surface has penetrated into the material. At a distance of three times the effective thickness the altitude of the cyclic temperature or vapor pressure is reduced to 5 % of the original value.

Compared to the thermal model, in the hygric model smaller spatial steps are needed near the surface. Close to the surface the space discretization for heat and vapor transfer is separated. As calculation time would be very long by the small steps the interpolation is only applied to the layers near the surface. For vapor transfer the first thermal layer is divided into a number of sub-layers. To avoid the inaccuracies associated with sudden changes in the grid-point interval, a graded grid is used (Schellen, 2002). In the wall model the first layer therefore is split into 3 in such a way that from surface to the inside each step is twice the step until the same stepsize is reached as for temperature.

2.2 *Comparative study*

Simulations were made to examine the effect of several input parameters on the energy consumption and the heating capacity. This research was performed for 8 different churches (Table 1).

In order to compare these churches with each other the churches were simulated on the basis of the same standard input. This standard input was based on the situation in which all churches would be equipped with the same heating system, e.g. a warm air heating system. Each time one input parameter was varied in comparison to the standard input. Parameters that varied were: the primary temperature that is maintained in a church continuously, the comfort temperature that is desired during a service, the ventilation rate and the heating rate of a church. The influence of additional protective glazing and heat insulation of the vaults on the energy consumption of the building was examined.

2.3 *Basic input*

As mentioned before the churches were simulated on the basis of the same standard input. The standard values of the input parameters are represented in the second column of Table 2. The third column represents the new values of the parameters that were varied in the simulations. For each simulation only one input parameter was varied in comparison to the standard input.

Table 2. Input parameters

Parameter	standard value	variable value		
$\theta_{primary}$ [°C]	8	0	6	10
$\theta_{comfort}$ [°C]	18			
Heating rate [K/h]	100 (no restriction)	1	2	
Ventilation rate [1/h]	measured value	0.2	0.9	
Uglass [W/m^{2}K]	5.2	3.5		
Uvault [W/m^{2}K]	from drawing	1/(R_l+1)		
Church usage	once a week on Sunday from 12-14h			

Because the influence of additional glazing and heat insulation of the vaults had to be examined, it was assumed that these were not present in the churches in the standard input. In order to do not change the characteristic features of the building, the ventilation rate measured in the churches was used for the standard input. The simulation results of the standard input are represented in Table 3. The results of the alternative simulations are compared to these values.

2.4 *Changing the primary temperature*

Figure 1 represents the influence of lowering the primary temperature in the churches on the heating capacity and the energy consumption. The figure shows that lowering the primary temperature in most of the examined churches results in an energy saving of 30 to 50%. The explanation is that less energy is needed to maintain a lower primary temperature. On the other hand more energy is needed to heat the air in the church from the primary temperature to the comfort temperature, which is desired during the services. But the total results in an energy saving.

Lowering the primary temperature also results in an increase of heating capacity, if the air in the church has to be heated from primary to comfort temperature in the same period of time as before. Another possibility is to maintain the available heating capacity and start heating the air earlier.

Table 1. Basic data of the churches

Church	Volume [m^3]	Awalls [m^2]	Awindow [m^2]	Floor [m^2]	Vault [m^2]	Ventilation rate [1/h]	Uvault [W/m^{2}K]
Grote Kerk, Alkmaar	45720	4110	970	2180	4190	0.5	3.3
H.Donatuskerk, Bemmel	10600	1445	195	840	1090	0.6	2.4
N.H. Kerk, Beusichem	4730	535	85	360	540	0.6	2.5
Waalse Kerk, Delft	3050	585	160	210	330	0.2	3.5
H.Gerlachuskerk, Houthem	6680	1010	230	475	600	0.2	2.0
Sypekerk, Loosdrecht	3330	500	85	365	450	0.9	2.5
H.Liduïnakerk, Schiedam	10330	2255	560	850	2150	0.5	2.3
St.Martinuskerk, Weert	18690	1720	610	1260	1665	0.1	1.2

Table 2. Simulation results standard input

Church	Heating capacity [kW]	Energy consumption [*10^4 kWh]
Grote Kerk, Alkmaar	900	33.7
H.Donatuskerk, Bemmel	270	10.6
N.H.Kerk, Beusichem	120	4.6
Waalse Kerk, Delft	75	2.1
H.Gerlachuskerk, Houthem	140	3.9
Sypekerk, Loosdrecht	100	4.2
H.Liduïnakerk, Schiedam	280	10.1
St. Martinuskerk, Weert	340	9.9

An exceptional case is the church in Delft. Figure 2 shows that the minimum temperature in this church is 3.7°C. This is higher than the minimum temperature reached in the other churches. Because of this higher minimum temperature in this church, less energy is needed to maintain the primary temperature in the church during the whole week

The largest amount of energy is needed to heat the air in the church from the primary temperature to the comfort temperature. If the primary temperature is decreased below the minimum temperature in the church, no energy is needed to maintain the primary air temperature in the church. This results in an energy saving. On the other hand the difference between the primary temperature and the comfort temperature increases, so there is more energy needed to heat the air in the church from primary temperature to comfort temperature. Since the service is held only once a week, the extra needed energy is less than the amount of energy saved due to the decrease of the primary temperature.

Because in the church in Delft the amount of energy needed to maintain the primary temperature at 8°C is less than the amount of energy needed in the other churches, the amount of energy saved is in terms of percentage smaller than in the other churches.

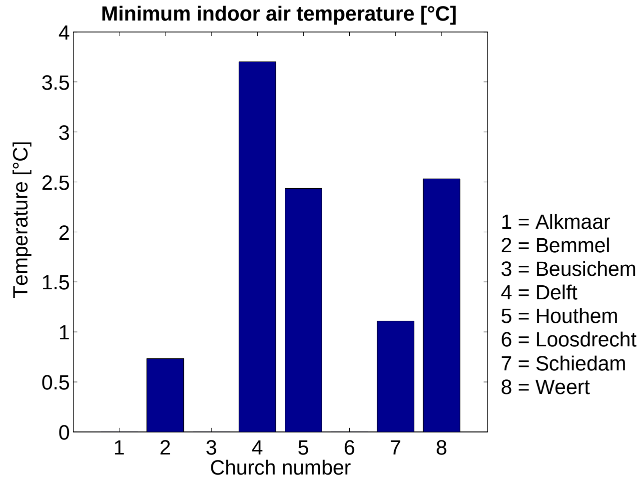


Figure 2. Minimum indoor air temperature

2.5 *Changing the comfort temperature*

Figure 3 shows the influence of lowering the comfort temperature in the churches on the heating capacity and the energy consumption.

The figure shows that lowering the comfort temperature 4°C results in an energy saving of 17 to 30%. Because the difference between the primary and comfort temperature decreases, less energy is needed to heat the air in the church to the desired comfort level. Because of this, there is also less heating capacity needed.

In figure 3 the church in Delft is also an exceptional case. The amount of energy saving even comes to 40%. The explanation for this is that the mean air temperature in this church is higher than in the other churches (see Figure 4). The church in Delft is rather warm due to the well-insulated roof

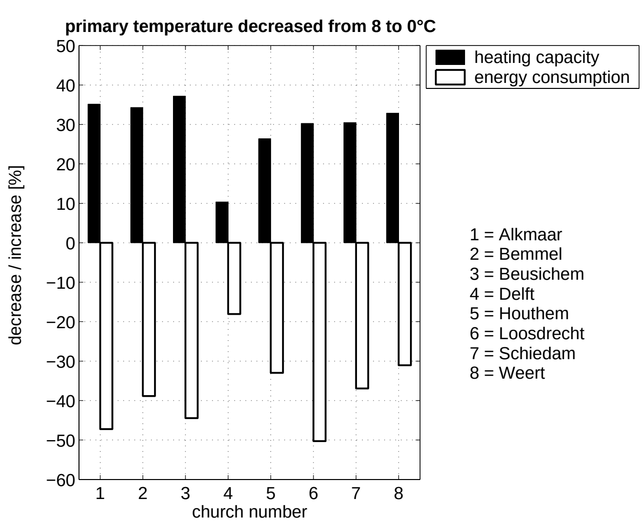


Figure 1. Influence of lowering the primary temperature

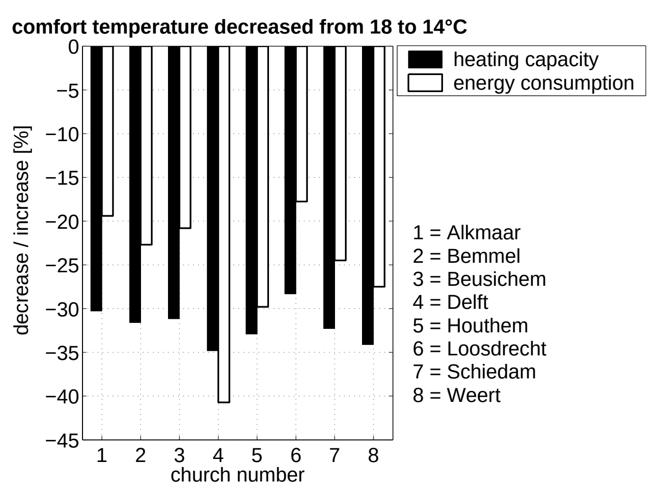


Figure 3. Influence of decreasing the comfort temperature

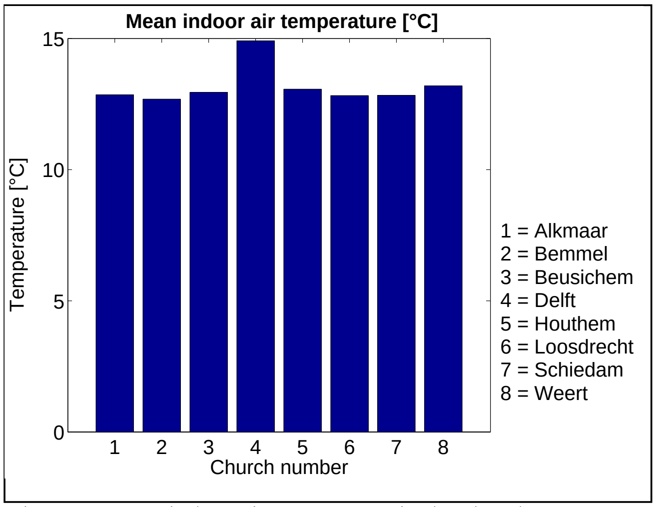


Figure 4. Mean indoor air temperature in the churches

2.6 *Changing the ventilation rate*

Lowering the ventilation rate results in an energy saving. Figure 5 shows little influence for the church in Loosdrecht. This is because the ventilation rate in this church already was 0.9 h^{-1} so it has not changed. A larger influence is shown for the churches in Delft, Houthem and Weert, because the ventilation rate in these churches was highly raised from approximately 0.15 to 0.9 h^{-1}.

2.7 *Restriction of the heating rate*

In case the heating rate is limited, 18 to 26% less heating capacity is needed to heat the air in the church (Figure 6). There has to be taken into account that the heating of the air should start earlier in order to reach the desired indoor air temperature on time. In literature (Schellen,2002) a preference was shown for a heating rate of 1 to 2 K/h in order to avoid causing damage through internal stresses and strains to objects in the churches.

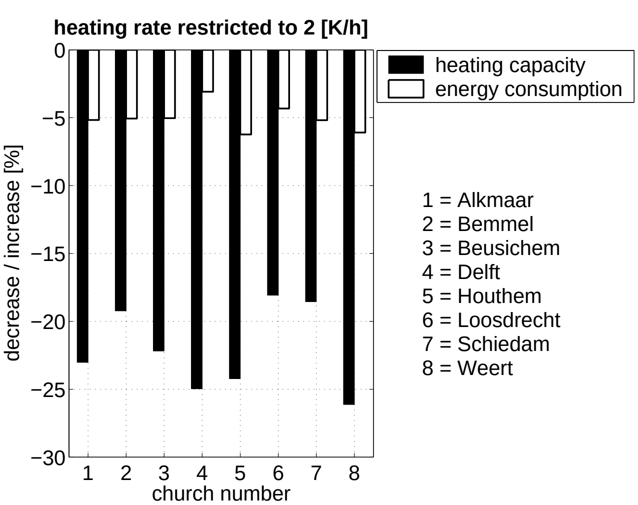


Figure 5. Influence of restricting the heating rate

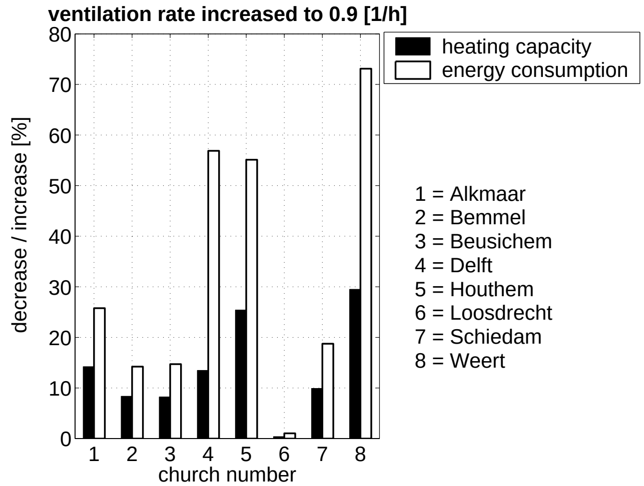


Figure 6. Increased ventilation rate from measured value to $0.9h^{-1}$

2.8 *Application of additional glazing*

Additional protective glazing will reduce the heat transmission through the windows. Figure 7 shows the effect of applying additional glazing on the energy consumption and the needed heating capacity.

In this research the simulations for determining the effect of additional glazing assume that there is only a change in U-value of the glazing. In real terms there may also be an effect on the ventilation rate of the church. This ventilation rate may decrease which will lead to even more energy saving.

Figure 7 shows that applying additional glazing in some churches is more useful than in others. Apparently, in churches with a low ventilation rate (see Table 2) and/or a certain minimum percentage of glass in the façade that is higher than 18%, applying additional protective glazing is more efficient.

The churches in Delft, Houthem and Weert have a low ventilation rate (0.1 – 0.2 h^{-1}). As a result of this the heat loss by ventilation is smaller than the heat loss by transmission (Figure 8)

Figure 7. Influence of applying additional glazing

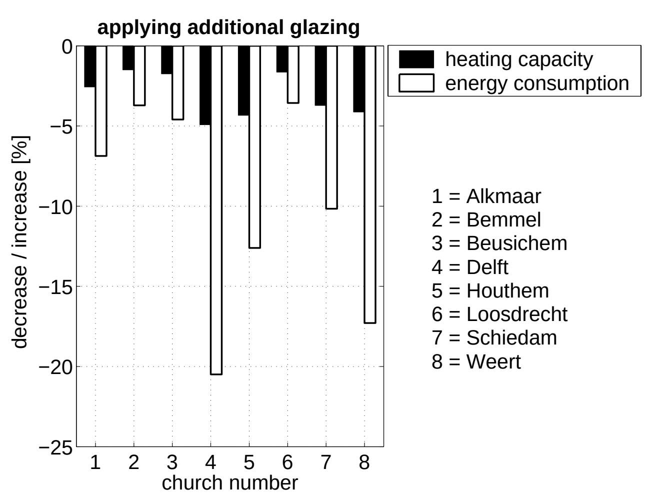
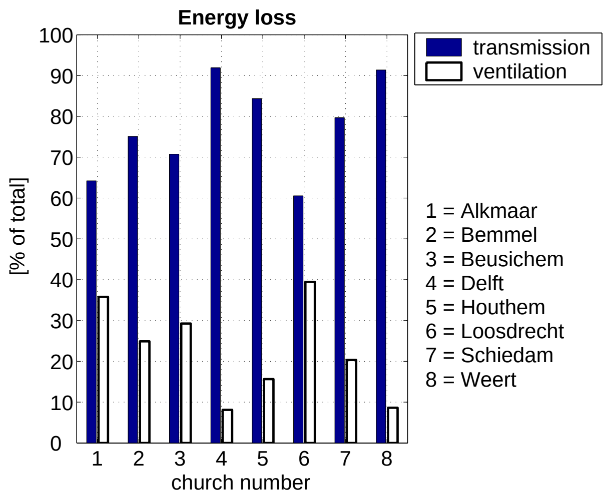


Figure 8. Energy loss by transmission and ventilation



In order to save energy, the heat loss by transmission should be handled. Since most of the heat is lost through the glazing, applying additional protective glazing should work out favorably. The ventilation rate in the church in Bemmel and Beusichem is 0.6, which is rather high. On the other hand the glass percentage in these churches was 13%, which is rather low as compared to the other churches in this research. So in terms of percentage the amount of energy saved due to additional glazing, will be less than in the other churches.

2.9 *Applying heat insulation on the vaults*

Simulation results proof that applying heat insulation on the vaults can lead to a considerable energy saving (Figure 9). In particular in churches with a wooden vault and a roof, which is not isolated. In churches with a stone vault or an insulated roof, applying heat insulation is of less benefit. Although the simulation results point out an advantage by applying heat insulation on the vaults, the building physical consequences have not been examined. Internal condensation has to be taken into account, under winter and summer conditions.

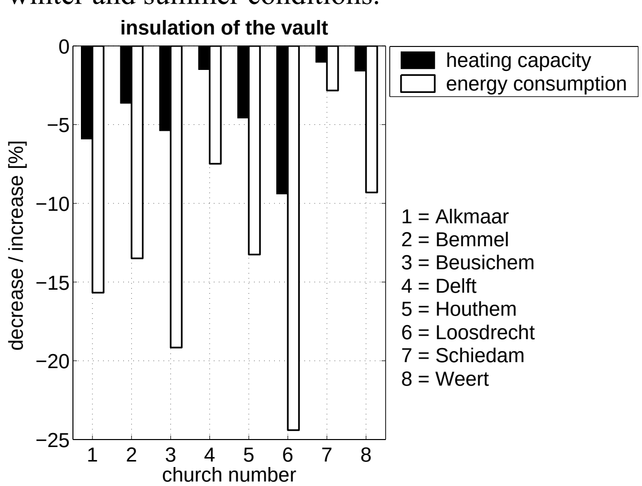


Figure 9. Influence of insulating the vaults

3 THE WALLOON CHURCH IN DELFT

3.1 *Introduction*

The Walloon Church (Waalse kerk) in Delft is a relative small church with an air volume of 3050 m^3 and a ventilation rate of 0.2 h^{-1} (Table 2). In this church a monumental Bätz/Witte organ, which dates from 1869, is present. In the spring of 2000 the organ has been restored. During restoration it turned out that the organ was heavily damaged due to excessive heating of the church. To prevent causing damage to the organ again, the indoor climate had to meet certain requirements before re-installation of the organ. In the years 1999 and 2000 research has been performed for the preservation of the monumental organ (Stappers, 2000). As a result of these research studies several adjustments have been made to the heating system. Preservation criteria for monumental buildings and their interior have been formulated (Schellen, 2002).

The measurements that were carried out in the Walloon Church after adjusting the heating system showed that the indoor climate did meet the requirements for preservation of the organ. The Walloon Church however, is not only used for services, but also for several other activities e.g. organ recitals. Since people are sitting in the church without wearing their overcoat, an indoor air temperature of 18 to 20°C is desirable. As a result of this rather high temperature for churches the relative humidity of the indoor air becomes very low (<30%)

Since low relative humidity caused damage to the organ, the heating system was restricted. As soon as the relative humidity of the indoor air threatens to drop below 40%, the heating system is shut down. As a result of this restriction it was not possible to reach an indoor air temperature of 18°C during winter when it was freezing outside.

In order to prevent deterioration of the monumental organ, and yet reach an indoor air temperature of 20°C, the idea was given to install a moistener in the air duct. By increasing the specific humidity the relative humidity of the indoor air remains high enough for preserving the organ. At the same time the indoor air can be heated from the primary temperature of 10°C to the required comfort temperature of 18°C.As a consequence of the humidification of the indoor air under winter conditions, there is a risk at high near surface relative humidity. Condensation may even occur on cold surfaces. Furthermore a long-lasting high relative humidity near the surfaces can lead to fungal growth, while algal growth can occur at the glazing. For that reason a request for further research through simulations was received from the church council. With the help of these simulations an assessment was made of the potential risks.

3.2 *Approach of the research*

First of all a simulation run was made of the present situation in the Walloon Church. This means a situation with a primary temperature of 10°C and a comfort temperature of 20°C and no humidification of the indoor air to prevent the relative humidity to drop too low. The relative humidity was restricted so it did not rise above 70%: when it reached 70% the hygrostatic control heated the air to reduce the relative humidity. The results of this simulation were compared to the measurements that were taken in November and December 2000.

After that, simulations were made of the situation in which the indoor air should be humidified. Humidification will take place by means of a steam moistener placed in the inlet air duct, before the air is blown into the church. This moistener will have a maximum capacity of 8 kg/h. As a result of this simulation a prediction was made with regard to the appearance of condensation on cold surfaces and high near surface relative humidity during wintertime.

In conclusion measurements were taken to check the indoor climate in the church after installing the moistener.

3.3 *Predicting the indoor climate after installing the moistener*

The adjustment control of the moistener is closely connected to the adjustment control of the air heating system. If the relative humidity drops below 45% the moistener starts working to reach its full load (*maximum capacity of 8 kg/h)* at a relative humidity around 42%. The simulations show that a capacity of 5.5 kg/h is needed to restrict the relative humidity to a lower limit of 40% during a period with an outdoor temperature of -5°C.

When we take a look at the walls, the relative humidity near the northern wall reaches a maximum value of 60 to 70% the moment the moistener is working. There will not be a long-lasting moistness resulting in fungal growth. However, near the windows the relative humidity reaches a value of 90% during the services. After the service the temperature drops and the relative humidity will increase resulting in condensation on the glazing in the north façade.

In order to gain a clear understanding of the period in which the indoor air has to be moistened and the consequences of it, a one-day period is shown in the next figures. We start with a weekday in November when there is no service. Second a Sunday in November is shown with a service held and a minimum air temperature outdoor of 4°C. At last a Sunday in December is shown with a service held and a minimum outdoor temperature of -5°C.

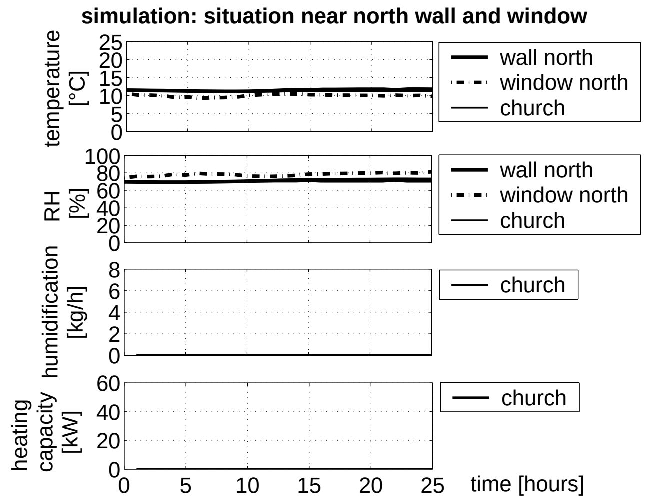


Figure 10. Weekday without a service, situation near wall and window in north façade

3.3.1 *Weekdays without a service*

Figure 10 shows the situation during a weekday without a service. The indoor air temperature and the relative humidity remain quite stable at 10°C and 74% respectively. The relative humidity does not drop below the 40% so there is no need to moisten the indoor air.

The temperature near the northern wall follows the indoor air temperature and is about 10°C. The relative humidity remains around 70-75%.

The temperature near the northern glazing varies from 8 to 10°C while the relative humidity near the glazing is about 75-80%. There is no condensation on the glazing.

3.3.2 *Sunday with service and a minimum θ_e of 4°C*

This paragraph shows the situation during a Sunday, with a service held and a minimum outdoor temperature of 4°C. Figure 11 shows that the air in the church is heated up to the desired value of 20°C. As a result of this temperature rise the relative humidity drops from 70 to almost 40%. However, the moistener does not have to be put into operation. During the service the relative humidity increases slightly as a result of the moisture produced by the people present in the church. When the heating system is shut off after the service, the relative humidity returns quickly to a value of 75%, which is about the same value as before the service. The relative humidity does not drop below 40% so the moistener does not have to be put into action.

The temperature near the walls follows the indoor air temperature with a slight delay. The relative humidity near the walls fluctuates between 60 and 70%.

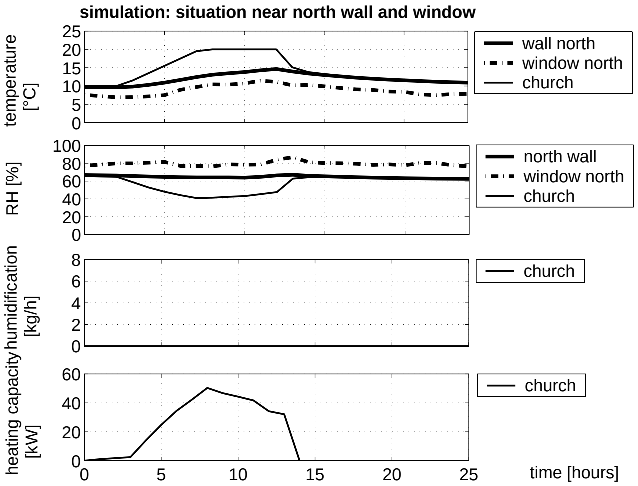


Figure 11. Sunday with a service and a minimum outdoor temperature of 4°C

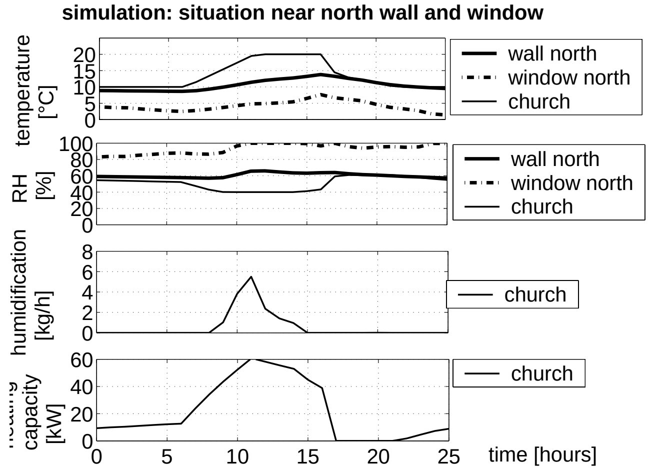


Figure 12. Sunday with a service and a minimum outdoor temperature of -5°C

Near the glazing the air temperature is almost equal to the outdoor air temperature. During the service the indoor air heats the glazing, but as a result of the low surface temperature of the glazing, the relative humidity near the glazing fluctuates around 80%. The risk of condensation on the glazing is present. As a result of the temperature raise, the relative humidity decreases during the service to 80%, but increases to 90% when the heating system is shut down right after the service.

3.3.3 *Sunday with service and a minimum outdoor temperature of -5°C*

In this paragraph is pointed out the situation on a Sunday with a service held while the outdoor air temperature drops below freezing.

Figure 12 shows that the indoor air is heated from the primary temperature of 10°C to the desired comfort temperature of 20°C. As a result of this raise in temperature, the relative humidity drops from 52 to below 40% and the moistener has to be put into action. While heating the indoor air, the relative humidity is held at 40% with help of the moistener. During the service the relative humidity increases slightly as a result of the moist produced by the people present. When the heating system is turned off right after the service, the relative humidity increases rapidly to a value of 65%. This is a higher value than before the service.

As shown in Figure 12, the temperature near the walls follows the indoor air temperature with a slight delay. The relative humidity near the wall drops as a result of heating the indoor air, but it rises as soon as the moistener is put into action. The relative humidity reaches a value of 66% at the point t=11. After that the temperature of the wall increases and the relative humidity near the wall decreases again.

At a primary temperature of 10°C in the church the air temperature near the glazing is about 3°C and the relative humidity about 85%. Humidifying the indoor air during the service will enlarge the relative humidity near the glazing even more. As a result of this, there will be condensation on the glazing. This condensation period is shown in Figure 12 at t=10 to t=17 hours.

These simulations predict the situation near the wall and the glazing in the north façade. The simulation results show a risk of condensation on the cold windows under winter conditions. In practice, however, no condensation on walls or windows was detected. The reason for this is probably that maintaining a primary temperature of 10°C leads to higher surface temperatures of the walls and glazing. These surface temperatures are higher than the dew point temperature, so the risk of condensation on the walls and windows is decreased. In order to check if the system functions properly, control measurements will be taken in the winter of 2002.

4 VALIDATING THE SIMULATION MODEL

The simulation model is validated by comparing the simulation results with the measurements that were taken. From the long-term measurements and simulations performed for the Walloon Church in Delft, a one-week period from November 11th until December 10th of the year 2000 was used to validate the model. There were a couple of reasons for choosing this period:

- During this period measurements have been taken in this church to find out why the indoor climate did not meet the requirements for preservation of the organ.
- The outdoor temperature during this period is around freezing, as a result of which the relative humidity of the indoor air drops below 40%.

The problems concerning a relative humidity that is too low become visible.
- The climatic (outdoor) data of this period were retrieved from the weather station of the KNMI in Rotterdam. KNMI is the Dutch national research and information center for climate, climatic change and seismology.

In order to make a good comparison between the measurements and the simulations, the services (the moment they took place and the duration) were entered in the model as they were measured. And thus the actual services were simulated. Not only the moment and duration of the service were entered, but also the comfort temperature during the service and the amount of people present in the church.

The simulations showed a similar tendency in the simulated and measured indoor air temperature and relative humidity. But there still were some differences between the two. As a result of these results the simulation model was examined more closely.

4.1 *Temperature*

First of all the difference in air temperature was examined. After the services the air temperature in the simulations dropped more rapidly than actually was measured. While the indoor air is heated the inner surface temperature of the walls will increase. During the service these walls will act as a buffer and they will lose this heat when the indoor air cools down after the service. As a result of this wall heat loss the indoor air temperature will drop less rapidly.

The heat transfer between the walls and the air is caused by radiation and convection. The transfer by radiation depends on the differences in temperature between the wall and the other walls. The heat transfer by convection not only depends on the difference in temperature between the wall and the air, but also on the velocity of the air near the wall

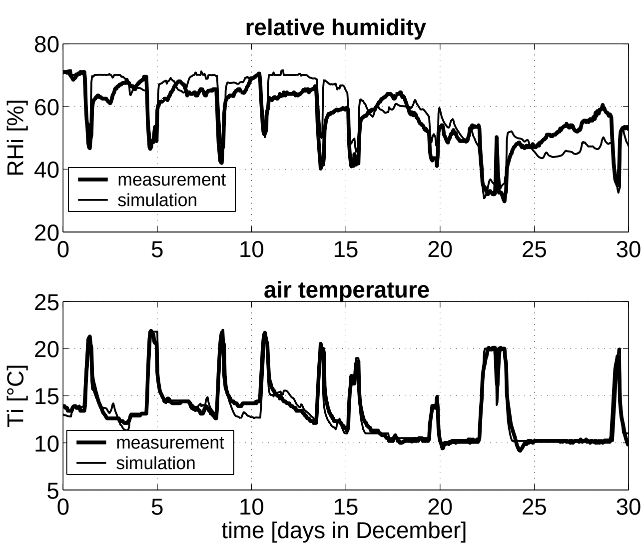


Figure 13. Comparison between simulation and measurements

However, usual the heat transfer coefficient, in which this effect is represented, is not known.

The walls in churches are much higher than in most other buildings. Because of downdraught near the walls, the air velocity will be higher as assumed in other buildings. Literature mentions that if the air velocity amounts to 0.3 m/s, the heat transfer rate comes up to a value of 5 to 10 W/m^2K (Kriegel, 1973; Loomans, 1998; Wit, 2001).

Since in the Walloon Church in Delft an air velocity of 0.2 to 0.3 was measured, the heat transfer coefficient of the walls in the simulation model was adjusted to 5 W/m^2K. After making these adjustments the course of the indoor air temperature is real close to the measured values (Figure 13). But still there are some slight differences, probably due to several causes:
- There is still a difference between the heat accumulation and heat emission of the walls in the simulation and the measurements.
- The control of the heating system in the simulation model is not as flexible as in practice. In real terms the starting point of heating the air is determined on the basis of the present indoor air temperature and the comfort temperature that has to be reached just before the service. At the moment this anticipating control is not possible in the simulation model, so the starting point is entered manually. As a result of this the air temperature in the simulation sometimes reaches the desired level too early.

4.2 *Specific moisture content*

Because of the temperature dependence of the relative humidity it is difficult to compare the measurements and the simulations. Therefore it is better to compare the specific moisture content of the indoor air. Figure 14 shows differences in the specific moisture content between the measurement and the simulation. These differences can have several causes:
- The moisture production entered in the simulation differs from the moisture production in real terms. In order to make one certain about the moisture production in the church in future researches, the number of people in the church during the service has to be registered.
- The adsorption and desorption of moisture at the walls differs from the actual situation. This is due to the lack of precise material properties of the structures. Because the construction of the building structures mostly is unknown, the construction is determined on the basis of visual judgement. These material properties are entered in the simulation model.

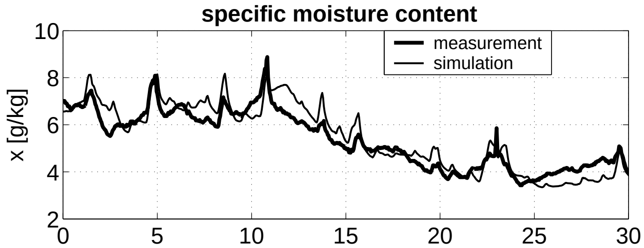


Figure 14. Comparing measurements and simulations

5 CONCLUSIONS

The results from this research led to the following conclusions:

- Maintaining a primary temperature leads to higher surface temperatures of walls and windows, thus decreasing the risk of condensation.
- Lowering the comfort temperature leads to considerable energy savings and decreases the risk of damage to the interior by internal stress.
- In churches with a wooden vault and no insulation of the roof, the ventilation rates are rather large compared to churches with a stone vault or an insulated roof.

REFERENCES

Gossens, H. 1979. *Energie sparen in Kirchen: Vorschläge*. Brochure. Aachen: MAHR Kirchenheizungen

Gossens, H. 1982. *Einflüsse des Groß- und Kleinklimas auf Kirchenorgeln und Kircheneinrichtungen*. Brochure. Aachen: MAHR Kirchenheizungen

Kriegel, B. 1973. *Fallströmungen vor Abkühlungsflächen in Gebäuden und mögliche Schutzmaßnahmen* Berlin : Technische Universität Berlin.

Loomans, M.G.L.C. 1998. *The Measurement and Simulation of Indoor Air Flow.* PhD thesis. Eindhoven University of Technology ISBN: 90-6814085-X

Neilen, D. 2002. *Monumentale kerken met verwarming; een bouwfysische vergelijking aan de hand van kengetallen.* Master thesis: FAGO-report 02.07.W. Eindhoven University of Technology

Schellen, H.L. 2002. *Heating Monumental Churches, Indoor Climate and Preservation of Cultural Heritage.* PhD thesis. Eindhoven University of Technology ISBN: 90-386-1556-6

Stappers, M.H.L., 2000: *De Waalse Kerk te Delft. Een onderzoek naar het behoud van een monumentaal orgel*. Master thesis, FAGO-report 00.03.W. Eindhoven University of Technology

Wit, M.H. de, 2000. *WAVO A simulation model for the thermal and hygric performance of a building.* FAGO report. Eindhoven University of Technology

Wit, Sten de 2001. *Uncertainty in predictions of thermal comfort in buildings*. PhD thesis. Eindhoven University of Technology ISBN: 90-9014884-1