# Indoor air humidity of massive buildings and hygrothermal surface conditions

# Indoor Air Humidity of Massive Buildings and Hygrothermal Surface Conditions

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**ABSTRACT**

*The indoor air humidity of massive buildings is important for the preservation of the building and its valuable interior parts. Open air gas infrared heating, for example, produces a lot of vapor, which may lead to high indoor air relative humidities and condensation on cold exterior walls and glazing. Due to (air) heating under cold winter conditions, the relative humidity drops and this may lead to very low indoor air relative humidities for interior objects such as church organs, resulting in cracking of wooden parts and other problems of drying out. Humidification would be a solution, but it may lead to high relative humidities near cold exterior surfaces. A method was developed for a graphical representation of the near surface relative humidity by measuring the surface temperatures as a function of time by infrared thermography and simultaneously determining the mean vapor pressure of the air. From these measurements, mold germination on indoor surfaces can be predicted in an early state, making use of a representation in so-called hygrographic pictures.*

## INTRODUCTION

One popular heating system for churches in The Netherlands is an "open air" gas infrared heating system, without exhaust air extraction. Compared to other heating systems, it is low cost in apparatus investment and energy use. In a recent study, however, the dramatic moisture-source effect of this kind of "open air" gas infrared system on largel churches was clearly predicted and demonstrated experimentally (Schellen 2002).

Another popular heating system is (hot) air heating. For this kind of system, deterioration of indoor parts, due to low relative humidities, is well known. In order to prevent deterioration of the organ in a church with air heating, and yet reach an indoor air temperature of 18°C to 20°C, it was suggested that a humidifier be installed in the air duct. By increasing the specific humidity, the relative humidity of the indoor air remains high enough for preservation of the organ. The indoor air can be heated from a primary temperature of 10°C to the required comfort temperature of 18°C to 20°C. As a consequence of humidifying the indoor air under winter conditions, there is a risk of high relative humidities near cold surfaces, where condensation may occur. Furthermore, a long-lasting high relative humidity near the surfaces can lead to fungal growth, while algal growth can occur at the glazing.

A method was developed for the determination of the potential risks for high relative humidities near cold surfaces by monitoring the spatial distribution of high RH near the surface by infrared thermography, in combination with measuring the mean vapor pressures as a function of time. Infrared "hygrographs" can be constructed from it as they develop during time. Furthermore, the long-term relative humidity at the most critical points can be monitored as a function of time by monitoring the RH of the air and simultaneously monitoring the surface temperatures.

## METHOD

For mold germination on an indoor surface, the water activity at the surface is an important quantity. In steady-state or slowly changing conditions, the water activity is the relative air humidity $\varphi$ at the surface. It can be calculated from the

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vapor pressure $p_v$ near the surface and the saturation pressure $p_{sat}$ at that surface. In buildings of large volume such as churches, we found that there are only small spatial differences between the vapor pressures measured. In fact, the measured spatial deviations of vapor pressures, calculated from measured air temperatures and relative humidities, were within about ±5% of the calculated vapor pressures. The air, therefore, is well mixed, and differences in measured relative humidities arise from differences in the saturation pressures near the surfaces. The vapor pressure $p_v$ near the surface thus may be taken from indoor air relative humidity measurements or dew-point measurements.

The saturation pressure at the indoor surface is related to the indoor surface temperature $\theta_{si}$ and can be derived from infrared thermal images of the indoor surface. Each pixel in an infrared thermograph represents an infrared measured surface temperature. A Matlab routine has been written to calculate the relative humidity near the surface at each pixel in the thermograph from the saturation pressure of the measured surface temperature at that pixel and the measured vapor pressure. The result is what will be called a surface "hygrograph," a two-dimensional representation of the relative humidity close to the surface.

## INFRARED GAS HEATING IN LARGE CHURCHES

In The Netherlands "open air" gas infrared heating system, without exhaust air extraction, are mostly used. The dramatic moisture-source effect on large churches, due to release of the combustion gasses in the open air volume of the church, has been predicted by computer simulation and has been demonstrated experimentally (Schellen 2002).

### Moisture Sources

The heating systems are so-called open air gas infrared heating systems and in The Netherlands they make use of Groningen natural gas. The most important constituents of the gas are methane and nitrogen. The exhaust combustion gasses are released directly into the room. The most important pollution sources are vapor and $CO_2$.

To simplify the gas combustion equation, the assumption was made to model the gas as methane only. The equation for combustion of methane then is as follows:

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O \quad (1)$$

Full combustion of methane with a theoretical full amount of oxygen, therefore, leads to the production of carbon dioxide and water (vapor).

Table 1 summarizes the molecular weights of the gasses and the hourly production of gasses per kW installed capacity, based on a heating capacity of 9.3 kW per $m^3$/h of used gas.

People produce carbon dioxide and vapor, too. A resting person produces about 0.5 $m^3$ air exhaust per person per hour with a $CO_2$ content of about 70 g/$m^3$. The $CO_2$ production, therefore, is about 35 g $CO_2$ per hour. The human production of vapor is by respiration and perspiration. In this research, the perspiration term is neglected. The vapor production by respiration is approximated by 24.66-0.6 $x_i$ g per person per hour, where $x_i$ is the moisture content of air in g/kg.

### WaVo Simulations

To account for the expected behavior of a church for yearly or more extreme winter weather conditions, and to account for realistic thermal and hygric surface behavior, WaVo, a computer simulation program for heat and moisture, was used. To take into account moisture adsorption and desorption processes near the walls, WaVo was adapted (Wit 2000) to account for the hygroscopic behavior and vapor diffusion process in the mostly very thick church walls, as well as different heating and humidifying systems and controls, to describe the temperature and humidity of a large church. The model originated from two early simulation models, the simplified multizone thermal simulation model ELAN (Wit 1987) and the second-order model AHUM for the prediction of indoor air humidity (Wit and Donze 1990). The geometrical complexity, together with the uncertainties regarding material properties, dimensions and construction assemblies, air infiltration, outdoor rain exposure, etc., make a real prediction of the indoor climate almost impossible. A calibration or fine-tuning of the model with measurements in a church is unavoidable. A small number of calibration parameters, the fine-tuning "knobs," is an advantage and the risk of dependant parameters is smaller. This is an argument to keep the model simple. With the calibrated model, changes of the indoor climate by a heating system then can reasonably be predicted with a model that has essentially the same physics.

The thermal network of the room model basically consists of two 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

**Table 1. Molecular Weight and Hourly Production of Gasses per kW Installed Heat Capacity**

| Formula | Molecular Weight [g] | Production [kg/(kWh)] |
|---|---|---|
| $CH_4$ | 16 | 0.077 |
| $2O_2$ | 64 | 0.310 |
| $CO_2$ | 44 | 0.213 |
| $2H_2O$ | 36 | 0.174 |

is corrected for the shortwave radiation falling from the interior side on the windows. The total transmission heat flow is calculated with the heat diffusion equations of the multilayer walls. The original ELAN model (Wit 1987) uses a simplified approach for the influence of walls on the thermal climate. This is reasonably accurate for normal well-insulated walls but not for the massive walls of a church. In this 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 hygric room model is analogous to the thermal room model. The moisture storage in the air volume, however, 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 materials are very hygroscopic. The total moisture flow from walls is calculated with the vapor diffusion equation of the multilayer walls. By linearization of the hygroscopic curve ($\xi$ 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 area ratio in churches).

For isothermal transport, the moisture diffusion equation is analogous to the heat diffusion equation, with the thermal diffusivity $a = k / \rho c$ replaced by the hygric diffusivity $D_v = \delta_a p_{sat} / \mu\zeta$ and $\theta$ replaced by $p_v$.

## Church in Bemmel

In the Roman Catholic Church in Bemmel an open air gas radiant heating system was in use for about 10 years. Because of complaints about moisture condensation on walls, floor, and glazing, the decision was made to remove the system from the church in the summer of 1999. Before the removal of the heaters, the opportunity was taken to do some measurements on the moisture and radiant heating effects during wintertime in February 1999.

The heating system consisted of 17 radiant heaters: two 26.4 kW heaters in the chancel, four 13.2 kW heaters in the side aisles, ten 13.2 kW heaters in the nave of the church, and one 6.6 kW heater near the choir. The two heaters in the chancel were symmetric ones, and the rest of the heaters were of an asymmetric type.

To get an impression of the moisture and radiant heating effects and to determine the infiltration characteristics of the church, the infiltration rate was determined by the decay of the $CO_2$ produced by the radiant heating system. For that reason a B&K multigas monitor was used, together with a multiplexing system. The infiltration rate was about 0.6 $h^{-1}$. To determine the moisture effects of the heating system, one-minute-interval air temperature and relative humidity measurements were taken near the altar, in the nave of the church, and near the organ. Furthermore, vapor concentration measurements with a sample time of two minutes were done with the multigas monitor. To calculate near surface moisture effects, surface temperatures were measured by thermistors at walls, glazing, floor, and paintings. Furthermore, infrared thermography measurements were done with intervals of five minutes.

## Measurement Results

Figure 1 shows the results of the near surface relative humidity as it was calculated from the measured absolute humidity and the thermal infrared imaging measurements. For some points on the glass and on the walls, the results were compared with local temperature and relative humidity measurements. The results were within the calculated accuracy (about ±5%).

A two-hour operating period of the gas infrared heating devices led to most serious surface condensation on stained glass windows, walls, and floor. The figures show the most critical condensation surfaces to be lying in the shadow of the infrared heating devices in the choir. Furthermore, it is clear from these images that the most critical time for surface condensation on cold surfaces is a little while after stopping the heating: the temperatures decrease in a short time and where the infiltration rate is low, the relative humidity nearly reaches its maximum. In this Bemmel church the combination of a large source of moisture production and a relatively small infiltration rate was a serious threat to the building and its interior.

## WaVo Calculations

A simulation run with WaVo on the Bemmel church's characteristics was completed and the results have been compared with measured results. A typical graphical representation of the measured and simulated results is shown in Figure 2. The figures represent the air temperature (left above), relative humidity (right above), choir wall temperature (left below), and relative humidity near the choir wall (right below). The agreement at that time of simulation (1999) was not very good, mainly due to the restriction of one-hour time steps, enforced by the time steps of the weather file. Later (2000, see Walloon church below) linear interpolation of weather data improved the quality of the results.

When we look at the relative humidity in the church, we note that due to the temperature effect it will drop during heating. Directly after heating, however, the relative humidity will increase due to the enlarged specific humidity in combination with the cooling down of the church and the relatively small infiltration rate. From the pictures of the relative humidity near the choir walls, it is clear that a two-hour use of the system will lead to severe condensation on the choir walls and glazing in the church.

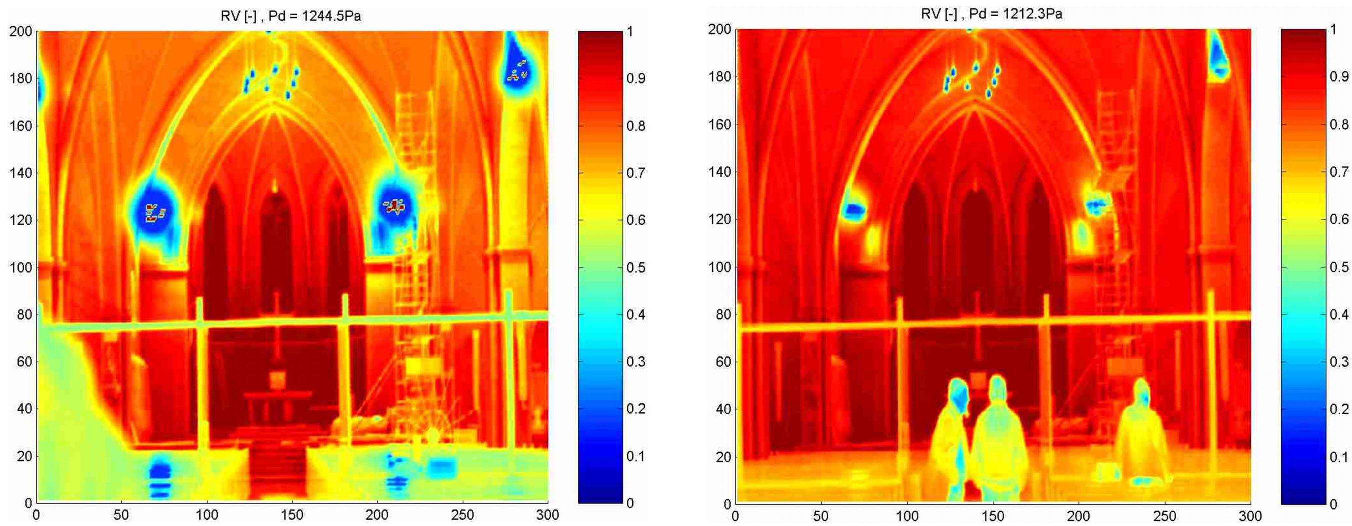


***Figure 1*** *Relative humidity near the surface as calculated from absolute humidity and thermographic surface temperatures (left) during two hours of heating and (right) directly after heating.*

## HUMIDIFICATION OF LARGE CHURCHES

### The Walloon Church in Delft

The Walloon Church in Delft is a relatively small church with an air volume of 3050 $m^3$ and a ventilation rate of 0.2 $h^{-1}$. In this church is a monumental Bätz/Witte organ, which dates from 1869. In the spring of 2000 the organ was restored. During restoration it turned out that the organ was heavily damaged due to excessive (air) heating of the church. To prevent 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 was conducted for the preservation of the organ. As a result of these research studies, several adjustments have been made to the heating system. Preservation criteria for large church buildings and their interiors have been formulated (Schellen 2002).

The measurements that were carried out in the Walloon Church after adjusting the inlet air temperature and velocity of the heating system showed that the indoor climate met the requirements for preservation of the organ. Since low relative humidity caused damage to the organ, the heating system was restricted. As soon as the relative humidity of the indoor air drops below 40%, the heating system is shut down. The Walloon Church, however, is not only used for services but also for several other activities, e.g., organ recitals. Since people sit in the church without wearing their overcoats, an indoor air temperature of 18°C to 20°C is desirable. As a result of these rather high temperatures for churches, the relative humidity of the indoor air tends to become very low (<30%). As a result of the RH restriction, it was not possible to reach an indoor air temperature of 18°C during winter when it was freezing outside.

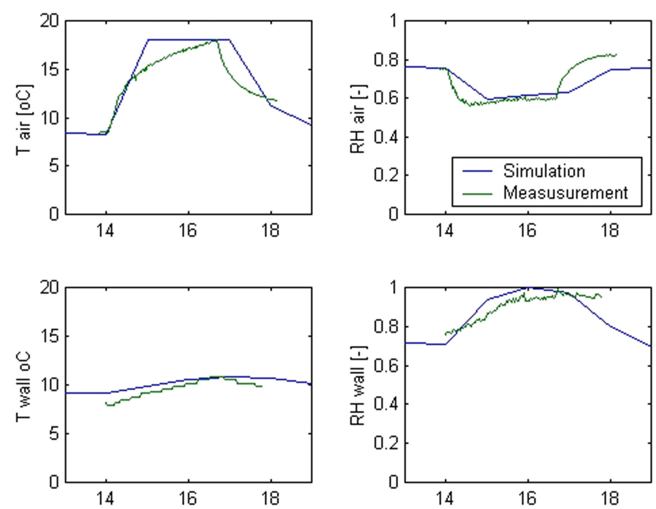


***Figure 2*** *Comparison of WaVo calculation results (blue) and results of measurements (green): air temperature (left above), relative humidity (right above), choir wall temperature (left below), and relative humidity near choir wall (right below).*

In order to prevent deterioration of the organ and yet reach an indoor air temperature of 18°C to 20°C, the idea of installing a steam humidifier in the air duct was investigated. By increasing the specific humidity of the supply air, the relative humidity of the indoor air then 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 to 20°C. As a consequence of the humidification of the indoor air under winter conditions and

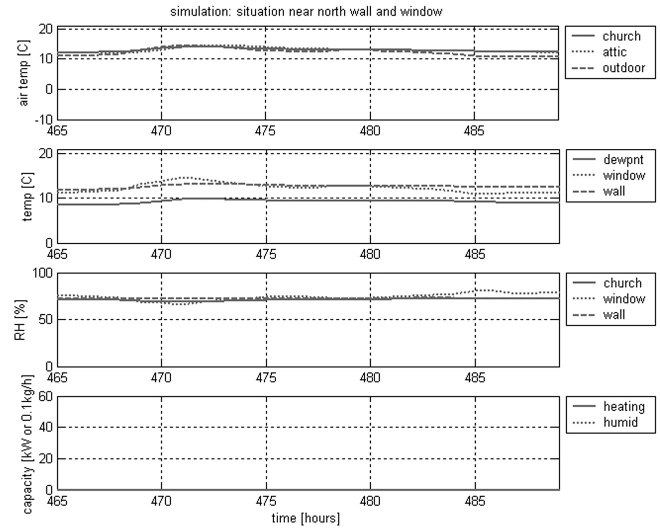


***Figure 3*** *Weekday without a service, situation near wall and window in north façade.*

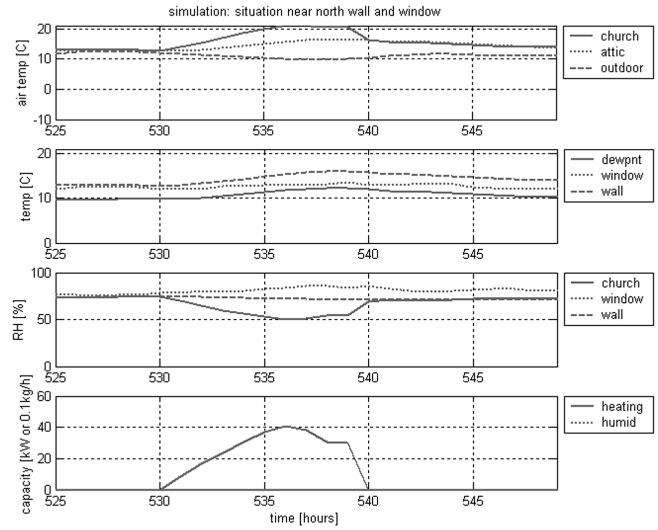


***Figure 4*** *Sunday with a service and a minimum outdoor temperature of 10°C.*

the low surface temperatures, however, there is a risk of high relative humidities near the cold surfaces. Condensation may occur on cold surfaces such as leaded glass. Furthermore, a long-lasting high relative humidity near the surfaces can lead to fungal growth, while algal growth may occur on the glazing.

## Method

First of all a simulation run was carried out of the present situation in the Walloon Church. The input data for dimensions, physical material properties, technical heating system specifications, church usage, and energy consumption are summarized in the appendix to this paper. (A complete set of data is in the appendix of Schellen [2002]. This Ph.D. thesis can be downloaded as a PDF file at http://alexandria.tue.nl/extra2/200213875.pdf.).

The first simulation was run with a primary temperature of 10°C and a comfort temperature of 20°C and no humidification. The relative humidity was restricted to a maximum of 70%—when the RH 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 humidifier placed in the inlet air duct before the air is blown into the church. This humidifier 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. Finally, measurements were undertaken to check the indoor climate in the church after installing the humidifier.

**Predicting the Indoor Climate after Installing the Humidifier.** In order to gain a clear understanding of the period in which the indoor air has to be humidified and the consequences of it, a one-day period is shown in Figure 3. In the upper part of the figure, the indoor air temperature and surface temperatures of the northern wall and glazing are shown. The relative humidities of the indoor air and near the mentioned surfaces are shown. In the lower part of the figure, the loads of the humidifying and heating systems are presented. 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 outdoors of 4°C. At last a Sunday in December is shown with a service held and a minimum outdoor temperature of about –5°C.

**Weekdays Without a Service.** Figure 3 shows the situation during a weekday without a service. The indoor air temperature and the relative humidity remain quite stable at about 10°C and 75%, respectively. The relative humidity does not drop below 40% so there is no need to humidify 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 10°C to 15°C while the relative humidity near the glazing is about 70%-80%. There is no condensation on the glazing.

**Sunday with Service and a Minimum Outdoor Temperature of 10°C.** Figure 4 shows the situation during a Sunday, with a service held at a minimum outdoor temperature of 10°C. The air in the church is heated up to the desired value of 20°C, and, as a result of this temperature rise, the relative humidity drops from 75% to almost 50%. However, the humidifier 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 temperature near the walls follows the indoor air temperature with a slight delay. The relative humidity near the walls fluctuates around 75%.

During the service the indoor air warms up the glazing, but as a result of the remaining 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 rise, the relative humidity near the glazing surface decreases during the service to 80% but increases to 90% when the heating system is shut down right after the service.

**Sunday With a Service and a Minimum Outdoor Temperature of –5°C.** Figure 5 shows that the indoor air is heated from the primary temperature of 10°C to the desired comfort temperature of 20°C. The hygrostatic control starts the humidifier at a minimum value of 40% RH. As a result of the rise in temperature, the relative humidity tends to drop from 52% to below 40% and the humidifying load shows the humidifier has to be put into action. While heating the indoor air, the relative humidity is held at 40% with help of the humidifier. When the heating system is turned off right after the service, the relative humidity increases rapidly to a value of 65%. This is a clearly higher value than before the service.

The adjustment control of the humidifier is closely connected to the adjustment control of the air heating system. If the relative humidity drops below 40% the humidifier starts working to reach its maximum load at $t$ = 1040. 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.

As shown in Figure 5, 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 humidifier is turned on. The relative humidity reaches a value of 65% at the point $t$ = 1040. After that the temperature of the wall increases and the relative humidity near the wall again decreases. The relative humidity near the northern wall thus reaches a maximum value of 60% to 70% the moment the humidifier is working. There will not be a long-lasting moistness, resulting in fungal growth. At a primary temperature of 10°C in the church, the air temperature near the glazing is about 2°C and the relative humidity about 85%. Humidifying the indoor air during the service will increase 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 5 from $t$ = 1038 to $t$ = 1043 hours. This period can be detected from the RH graphs as well as from the dew-point/surface temperature graphs.

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 were taken in the winter of 2002.

## Validating the Simulation Model

The simulation model was 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 a month (November 11 until December 10 of the year 2000) was used to validate the model. There were a couple of reasons for choosing this period:

1. During this period measurements were taken in this church to find out why the indoor climate did not meet the requirements for preservation of the organ.
2. The outdoor temperature during this period was around freezing, as a result of which the relative humidity of the indoor air dropped below 40%. The problems concerning a relative humidity that is too low became 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.

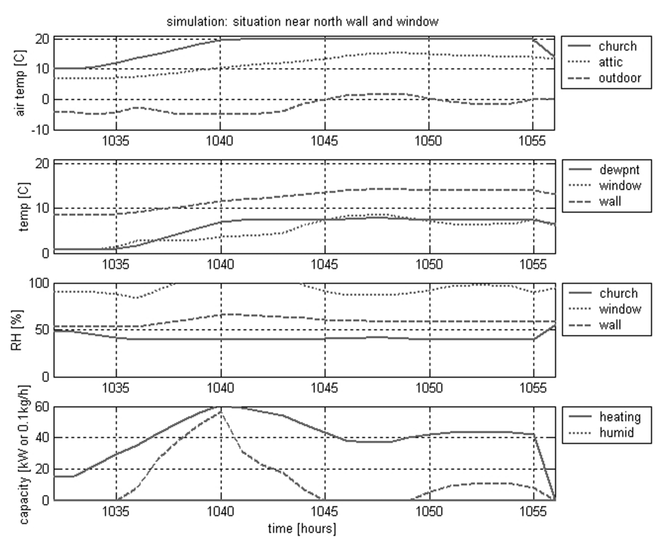


***Figure 5*** *Sunday with a service and a minimum outdoor temperature of –5°C.*

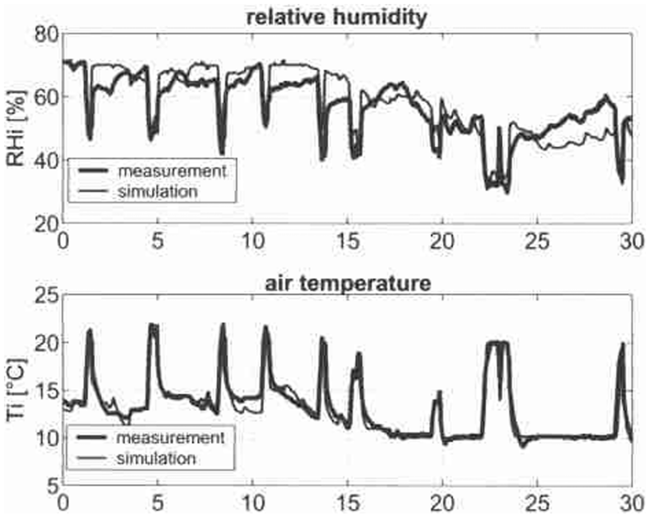


***Figure 6*** *Comparison between simulation and measurements.*

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—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 estimated 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 them. As a result of these differences, the simulation model was examined more closely.

**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 depends, not only on the difference in temperature between the wall and the air, but also on the velocity of the air near the wall. However, usually the heat transfer coefficient, in which this effect is represented, is not known. The default value in the simulations was a convective heat transfer coefficient of 2.5 W/m$^2$K.

The walls in churches are much higher than in most other buildings. Because of downdraft near the walls, the air velocity will be higher than is assumed in other buildings. The literature mentions that increasing the air velocity to 0.3 m/s increases the heat transfer coefficient to a value of 5 to 10 W/m$^2$K (Kriegel 1973; Loomans 1998; Wit 2000).

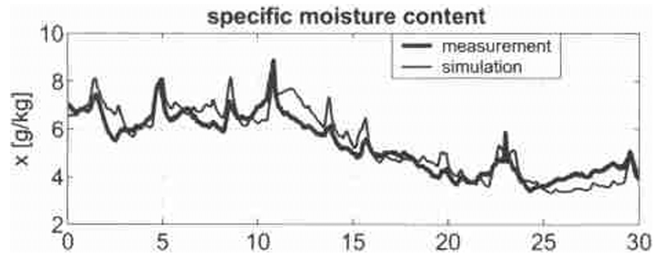


***Figure 7*** *Comparing measurements and simulations.*

Since in the Walloon Church in Delft an air velocity of 0.2 to 0.3 m/s was measured, the heat transfer coefficient of the walls in the simulation model was adjusted from 2.5 to 5 W/m$^2$K. After making these adjustments, the course of the indoor air temperature is very close to the measured values (Figure 6), but there are still 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.

**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 7 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 research, the number of people in the church during the service (until now estimated from interviews) has to be registered. Furthermore, the moisture production for a person may be estimated better.

The adsorption and desorption of moisture at the walls differ 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.

## CONCLUSIONS

The results from this research led to the following conclusions:

- Gas infrared radiation heating systems without exhaust air extraction are dangerous heating systems for large buildings. The gas burning process leads to serious moisture and carbon dioxide production sources. For every 100 kWh burned gas, about 17 L $H_2O$ is brought into the church and is released into the air.
- Measurements in a church in Bemmel proved the calculations to be fail-safe: a two-hour operating period of the gas infrared heating devices led to surface condensation on stained leaded glass, walls, and floor. Furthermore, the direct radiation of the heaters led to severe surface temperatures of interior parts like furniture and paintings.
- Humidification of churches is a possibility to prevent too-low relative humidities during heating in wintertime. Condensation and high relative humidities near cold surfaces, however, may result. Maintaining a higher primary temperature leads to higher surface temperatures of walls and windows, thus decreasing this risk of condensation. Lowering the comfort temperature also will have a positive effect on indoor air humidity and will lead to considerable energy savings.

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## APPENDIX
## BASIC DATA SETS
## WAALSE KERK (WALLOON CHURCH) IN DELFT

**Table A1. Dimensions**

| | Total Area [$m^2$] | Thickness of Construction [m] | Closed Facade [$m^2$] | Glazing [$m^2$] | Percentage Glass in Facade [%] |
|---|---|---|---|---|---|
| **Outdoor walls** | | | | | |
| North | 234 | 0.75 | 179 | 55 | 24 |
| North-northeast | 29 | 0.75 | 19 | 10 | 34 |
| East-northeast | 29 | 0.75 | 29 | 0 | 0 |
| East | 29 | 0.75 | 20 | 9 | 30 |
| East-southeast | 29 | 0.75 | 29 | 0 | 0 |
| South-southeast | 29 | 0.75 | 19 | 10 | 34 |
| South | 234 | 0.75 | 156 | 78 | 33 |
| Total outdoor wall | 745 | | 585 | 160 | 22 |
| **Adiabatic walls** | | | | | |
| church - museum | 133 | 0.34 | | | |
| church – vicarage | 100 | 0.76 | | | |
| Total adiabatic walls | 233 | | | | |
| **Vault** | 330 | 0.02 | | | |
| **Roof**<br>North | 200 | 0.145 | | | |
| North-northeast | 13 | 0.145 | | | |
| East-northeast | 13 | 0.145 | | | |
| East | 13 | 0.145 | | | |
| East-southeast | 13 | 0.145 | | | |
| South-southeast | 13 | 0.145 | | | |
| South | 200 | 0.145 | | | |
| Total roof area | 465 | | | | |
| **Floor** | 210 | 0.1 | | | |

| **Volume** | **[$m^3$]** | | | | |
|---|---|---|---|---|---|
| church | 3050 | | | | |
| attic | 195 | | | | |

## Table A2. Physical Properties of Materials

| Building Part | Material | d [m] | k [W/m·K] | $[kg/m^3]$ | c [J/kg·K] |
|---|---|---|---|---|---|
| outdoor wall | plaster | 0.02 | 0.8 | 1900 | 840 |
| | brick | 0.73 | 1.3 | 2100 | 840 |
| wall between church and vicarage | plaster | 0.02 | 0.8 | 1900 | 840 |
| | brick | 0.72 | 1.3 | 2100 | 840 |
| | plaster | 0.02 | 0.8 | 1900 | 840 |
| wall between church and museum | plaster | 0.02 | 0.8 | 1900 | 840 |
| | brick | 0.3 | 1.3 | 2100 | 840 |
| | plaster | 0.02 | 0.8 | 1900 | 840 |
| pillars (organ) | plaster | 0.01 | 0.8 | 1900 | 840 |
| | brick | | 1.3 | 2100 | 840 |
| | plaster | 0.01 | 0.8 | 1900 | 840 |
| floor | natural stone | 0.10 | 2.9 | 2750 | 840 |
| | sand | 2.0 | 3 | 1650 | 840 |
| vault | wood | 0.02 | 0.14 | 550 | 1880 |
| roof | wooden panelling | 0.02 | 0.14 | 550 | 1880 |
| | insulation | 0.05 | 0.036 | 35 | 1470 |
| | air spalt | 0.05 | 0.023 | 1.2 | 1000 |
| | wood | 0.02 | 0.14 | 550 | 1880 |
| | slate | 0.005 | 2.9 | 2750 | 840 |

| Windows | Type | Spalt | $U [W/m^2·K]$ | ZTA [-] |
|---|---|---|---|---|
| leaded glass | colored glazing | | 5.2 | 0.3 |

## Table A3. Heating System Properties

| | | Unit |
|---|---|---|
| **Boiler** | | |
| number of boilers | 2 | |
| manufacturer | Remeha | |
| type | Quinta 45 | |
| nominal capacity | 45 kW | each |
| efficiency | 109* | % |
| **(Warm) Air heating** | | |
| supply temperature | 40 | °C |
| inlet grille | air jet grille with 6 jets | |
| made, type | Solid Air, JGTA | |
| dimensions (h x w) | 800 × 1200 | mm |
| height to floor | 3 | m |
| direction jets | variable | |
| flow rate | | |
| - before service | 7500 | $m^3/h$ |
| - during service | 3750 | $m^3/h$ |
| air velocity near grille | | |
| - before service | 8 | m/s |
| - during service | 4 | m/s |
| re-circulation | 100% | |
| return grille in floor | 1000 × 1200 | mm |
| **Hygrostatic control** | | |
| lower level (stop heating) | 40 | % |
| upper level (extra heating) | 70 | % |
| **Control devices (position)** | | |
| position 1 | pulpit, 3 m height | |
| position 2 | organ, 7 m height | |

* At a load of 30% and a return water temperature of 30°C

## Table A4. Church Usage

| | | Unit |
|---|---|---|
| **Interior:** | organ<br>wooden pews | |
| **Indoor climate** | | |
| primary temperature | 10 | °C |
| comfort temperature (during service) | 20 | °C |
| RH min at organ* | 40 | % |
| RH max at organ | 70 | % |
| **Church usage** | | |
| Standard service | | |
| number of persons | 50 | |
| additional internal moisture production | | kg/h |
| additional internal heat load | | W |
| Special usage (holidays, concerts etc.) | 200 | |
| number of persons | | |
| additional internal moisture production | | kg/h |
| additional internal heat load | | W |
| **Natural ventilation** | | |
| ventilation flow - church | 488 | $m^3/h$ |
| - attic | | $m^3/h$ |
| ventilation rate - church | 0.16 | $h^{-1}$ |
| - attic | | $h^{-1}$ |

* A moisture source with a capacity of 8 kg/h was installed in November 2001.

## Table A5. Energy Consumption

| Energy Consumption | 2000 | 1999 | 1998 | 1997 | 1996 | 1995 |
|---|---|---|---|---|---|---|
| Gas [$m^3$] | 5,131 | 8,011 | 9,548 | 9,252 | 9,145 | 10,703 |
| Electricity [kWh] | | | 4,956 | 4,424 | 4,194 | 4,494 |