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Damage to a monumental organ due to wood deformation caused by church heating

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ABSTRACT: In a PhD study on the heating of monumental churches one of the problems, which was encountered, was the damage to wooden interior parts due to the changing of the indoor climate. Particularly warm air heating frequently leads to sudden changes in relative humidity, which turned out to be dramatically hard for monumental organs during wintertime.

The warm air inlet conditions and their result on the airflow and air conditions were examined experimentally and by CFD-simulation. These results provided boundary temperature and humidity conditions, to which the monumental organ was exposed.

In an experimental study the response of wooden parts to changing indoor conditions was tested. In a Nuclear Magnetic Resonance (NMR) test setup the moisture content of samples was measured as a function of time and place. These moisture content changes were related to the free mechanical deformation of samples. Together with the measurement of typical material properties of wood, a two-dimensional model was developed in FlexPDE: a finite element program to solve partial differential equations simultaneously.

1 INTRODUCTION

The Walloon Church in Delft is an important monumental church in the Netherlands. The original chapel of St. Agatha's Convent was built between 1430 and 1480. William of Orange frequently attended the French spoken services from 1573 to 1584. The name 'Prinsenhofcomplex' is a result of this.

In 1585 the church was handed over to the Walloon Community. Because the length of the church was not appropriate for Protestant services, one half of the church was separated. Nowadays the building is still one half of the original church building: the other part is a museum: the Prinsenhof Museum. The Prinsenhof complex as a whole was restored from 1950 to 1962.

The monumental interior parts consist of a monumental pulpit, monumental pews, monumental escutcheons and an important burial monument. The monumental Bätz/Witte organ in the church dates back to 1869 and was last restored in 2000.

The heating system in the building was originally a direct hot air system, Mark Fohn type 115RH of Mark Heating Systems. The heat capacity of the heating system was 115/77 kW (high/low). The hot air was brought into the church by a re-circulation system with an airflow rate of 7400/5000 m^3/h (high/low).

Figure 1. The monumental Bätz/Witte organ and interior of the Walloon Church in Delft (The Netherlands)

The warm air inlet consisted of a single grille at about 3 m above floor level. The outlet was a single grille in the floor. The air was re-circulated for 100 %. The thermostatic device in the church was located near the pulpit at a height of about 3 meters.

2 PROBLEM DEFINITION

In the church before the restoration of 2000 the monumental organ was in bad shape and a major restoration was inevitable. From a literature study (Schellen 2002) it was known that air heating might cause severe problems for monumental organs and other monumental objects in the interior of a church. The assumption was made that high air inlet temperatures cause large thermal stratification and thus lead to high air temperature at elevated levels, where the monumental organ was to be found. A high air temperature involves a low relative humidity. Dramatic low relative humidity values and related drying out and shrinkage of the organic parts could therefore be the result. Cracks and other indications of shrinkage in the wooden cabinet of the organ supported this theory.

3 OBJECTIVES

The most important target of the study was to determine the main cause of the deterioration of the organ and to save the organ from demolition in the future. Furthermore the study gave an occasion to study the characteristics of a warm air heating system in a church. The assumed thermal stratification could be examined and the relationship between heating and assumed relative humidity drops could be investigated. Apart from that the hygrothermal effects of heating on wood could be examined.

4 ANALYSIS

The analysis consisted of a damage analysis on the monumental organ, building physical measurements, a simulation study of the church in situ (Neilen, 2002) and laboratory study on the behavior of wooden parts under changing climatic conditions.

5 DAMAGE ANALYSIS

During the restoration of the organ at the restoration workplace of Gebroeders Reil BV, the inner parts of the organ were analyzed on the occurrence of damage by the Reinwardt Academy, a Dutch school for museum science based in Amsterdam.

The bellows were severely damaged; severe cracks occurring within the wooden parts of the bellows; their sheepskin parts were torn.

Figure 2. Damage to bellows

The bank of keys, the clavier, had a problem with 'hanging' keys due to the shrinkage or swelling of parts of the playing mechanism.

The wind drawer, the heart of an organ, was damaged most severely. At the glued parts of the wood open joints occurred. At the wind holes of the drawer cracks separated the wooden parts. This kind of damage is most disastrous for an organ: the leakage of the wind drawer will have the effect that other organ pipes will sound during playing of the separate pipes.

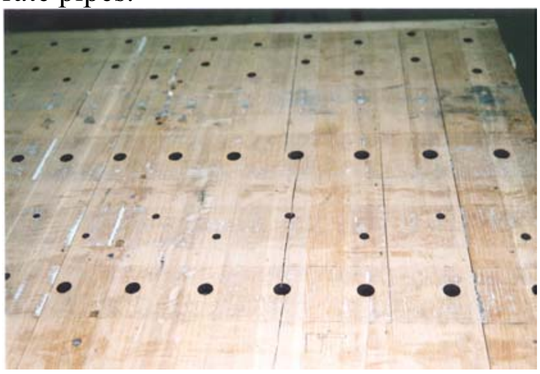

Figure 3. The winddrawer and its cracks

The wooden organ pipes had cracks at the tuning caps due to warping and shrinking of the wooden edges. Furthermore the organ was out of tune due to displacements of the tuning caps.

At the wooden cabinet of the organ in the church the following damage has been observed. The joints of the wooden panels in the wooden frames showed shrinkage damage.

Figure 4. One of the panels hanging loose in the frame

Within the wooden cabinet large cracks occurred and the door of the cabinet was stuck due to warping.

Figure 5. Cracks in the wooden cabinet

The lacquer of the wooden cabinet flaked off (in different parts).

Figure 6. Flaking off lacquer

6 FIELD MEASUREMENTS

The measurements in Delft can be grouped into short time or one-day measurements, and long-term or one-year measurements.

6.1 *Smoke analysis*

During the one-day measurements a smoke analysis of the indoor airflow pattern took place. Smoke was generated by evaporation of paraffin oil and introduced at the re-circulation outlet and thus, by re-circulation, introduced in the church by the air inlet. The flow pattern of the smoke can be described as follows: smoke entered the church at the air inlet grille in a vertical east oriented wall with a certain horizontal velocity. Due to its temperature difference with the surrounding church air temperature, the inlet air had an upward directed thermal driven velocity component and directly moved to the ceiling, sticking close to the ceiling and moved to the opposite west wall of the church. Ventilating devices, hanging from the ceiling in front of the organ and blowing downward, could not improve the temperature stratification *above* the propeller blades; the sucking effect of the propeller blade was negligible and warm air kept sticking to the ceiling. The smoke finally cooled down at this wall and was redirected downwards, directly moving to the monumental Bätz/Witte organ cabinet at the upper floor organ department. From here the air moved down into the church and followed its way to the air exhaust grille in the floor, located a few metres in front of the east wall with the air inlet grille.

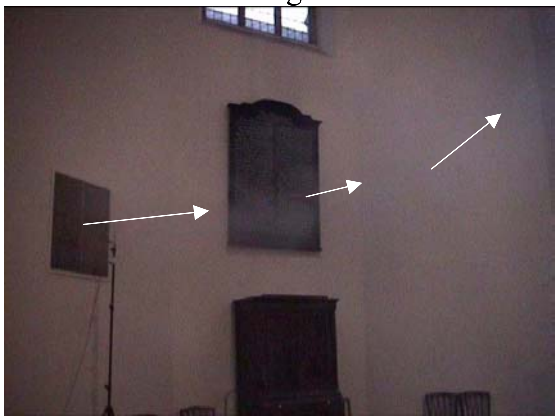

Figure 7. Smoke pattern at the outlet grille

From the smoke analysis it was concluded that thermal stratification probably was inevitable.

6.2 *Inlet air conditions*

The inlet air conditions were measured at the inlet grille. Inlet air temperature was measured continuously during the long-term measurement period and inlet air velocity measurements took place during the one-day measurement period.

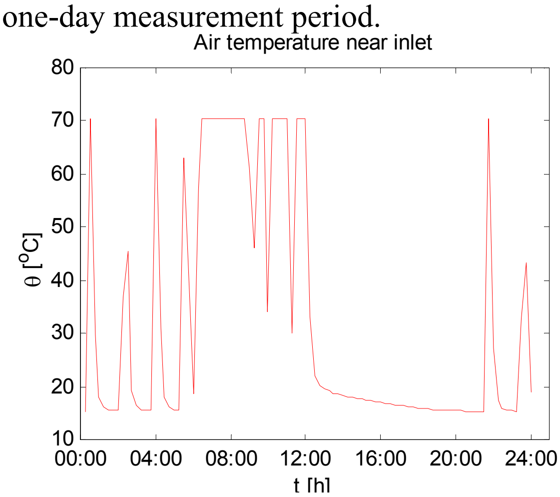

Figure 8. Air temperature at the inlet grille

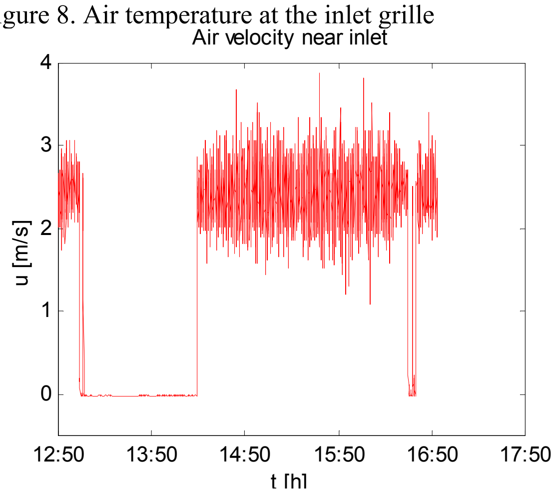

Figure 9. Air velocity at the inlet grille

6.3 *Indoor air conditions*

To determine the temperature stratification, the air temperatures and relative humidities were measured at four different height levels in front of the organ. From the data measured a typical period was extracted. Figures 12 and 13 indicate air temperatures and relative humidities measured at four different heights, 15 m being the total height of the church. From the indoor air conditions measured during a year a typical Sunday service (January 17th 2000) was extracted. Figures 10 and 11 indicate air temperatures and relative humidities in front of the organ at a height of 15 metres, just beneath the vault.

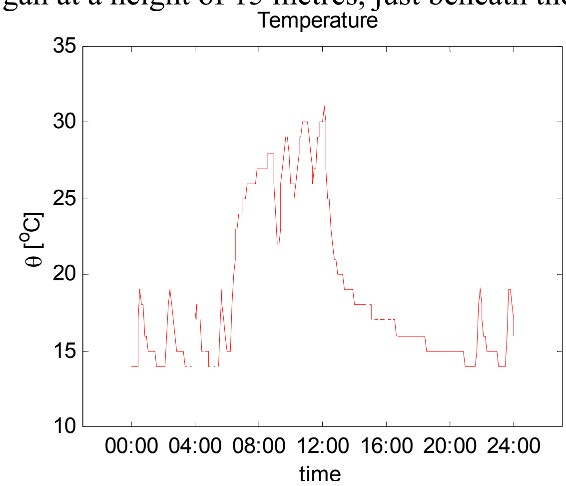

Figure 10. Air temperature in front of the organ

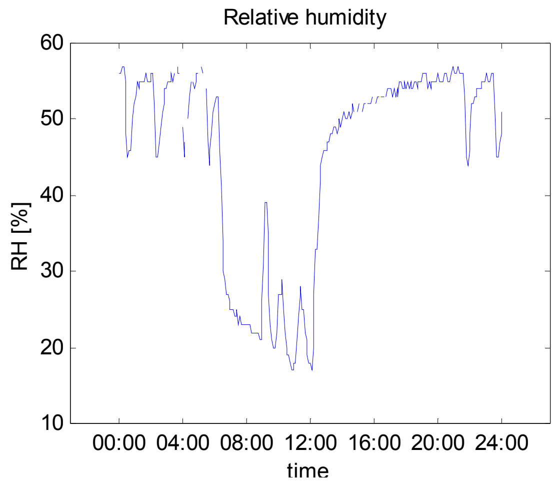

Figure 11. Relative humidity in front of the organ

6.4 *Temperature and relative humidity stratification*

From the data of the temperatures at different heights the temperature stratification can be extracted. Figures 12 and 13 give a typical representation of the temperature and relative humidity stratification.

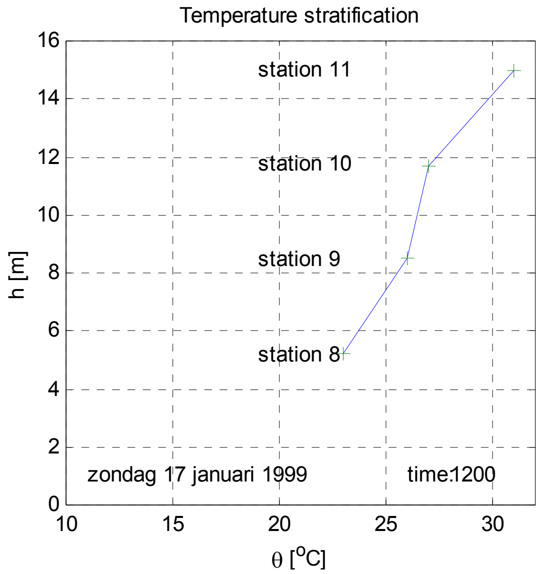

Figure 12. Typical temperature stratification during a service

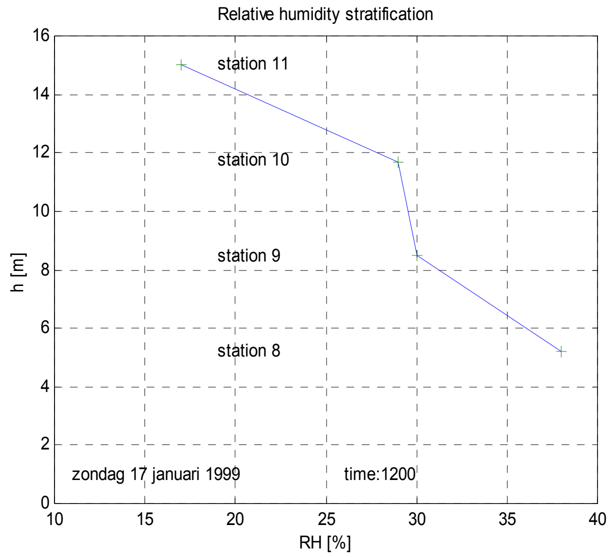

Figure 13. Typical relative humidity stratification during a service

6.5 *Conclusions drawn from field measurements*

The air heating with high air inlet temperatures led to high temperature stratification and thus to very low relative humidity in the upper part of the church. Ventilator devices, hanging at the ceiling of the church and mixing the air below the propellor blade, could not prevent the warm air to stick to the ceiling and move above the propellor blades to the organ.

The actual indoor climate conditions at the monumental organ were compared with recommendations from literature to protect it from deterioration. It was clear that the relative humidity dropped to very threatening low levels of 20 to 25 % RH. This must have had a great impact on the wooden parts and cabinet.

7 LABORATORY MEASUREMENTS ON WOOD

7.1 *Moisture content*

To study the effects of drying on wood it is very important to measure moisture profiles as a function of time. Nuclear magnetic resonance (NMR) is a powerful technique to measure the time evolution of moisture profiles with a high spatial resolution. The dynamically changing moisture content of wood due to changing climatic conditions was measured in an NMR set-up at the Centre for Material Research with Magnetic Resonance, Eindhoven University of Technology. The method is extensively described by (Pel, 1995). In an NMR experiment the magnetic moments of hydrogen nuclei are manipulated by suitably chosen electromagnetic alternating radio frequency (RF) fields. In a pulsed NMR experiment the orientation of the moments of the spins in a static magnetic field is manipulated by short electromagnetic pulses at the resonance frequency, bringing the system in an excited state. The amplitude of the resulting so-called spin-echo signal is proportional to the number of (hydrogen) nuclei excited by the radio frequency field. Because of the resonance condition for nuclei the method can be made sensitive to hydrogen only and therefore the spin-echo signal is a measure for the moisture content.

The NMR measurement set-up consists of a cylindrical coil inserted between two magnets. The cylindrical samples can be inserted in the cylindrical coil. In this scanner it is possible to measure quantitatively the moisture profiles with a spatial resolution of 0.5 mm in two dimensions. To enable the exposure of the sample to temperature and humidity conditioned air, one cylindrical wooden sample with a diameter of 25 mm and a length of 200 mm is placed in a cylindrical tube with an inner diameter of 50 mm and a length of 1500 mm. Conditioned air is prepared by mixing dry and moist air. It is brought into the tube at a temperature of 23 ^{o}C and is blown along the cylindrical surface of the wooden sample. To smooth the airflow along the cylinder a cylindrical synthetic sample with a pointed front is placed in front of the cylindrical wooden sample. Temperature and relative humidity of the air are measured at the in- and outlet of the perspex tube. The radial and tangential deformation of the wooden beech sample is measured by resistance strain gages, which are connected to clips over the diameter of the cylinder. The typical accuracy of this measurement is in the order of 1 µm. Figure 14 shows the NMR-setup and figure 15 shows the prepared beech wooden sample.

The NMR measured moisture profiles were used to determine the moisture diffusivity of one sample of beech wood (average oven dry density $\rho_0 \approx 520$ kg/m^3; other material properties of the beech wood used, are measured and summarized in (Schellen, 2002)).

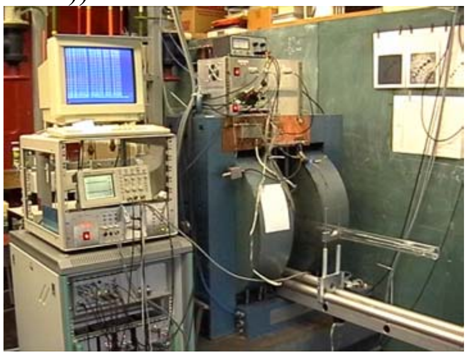
Figure 14. NMR set-up

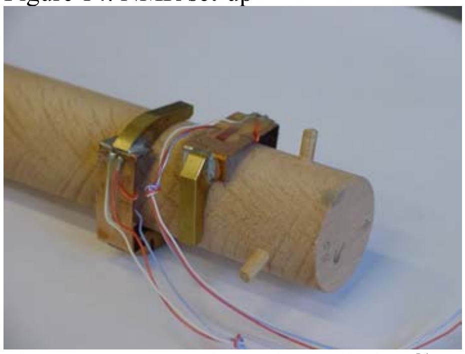
Figure 15. Prepared wooden cylinder ∅ 25 mm

7.2 *Moisture diffusivity*

We made use of partial differential equations to describe the isothermal moisture transport in wood.. The moisture diffusivity of porous materials is dependent on the moisture content of the material. In a first approximation, however, the moisture diffusivity will be considered to be a constant. The moisture profiles from the drying experiment are used as a reference. Femlab is used to simulate the moisture profiles using an initial guess for the moisture diffusivity (Schijndel 2003). The guess for the diffusivity is updated until the optimal value for it is reached, i.e. when the sum of the squares of the deviations is minimal. The geometry of the model was the 2D circular section of the cylindrical wooden sample with diameter 0.025 m.
The Femlab PDE model used to describe the moisture evaluation in wood was the following:

$$\frac{\partial w}{\partial t} = \nabla \cdot (D_v \nabla w)$$

where

w	= moisture content	[kg/m^3]
D_v	= vapor diffusivity	[m^2/s]
t	= time	[s]

The initial value for the moisture content at t=0 was the moisture profile first measured. The moisture content at the surface was considered to be w=0 for t>0. Because the NMR signal for moisture contents below 7 mass% returned values for the moisture content of 7 mass%, these lower values were not accounted for.

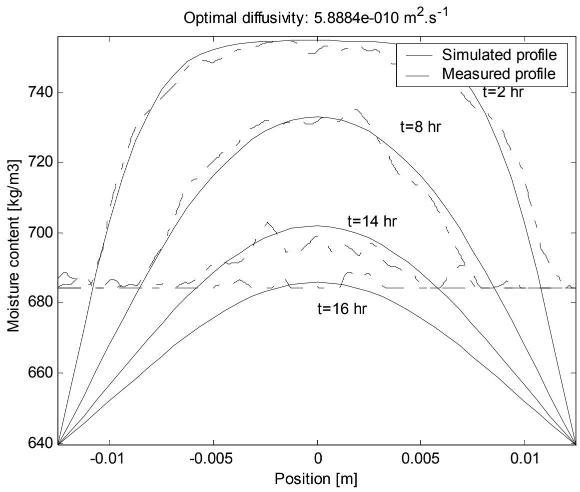

Figure 16. Fitting the diffusivity from simulated moisture profiles to measured moisture profiles

The result of the fitting of the measured moisture profile to the simulated profile is indicated at the top of figure 16: D_v=5.9·10^{-10} m^2/s. The order of magnitude is the same as reported in (Olek, 2000): they reported the diffusivity of Scots pine wood to vary from 2.35·10^{-10} m^2/s to 3.13·10^{-10} m^2/s for moisture contents varying from 8 to 15 mass%.

8 MODELING

8.1 *Actual airflow situation*

A CFD airflow study using Fluent was carried out to predict the effects of inlet air conditions on the stratification in the church (Loomans 1998). First airflow simulation results were compared with measurements in the actual situation, in order to estimate the accuracy of the CFD simulations. The boundary conditions for the simulation study were extracted from the measured inlet air conditions (inlet air temperatures and velocities as a function of time and turbulence intensity) and wall, floor and ceiling surface temperatures as a function of time. The geometry of the church was simplified to a global 3D model of it. Figure 17 indicates the flow pattern during the heating of the church.

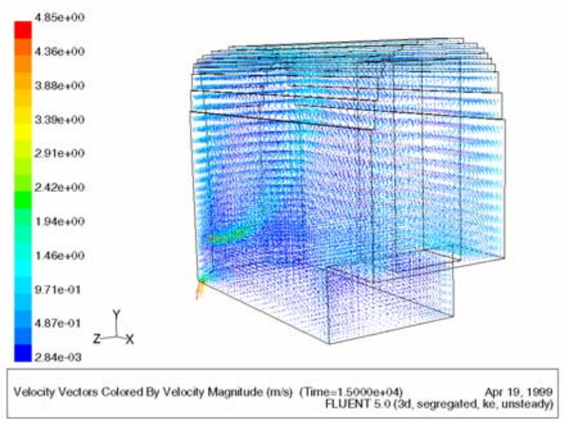

Figure 17. CFD computed velocity vectors

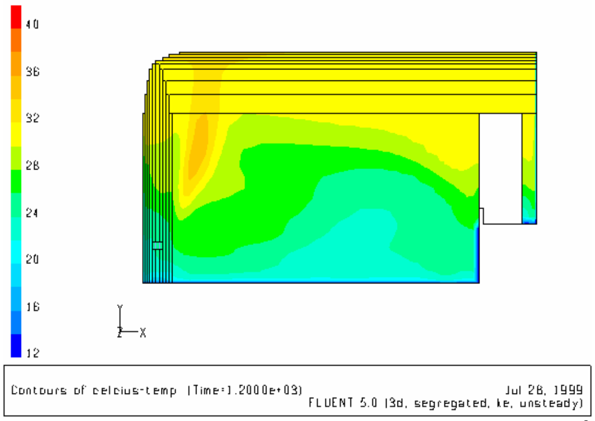

Figure 18. Heating up the church; interval 5', θ_{in}=70 °C, θ_i=20 °C, u_{in}=2.4 m/s, Ar=0.29, Re=2.4*10^5

In figure 19 the measured and CFD calculated temperature stratification is derived.

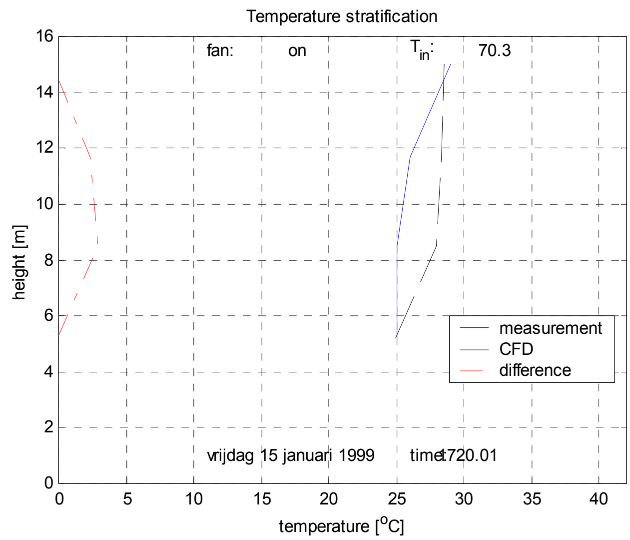

Figure 19. Measured and CFD calculated temperature stratification

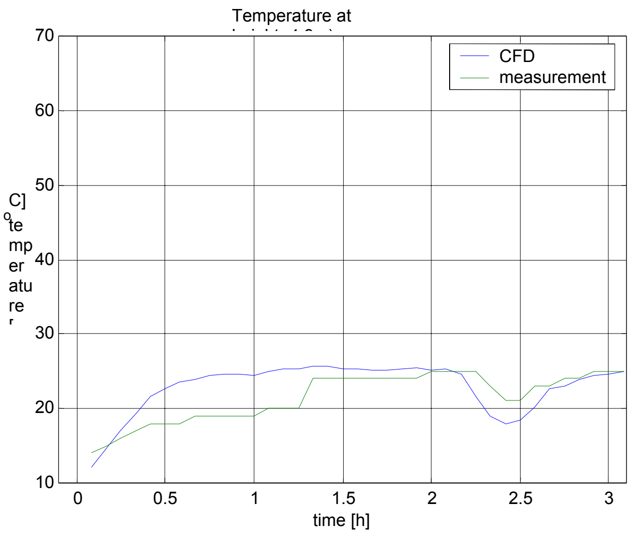

Figure 20. Measured and CFD calculated temperatures as a function of time

8.2 *Conclusions drawn from simulations of the actual situation*

The actual results measured, compared with the simulation results, show differences in the curve of stratification. At low and high heights the agreement is rather good, at half height there is a difference of about 3 K. The trend in time of the measured and simulated results is reasonable. Absolute differences however vary from 0 to 5 K.

8.3 *Future situation*

To prevent damage in the future, a simulation study was undertaken to show the effects of different heating strategies. To predict the airflow pattern in the church under different inlet air temperature and velocity conditions of the church air heating system, a further CFD simulation study with Fluent took place.

The inlet air conditions have been derived from literature recommendations (Schellen 1998/2): the inlet air temperature was reduced from 70 °C to 40 °C . Two variants have been studied: an air velocity of 2.4 m/s and an according airflow of 4200 m^3/s (Ar=0.17) and an air velocity of 4.1 m/s and an according airflow of 6700 m^3/s (Ar=0.05). The primary (initial) air temperature was 8 °C.

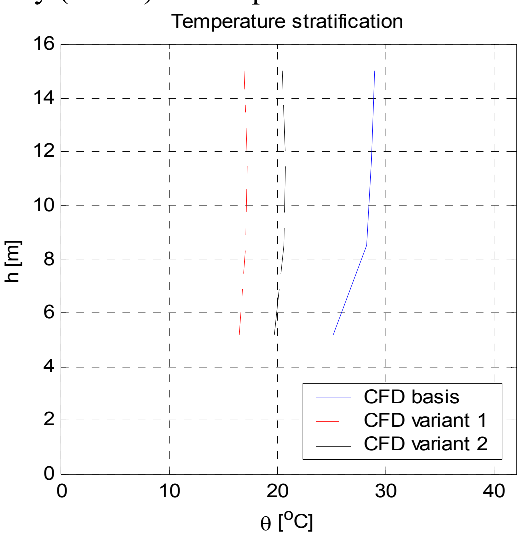

Figure 21. The expected temperature stratification for the CFD variants: Ar=0.29 (basis 1), Ar=0.17 (variant 1) and Ar=0.05 (variant 2)

Figure 22 shows the trajectory of the air jet for different numbers of Archimedes as they have been calculated from (Katz 1974). The figure indicates the thermal upward component due to temperature differences in combination with air velocity.
The Archimedes number in figure 22 is defined as:

$$Ar = \frac{g\Delta\theta_o D_h}{T_i u_0^2}$$

where

g	=	gravitational acceleration	[m/s^2]
$\Delta\theta_0$	=	temperature difference air - inlet	[K]
D_h	=	hydraulic diameter inlet grille	[m]
T_i	=	indoor air temperature	[K]
u_0	=	air supply velocity at inlet	[m/s]

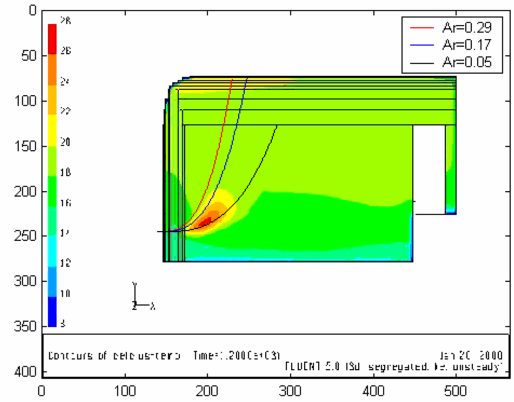

Figure 22. Trajectory of the air jet for different Archimedes numbers, resp. Ar=0.29, Ar=0.17 , Ar=0.05

A high Archimedes number indicates a high thermal upward component at high temperatures in combination with low velocities: the flow will rise to the ceiling quickly. A low Archimedes number represents airflow deep into the church.

8.4 *Organ stress analysis*

The results of the NMR measurements were used to predict the moisture content in a wooden element. From the results of the strain gauge measurement the free deformation of wood as a function of the measured moisture content was assumed to vary linearly with moisture content (Camuffo, 1998). A linear elastic 2D strain and stresses model was used to reproduce the strains and stresses in a wooden organ pipe and a wooden wind drawer (Lekhnitskii, 1963). A block shape change of a sudden drop in relative humidity was simulated. The drop in RH was simulated from 85 to 25 % RH. The first simulations took place with a wooden organ pipe with cross square dimensions of 100 mm * 100 mm * 5 mm. The cross section was taken at the place of the tuning cap. The wood direction of the tuning cap was assumed to be perpendicular to the wood direction of the pipe. Due to the drop of humidity at the outline of the pipe, the wooden pipe will shrink, which is limited by the tuning cap. Stresses will be the result.

Figure 24 shows the moisture content of the square section, one hour after the drop in RH.


Figure 23. Wooden organ pipe with tuning cap

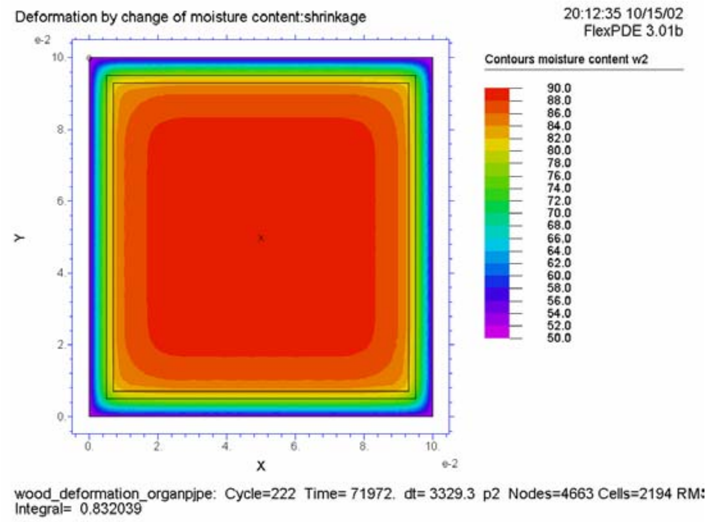

Figure 24. Moisture content in a wooden organ pipe at the cross section of a tuning cap

Figure 25 shows the calculated stress σ_x along the outer perimeter of the square section. The order of magnitude is 10^7 N/mm^2.

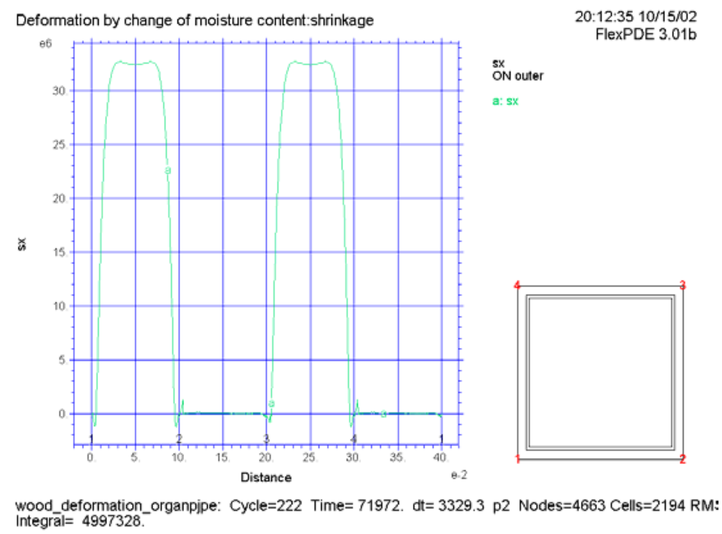

Figure 25. Stresses σ_x along the outer perimeter of the square section

When we look at the order of magnitude of the stresses in both simulation studies, $\sigma \approx 10^7$ N/m^2 (10 N/mm^2), and compare these results with the maximum allowed stresses of hard wood parallel to the fibers (ft;0;rep=14 N/mm^2), and in the direction perpendicular to the fibers (ft;90;rep = 0.4 N/mm^2) cracks will probably occur parallel to the fibers. Therefore cracks in the wooden organ pipes could be explained by changes in relative humidity. In the model, however, no relaxation was involved. In practice the situation might be less critical.

9 CONCLUSIONS

In comparison to e.g. the measured air temperature stratification of floor heating, the temperature stratification with air heating may be very large. The hot air heating system in the Walloon Church in Delft led to a large thermal stratification (up to 15K over the height of the church). Very high air temperatures (up to 30 to 35 °C) have been measured at the height of the monumental organ. These were the result of a combination of too high air inlet temperatures and too low air inlet velocities. Dramatic low relative humidities near the monumental organ resulted from these conditions. The organ proved to be in a very bad state. Measured air conditions and simulations of stresses in wood showed that the damage to the organ was the result of excessive shrinkage of the wooden parts.

Reducing the Archimedes number can reduce the temperature stratification. This can be accomplished by reducing the temperature difference between inlet air and indoor air to e.g. 25 K and to increase the inlet air velocity. The latter is needed to keep up the heating capacity.

To predict the effects of changing air temperature, velocity and the heating rate the dynamic air heating can be modelled by CFD: Computational Fluent Dynamics.

A new air heating system was proposed. The new inlet conditions were based on a combination of low inlet air temperatures (up to 40 °C) and high air velocities (up to 4 m/s), leading to an Archimedes number less than 0.05. Afterwards the air stratification proved to be less than 2 K over the total height of the church.

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