CFD STUDY ON A LOCAL RADIANT HEATING SYSTEM AND THE RESULTING INDOOR CLIMATE

Dionne Limpens-Neilen[1], Mariëlle Schoffelen[1], and Henk Schellen[1]
[1]Eindhoven University of Technology, Unit BPS, Vertigo floor 6, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
Email: d.limpens.neilen@bwk.tue.nl http://sts.bwk.tue.nl/friendlyheating/

ABSTRACT

This paper is about the application of a local (radiant) bench heating system in a church. This local heating system could be a nice alternative to heating the large air volume of the building, because it radiates the heat to the people directly without influencing the overall indoor climate of the church. This would save energy costs and reduce the risk of damaging the monumental building and its interior, but it would still provide human thermal comfort. In this paper, the modeling in CFD and the verification of this CFD model, as well as the resulting local indoor climate is presented.

INTRODUCTION

The energy costs for heating large rooms/buildings are usually quite high. Especially when it concerns large spaces with only a small zone in which thermal comfort is needed. A local heating system could be a nice solution for minimizing the heating costs, but still providing human thermal comfort.

To address this issue, in this paper a part of the European research project “Friendly Heating” is presented, in which the performance of a local bench heating system in the church of Rocca Pietore in Italy (Dolomites) is investigated [FH].

Apart from the high energy costs, there is another problem in the church when it is heated during winter. In order to heat the air in the church for the service in Rocca Pietore, this air is heated rapidly using a hot air heating system (T_{supply}=70°C), thus introducing abrupt variations in temperature and, more importantly, in the relative humidity of the indoor air. These variations have been known to cause damage to the monumental building and its interior objects, e.g. organ, wooden sculptures, paintings etc [Schellen 2002].

In order to find a solution, a local bench heating system was designed, of which several prototypes were tested. First, the CFD model of this local bench heating, as well as the verification of the CFD results with help of measurements is presented. After that, the influence of the local heating system on the overall (whole church) and the local (in and around the benches) indoor climate in the church is shown.

LOCAL BENCH HEATING SYSTEM

Three heating elements are combined into a local bench heating system. Figure 1 shows the position of the heating elements in the church bench. The prototypes of the heating elements consist of two types of electrical heat sources: heating foil and heating resistance cables.

The heating foil of the brand Thermotex, consists of glass fabrics that are impregnated with electrical conducting plastics "PTFE-Carbon". Tin plated copper foils are stitched to the edges of the heating foil as bus bars. The electrical insulation is obtained by laminating a compound of polyester/polyethylene foils. This heating foil is used in the elements that are placed in the back and under the seat of the bench. The power supply of the heating foil is 220V. The electrical wires are concealed in gutters which are placed underneath the wooden floorboard.

Seat heating element

The heating element applied under the seat of the pews is a semicircular element with a length of 99 cm and a radius of 11 cm. Two heating elements, each with a load of 155W, are applied in one pew. The element is designed to radiate heat to people’s legs. To prevent overheating of the seat, which can cause the wood to crack, insulation is applied behind the heating foil. So the heat is only radiated to the floor and the front and back of the bench. In order to

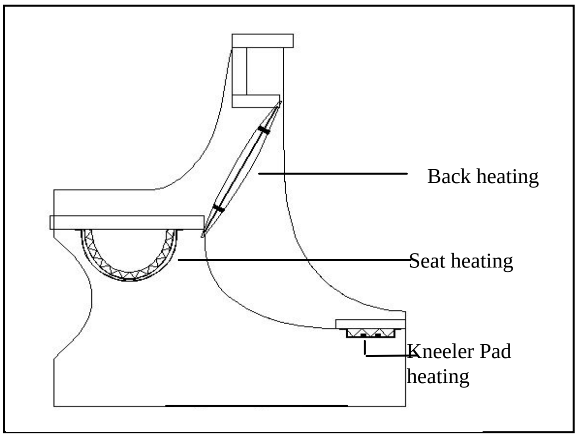


Figure 1. Position of the heating elements

protect the heating foil, it is covered with a perforated metal grid that is kept at a distance of 1 cm from the foil with help of spacers. The perforation rate of the metal grid is 50% so the IR radiation from the heating foil can reach the people directly. The maximum temperature of this grid is 35°C, thus prevent people from burning their skin or clothes when touching the heating element.

Back heating element

The dimensions (l × w × h) of the back heating element are 200 × 2 × 35 cm^3 and its electrical load is 370W. In this element, the heating foil is covered on both sides (back and front) by the metal grid mentioned before. The metal grid in this heating element is also kept at a distance of 1 cm from the foil using spacers. The heating element is attached between the back and the seat; in fact it closes the back of the bench and radiates the heat to the front and the back.

Kneeler pad element

The heating element that is applied beneath the kneeler pad consists of an electrical resistance wire (Raychem Electromelt EM2-R) that is folded double. The electrical resistance of the wire has a positive temperature coefficient and increases when the temperature of the wire increases. Therefore the wire has a peak load of 970W right after switching on the power and decreases to 130W when the equilibrium temperature is reached after about 3 minutes. To prevent overheating of the kneeler pad, which can damage the wood, insulation is applied between the electrical resistance wire and the kneeler pad. This combination of insulation and heating wire is covered with a metal sheet. The sheet is heated and then radiates to the wooden floorboard and people's feet that are placed beneath this kneeler pad.

CLIMATE ROOM SET-UP

Introduction

Non-stationary time and place dependent air flows in the church, make it very complicated to study the effect of the heating system on the local climate in the real situation. Therefore, as a first step, we used a stationary controlled environment (climate room set-up). This allowed us to investigate how the local bench heating system should be modeled in CFD, and to perform the measurements needed for the verification of the CFD model.

The climate room which is used, is a research facility at the Eindhoven University of Technology. For this research, the room boundaries (walls, ceiling and floor) are controlled at a temperature of about 6°C, which is about the average indoor air temperature during the winter in the church in Italy. In the climate room (l*w*h = 970*520*270cm^3), a measurement set-up is built around three church benches that are equipped with the prototype of the local bench heating system (see figure 2)

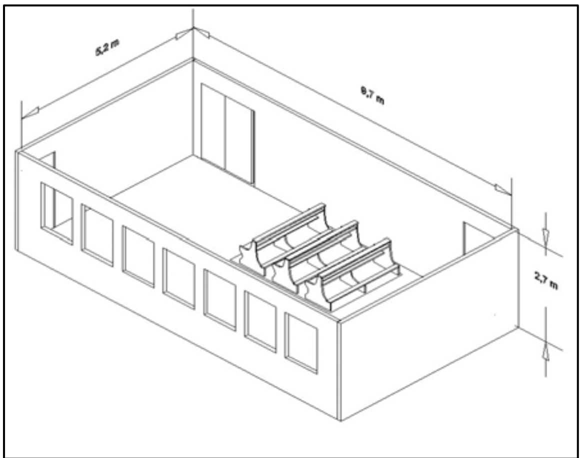


Figure 2. Overview of climate room with three church benches

Table 1. Overview of the specifications of the heating elements in the measurement set-up

POSITION	SHAPE	PROTECTIVE COVER OF THE ELEMENT	HEAT SOURCE	LENGTH [cm]	WIDTH [cm]	HEIGHT [cm]	ELECTRICAL POWER [W]	NUMBER OF ELEMENTS PER PEW	MAXIMUM TEMPERATURE [°C]
seat	semicircular	metal grid, 50% open	Electrical foil	99	Radius = 11		155	2	35
back	rectangular	metal grid, 50% open	Electrical foil	200	2	35	370	1	30
kneeler pad	rectangular	metal sheet	Electrical Resistance wire	200	9	2	130 (start peak 970W)	1	55

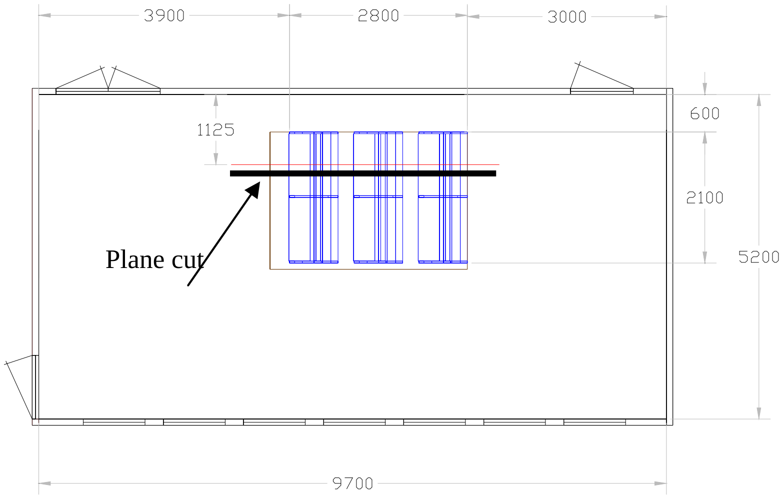


Figure 3. Overview dimensions (mm) of climate room, benches and plane cut.

Figure 4. Plane cut (measurement positions between the benches)

Measurements

The measurements for the verification of the CFD model are performed in a plane cut in the bench area (see figure 3). The plane cut is located at 112.5cm from the wall boundary of the room. The benches are placed at 60cm from this wall, thus the measurements are performed at ¼ of the length of the bench. The parameters measured in this plane cut are surface temperatures, air temperature and air velocity. The air temperature was measured at 16 positions on the measuring grid using Negative Temperature Coefficient (NTC) sensors. The surface temperature was also measured using NTCs at 24 positions (on the benches, heating elements, wooden floorboard and the room boundaries). The air velocity was measured using 8 hot sphere anemometers (Dantec). The anemometers were placed at the 8 most important positions determined on the basis of smoke tests performed earlier. A picture of the measurement positions in the plane cut is presented in figure 4.

The detailed results of the measurements can be found in [Schoffelen, 2003] and [Limpens-Neilen et al. 2004].

COMPUTER SIMULATIONS

Within this research, the CFD package Fluent, version 6.1.22 was used [Fluent 2003]. A multi-grid CFD model was built, in which the model of the benches (model A, small grid cells of about 3cm) and the model of the climate room (model B, larger grid cells growing from 3 to about 21cm) are merged into one according to figure 5. The model is build using Cartesian coordinates, in which a structured grid is applied. The grid cell distribution as well as a picture of the laboratory set-up in the climate room is presented in figure 6.

The idea behind the multi-grid model was to verify the proper modeling in CFD of the local heating system with help of the climate room set-up. After that, we should be able to apply this verified bench model in the CFD model of the whole church.

Within this CFD model, the equations for Flow, Turbulence, Energy and Radiation (Discrete Ordinates) were solved. The discretization schemes used for these equations are: Standard, SIMPLE, and the First Order Upwind scheme for Momentum, Turbulence Kinetic Energy, Turbulence Dissipation Rate and Energy.

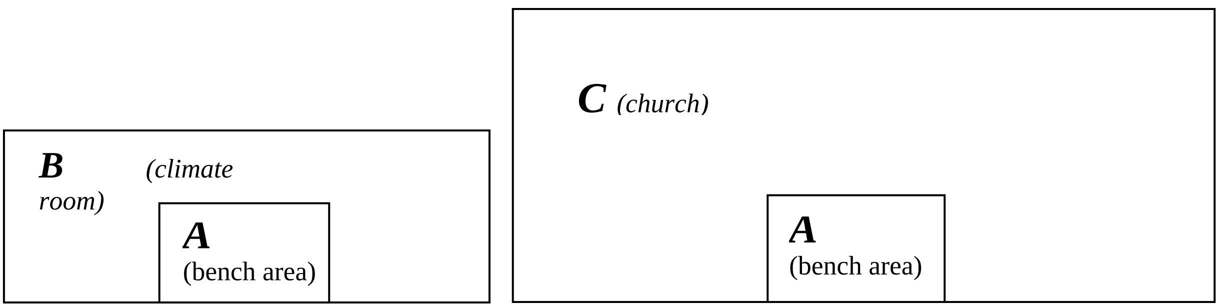


Figure 5. Multi-grid approach. left: bench model (A) coupled to the climate room model (B). right: bench model (A) coupled to the church model (C).

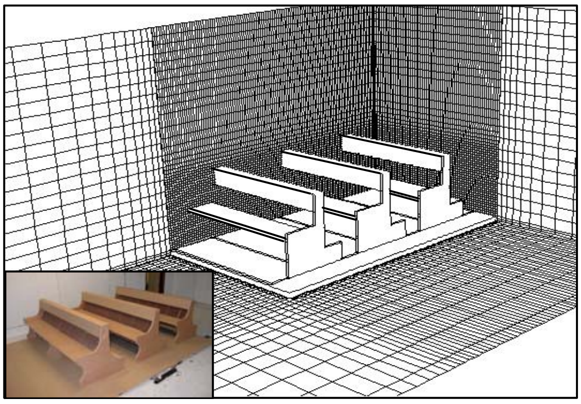


Figure 6. Climate room set-up: photograph and the CFD geometry with grid cell distribution.

The standard k-ε model and the RNG k-ε model, both with standard wall functions, were used to perform the first CFD simulations. Because the heat was not introduced by forced ventilation, but by radiation and natural convection from the heating elements, the Boussinesq approximation was used for the air density. In case of a buoyancy driven air flow problem, a steady state solution cannot be achieved. Therefore a transient computer calculation was performed, with time steps of 10 minutes, and 200 iterations per time step. The radiation model used was the Discrete Ordinates model.

Table 2 presents the dimensions and boundary conditions of the heating elements, used for this first simulation. Instead of implementing the seat heating elements as a combination of insulation, heating foil and a metal grid, they were implemented as solid blocks with a fixed temperature (average value of the temperature of the foil and the grid) and an emissivity of 0.9 [-]. Only these heating elements below the seat where operated during this computer simulation.

From a former PhD research that was carried out at our research department [Loomans 1998], the knowledge about how to build the CFD model and what boundary conditions should be used for simulating the situation in the climate room at the University in Eindhoven with help of CFD, was obtained. The measured boundary conditions for the walls, ceiling and floor are applied in the model, and as a first grid type, a structured grid was used.

Table 2. Overview of dimensions and boundary conditions of the heating elements

POSITION	SHAPE	LENGTH [cm]	WIDTH [cm]	HEIGHT [cm]	FIXED TEMPERATURE [°C]
seat	rectangular	204	21	9	40
back	rectangular	204	2	35	--
kneeler	rectangular	204	9	2	--

COMPARING CFD RESULTS WITH THE EXPERIMENTAL DATA

The comparison of the CFD results with the experimental data is done both qualitatively and quantitatively.

Qualitative verification

Figure 7 presents the qualitative comparison in air velocity between the simulation results and measurements (smoke tests). The figure shows, that the direction in air movement in both measurements and simulations is quite the same.

Figure 8 presents the qualitative comparison in air temperature between the simulation results and measurements (IR thermography). The pictures in this figure show the same tendency in the temperature distribution in and around the church benches.

Quantitative comparison

To get an idea of the accuracy of the used models in CFD, we present a comparison between the CFD results and the results of the performed indication measurements. Since it is hard to validate CFD results with only a few measurement points in such a complicated air flow and temperature distribution, more detailed measurements are being carried out at our laboratory.

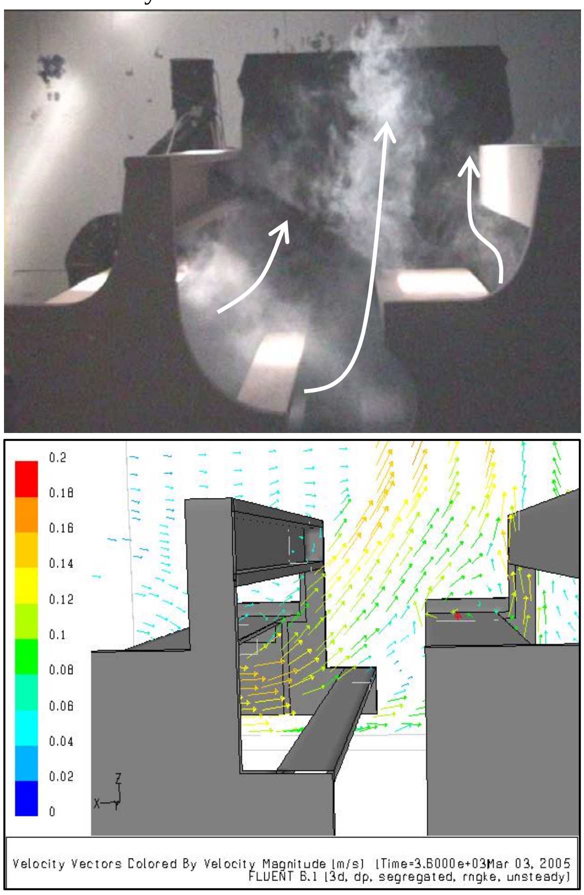
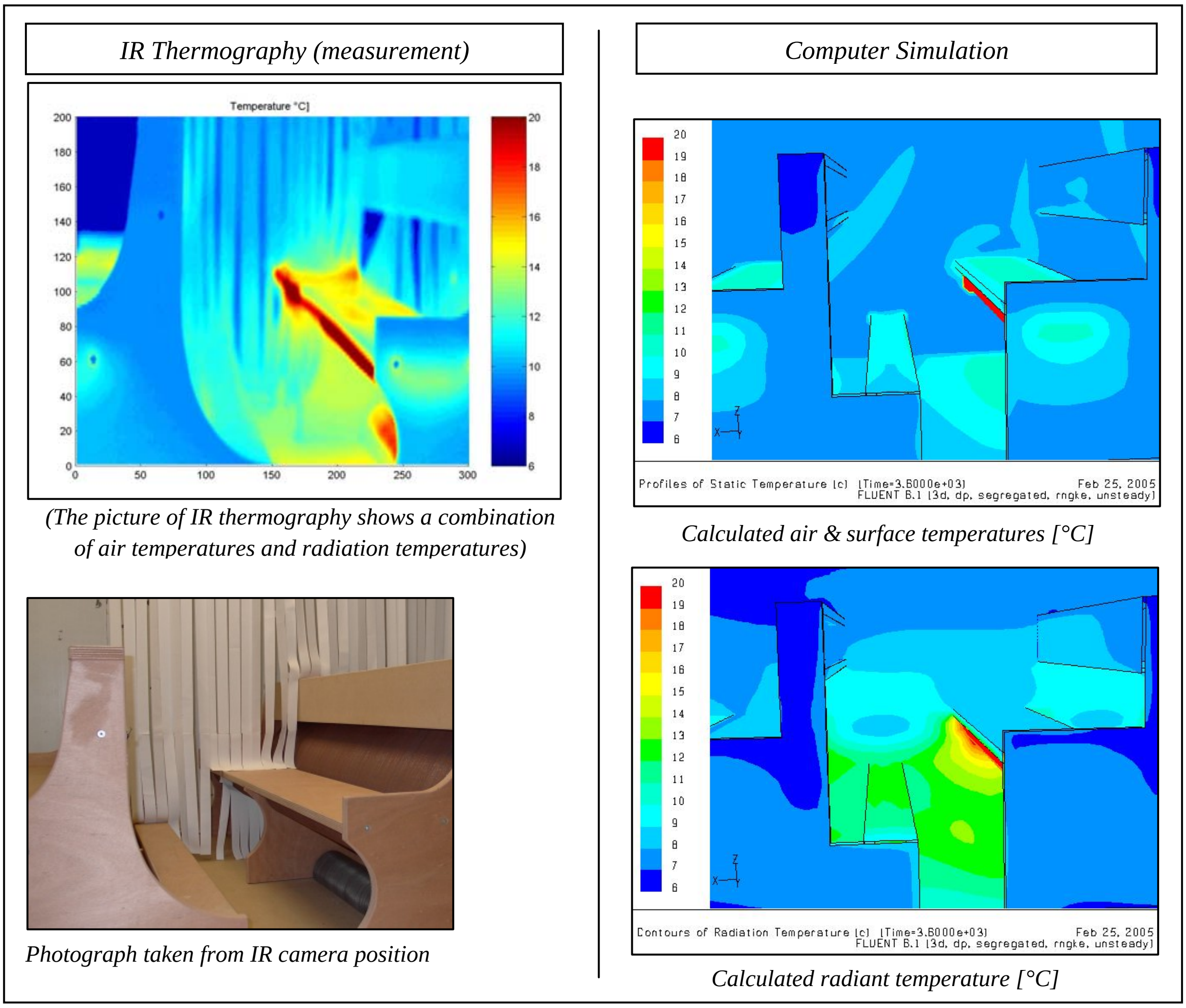


Figure 7. Top: Air flow visualization by smoke tests. Bottom: Calculated air velocity [m/s]



(The picture of IR thermography shows a combination of air temperatures and radiation temperatures)

Photograph taken from IR camera position

Calculated air & surface temperatures [°C]

Calculated radiant temperature [°C]

Figure 8. Qualitative comparison between measured temperatures (left) and calculated temperatures (right)

Figure 9 shows the quantitative comparison of the air and surface temperatures over a vertical line in the plane cut after operating the heating element under the seat for one hour. It shows that there is a reasonable agreement between the measurements (Ta_m, Ts_m) and the simulation results (T_sS= standard k-ε model, T_sRNG = RNG k-ε model) . The surface temperature of the wooden floorboard is increased from 6 to 10°C, and the temperature of the seat is increased from 6 to 14°C. The air temperature right beneath the seat is also higher, because the seat prevents the warm air coming from the heating element to rise up directly. Figure 10 shows the same kind of comparison, but now for a horizontal line right through the upper surface of the kneeler pads. The surface temperature of the kneeler pad which is calculated in the CFD simulation corresponds to the measured surface temperature. But, when we look at the air temperature sensors, a difference (with a maximum of 1.3K) between the measurements and simulation results is noticed. This deviation mainly occurs at the sensors that are positioned in the sight of the heating system and can be explained by a radiation effect from the heating system on the air temperature sensors. In further research, a radiation shield should be applied to measure the real air temperature instead of a kind of "operating temperature", which is a combination of the air temperature and the radiant temperature at the sensor position. In figure 11 and 12, the quantitative comparison of the air velocity is presented. This comparison is performed over the same vertical and horizontal line as the verification of temperatures.

Table 3. Dimensions and boundary conditions of the heating elements applied in the church

POSITION	SHAPE	LENGTH [cm]	WIDTH [cm]	HEIGHT [cm]	FIXED TEMPERATURE [°C]
seat	rectangular	204	21	9	40
back	rectangular	204	2	35	30
kneeler	rectangular	204	9	2	35

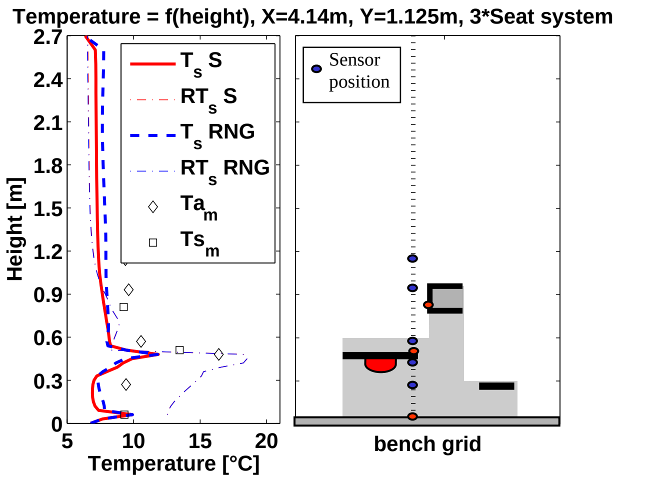


Figure 9. Comparison of temperatures over a vertical line at the back of the seat

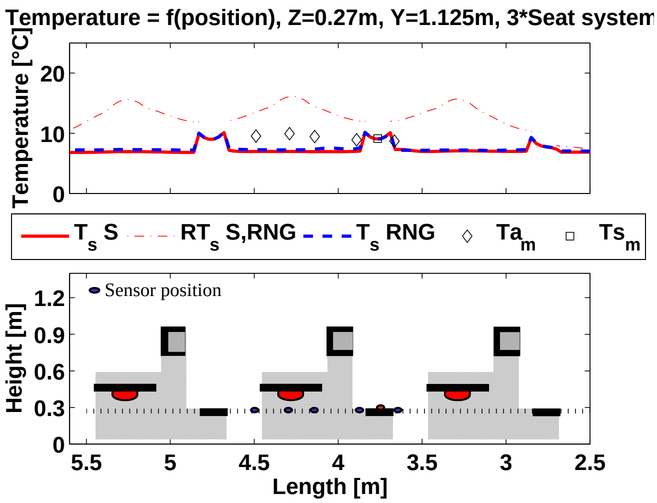


Figure 10. Comparison of temperatures over a horizontal line at kneeler pad height

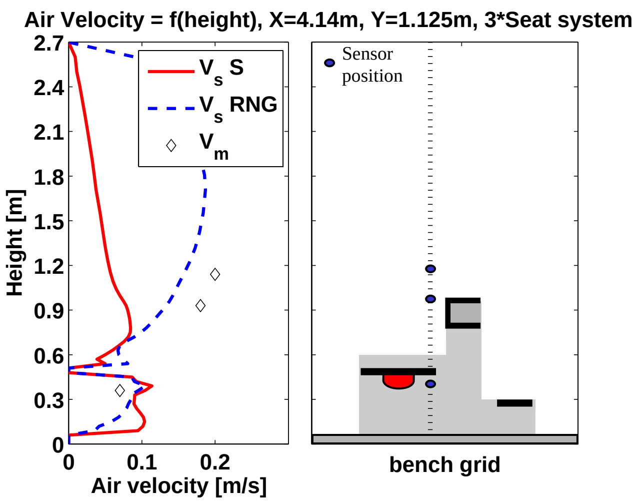


Figure 11. Comparison of air velocity over a vertical line at the back of the seat

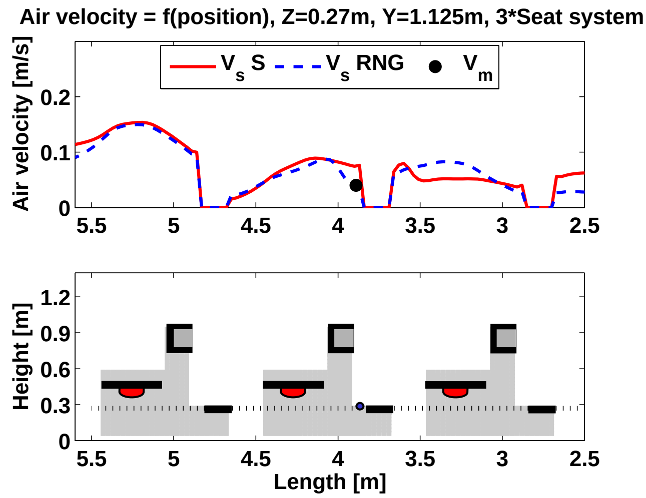


Figure 12. Comparison of air velocity over a horizontal line at kneeler pad height

APPLICATION OF THE LOCAL BENCH HEATING SYSTEM IN THE CHURCH

Figure 13 shows the multi-grid CFD model of the church in Rocca Pietore. In this model, the verified CFD model with the small grid cells, model A, is merged several times with the CFD model of the whole church, model C (see also Figure 5). The boundary conditions of the heating elements are presented in table 3.

The CFD results presented in figure 14, show the air temperature and the radiant temperature between the church benches when all three heating elements are operated. From these pictures we can see that the radiant temperature under the seat (at the legs of the people) reaches 15 to 20°C. But the radiant temperature at the level of the upper body only reaches 10 to 12 °C. This (maximum) radiant temperature is already reached after 15 minutes. But the air temperature between the benches rises slowly from 6°C at the beginning (when switching on the heating system) to about 12°C after the heating system is operated for one hour.

In this paper, people which are seated in the benches are not taken into account. Therefore, no conclusions can be drawn for thermal comfort. We do know that the people receive the radiation from the heating elements. The people in the benches also prevent the air from flowing horizontally through the benches, which decreases the risk on draught because the air velocity near the people remains rather low. The situation with people in the benches will be investigated in ongoing research.

DISCUSSION & CONCLUSIONS

From the first comparison between the CFD results and the measurements, we can conclude that there is a reasonable agreement in case the RNG k-epsilon model is used. The CFD model of the three benches equipped with the heating elements (model A) will be merged with the CFD model of the whole church (model C). In ongoing research, the CFD models will be further improved by using different viscous models, radiation models and discretization schemes. Also the grid (in)dependency will be checked in ongoing research.

In this case study, the local radiant heating system seems to be a nice alternative for the “old” hot air heating system that heats the whole air volume of the church. First, the heating capacity of the local system is lower than that of the churches hot air heating system. Secondly, whereas the hot air heating system needs to be operated for several hours before the service starts, the local heating system needs only to be operated from 15 minutes before the service until the end of it. Besides, if only a few people attend the service, not all benches have to be heated. Therefore, the heating costs of the local bench heating system will be lower than those of the hot air heating system.

From the viewpoint of thermal comfort, more research has to be performed in order to rate the human thermal comfort in the church benches. The situation is very complex, because it is a quite cold indoor climate (6°C), in which people are wearing thick winter cloths while sitting very still in the benches. At the moment, a parallel study on this thermal comfort is being carried out at our department.

ACKNOWLEDGMENT

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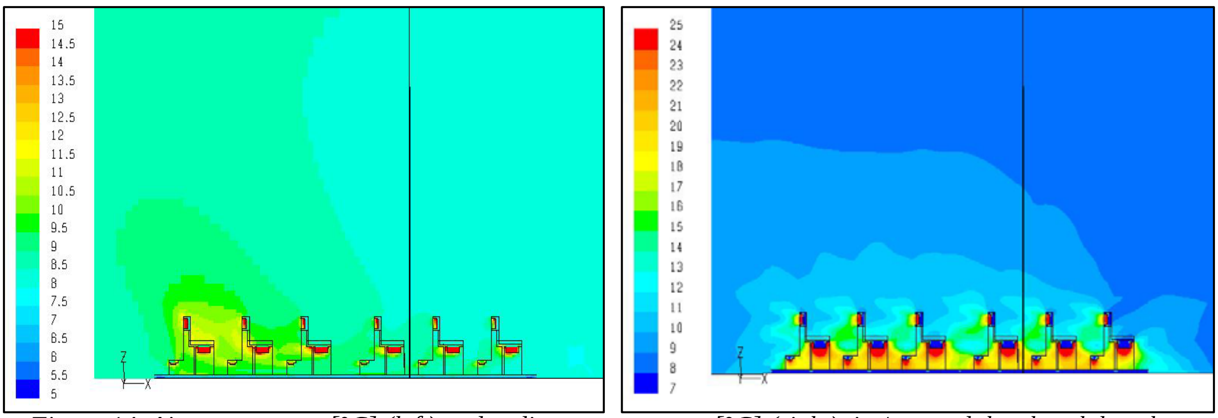

Figure 14. Air temperature [°C] (left) and radiant temperature [°C] (right) in / around the church benches.