EXPERIENCIES OF PREDICTING TRANSIENT SURFACE TEMPERATURES

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ABSTRACT

The thermal performance of a building is closely related to both energy consumption and thermal sensation. Therefore, the thermal environment within a building is a key issue when assessing thermal comfort and dimensioning heating devices. Predicting transient surface temperatures requires physically reliable modeling, and integration of a heating device and heat transfer through building structures. A fireplace is selected as an example of a highly time-dependent heating device. Transient thermal behaviour of a test fireplace, and interaction between this heating device and building elements are modeled. All models are based on conservation of energy, and multi-mode heat transfer is allowed. Thermal radiation is taken into account by including surface net radiation components, and an improved progressive refinement method (IPRM) is applied to solve the surface radiosities in a room. The simulation results are presented in 3D graphics, and the results are compared with empirical data with quite good agreement.

INDEX TERMS

Temperature, Fireplace, Simulation, Measurements

INTRODUCTION

Both measurements and simulations are widely used to predict building surface temperatures. However, thermal interaction between heating devices and building structures is rarely documented in highly transient conditions. The aim of this study is to present experiences of predicting surface temperatures by comparing the measured and simulated surface temperatures during a cyclic heating of a fireplace in a laboratory test chamber.

METHODS

When comparing the measured and simulated transient surface temperatures, a fireplace is selected as an example of a highly time-dependent heating device. The measured surface temperatures were obtained by monitoring a full-scale fireplace in laboratory conditions, and thermal behaviour of the similar system was also simulated by a new building simulation tool BUS++ (Tuomaala et al. 2002).

Laboratory measurement arrangements

A wood-burning fireplace, with a separate combustion air inlet and flue gas outlet, was located in a test chamber (Figure 1) with a floor area of 12.67 m^2 (inside width 3.61 m, length 3.51 m, and height 2.89 m). The test chamber was located in a large laboratory hall. During the test, heat was generated by burning two batches of wood (3.76 kg at time 0 h, and 3.01 kg 45 min after the first batch) in the combustion chamber. The temperature of the air in the test chamber was controlled by a cooling coil with an air mixing fan and maintained at 20 °C,

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which is a typical indoor air temperature value in many homes. All surface and air temperatures, as well as temperature gradients within both the fireplace and test chamber structures were monitored every 60 s.

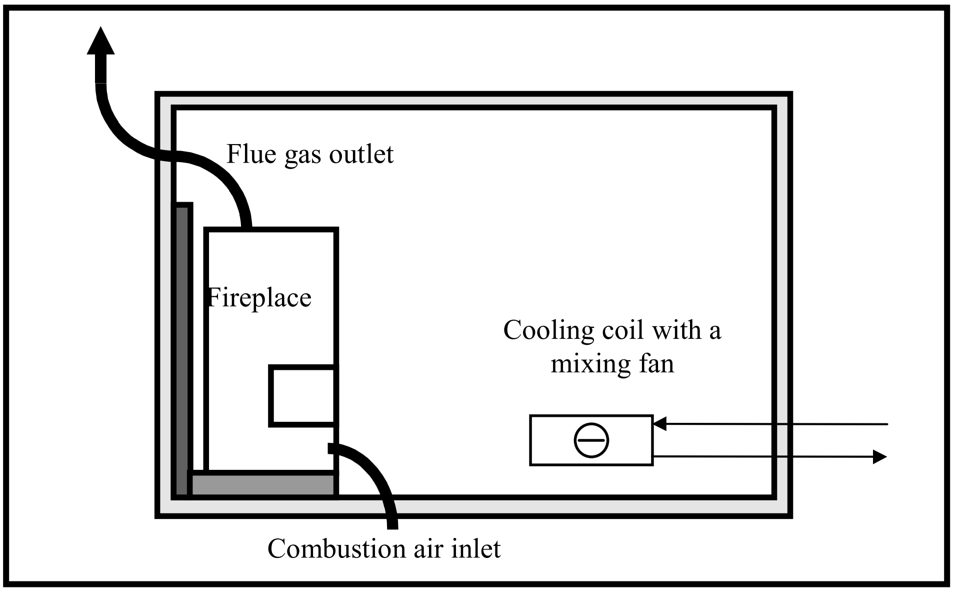

Figure 1. Test arrangements for the fireplace experiment.

The test chamber walls were made of 50 mm thick expanded polystyrene, and the thermal conductivity, density, and specific heat capacity were assumed to be 0.029 W m^{-1} K^{-1}, 60 kg m^{-3}, 800 J K^{-1} kg^{-1}, respectively.

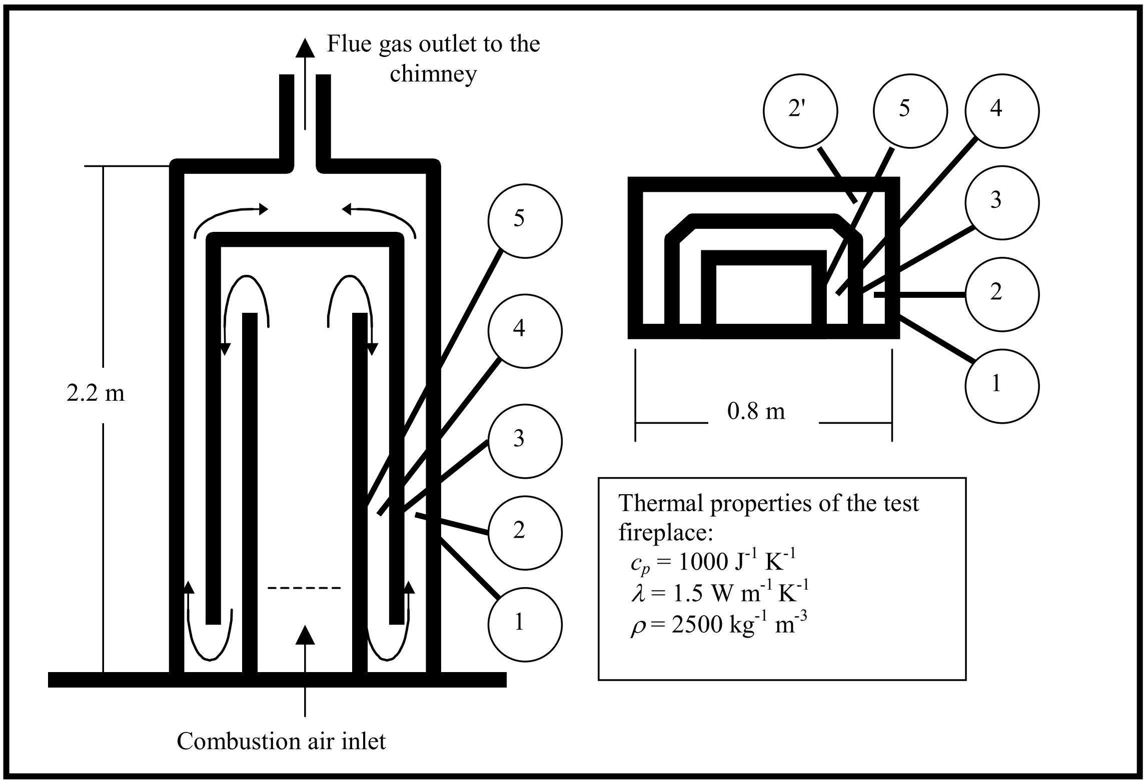

Figure 2. Inside structure of the fireplace showing the locations of the temperature measurements.

Figure 2 shows the internal structure of the test fireplace, and the estimated thermal properties of the fireplace material. Temperatures were monitored in flue gas channels (nodes 2 and 4 in Figure 2), and on the internal and external surfaces of the inner flue gas channel (nodes 1, and 3 in Figure 2). Perimeters of these layers were 1.0 m, 1.3 m and 2.8 m, and the thickness of these structures were 0.05 m, 0.05 m and 0.04 m, respectively. The total mass of the test fireplace was 1350 kg.

Simulation boundary conditions

Transient thermal behaviour inside the test fireplace and interaction with the test chamber are modeled. All models are based on conservation of energy, and multi-mode heat transfer (i.e., convection, conduction and radiation) is allowed. Thermal radiation is taken into account by including surface net radiation components both inside the fireplace and in the test chamber. An improved progressive refinement method (IPRM) is applied to solve the surface radiosities (Tuomaala and Piira 2000). All elements of the test fireplace and the measurement chamber are modeled by a thermal network allowing realistic temperature gradient inside the individual thermal elements and storage of heat (Tuomaala et al. 2000).

The heat power generation from the burning wood as function of time was modeled using the log-normal distribution function (Tuomaala et al. 2002)

$$q(t) = \frac{1}{t(\ln\sigma)\sqrt{2\Pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(t/\bar{t})}{\ln\sigma}\right)^2\right]. \tag{1}$$

The parameter values $\bar{t}_1$ = 18 min and $\bar{t}_2$ = 14 min (logarithmic mean time), and σ_1 = 1.9 and σ_2 = 1.9 (logarithmic standard deviation) were chosen for the two wood batches. The log-normal distribution function (Equation 1) was then scaled such that the integral of the power curve equaled the estimated net energy content of the wood (17.0 kWh and 13.6 kWh for the two burned batches). The heat emitted from the wood batches was divided into two parts: 30 % convection into the air of the combustion chamber, and 70 % thermal radiation from flames to the adjacent surfaces. All surfaces were assumed to have an emissivity of 0.93, which was an average value of manually measured surface emissivities.

RESULTS

Figure 3 presents the measured and simulated flue gas temperatures, and Figure 4 presents the measured and simulated inner flue gas channel surface temperatures of the fireplace during the first 5 h. In general, there is a quite good correlation between the measured and simulated flue gas temperatures at different locations in the test fireplace. However, the results clearly show the approximate nature of the log-normal heat power generation model used as a boundary condition for the simulation, while the real burning of wood logs proceeds in a somewhat random order causing unpredictable fluctuations of heat power generation in the combustion chamber. Another important observation can be noticed from Figure 3, which contains the measured temperatures at two different locations in the same flue gas channel (i.e., the measurement points 2 and 2' in Figure 2). Significantly higher temperatures (and air flow rates) are found in the enlarged corner of channel 2 (location 2') than in the middle of channel 2 (location 2). These results clearly show that the flow pattern inside this flow channel is not uniform as assumed in the simulations.

Simulation of the transient thermal behavior of the internal surfaces of the fireplace is quite reliable as shown in Figure 4. However, there are obvious deviations between the measured and simulated temperatures, especially during the burning phase. These deviations are partly due to measurement inaccuracies (i.e., the real location of the measurement points vs. the location of the simulated thermal nodes, and the actual measurement errors), but the main part of the deviations seems to be caused by inaccuracies in the heat power model (i.e., differences between the real and simulated transient heat power output from the wood batches).

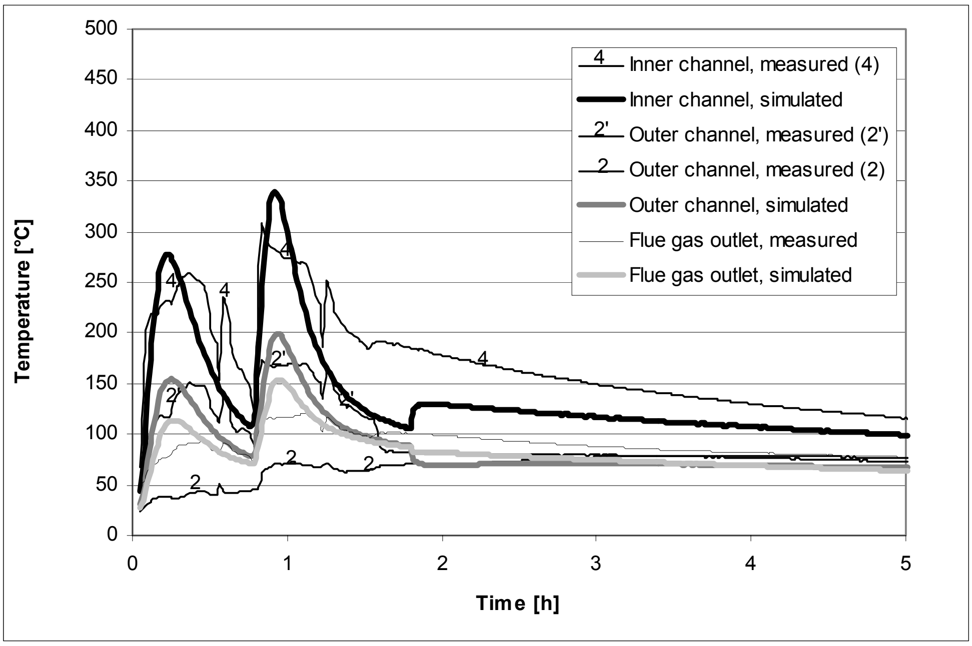

Figure 3. The measured and simulated flue gas temperatures inside the test fireplace during the first 5 h of the test run.

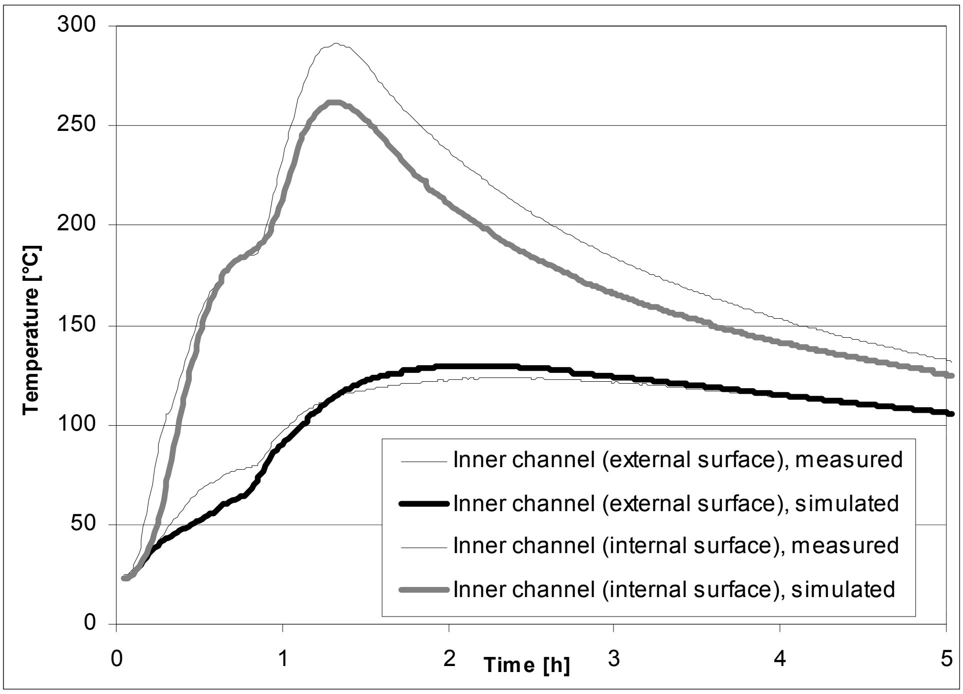

Figure 4. The measured and simulated inner channel (internal end external) surface temperatures of the test fireplace during the first 5 h of the test run.

Figure 5 shows the measured and simulated surface temperatures of both fireplace and the measurement chamber. These results show quite good agreement between measurements and the simulation. However, there are obvious deviations due to both simulation initial values and inaccuraces in predicting heat transfer in the early phase of the test run.

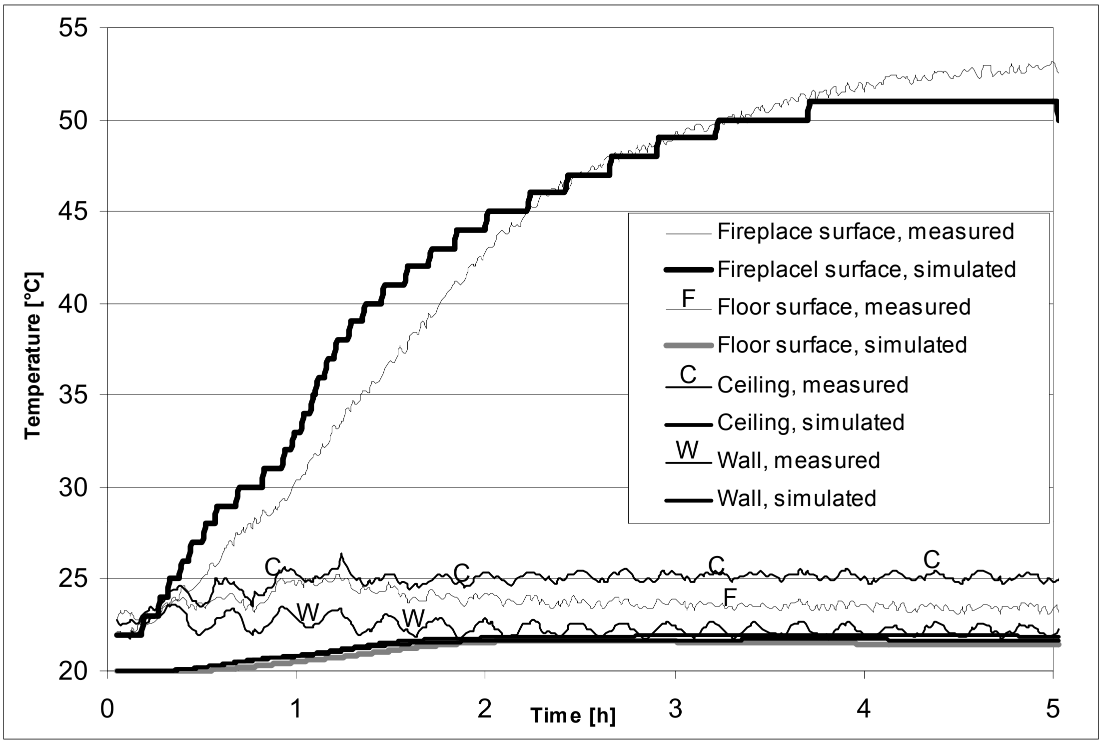

Figure 5. The measured and simulated surface temperatures [°C] of the fireplace and the measurement chamber during the test run of 24 h.

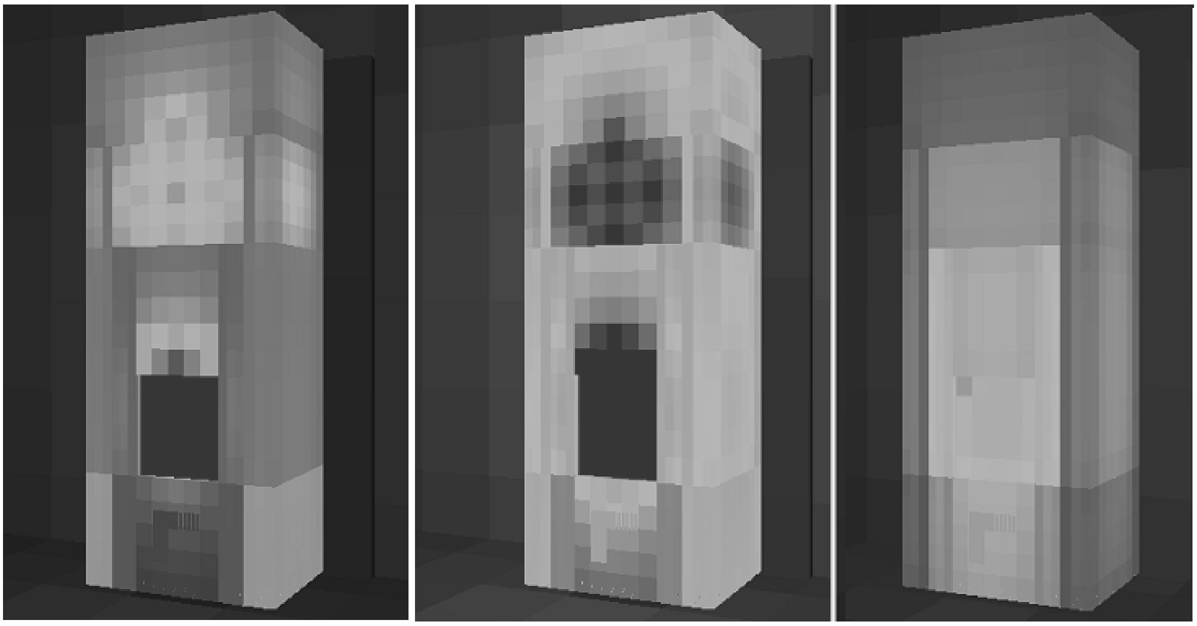
0.5 h *1.5 h* *14 h*

Figure 6. Simulated 3D graphics of the fireplace surface temperatures showing non-uniform gradients over the fireplace faces 0.5 h, 1.5 h, and 14 h from the beginning of the test run.

The simulated fireplace surface temperature results are presented in 3D graphics in Figure 6, where dark surfaces correlate with high temperature values. There clearly occurs temperature gradients, not only inside individual structures, but also across surfaces. This phenomena is due to non-uniform heat transfer from the combustion chamber to the fireplace surfaces. In addition, these surface temperature gradients have different shapes depending on time.

CONCLUSIONS

This study presents experiences of predicting transient surface tempetaratures. The measured and simulated surface temperatures are compared during a cyclic heating of a test fireplace in a laboratory test chamber. Simulation results are obtained by a new building simulation tool BUS++, which is based on concervation of energy allowing multi-mode heat transfer (i.e., convection, conduction and radiation).

The measured and simulated surface temperature results show quite good agreement. The simulated fireplace surface temperature results are presented in 3D graphics, and these results clearly indicate the need to understand internal heat transfer mechanisms of a heating device when predicting surface temperatures and overall heat transfer between a heating device and it's environment.

This study clearly shows the approximate nature of the log-normal heat power generation model adopted as a boundary condition for the simulation. In order to obtain more reliable simulation results, this model needs further development and more thorough testing.

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