Computational Modelling of the Impact of Solar Irradiance on Chemical Degradation of Painted Wall Hangings in an Historic Interior

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Abstract:
In this study Comsol Multiphysics is applied to simulate heat transfer with surface-to-surface radiation in the rear salon of a historic interior. Three walls in this room are covered with oil paintings on canvas. Currently, different degrees of chemical degradation can be observed on the wall hangings. This degradation may be attributed to temperature variations near the surface. The purpose of the Comsol model is to predict surface temperature and surface radiosity of the wall hangings based on the outdoor temperature, solar irradiation and building properties. The predicted thermal conditions can indicate possible scenarios that could have caused climate-induced chemical degradation of the paintings.

Keywords: Heat transfer modelling, solar irradiance, historic interior, chemical degradation

1. Introduction

The historic Hofkeshuis in Almelo, The Netherlands, locates a unique work of art: three walls in the rear salon on the first floor of the private house are covered with painted wall hangings [1]. The house was built around 1775 and the paintings date from 1778. Figure 1 shows the back side of the first floor of the Hofkeshuis and the interior of the rear salon is shown in Figure 2. The simple and similar pigmentation of the paintings, their original hanging, and the few cleaning interventions make it possible to use the degree of the formation of lead soaps, so-called saponification, as an internal marker for the chemical degradation of the oil paint. This degradation process that frequently occurs in oil paintings is described by [2]. Microscopic image analysis of paint samples revealed that that the degree of saponification at various positions on the paintings considerably differs. Because temperature and relative humidity can strongly influence chemical degradation processes of artefacts [3], a research project was started to investigate the relation between climate conditions of wall surfaces and lead soap formation. The results will be of importance for establishing climate guidelines for exhibition and storage spaces that house oil paintings of canvas.

Figure 1. Back side of the first floor of the Hofkeshuis (the annex on the ground floor is a modern addition). The first three windows from the left are those of the rear salon (photo: Cultural Heritage Agency of the Netherlands (RCE), 1974).

Figure 2. Interior of rear salon in the Hofkeshuis (photo: Cultural Heritage Agency of the Netherlands (RCE), 2004).

The present study consists of an experimental and numerical analysis of the indoor climate conditions in the rear salon of the Hofkeshuis. From October 2012, measurements of the indoor climate conditions in the salon have been conducted with combined temperature/relative humidity sensors and a thermographic camera. From 19 September 2013 at 12 p.m. until 20 September 2013 at 11.40 a.m., infrared thermographs of the north canvas were taken with a ten-minute interval. The analysis shows that the highest surface temperature difference occurred on 20 September at 9 a.m.: the maximum temperature difference was approximately 6°C during this time (Figure 3).

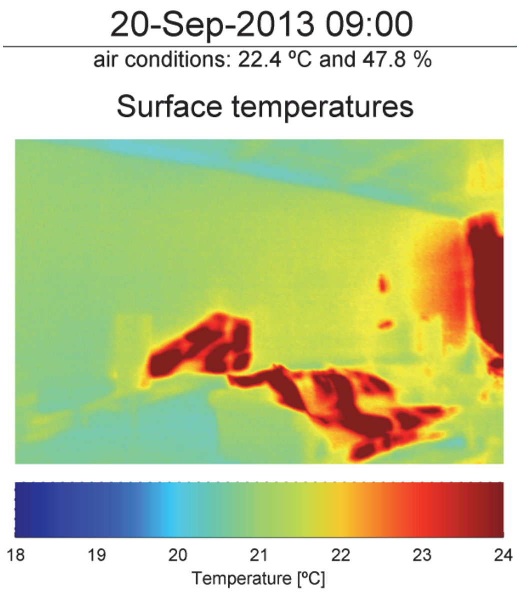

Figure 3. Infrared thermogram showing surface temperatures of the north canvas on 20 September 2013 at 9 a.m.

The numerical analysis was carried out with Comsol Multiphysics version 4.4. We expect that incoming solar irradiation in the salon critically affects the microclimate near the paintings and may therefore be an important cause of chemical degradation of the paint layers. The purpose of the Comsol model is therefore to calculate the surface temperature of the wall hangings during a summer period as a result of the outdoor temperature, wall conditions, air flow, and external radiation source. In comparison with multi-zone hygrothermal building simulation models that characterize the indoor climate by uniform values for radiant temperature, air temperature and relative humidity per zone, such as HAMBase [4], the advantage of the Comsol model is that microclimate conditions can be analysed at every position on the walls. This is of high importance for the present study that focuses on predicting local thermal conditions. Additionally, boundary conditions such as glazing types, curtains, and internal heat sources in the salon, can easily be adjusted in the Comsol model. In this way both the present indoor climate as well as the historical indoor climate can be simulated and assessed.

Section 2 describes the use of Comsol Multiphysics and explains the geometry and boundary conditions of the model. The validation of the model with on-site measurements and the analysis of the time-averaged surface conditions is described in Section 3. Section 4 contains conclusions and recommendations for future research.

2. Use of COMSOL Multiphysics

The Comsol model consists of a heat transfer with surface-to-surface radiation model with a solar position as an external radiation source. The model combines conductive heat transfer trough the building envelope, convective heat transfer through indoor air, non-isothermal flow in the indoor air, and radiant heat transfer. Because the prediction of local temperature in the air and walls is of high importance in the model, assuming a well-mixed air zonal model is insufficient [5]. Including CFD would therefore be required to predict temperature distributions in indoor air and the heat transfer between the indoor air and building materials. However, this would considerably increase the model complexity and the required calculation time. Therefore, in this simplified model, a constant convective heat transfer coefficient was assumed at the walls. The solar loading calculation includes all of the ambient surfaces of the model and the shadowing effects. All internal walls in the room, the external east façade and part of the south façade that is not permanently shaded by the adjacent building were modelled as irradiated surfaces.

A geometry of the salon was created with an external east façade, including three single-glazed windows, and an external south façade. The internal north wall and west wall, floor and ceiling were modelled as adiabatic walls. The outdoor temperature and solar irradiance were based on meteorological data that were collected at the building site. The paintings on canvas are fixed to wooden battens that are fitted to the wall. This was incorporated in the model by an air layer between the wall and canvas. The material properties for brick, concrete, glass and air were obtained from the Comsol materials database.

The heat transfer trough building envelopes is defined by Equation 1:

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \cdot \nabla T\right) = -\nabla(-k\nabla T) \quad (1)$$

where:
ρ = density [kg/m^3]
c_p = specific heat capacity [J/(kg·K)]
T = temperature [°C]
k = thermal conductivity [W/(m·K)]

The boundary condition for the heat flow rate q was defined as following:

$$q = h_{cv}(T_a - T_s) + h_r(T_r - T_s) + \sum_j a_j E_j - \varepsilon(\sigma {T_e}^4 - E_{at}) \quad (2)$$

where:
q = heat flow rate at surface [W/m²]
h_{cv} = surface coefficient of convective heat transfer [W/(m²·K)]
h_r = surface coefficient of radiant heat transfer [W/(m²·K)]
T_a = air temperature near the surface [°C]
T_s = surface temperature [°C]
T_r = mean radiant temperature perceived by the surface [°C]
T_e = outdoor temperature [K]
α_j = absorptivity of the surface for radiation of source j [-]
E_j = irradiance of radiant source j [W/m²]
ε = surface emissivity [-]
σ = Stefan-Boltzmann constant [W/(m²·K^4)]
E_{at} = Atmospheric radiation [W/m²]

Table 1. Model properties

Physics module	Conjugate heat transfer with surface-to-surface radiation
Solar position	Latitude: 52.357 Longitude: 6.665 Time zone: 1
External surface coefficient of convective heat transfer	25 W/(m²·K)
Internal surface coefficient of convective heat transfer	7.7 W/(m²·K)
Surface emissivity	0.9
Glass refractive index	1.5

A user-controlled mesh was applied: the building envelopes were composed of free tetrahedral elements calibrated for general physics with a normal element size, and the air volumes were composed of free tetrahedral elements calibrated for fluid dynamics with a normal element size. The mesh consists of 112,667 elements (Figure 4). The simulated periods varied between 14 and 21 days with a time interval of one hour. Longer periods could not be analysed due to long calculation times and required computational resources. To maintain good convergence of the nonlinear solver, the maximum time step was set at 15 minutes.

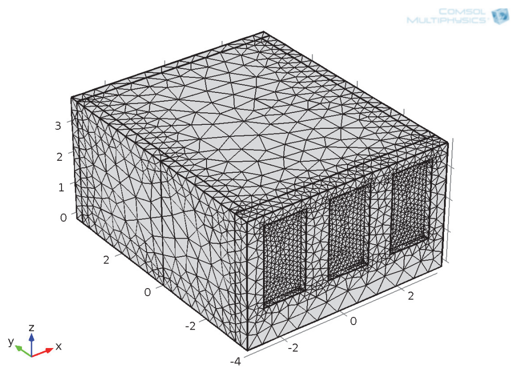

Figure 4. Mesh consisting of 112,667 elements

3. Results

3.1 Model validation

The microclimate conditions at various positions on the wall hangings were compared to the observed degree of formation of lead soaps at these positions. Four positions were investigated in the present study: position A is located nearby the northeast corner of the room, position E is nearby the northwest corner, position K is nearby the southeast corner and position I is approximately 1.5 m right from the centre of the south wall. Samples at these positions indicated a high degree of saponification at position A, a middle degree of saponification at position E and a low degree of saponification at position K and I (Figure 5).

The room is heated by two radiator panels that keep the temperature to approximately 21 °C during the day and 18 °C during the night. The model was validated for the month September 2013 because both surface temperature measurements and infrared thermograms were available for this month.

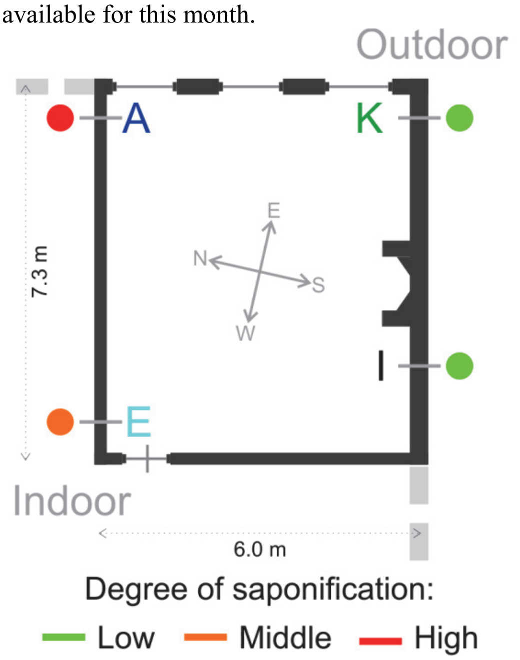

Figure 5. Plan of the room indicating sample locations and observed degree of saponification

Figure 6 and 7 give a comparison between the measured and simulated surface temperature at the four positions. The Comsol model was able to generate an adequate prediction of the surface temperatures of the two positions on the north wall, position A and E: the simulated temperature varies within a range of ±1 °C from the measurements. For position K, the measured temperature fluctuations are considerably higher than the simulated temperature fluctuations: although the minimum temperatures are approximately equal, daily fluctuations up to 4 °C were measured, while the daily fluctuations in the Comsol model were 2 °C at maximum. It could be possible that the impact of solar irradiation on the surface temperature at position K is not correctly modelled. For position I, the simulated temperature is approximately 1-2 °C higher than the calculated temperature. The Comsol model may underestimate the heat loss through the external wall.

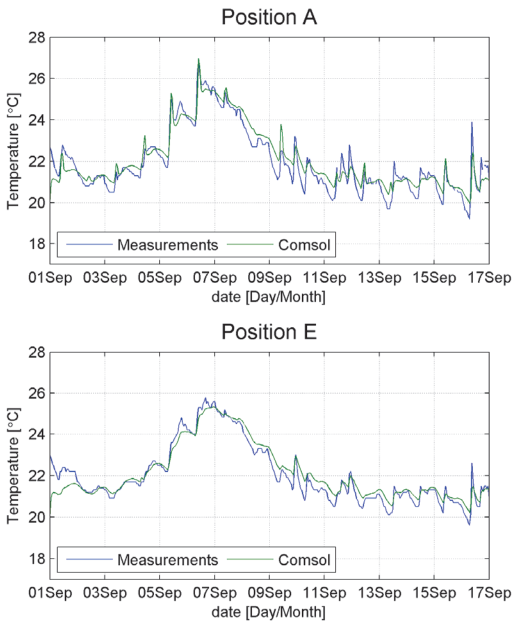

Figure 6. Comsol model validation, position A and E

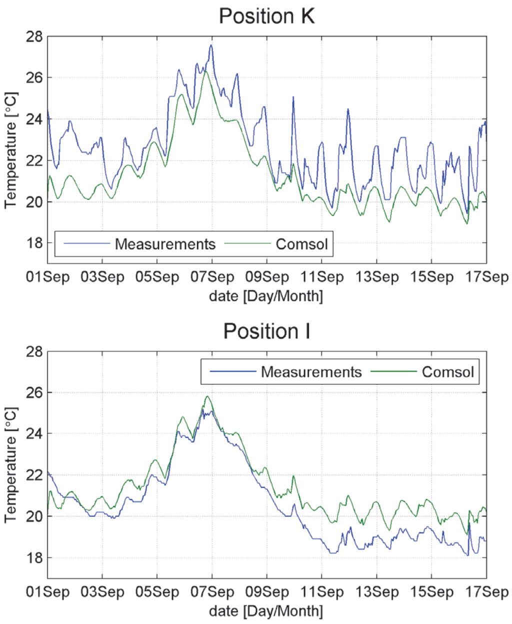

Figure 7. Comsol model validation, position K and I

3.2 Surface temperature analysis

In this section, the measured indoor and outdoor air temperature and surface irradiation from 1 until 21 July 2013 were applied to predict surface temperatures in one of the warmest months during the research period. The results are compared with the observed degree of saponification at various positions on the paintings. Figure 8, 9 and 10 visualise the surface temperature of the north wall on 2 July: at 9 a.m., incoming solar irradiation affected a large area of the wall, but the surface temperature differences on the wall were small (1-2 °C). Surface temperature differences up to 4 °C were calculated around 12 a.m., but the warmest area covered only a small part of the north wall. Around 3 p.m., the surface temperature differences were less than 1 °C.

Figure 11 shows the average surface temperature of the north wall from 1 until 21 July 2013. It can be seen that incoming solar irradiation affected the surface temperature to a distance of approximately 3 m from the window. The average surface temperature of the north wall varied between 23.3 and 24.0 °C.

The average surface temperature of the south wall during the 3-week simulation period is shown in Figure 12. Because the right part of the wall is permanently shaded, the left part of the wall has a slightly higher average surface temperature than the right part. The average surface temperature of the south wall varies between 22.0 and 22.6 °C.

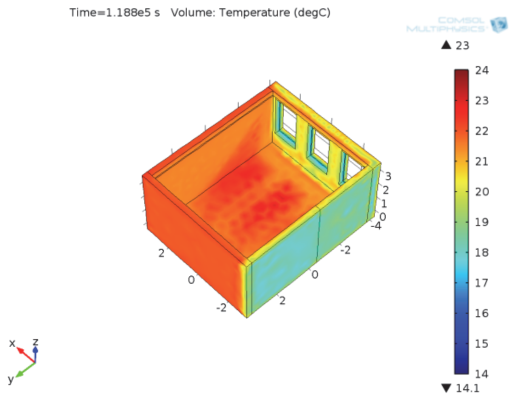

Figure 8. Surface temperatures on 2 July at 9 a.m.

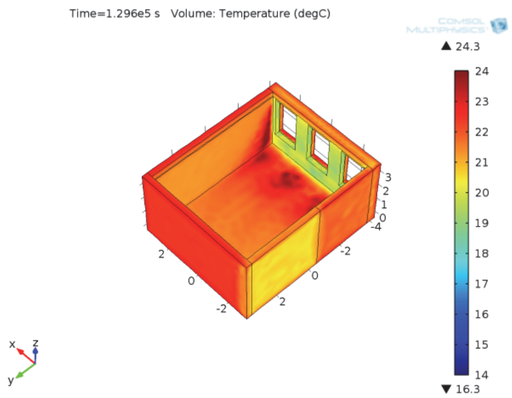

Figure 9. Surface temperatures on 2 July at 12 a.m.

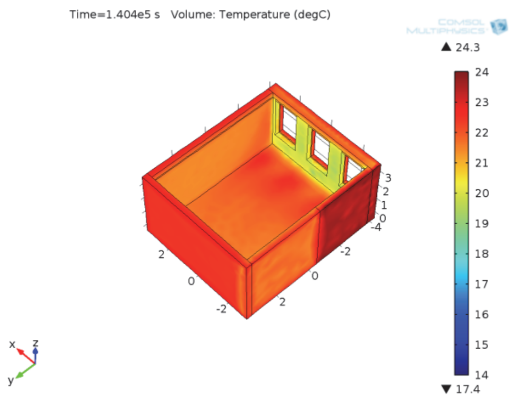

Figure 10. Surface temperatures on 2 July at 3 p.m.

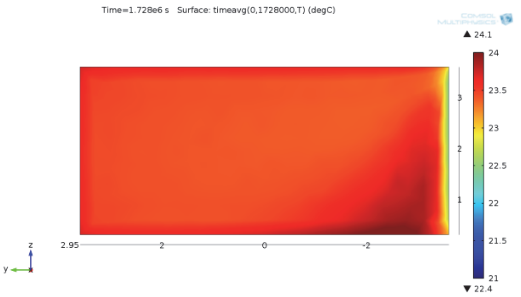

Figure 11. Average surface temperature of the north wall from 1 until 21 July 2013

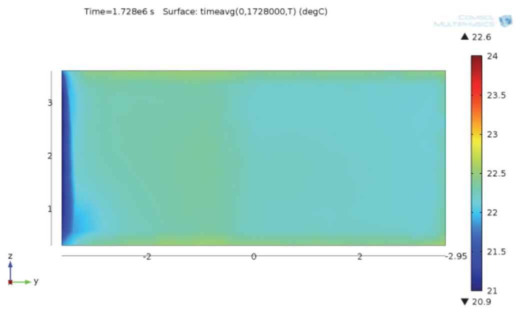

Figure 12. Average surface temperature of the south wall from 1 until 21 July 2013

4. Conclusions and recommendations

The Comsol model was able to generate an adequate prediction of the surface temperature of the north wall, but more research is required to obtain a correct validation of the surface temperature of the south wall. The experimental and numerical analyses did not indicate significant surface temperature differences between the four positions on the wall hangings: the maximum calculated surface temperature difference is approximately 4 °C between position A and E, and 1 °C between position K and I. The average surface temperature of the north wall in July 2013 is 1-2 °C above the average surface temperature of the south wall. Further research will be carried out to investigate if these small temperature differences could have caused a considerable difference in chemical degradation of the oil paintings.

To improve the Comsol model, two limitations of the present model will also be addressed in future research: (1) The Comsol model assumes well-mixed air in the room. To model convective heat transfer more accurately, a turbulence model should be included. (2) Some material properties and dimensions are based on estimations. Additional measurements will be carried out to obtain boundary conditions that are more accurate.

5. References

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7. Acknowledgements

This work was supported by European Commission funding through the EU Climate for Culture project 226973 within FP7-ENV-2008-1 and by the Netherlands Organisation for Scientific Research (NWO: Innovational Research Incentives Schemes Vidi Grant) within the research project: 'From isolation to coherence: an integrate technical, visual and historical study of 17th and 18th century Dutch painting ensembles'. The authors would like to thank Ruud Börger of Comsol Multiphysics for providing technical support.