Heat, Air and Moisture (HAM) modeling of historic windows

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Abstract: Regarding the thermal resistance of the external envelop of buildings, windows are the weakest places. This is especially true for historic windows with original single pane glazing in historic buildings. To reduce the energy consumption and to improve thermal comfort of historic buildings, replacing these windows by modern double glazed windows would be a logical choice. The authentic character of these buildings, however, would be affected too much. Therefore, special effort has to be given to this kind of windows.

There are a number of ways to improve the thermal performance of these windows. One approach is to add a single glazing pane from the inside or outside to the existing single pane glazing, making use of a (ventilated) cavity. To predict the thermal performance of these windows, a multi-physical simulation approach is necessary.

The paper will deal with the modeling approach of these types of glazing. The typical total thermal transmittance of these windows will be calculated, making use of the three-dimensional thermal bridge coupling effects on the thermal performance of the glazing panes. Comsol will be used to solve the multi-physical coupling of the differential equations for Heat, Air and Moisture (HAM).

The results of the three-dimensional simulations have been compared with measurements in a so-called hot-box measurement laboratory device and also with in-situ measurements. Generally, good results are obtained by numerical simulation, compared to measurement results. For a number of glazing types, 1-dimensional calculations by hand give a good impression of the thermal performance of rather complex glazing configurations. Surface temperatures of the glazing panes, risks on condensation and energy losses can be estimated with a reasonable accuracy. If the boundary conditions are more complex and if ventilation of air in the cavity is introduced, calculations by hand are not sufficient or possible anymore and more complex computer simulations like with COMSOL are necessary.

Keywords: Windows**,** historic, modeling, heat, air, moisture, thermal bridges.

1. Introduction

Originally, old buildings were hardly insulated. At that time that was not necessary, because energy supplies seemed to be endless and prices of energy were very low. At that time thermal comfort was treated in another way: if one felt cold, he put on a pullover. The energy crises and the Report of the Club of Rome awakened us of the ending character of fossil energy supplies.

Therefore, newly built dwellings are insulated well. Old buildings are insulated afterwards. Originally, the windows were one of the weakest points of thermal insulation. They mostly consisted of single glazing. To improve the thermal quality, the choice of double glazing seemed obvious. The groove of the windows was often too small, or the mass of the windows became too large for the mechanical construction. Moreover, historic windows are most important for the esthetic view of the exterior of historic buildings. The exchange of historic, authentic windows by modern ones may affect the authentic view of the building in a severe way. See figure 1.

Figure 1: Replacement of single glazing in a wooden window frame by standard double glazing in a plastic window frame. Photographs: E.J. Nusselder

That is why alternatives have been introduced: additional glazing at the in- or outside of the original glazing with a non- or ventilated cavity, vacuum glazing and other slim profile, double glazing (1,2).

2. Additional in- or outdoor glazing

2.1 additional indoor glazing

In a museum climate with a rather high relative humidity of approximately 50%, surface condensation at the inside of a single pane glazing would already occur at outdoor temperatures of less than 5^{o}C. For reasons of thermal comfort or to protect windows from surface condensation, additional glass panes are added to the single glazing therefore. Because of the authentic external view the additional glazing in museums is mostly added to the inside of the original single pane. From the point of view of building physics this technical solution is right, if the indoor glazing is air tight and the cavity between in- and outdoor glazing is ventilated from the outside. If the indoor glazing is not air tight, surface condensation may occur at the inside of the original single pane.

2.2 Additional outdoor glazing

To protect valuable leaded (church) glazing against vandalism, but also to protect it from corrosion by condensation, an additional glass pane is placed at the outside of the original pane. Also in this case outdoor ventilation of the cavity mostly is a good choice. But if condensation occurs in this way, it is at the inside of the original, valuable leaded window, because of the cooling at the entrance of cold winter air. See figure 2, right. That is why internal ventilation often is applied (figure 2, left).

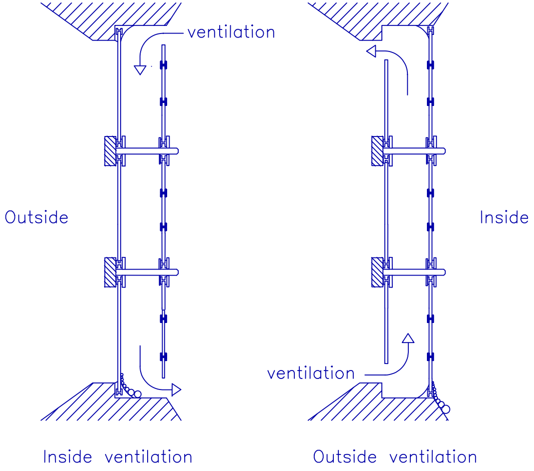

Figure 2: Additional glazing and ventilation of the cavity

3. 2D calculations

To be able to calculate the thermal and hygric effects of this type of glazing and ventilation, a 2D calculation of the window system with outdoor or indoor ventilated cavity is a good method of approach, if 3D corner effects are not important. For the calculation it is necessary to include a thermal calculation, a hygric approach and to include the air velocity. That is why the

calculation with a multi physics program like COMSOL is obvious.
The COMSOL model is based on the following equations for steady state conditions:

Thermal transport by conduction and convection:

$$\nabla\cdot(-\lambda\nabla\theta) = -\rho c_p \vec{u}\nabla\theta \tag{1}$$

ρ = Density [kg/m^3]
c_p = Constant pressure specific heat [J/kg.K]
$\vec{u}$ = Air velocity [m/s]

Vapour transport by diffusion and convection:

$$\nabla\cdot(-\frac{\delta}{\mu}\nabla c) = -\frac{\vec{u}}{RT}\nabla c \tag{2}$$

c = Vapour concentration [kg/m^3]
δ = Water vapour permeability [s]
μ = Vapour diffusion resistance number [-]
R = Specific gas constant for water vapor [J/kg.K]
= 462 J/kgK

Incompressible air flow:

$$\rho\vec{u}\nabla\vec{u} = \nabla\cdot\left[-pI+\eta(\nabla\vec{u}+(\nabla\vec{u})^T)\right] \tag{3}$$

$$\nabla\cdot\vec{u} = 0 \tag{4}$$

I = Identity matrix [-]
p = Pressure [Pa]
η = Dynamic viscosity air [Pa.s]
= 1.7E-5 Pa.s

The stationary boundary conditions were:
Thermal:

$$q = h_o\cdot(\theta_o - \theta_s) \tag{5}$$

q = Heat flux at surface [W/m^2]
h = Heat transfer coefficient [W/m^2.K]
h_i = 7.7 W/m^2.K
θ_i = 20 ^{o}C
h_e = 25 W/m^2.K
T_e = 0 ^{o}C
Hygric:

$$g = \frac{\beta_o}{\rho}\cdot(c_o - c_s) \tag{6}$$

g = Vapor flux at surface [kg/m^{2}s]
β = Vapor transfer coefficient [kg/m^{2}s]
β_i = 7.1E-3 kg/m^{2}s
c_i = 0.5*csat(θ_i)=0.0088 kg/m^3
β_e = 22.9E-3 kg/m^{2}s
c_e = csat(θ_e)=0.0035 kg/m^3
csat = Saturation concentration [kg/m^3]

Air flow:
u_o = inlet velocity [m/s]
u_o = 0 (no ventilation)
u_o = 0.1 (no insulation in gap, assumed on basis of earlier cavity measurements)

Indices:
o,i,e : environmental
s : surface

4. Results

The figures below show the results of a stylistic 2D geometry of a double glazed window with a ventilated cavity.

4.1 Internal ventilation

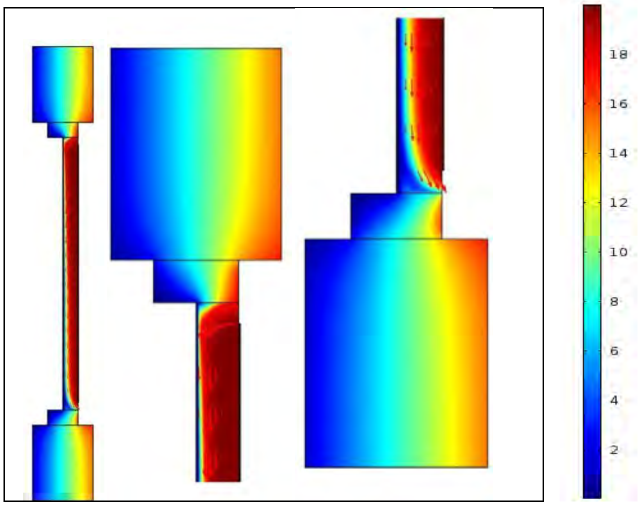

Figure 3: Temperatures in a vertical indoor ventilated window section

Fig 3 shows the temperatures in a vertical section of the window with internal ventilated cavity. We can see the entrance of the warm indoor air (20^{o}C) at the upper right corner of the window section.

The air is cooled down at the left, cold outdoor window pane and leaves the cavity with a lower air temperature of approximately16^{o}C. Near the cold external window pane we can observe that the air has been cooled down to approximately 4^{o}C.

This is far below the dew point temperature of 9.3^{o}C and therefore condensation at the lower left cavity side of the external window pane will occur.

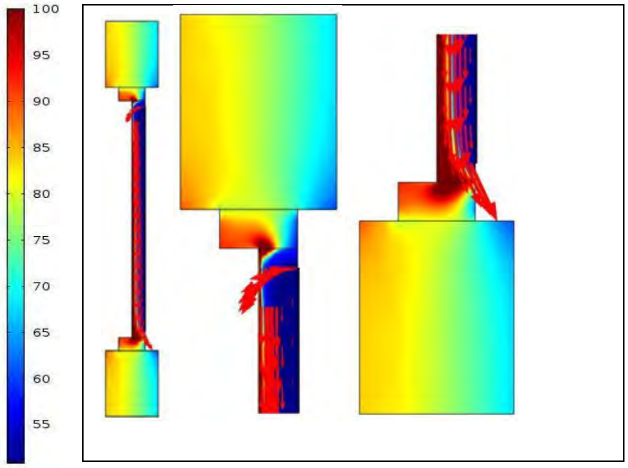

Figure 4: Relative humidities in a vertical indoor ventilated window section

Figure 4 shows the hygric effects. The relative humidity in the vertical section of the window construction is presented. One can see that the air enters the cavity at the upper right corner of the window section with a relative humidity of 50% (museum condition). Because of the thermal cooling down of the air at the external left window pane, the relative humidity increases until it reaches 100%RH at the lower part of the cavity. Thus, condensation at the lower left cavity part of the external window pane is the result.

4.2 External ventilation

The temperatures in the external ventilated window section are presented in Figure 5. The cold outdoor air (0^{o}C) enters the cavity at the lower right part of the window construction and is heated up by the warm internal window pane. Because of the heating up of the air, the air density decreases and an upward flow in the cavity is the result of it. The air leaves the plane with an air temperature of approximately 12^{o}C.

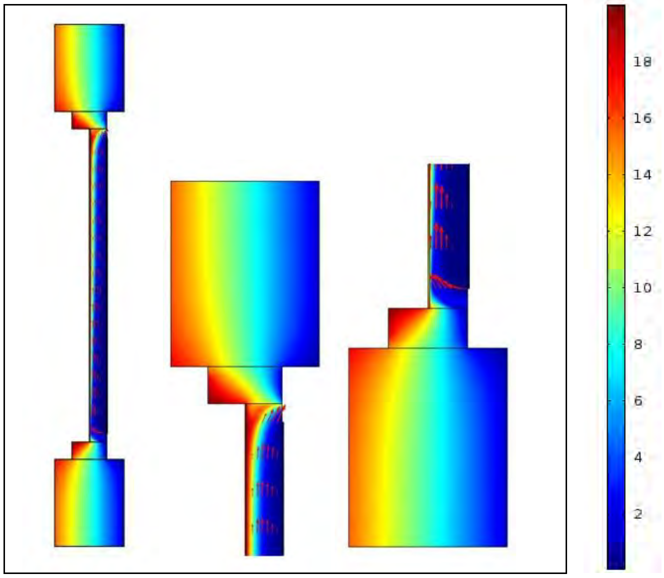

Figure 5: Temperatures in a vertical outdoor ventilated window section

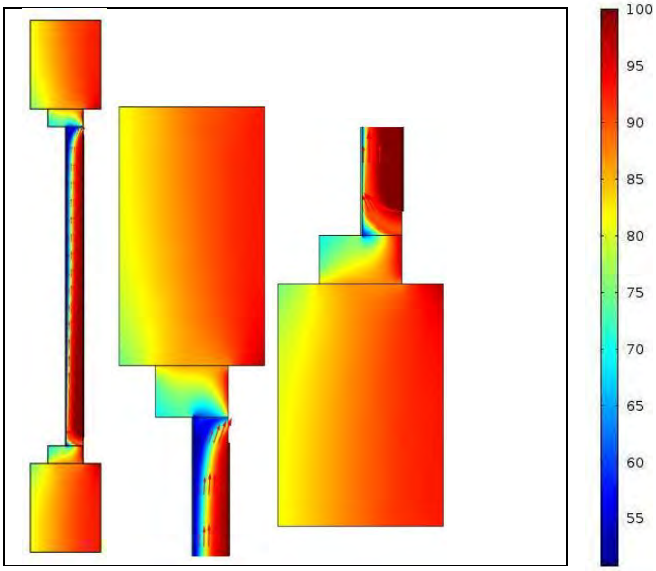

Figure 6: Relative humidities in a vertical outdoor ventilated window section

In Figure 6 the relative humidity is presented. The outdoor air enters the cavity with a relative humidity of the outdoor air of about 100%RH. Because of the heating up of the air, the relative humidity decreases and the air leaves the cavity with a relative humidity of approximately 85%RH. Nowhere in the cavity the relative humidity reaches 100%RH and therefore no condensation occurs in the cavity. The cold air, however, cools down the lower part of the internal pane and higher relative humidities might occur at the lower inner part of the internal pane.

5. Measurements

When making calculations a number of assumptions have to be made. In 1D calculations 1D assumptions have to be made, while the real transport might be 2D. The same counts for 2D calculations: 3D effects might be important. Heat- and moisture boundary transfer coefficients are assumed to be constant and known, while reality is different: they are a function of the air velocity and not exactly known. Material properties are looked up in a table, while they might have been measured. To become an order of uncertainty in the calculations, measurements on mock-ups of window systems are done in a so-called hotbox-cold-box measurement setup. A hotbox-cold box consist of 2 climate chambers, in between a mock-up of of the window system is placed. Figure 7 indicates such a device. Figure 8 shows the mock-up of the ventilated window systems.


Figure 7: Hot-box device TU/e

6. Verification

The U-value of the window mockup was measured (3) and compared with the calculated U-value by COMSOL. The results of the calculations were within the measurement error of 10%.


Figure 8: Mock-up of in- and outdoor ventilated window systems

7. Conclusions

In earlier times one had to make models for this kind of building physical problems by programming in a programming language like Fortan or Pascal (3). Later on, more sophisticated mathematical software like Matlab was used. Custom made software for calculating for example thermal bridge problems was developed by (5). A multiphysical programming package like COMSOL, however, is able to solve this kind of problems too, and a lot more, in a rather convenient way. Furthermore, an extension to 3D and with more sophisticated physical properties like radiation, air flows etc., is rather easy within the possibilities of COMSOL.

8.References

1. Baker, P. (2008). Thermal performance of traditional windows. Centre for Research on Indoor Climate & Health, Caledonian University Glasgow, Scotland.

2. Baker, P. (2010). Slim-profile double glazing. Centre for Research on Indoor Climate & Health, Caledonian University Glasgow, Scotland.

3. COMSOL (2011). Comsol Multiphysics software, version 4.2. COMSOL, inc. US, www.comsol.com.

4. Oidtmann, S.J.C. Schellen, H.L. (1992). Schutzverglasung vor historischen Glasgemälden, eine theoretische Betrachtung. Artikel Bauphysik (D) Oktober 1992, Heft 5, pp 138-145

5. Oidtmann, S.J.C. (1994, December 6). Die Schutzverglasung, eine wirksame Schutzmaßnahme gegen die Korrosion an wertvollen Glasmalereien. TUE: Technische Universiteit Eindhoven (255 pag.) (Eindhoven: Technische Universiteit Eindhoven). Prom./coprom.: prof.ir. J. Vorenkamp & prof.ir. N.A. Hendriks. Coaching ir. H.L. Schellen.

6. Physibel (2012). Physibel Pilot Book version2. CDROM. Physibel c.v. Consulting Engineers, Maldegem, Belgium.

7. Schellen, H.L., Schijndel, A.W.M. van & Briggen, P.M. (2008). The use of COMSOL for Building Constructions Engineering regarding Heat and Moisture transport. In *European COMSOL Conference, Frankfurt* (pp. 1-8).

8. Schellen, H.L. & Oidtmann, S.J.C. (1992). Physical model to predict surface condensation on naturally ventilated church windows. In A.Th. Vermeltfoort (Ed.), *Research on building structures and building physics : proceedings of an interuniverity research seminar, Eindhoven, November 18-20, 1992* (pp. 89-100). Eindhoven: University of Technology.

9. Schellen, H.L., Schot, B., Oidtmann, S. (1994). Surface condensation on leaded windows and the indoor climate of a church. Paper presented at the European Simulation Multiconference Barcelona 1994

10. Schellen, H.L., Schijndel, A.W.M. van & Neuhaus, E. (2008). The use of finite-element software to solve hygrothermal builiding physical problems related to insultating high rise buildings facades. In Hensen (Ed.), *IBPSA-NVL 2008 Event* (pp. 1-9). Eindhoven: IBPSA.