Heat transfer evaluation of a window with a "hot box" set-up in a 18th century stone building by using COMSOL software

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Preface

First of all, I would like to mention Magnus for introducing me to the hot box world, a technique that I had not heard before but that has been very interesting to develop the thesis on it. The visits we made to Rådhuset were fascinating. I have also greatly appreciated your suggestions and ideas to improve the document.

On the other hand, I want to thank Arman, for helping me and giving me hints on how to use COMSOL software. You were always willing to help me with any problem with COMSOL.

Last but not least, I want to mention my family, my mother, my father and my little sister, who have supported me since I started studying engineering 6 years ago.
Abstract

The hot box technique is an experimental method to achieve the U-value of elements in stationary conditions; however, it is not always possible to work in stationary conditions in real world. This thesis consisted of evaluating the heat transfer of a window of a historical building with a unique hot box set-up. The window had a low emissivity plastic film to improve thermal efficiency, and the hot box was unique because the outside temperature could not be controlled. The applicability of the hot box technique to dynamic conditions was assessed using COMSOL Multiphysics 5.3. COMSOL Multiphysics is a finite element method solver software with a heat transfer module. Two heat transfer simulations were conducted in 2D based on the indoor and outdoor temperature when the hot box was in operation. First, a stationary study was carried when the outdoor temperature remained stable for 1 day. Then, the study was extended to a transient study to analyze in detail the effect of the external temperature fluctuations for 5 days. The results indicate that a cautious approach should be taken when applying the hot box technique under transient conditions, but that stationary conditions could not be achieved during one day. Nevertheless, the reliability of the simulation solution could have improved more.

Keywords: window, hot box, simulation, COMSOL, outdoor, dynamic.
Nomenclature

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>ΔT</td>
<td>Temperature difference</td>
<td>(ºC)</td>
</tr>
<tr>
<td>q</td>
<td>Heat flux</td>
<td>W·m⁻²</td>
</tr>
<tr>
<td>Q</td>
<td>Heat transfer rate</td>
<td>W</td>
</tr>
<tr>
<td>U</td>
<td>Thermal transmittance</td>
<td>W·m⁻²·K⁻¹</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity</td>
<td>W·m⁻¹·K⁻¹</td>
</tr>
<tr>
<td>h</td>
<td>Heat transfer coefficient</td>
<td>W·m⁻²·K⁻¹</td>
</tr>
<tr>
<td>ε</td>
<td>Emissivity</td>
<td>-</td>
</tr>
<tr>
<td>σ</td>
<td>Boltzmann constant</td>
<td>W·m⁻²·K⁻⁴</td>
</tr>
<tr>
<td>c</td>
<td>Specific heat</td>
<td>kJ·kg⁻¹·ºC⁻¹</td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
<td>m·s⁻¹</td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity</td>
<td>kg·m⁻¹·s⁻¹</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>m²·s⁻¹</td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
<td>m·s⁻²</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg·m⁻³</td>
</tr>
<tr>
<td>H</td>
<td>Height</td>
<td>m</td>
</tr>
<tr>
<td>d</td>
<td>Depth</td>
<td>m</td>
</tr>
</tbody>
</table>

Abbreviations and acronyms

<table>
<thead>
<tr>
<th>Letters</th>
<th>Description</th>
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<tbody>
<tr>
<td>Low-e</td>
<td>Low-emissivity</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional, integral and derivative</td>
</tr>
<tr>
<td>2D/3D</td>
<td>2 or 3 dimensional</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>XPS</td>
<td>Extruded polystyrene</td>
</tr>
<tr>
<td>N⁰</td>
<td>Number</td>
</tr>
<tr>
<td>R²</td>
<td>Correlation</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
</tbody>
</table>
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1 Introduction

This section provides a brief description on the background of this work. In addition, an extensive literature review was also conducted to set this work in context. Finally, the scope and methodology used in this thesis work are explained.

1.1 Background

Many historical buildings are characterized by poor insulation. In order to reduce the use of energy in these buildings, measures have begun to be taken at the component level and the entire building. Rådhuset, which is the town hall of the city of Gävle (Sweden), constructed in the late 18th century is one of the examples Figure 1. Rådhuset received several complaints about thermal comfort, including draught in winter and overheating on the southern side in summer. In addition, substantial heat loss is expected to occur at the old window. As a result, an attempt was made to improve the thermal efficiency of this building.

![Figure 1. Building in which the study window is located.](image-url)
However, as it is an historical building, it was not possible to make any modifications that affected the aesthetic of the envelope. One of the possibilities was to implement low-e (low emissivity) or solar control plastic films on the window panes. The plastic films chosen were 3M™ Thinsulate™ climate control 75 [1]. The windows were double glazed and the low-e plastic films were added in the interior pane. They increased the insulation with little influence on the appearance. In addition, a hot box was built to assess the thermal performance of the windows with the plastic films and estimate the energy saving potential of the building. The hot box was built on the first floor of Rådhuset, in a room facing south east (Figure 1). The hot box construction started in 2017, externally financed by the Swedish Energy Agency, but the built hot box was not standard. The hot box design differed as the window was already mounted in the exterior, and the cold chamber could not be built, thus, the outdoor temperature could not be controlled. The warm chamber was built in the interior taking advantage of the space formed by the walls around the window.

At first, the objectives were to evaluate the amount of energy that could be saved with the incorporation of the plastic films as well as to test the reliability and accuracy of the newly designed hot box. This thesis includes dynamic simulation where the outdoor temperature changes and how this affects the heat transfer of the window section and the results of the hot box.

1.2 Literature review

The literature review was conducted using Discovery, a search engine of the University of Gävle, and Google Scholar. Most were peer review articles found in ScienceDirect, but there were conference proceedings as well. First, heat transfer mechanisms of the windows were described in order to improve their thermal performance, and then the application of the hot box was studied in various cases. Key words: window, heat transfer, coating, hot box, dynamic, simulation.

1.2.1 Overview of heat transfer in windows

The building sector is responsible for 40% of the total energy use in Sweden and many European countries, and it has a great potential for energy savings [2]. In order to improve the energy performance of the buildings, windows have been identified as one of the elements where most heat is lost. It is considered that a building with 20-30 % of window surface area can led to 50-60 % of all the heat loss [3].
According to Arasteh et al. and Bakonyi et al., heat transfer calculation through a window system is usually done in three different steps: heat transfer through the center of glass, edge of glass and frame regions [4],[5]. Radiation and convection contribute above all to the heat transfer through the center of glass. Solar radiation (short wavelength) is absorbed by glazing layers and increases the temperature of the interior. Nevertheless, all the materials emit radiation in form of longwave (radiant heat) and these emissions are one of the main sources of heat loss. Convection takes place inside the air gap when the window consists of more than one glazing pane. Besides, convection plays an important role at the inner and exterior pane: natural convection occurs between the inner pane and the room air, and forced convection dominates between the outer pane and the exterior because of the wind. Heat transfer by conduction might have more or less weight depending on the thickness of the glass layers. Heat transfer at the edge of the glass can be different due to the greater influence of conduction. Ultimately, frames are made out of solid materials, thus, heat transfer is primarily by conduction.

Arici et al. conducted a numerical simulation of heat transfer in double, triple and quadruple windows by changing the gap width and the outdoor temperature [6]. The study showed that the temperature distribution through the window was more lineal reducing the gap width and the outside temperature. In summary, many factors take part in the heat transfer making its calculation complicated. Figure 2 shows the heat transfer mechanisms that take place in the window.

![Figure 2. Windows heat transfer](image-url)
The U-value (thermal transmittance) is of great interest to estimate the amount of heat that is lost through the elements of the building envelope [7]. The U-value is the rate of heat transfer through a structure divided by the temperature difference across, measured in W/m²·K and the better insulated a building component is, the lower its U-value is [8]. The Technical University in Denmark calculated that the best performing window has a U-value of 1.20 W/m²·K since lower U-values can lead to condensation problems at the exterior pane [9]. Although windows are easy to replace comparing to other building components, there are some restrictions in historical buildings since their architecture must be preserved [10]. This constraint encourages to find new solutions, for instance, upgrading only the transparent component with low-e (low emissivity) film that allows solar radiation to be transmitted through the glass, but decreases the amount of radiant heat emitted to outdoors [3].

Rosencratz et al. researched that the U-value for a typical double glazed window from 1880 can be reduced from 2.44 to 1.60 W/m²·K by applying low-e film, meaning a higher performance [11]. The study demonstrated that reduction is beneficial for the indoor climate in winter, but can lead to overheating in summer. This could sometimes be an issue also for northern countries, but it should be taken into particular account in countries where the solar intensity is higher. To solve these problems, the study was extended using selective coatings that reflect longwave radiation in a proportional way. Moreover, Becherini et al. stated that the coating not only has to improve the performance of the window, but also has to meet some conditions in order to apply to historical buildings [12]. The coating has to be compatible with the historic materials (physic and chemical), reversible, with low visual impact and durable. Today, to the authors knowledge, it is still being analyzed whether the coating meets these conditions.

1.2.2 Application of the hot box

Thermal properties of building components have to be evaluated precisely, as a lot of heat is lost through the building envelope. The hot box technique is widely known to evaluate accurately the thermal performance of building elements (windows, walls, thermal bridges) and derive their U-value [13]. Every hot box consists of a cold and a warm room maintained at a constant temperature. The element to be tested is placed at the aperture of the two rooms. The amount of heat flux from the warm room to the cold room at a specified temperature difference gives the U-value. The hot box design is standardized to operate in stationary conditions by European, American or International standards. For instance, in Europe the hot box technique is regulated by EN ISO 8990 [14] and EN ISO 12567 [15]. The latter describes the method to calculate thermal transmittance of doors and windows. Nevertheless, constructing any hot box is not an easy task and a robust equipment is needed [16].
In real life objects are in dynamic conditions and the need to carry out studies in transitory conditions increases. The hot box is only standardized to work in stationary conditions, however some researches have modified the hot box design to work in dynamic conditions [17]–[19].

Martin et al. analyzed a wall with and without a thermal bridge in stationary and dynamic conditions with a hot box and numerical simulations [17]. In stationary conditions, the difference between the two methods was 2%, therefore the simulation matched with the hot box results. Once the thermal bridge achieved stationary conditions, the dynamic study began. 5 sinusoidal excitations were applied in the cold room in 5 days, keeping the temperature of the warm room constant. The results were derived using the last cycle so that the thermal bridge could have reached a stabilized periodic regime. In this way, the inertia and the maximum heat flux through the thermal bridge were obtained. The maximum heat flux occurred 8 hours later than the minimum temperature in the cold room. Nonetheless, the hot box and simulation results varied more in dynamic conditions. Prata et al. performed a similar study with a wooden thermal bridge, beginning from a stationary condition for 48 hours and then extending the study by applying sinusoidal excitations to the cold chamber [18]. The hot box and simulation results were also compared, and in this case, the results showed good agreement for both stationary and dynamic conditions. Later, Baldinelli et al. studied different ways to analyze the hot box in dynamic conditions [19]. Apart from the sinusoidal excitation during 3 days, an impulsive solicitation for 24 hours was studied. The research showed that the sinusoidal excitation was more precise, but it needed more time to reach the periodic regime. The impulses yielded more uncertain results, but the experiments were shorter.

Moreover, the response of the building to external and internal changes can be estimated calculating the building time constant which is the result of internal heat capacity divided by the thermal transmittance of the building envelope [20]. Ferrari et al. conducted a study in which the walls had the same U-value but different heat capacities [21]. Nonetheless, the building time constant is still one of the least used parameters and there are only few studies applied to modern buildings.

Considering the amount of energy that can be lost through building components, it is interesting to evaluate the behavior of the building under different conditions to improve its performance. Besides, while preserving the aesthetics of the traditional window, one way to lower its U-value is with the implementation of more efficient coatings such as low-e or solar control coatings. Today, the hot box technique is considered accurate and reliable to evaluate the U-value in stationary conditions. To this end, the two rooms, both cold and hot, have to be under controlled temperatures.
Other researches showed that it is possible to use the hot box when one of the chambers is under dynamic conditions, although with more uncertainty. This means, that the hot box, as described above, is used in laboratories. In this thesis, one side of the tested component was directly in contact with the outside, but to the author’s knowledge, no other “hot box” was found subjected to real outdoors conditions.

1.3 Aims
The aim of this thesis work was to simulate the heat transfer of an existing window, tested with the hot box technique in a historical stone building where it was subjected to real outdoor temperatures. The goals of the simulation were:

- To accomplish the temperature and heat flux distribution analysis of the window section.
- To check out the applicability of the hot box technique under both steady and outdoor variable conditions.

However, this thesis work had some limitation due to time constraints:

- Although both radiation and convection were taken into account on the outer surfaces, only conduction was taken into consideration within the geometry.
- The study was performed in the middle cross section of the window in 2D (two dimensional).
- Half of the hot box set-up was studied.
- No comparison was made with the window without having low emissivity plastic film.
- Transient simulations were performed for 5 days.

1.4 Approach
Bearing the goals in mind, this thesis work was carried out simulating the window section with COMSOL Multiphysics 5.3, starting with a stationary study when the outdoor temperature remained quite stable and extending it to the transient case with more fluctuations on the outdoor temperature. Thus, after various simulations, the results were displayed in COMSOL Multiphysics 5.3 to evaluate the solution and to validate the hot box technique under outdoor variable conditions.
2 Theory

In this section, an overview of heat transfer is given. In addition, since this thesis mainly studies heat transfer by conduction, there are more details on conduction and heat transfer coefficients used as boundary conditions.

2.1 Heat transfer

Heat transfer is the process in which heat is transferred from a high temperature body to a low temperature body. According to the second law of thermodynamics heat is never transferred spontaneously from a cold body to a warmer body. Besides, when there is no heat transfer between the system and the surroundings the process is known as adiabatic [22]. Heat transfer implies a flow of heat: \( \dot{Q} \) (W), the heat transfer rate or \( \dot{q} \) (W/m\(^2\)), the heat flux, the rate of heat transfer per unit of surface [23].

The heat transfer rate allows to calculate values that indicate the thermal behavior of the component as the U-value, the thermal transmittance (equation (1)). The U-value is the heat loss through a surface under certain temperature difference (Figure 3).

\[
U = \frac{\dot{Q}}{A \cdot \Delta T} = \frac{\dot{q}}{\Delta T} \quad (W/m^2\cdot K) \quad (1)
\]

Three different mechanisms take place on the heat transfer: conduction, convection and radiation [22], [23].

- **Conduction** is the heat transfer through solids or stationary fluids.
- **Convection** is the heat transfer between a surface and fluid.
- **Radiation** is the heat transfer by electromagnetic waves. Contrary to conduction and convection, no solid or fluid medium is required between them and heat transfer is non-linear with temperature.
2.2 Conduction

The conductive heat transfer rate is determined by Fourier’s law (2) which is based on experimental observations.

\[ q_n = -k_n \frac{dT}{dn} \quad \text{(W/m}^2) \tag{2} \]

In equation (2), \( k_n \) (W/m·K) is the thermal conductivity and \( dT/dn \) the temperature gradient in the n direction. As the temperature gradient is negative, a negative symbol is added to obtain a positive value of the conductive heat transfer rate \( (q_n) \).

\( k \), thermal conductivity, is the capacity of a material to transfer heat and its value depends on the temperature and direction of the medium. The higher the \( k \) value of a material, the greater its capacity to transfer heat. According to the molecular and atomic structure of a material, some materials such as metals have more capacity to transfer heat, whereas gases and insulators make heat transfer more difficult. Determining the thermal conductivity can be difficult and the \( k \) values might have 10% of uncertainty unless being proven in the laboratory [24]. In Table 1 the generic \( k \) value of some materials at 25 °C are shown.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>( k ) (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>168</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>30</td>
</tr>
<tr>
<td>Concrete, stone</td>
<td>1.7</td>
</tr>
<tr>
<td>Building brick</td>
<td>0.5-1.2</td>
</tr>
<tr>
<td>Window glass</td>
<td>1.05</td>
</tr>
<tr>
<td>Wood, pine</td>
<td>0.15</td>
</tr>
<tr>
<td>Wood, oak</td>
<td>0.07</td>
</tr>
<tr>
<td>Insulating fiberboard</td>
<td>0.05</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.04</td>
</tr>
</tbody>
</table>

2.2.1 General equation for conduction.

The general equation for conduction is used to calculate the temperature distribution in a medium. Once knowing the temperature distribution of the geometry, the heat transfer rate can be quantified. To derive the conductive general equation, first Fourier’s law (2) is applied in the direction of the Cartesian coordinates, \( x \), \( y \), and \( z \) (3). If necessary, Fourier’s law (2) can be expressed in cylindrical or spherical coordinates as well [23].

\[ q_x = -k_x \frac{dT}{dx} \quad q_y = -k_y \frac{dT}{dy} \quad q_z = -k_z \frac{dT}{dz} \quad \text{(W/m}^2) \tag{3} \]
Then, an energy balance is applied (Figure 4).

![Figure 4. Cartesian energy balance.](image)

In the end, combining these equations (3) with the energy balance (Figure 4), the general conduction equation (4) is obtained [23].

\[
\frac{d}{dx} \left( k_x \frac{dT}{dx} \right) + \frac{d}{dy} \left( k_y \frac{dT}{dy} \right) + \frac{d}{dz} \left( k_z \frac{dT}{dz} \right) + q = \left( \rho c \frac{dT}{dt} \right)
\] (4)

In equation (4), \(q\) is the heat rate added per unit volume, \(\rho\) is the material density, \(k\) is the thermal conductivity, and \(c\) is the specific heat, the amount of heat that requires a material to raise its temperature in 1°C. In order to solve the general equation of conduction (4), that is a second order differential equation for Cartesian coordinates and first order for the time, boundary conditions are needed. Three types of boundary conditions are generally used [23]:

- **Constant surface temperature.**
  \[
  T(0,t) = T_s
  \] (5)

- **Constant surface heat flux.**
  \[
  -k \frac{dT(0,t)}{dx} = \dot{q}_s
  \] (6)

- **Convection or radiation in the surface.**
  \[
  -k \frac{dT(0,t)}{dx} = h \left( T_s - T_\infty \right)
  \] (7)

In equation (7), \(h\) is the *heat transfer coefficient* (W/m²·K), \(T_s\) is the surface temperature and \(T_\infty\) is the temperature of the fluid.
2.3 Heat transfer coefficients

In this section the heat transfer coefficients are explained because radiative and convective heat transfer coefficients were used as boundary conditions in this thesis.

2.3.1 Convective heat transfer coefficient

\( h_c \) is the convective heat transfer coefficient, an empirical value that relates the pattern of the flow, the properties of a fluid, and the geometry of the surface. In this thesis, three \( h_c \) coefficients were used according to the surface type (wall, window) or whether the surface was outside or inside.

2.3.1.1 Window inside

\( h_c \) of inner window surfaces are calculated using formulas related to natural convection, since the wind has no influence indoors. According to ISO 15099:2003 [25], \( h_c \) is obtained by calculating the Nusselt number (Nu), the ratio between the convection and the conductive heat transfer (equation (8)). In this case, the Nusselt number depends on the modified Rayleigh number (Ra) (equation (9)).

\[
h_c = Nu \frac{k}{H} \text{ (W/m}^2\text{·K)} \tag{8}
\]

\[
Nu = 0.13Ra_h^{1/3} \text{ (-)} \tag{9}
\]

\[
Ra_h = \frac{\rho^2H^3gCp(T_{int} - T_{surf})}{(T_{int} + 273.15 + \frac{H}{4}(T_{surf} - T_{int}))\mu k} \text{ (-)} \tag{10}
\]

In equation (8), \( k \) is the thermal conductivity of the air and \( H \) is the characteristic height of the surface. In equation (9), Rayleigh number takes into account the \( \rho \) density, \( c \) specific heat, \( \mu \) dynamic viscosity, \( k \) thermal conductivity at the temperature of the indoor air \( T_{int} \), as well as \( T_{surf} \) surface temperature, \( H \) characteristic height and \( g \) gravity. The air properties can be found in any tables of thermodynamic books.
2.3.1.2 Window outside

Regarding the external surface of the window, the coefficient is calculated taking into account the forced convection phenomenon, since the wind usually plays an important role outdoors. According to ISO 15099:2003 [25], the convective heat transfer is calculated using equation (11) when the wind speed is greater than 2 m/s.

\[ h_c = 4.7 + 1.9 \times v \quad \text{(W/m}^2\cdot\text{K)} \quad \text{when} \quad v > 2 \text{ m/s} \quad (11) \]

2.3.1.3 Vertical wall of a room

As for the vertical wall, \( h_c \) is calculated using Nusselt number (8). The Nusselt number is based on the Grashof (Gr) and Prandtl (Pr) numbers (equation (12)) [23]. Grashof number is calculated using equation (13) which is based on the g gravity, \( \nu \) kinematic viscosity, and \( T_{\text{surf}} \) and \( T_{\text{int}} \) temperatures of the surface and indoor air respectively. Prandtl number can be found in any air properties table.

\[ Nu = 0.59(GrPr)^{1/4} \quad (\text{-}) \quad \text{when} \quad Gr \cdot Pr < 10^9 \]
\[ Nu = 0.13(GrPr)^{1/3} \quad (\text{-}) \quad \text{when} \quad Gr \cdot Pr > 10^9 \quad (12) \]

\[ Gr = \frac{g(T_{\text{int}}+273.15)(T_{\text{int}}-T_{\text{surf}})L^3}{\nu^2} \quad (\text{-}) \quad (13) \]

2.3.2 Radiative heat transfer coefficient

The radiative heat transfer coefficient can be used when the temperature difference between two surfaces or a surface and a fluid is small [23]. In this thesis, equation (14) was used to calculate the radiative heat transfer coefficient in every case. In equation (14)\( \varepsilon \) is the surface emissivity \((0 < \varepsilon < 1)\), \( \sigma \) is Boltzmann’s constant \((5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4})\), and \( T_s \) is the absolute surface temperature.

\[ h_r = \varepsilon\sigma(T_s + 273.15)^3 \quad (\text{W}) \quad (14) \]
3 Method

The method section presents a description of the study, the materials used, and the steps to carry out the study.

3.1 Study object

The study object was a window of an historical building with a hot box construction around it.

The selected window was double glazed and recently low-e plastic films [1] were incorporated in the interior pane. The window also had wooden frames. Besides, the section of the wall that was near the window was cone-shaped towards the inside. The properties of the wall made out of stone were unknown since it was built in the late 18th century. In Figure 5, the window and the surroundings are shown before the construction of the hot box. The window dimensions can be found in Appendix A.

![Figure 5. Shape of the window.](image)
The hot box was built in 2017 surrounding a window facing south east on the first floor in Rådhuset (Gävle, Sweden). The hot box wanted to help quantify the U-value (1) of the window with the frames in an experimental way.

The design of the hot box is standardized when working in stationary conditions [26]. The hot box consists of a cold (environmental chamber) and a warm room (metering chamber) each maintained at a constant temperature. Two main types of hot box construction exist according to the configuration of the warm room: the guarded hot box and the calibrated hotbox. The guarded hot box contains the metering chamber inside the guarded chamber. The aim of the guarded chamber is to minimize the heat flow through the walls of the metering chamber to avoid any heat loss correction. The calibrated hot box only has a metering chamber located at a surrounding where its temperature is known. In this case, it is necessary to correct the heat loss through a calibration protocol, but larger elements can be tested.

The hot box evaluated in this thesis was constructed differently. The warm chamber looked like the calibrated hot box, but the construction especially differed since the window was already mounted into the wall and a cold chamber could not be built in the exterior. Hence, the indoor temperature was controlled, but not the outdoor temperature.

- The warm chamber was built on the inner part of the window to achieve stationary conditions as it can be seen in Figure 6a. The warm chamber was kept at 22°C during the measurements, at the same temperature of the room where the hot box was installed. Indeed, heaters were in charge of maintaining the temperatures at 22°C and some sensors with Proportional, Integral and Derivative (PID) control guaranteed the stationary conditions. PID controllers are quite reliable as the maximum temperature fluctuation around the set point is 0.32% [13]. Heaters are shown in Figure 6b.

The warm chamber was highly insulated and black painted, both the interior of the room and the walls, leaving the window free without insulation. The black painted insulation wanted to reduce the heat loss through the walls to quantify only the heat loss through the windows. In other words, so that the correction when estimating the heat losses through the window would be minimal. Sensors were placed on both sides of the insulation to estimate heat losses. However, where the insulation and the window joined, the insulation had a cut about 45° angle to avoid covering the right frame of the window; thus, heat losses increased in that area hindering its calculation. Extruded polystyrene (XPS) of 5 cm together with foam of 5 mm were used as insulation. XPS was in contact with the ambient, and the foam was attached to the wall. The thermal conductivity of XPS and foam were 0.022 and 0.058 W/m·K respectively.
The cold chamber could not be built since the window was already in the exterior. The outdoor served as a cold chamber and hence, its temperature could not be controlled. The outdoor temperature was a weather-related issue and it was measured with sensors placed outside. The temperature of both window or wall could vary.

Altogether, 70 temperature sensors and 5 heat flux sensors were implemented to quantify the U-value (see Annex 1). Besides, the sensors were connected to a laptop to extract the data every minute. Thus, the amount of heat lost through the window was calculated with the difference between the instant input power of the heater and the instant losses through the wall, in this way the U-value of the window with the frames could be estimated. The hot box was in operation throughout the month of December 2018 to test the behavior of the window in the most extreme conditions, this is, when the temperature difference between indoor and outdoor was greater.
In this thesis work, the thermal behavior of the window with the hot box was simulated on the basis of the indoor and outdoor real conditions measured in December 2018. The simulation would help to evaluate the heat transfer of the window displaying the temperature and heat flux distribution. Based on the heat transfer evaluation, it was to be decided whether the hot box is suitable for working with steady and transient conditions.

The goals were to be achieved simulating the horizontal middle cross section of the window in 2D. Half of the window with the hot box set-up was taken into consideration to simplify the model; however, with the aim of being able to extrapolate the results to the whole window. Furthermore, the heat transfer evaluation was carried out considering conductive heat transfer. Two studies were done, one when the outside temperature was fairly stable, and another with fluctuations in the exterior. The simulations were performed during the 18th and 22nd of December 2018. Figure 7 shows the outdoor temperature during the study period.

![Figure 7. Outdoor temperature during 19th and 20th of December 2018.](image-url)
3.2 Materials

Numerical models [26] solved with computer software are used to evaluate and visualize the thermal performance of building components. Numerical models assess in detail but have to be integrated with experimental methods. The software can also be used to validate the experimental data. Nowadays, there are several software to simulate and according to [27]: “the most complete mathematical models approach the problem from the perspective of thermal energy transfer in two or three dimensions”. COMSOL Multiphysics complies with these requirements due to its general character and the facility to introduce complex equation domains.

In this thesis work, the version 5.3 of COMSOL Multiphysics was used to simulate the heat transfer of the window section after the hot box construction in Rådhuset.

3.2.1 COMSOL Multiphysics 5.3

COMSOL Multiphysics 5.3 is a FEM (Finite Element Method) software that allow to evaluate heat transfer and mass transfer both stationary and time dependent [28]. In the FEM, the continuous analytical problem is subdivided into finite elements. The set of finite elements is also called discretization. The degree of discretization varies depending on the desired resolution. Besides, within each element a number of representative points called nodes are set. The group of nodes with their adjacent relation is called a mesh.

All software working with the FEM usually have three steps, and so does COMSOL Multiphysics 5.3 [28]:

- The first stage consists of the definition of the geometry, assignment of material properties, study (stationary or transient) and mesh generation.

- The second provides the results in the nodes of the mesh of the preprocess. In a stationary problem, the equations can be solved like linear equations. Nevertheless, when the problem is non-linear or time dependent, the calculation equations must be solved one after the other, and whose input depends on the result of the previous step. Therefore, it usually takes longer.

- In the last stage, the results obtained are treated to obtain graphic representations and derived magnitudes that allow conclusions to be drawn from the problem.

Nonetheless, COMSOL Multiphysics 5.3 as currently used has some limitations [27]. The software provides an approximate solution whose margin of error is generally unknown.
3.3 Process

The simulation of the horizontal middle cross section of the window with the hot box in Rådhuset was carried out with COMSOL Multiphysics 5.3 on the basis of the outdoor and indoor temperatures got from the measurements in December 2018. First a stationary study was carried when the outdoor temperature remained stable. Then, the study was extended to a transient study to analyze in detail the effect of the external temperature fluctuations in the hot box measurements. The geometry model used in both cases was the same, however, the conductive heat transfer equation and the boundary conditions differed. Thus, the first step was to create a geometry model and then the respective data was added for stationary and transient studies.

3.3.1 Window section model

The window section model after the hot box construction was created by adding the geometry, materials and mesh.

3.3.1.1 Geometry

The horizontal middle section of the window area was drawn up in the graphics window in 2D. The geometry took into account half of the window and part of the adjacent wall, so that the heat losses through the insulation could be estimated. The geometry was created dividing the window section into 13 components (Figure 8):

- The left wooden frame was separate into 2 components (components 1,2) and the right wooden frame into 3 components (components 6,7,8). The frames were split in two or three components to examine what happens in the middle.
- The double glazed window was made up of 2 glass panes (components 3,5) and a replacement (to consider the air gap and low-e films) (component 4).
- The insulation consisted of 2 parts, the XPS and the foam. The XPS in contact with the exterior was drawn as a single element (component 9). The foam in contact with the wall was divided into 3 parts (components 10,11,12), thus, to facilitate the heat transfer evaluation through the insulation. The outer part was subjected to the effects of radiation and convection, however, the inner part is only under the effects of conduction. Therefore, the results on the inner part could be more accurate.
- The wall was created as a single element (component 13).

As it can be seen in Figure 8, the whole inner box was not drawn because it was assumed that the interior of the hot box was at the same temperature as the room. After adding all the components and their real dimensions, the geometry was completed. In Figure 8, the model of the window with the hot box set-up is shown.
3.3.1.2 Materials

COMSOL Multiphysics 5.3 has a material library with a range of materials and properties. In this work, according to the general conduction equation (4), the thermal conductivity \( k \), the specific heat \( c \) and the density \( \rho \) of the materials were needed. Those properties were occasionally changed according to the information that the fabricants of the window section provided. However, the values of the wall were guessed carrying out simulations for educational purpose\(^1\). The \( k \) value of the air was 6 times higher to get a realistic \( U \)-value of the window since only conductive heat transfer was to be studied. Table 2 indicates the material properties of each component. The materials were considered isotropic, and the glass followed by the wall had the highest thermal conductivity values.

**Table 2. Material properties of each component.**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>Nº</th>
<th>MATERIAL</th>
<th>( \rho ) (kg/m³)</th>
<th>( C_p ) (J/kg·ºC)</th>
<th>( k ) (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frames</td>
<td>1,2,6,7,8</td>
<td>Wood, pine</td>
<td>532</td>
<td>2700</td>
<td>0.14</td>
</tr>
<tr>
<td>Glass</td>
<td>3,5</td>
<td>Quartz</td>
<td>2210</td>
<td>730</td>
<td>1.4</td>
</tr>
<tr>
<td>Replacement</td>
<td>4</td>
<td>Air</td>
<td>545</td>
<td>1215</td>
<td>0.124</td>
</tr>
<tr>
<td>Insulation</td>
<td>12</td>
<td>XPS</td>
<td>34</td>
<td>1450</td>
<td>0.022</td>
</tr>
<tr>
<td>Extra insulation</td>
<td>9,10,11</td>
<td>Foam</td>
<td>16</td>
<td>1450</td>
<td>0.058</td>
</tr>
<tr>
<td>Wall</td>
<td>13</td>
<td>Brick</td>
<td>2000</td>
<td>900</td>
<td>0.53</td>
</tr>
</tbody>
</table>

---

\(^1\) The \( k \) value of the wall was obtained from previous measurements by staff at Högskolan i Gävle.
3.3.1.3 **Mesh**

The model was discretized and the resolution of the finite element was predefined as finer and generated as free triangular (see Appendix A). The resolution was determined as finer rather than normal because there were corners and edges were more precision was desirable. The finer the resolution, the more accurate the results are. Furthermore, the mesh was calibrated for fluid dynamics.

3.3.2 **Stationary study**

The simulation was carried out when the outside temperature remained nearly constant. Considering the whole study period, the temperatures remained nearly constant between the 18th and 19th of December 2018 (Figure 9), almost an entire day. Before reaching that stable state, there were ups and downs of up to 7-8°C. More information about the temperature of the preceding days is shown Appendix A.

![Figure 9. Outdoor temperature between 18th and 19th of December 2018.](image)

According to sensor measurements, the hot box was at the temperature indicated in Figure 10 at the last 2 hours of the stationary period. Those values were used to study if the hot box had already reached stationary conditions in comparison with the results obtained in the simulation. To this end, a stationary study was chosen to understand the heat transfer over the window section and check the applicability of the hot box technique at steady state conditions.
3.3.2.1 Physics

COMSOL Multiphysics 5.3 performed a 2D stationary simulation of heat transfer in solids by solving a differential equation (15). Equation (15) is an equation derived from the general equation for conduction (4).

\[
\frac{d_z}{\rho C_p} \mathbf{u} \cdot \nabla T + \nabla \cdot \left( -d_z k \nabla T \right) = d_z Q + q_0 + d_z Q
\]  

(15)

The material properties, \( \rho, C_p \) and \( k \) were already introduced in the window section model and equation (15) was solved by adding \( d_z \) (a depth of 2 m as the window height) and boundary conditions. In this case, steady state boundary conditions were required and the three main type of boundary conditions were used (see equation (5),(6),(7)).

- Highlighted surfaces in Figure 11 met the boundary condition described in Equation (7), the convection and radiation heat transfer on the surfaces. For the outer wall near the window, it was assumed that the temperature difference would not be excessive, and the same heat transfer coefficient was assumed. This condition allowed the temperature to vary along the surface, and not to be constant for the entire surface. Thus, indoor and outdoor temperatures and heat transfer coefficients were required. In Table 3, the average values of the stationary indoor and outdoor temperatures are shown from 0:00 to 2:00 of December 19th 2018. In addition, three combined heat transfer coefficients were calculated (Table 4) as explained in 2.3. The calculations are shown in Appendix B.
Table 3. Indoor and outdoor temperatures for the stationary study.

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>T (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>21.6</td>
</tr>
<tr>
<td>Outdoor</td>
<td>-3.4</td>
</tr>
</tbody>
</table>

Table 4. Heat transfer coefficients of some surfaces.

<table>
<thead>
<tr>
<th>Heat transfer coefficient</th>
<th>h_c (W/m²·K)</th>
<th>h_r (W/m²·K)</th>
<th>h (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner window</td>
<td>8.61</td>
<td>0.52</td>
<td>9.13</td>
</tr>
<tr>
<td>Inner insulation</td>
<td>1.83</td>
<td>5.42</td>
<td>7.25</td>
</tr>
<tr>
<td>Outer window</td>
<td>12.3</td>
<td>4</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Figure 11. Surfaces where the heat transfer coefficients were calculated.

- The inside and outside of the wall had a fixed temperature as in equation (5). The temperature of those walls were of minor relevance as it was not part of the hot box and it did not vary much along the length. The average temperature of the interior and exterior walls were 19.62 ºC and -1.3 ºC (Figure 12), respectively.

Figure 12. Walls with preset temperatures.

- The other contours were considered adiabatic to simplify the calculation.
3.3.3 Transient study

The transient study simulation was carried out to evaluate the heat transfer of the window under outdoor temperature fluctuations for 5 days during 18th and 22nd of December 2018. The transient study wanted to analyze the applicability of the hot box in transient conditions and assess whether they are still acceptable or not.

3.3.3.1 Physics

COMSOL Multiphysics 5.3 performed a 2D transient simulation of heat transfer in solids by solving a differential equation (16) which is an equation derived from the general equation for conduction (4). Nevertheless, the initial values for the geometry of the transient study were obtained carrying out a stationary study with the indoor and outdoor conditions of the first instant of December 18.

\[
d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u + \nabla \cdot (-d_z k \nabla T) = d_z Q + q_0 + d_z Q \quad (16)
\]

In the transient study, boundary conditions changed overtime. 4 piecewise functions were defined to enter the corresponding temperature at one-minute intervals during five days. Figure 13 shows the temperatures during December 18th and 22nd 2018. The temperature indoors was hardly changed, on the contrary, the difference of the maximum and minimum temperatures reached up to 6.29°C outdoors. This difference allowed to evaluate the heat transfer when the outdoor temperatures varied. The heat transfer coefficients were assumed to be the same as in the stationary case (Table 4).

![Figure 13. Indoor and outdoor temperature during December 18th and 22nd 2018.](image-url)
3.3.4 Data treatment

The first step was to check out to what extent the solution of the simulation reflected the reality. The difference between both methods could somehow be adjusted with several simulations, for instance, changing the material properties.

Afterwards, the thermal behavior of the window with the hot box was analyzed. For that, a heat transfer evaluation was performed taking into account three points: the temperature distribution, the heat flux, and the U-value of the window. The temperature distribution and the heat flux were outputs directly obtained from the simulation, but the U-value was calculated based on those results.

As heat transfer depends on the temperature difference between two points, the temperature distribution was first analyzed. However, the conductive heat transfer depends not only on the temperature difference, but also on the properties of the materials. Thus, the heat flux of some elements was obtained by deriving the results using the **total normal heat flux function**. Emphasis was placed on the heat flux through the frames, glass, whole window and different parts of the insulation, since they affected the results of the hot box technique. In the end, the U-value of the window could be quantified with the heat that went through the inner surface of the window. The U-value was calculated to know if the heat transfer through the window was reasonable in the simulation, a U-value similar to 1.5 and 2.0 would be realistic².

To finish, on the basis of the data obtained from the heat transfer evaluation, this is, how the outside temperature affected the geometry, it was decided whether the hot box is suitable for working both steady and variable outdoor conditions.

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² Based on previous tests performed by staff at Högskolan i Gävle.
4 Results

The simulation solution of the window with a hotbox are presented in two sections: first the results of the stationary study are presented, and then, the results are expanded to the transient study. In each case, the heat transfer results with COMSOL Multiphysics 5.3 were shown (the temperature distribution, the heat flux, and the U value of the window) and the difference between the simulation and measurements results. In the end, based on all these results, it was decided whether the hot box is a way to evaluate elements in transient conditions.

4.1 Stationary study results

The stationary results were achieved when the outdoor temperature remained stable for 1 day.

4.1.1 Temperature distribution

Figure 14 shows the temperature distribution of the window section. Figure 14 can be seen that each component of the window section underwent different temperature changes from the inner side to the external face. In the window panes the temperature difference was about 14°C, from 14.5°C to 0.5°C; whereas, in the window frames, it was greater close to 18°C, from 17.5°C up to -0.5°C. In the wall it increased up to 21°C, from 20°C to -1°C. In the corner where the window and the wall joint, there was a large temperature difference in a very small area. All over the insulation the temperatures remained above 10°C.

![Figure 14. Temperature distribution of the geometry in stationary conditions.](image)
Figure 15 shows the isothermal lines with more precision. The distance between isothermal lines remained constant across the window and the wall, but isothermal lines were more dispersed on the wall than on the window. As a result, the temperature gradient per unit of thickness was lower in the wall than in the window. Overall, the temperature gradient was of 0.38°C per mm of thickness of the window. The temperature gradient in the wall was about 0.02°C per mm of thickness of the wall. Indeed, the wall was thicker and the thermal conductivity was lower than in the window. In addition, the right frame was the point of confluence between the wall and window, so the temperature range is large in such small environment. The temperatures behind the insulation were over 11.5°C, even if the temperatures decreased especially when getting closer to the 45° edge. Temperatures difference across the insulation near the window was of 10°C and further away of 4°C. Some cuts are found in Appendix C.

4.1.2 Heat flux

The average heat flux across the components of the window section were derived, and they are summarized in Figure 16. As the indoor temperature was higher than the outdoor temperature, the heat fluxes indicated the heat loss through each component. Moreover, even if the study was in 2D, COMSOL considered a depth of 2 m, so the results could be obtained as a function of the surface (W/m²). Emphasis was laid on the amount of heat loss through the window and also from the insulation (that was split into three components) because the hot box results are affected by the measurements on those points. In addition, Table 5 shows the total heat transfer rate.
4.1.2.1 Window

The heat flux through the glass panes was of 57.38 W/m², double of what was lost per meter square on the frames. Overall, the heat flux from the whole window including the frames was 47.22 W/m².

4.1.2.2 Insulation

The heat flux on the insulation was smaller compared to the window. In order to avoid radiation and convection effects on the surface, the heat transfer was measured behind the insulation. In total, 1.98W/m² were lost from the insulation. However, 13.68W/m² were lost mainly in the small area of the insulation closest to the window. In the farthest part from the window behind the insulation, the heat transfer did not go towards the wall, but on the contrary, from the wall to the insulation.

Considering the total length of the window and the wall (Table 5), 96.2% of the heat was lost through the window and 3.8% from the insulation.

4.1.3 U-value

At the end, the U-value of the window with frames was 1.87 W/m²·K under stationary conditions. Hence the heat transfer through the window was reasonable.

---

**Figure 16. Heat flux through different components of the hot box set-up.**

**Table 5. Total heat transfer rate in the normal direction**

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
<th>Length (mm)</th>
<th>Total normal heat rate (W/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left frame</td>
<td>73.74</td>
<td>2.27</td>
</tr>
<tr>
<td>2</td>
<td>Glass</td>
<td>498.2</td>
<td>28.59</td>
</tr>
<tr>
<td>3</td>
<td>Right frame</td>
<td>129.1</td>
<td>4.04</td>
</tr>
<tr>
<td>4</td>
<td>Insulation</td>
<td>52.0</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>Insulation</td>
<td>353.9</td>
<td>1.39</td>
</tr>
<tr>
<td>6</td>
<td>Insulation</td>
<td>339.7</td>
<td>-0.62</td>
</tr>
</tbody>
</table>
4.1.4 Simulation vs measurements

The comparison between the simulation and the hot box measurements was made in terms of the temperatures obtained at the points shown in Figure 10 during the chosen period with reasonably stationary outdoor temperatures (Dec 18 and 19). Table 6 shows the temperatures obtained with each method at the same points, as well as the difference between them. Overall, the temperature difference in absolute terms between both methods was 0.96 (SD 0.78) ºC.

Regarding the window, the temperatures on the inner surface were higher in the simulation, but on the outer surfaces the temperatures were lower in the glass and higher in the frames than in the hot box. As a result, the temperature difference through the window was 27% higher in the simulation than in the measurements. On the other side, on the insulation side in contact with the indoor environment the temperatures were higher in the simulation, but the temperatures slightly decreased behind the insulation. The insulation temperature difference was 17% higher in the simulation than in the measurements. Behind the insulation, lowering the k value of the wall from 0.53 to 0.49 W/m·K, the temperature in that stretch would rise closer to the values measured by the sensors, but this fact was checked in the transient stage.

<table>
<thead>
<tr>
<th>POINT nº</th>
<th>DESCRIPTION Component</th>
<th>SIMULATION T(ºC)</th>
<th>MEASUREMENTS T(ºC)</th>
<th>DIFFERENCE T_{simulation} - T_{measure} (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left frame inside</td>
<td>17.55</td>
<td>16.5</td>
<td>1.05</td>
</tr>
<tr>
<td>2</td>
<td>Left frame outside</td>
<td>-0.34</td>
<td>-1.29</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>Glass inside</td>
<td>14.53</td>
<td>12.22</td>
<td>2.31</td>
</tr>
<tr>
<td>4</td>
<td>Glass outside</td>
<td>0.4</td>
<td>1.78</td>
<td>-1.38</td>
</tr>
<tr>
<td>5</td>
<td>Right frame inside</td>
<td>18.6</td>
<td>16.11</td>
<td>2.49</td>
</tr>
<tr>
<td>6</td>
<td>Right frame inside</td>
<td>19.08</td>
<td>17.36</td>
<td>1.72</td>
</tr>
<tr>
<td>7</td>
<td>Right frame outside</td>
<td>-0.52</td>
<td>-0.58</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>Corner</td>
<td>20.42</td>
<td>19.22</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>Insulation</td>
<td>21.01</td>
<td>20.31</td>
<td>0.7</td>
</tr>
<tr>
<td>10</td>
<td>Insulation</td>
<td>21.2</td>
<td>20.75</td>
<td>0.45</td>
</tr>
<tr>
<td>11</td>
<td>Insulation</td>
<td>21.41</td>
<td>21.46</td>
<td>-0.05</td>
</tr>
<tr>
<td>12</td>
<td>Behind insulation</td>
<td>11.14</td>
<td>11.55</td>
<td>-0.41</td>
</tr>
<tr>
<td>13</td>
<td>Behind insulation</td>
<td>14.51</td>
<td>14.62</td>
<td>-0.11</td>
</tr>
<tr>
<td>14</td>
<td>Behind insulation</td>
<td>17.22</td>
<td>17.83</td>
<td>-0.61</td>
</tr>
</tbody>
</table>

The actual simulation model implied that heat losses would be higher through the window and insulation than what happened according to the measurements. Higher heat loss values were achieved because one day was not enough to get stable values within the real geometry, the temperature drop of the preceding days was probably still influencing it or due to several uncertainties of the simulation.
4.2 Transient study results

The transient study was performed to evaluate the effect of the outdoor fluctuations for 5 days.

4.2.1 Temperature distribution

The following figures show the temperature distribution when the outdoor temperature was maximum (Figure 17a) and minimum (Figure 17b). At first glance, the outdoor temperature did not have the same impact on the window and the wall. The outdoor temperature affected the thermal behavior of the whole window, while the wall was only affected on the first 400 mm from the outside due to its great thickness.

Figure 17. Temperature distribution A) when the maximum outdoor temperature was 1.14°C at 4:48:51 on the 20th December 2018; B) when the minimum outdoor temperature was -4.15°C at 00:09:31 on the 19th December 2018.
The change in temperature of the geometry due to changes in the outdoor temperature was analyzed more precisely over time. Emphasis was placed on the window and insulation temperatures. Figure 18 and Figure 19 demonstrate how the temperatures varied over time according to the simulation at the same points of Figure 10.

4.2.1.1 Window

Figure 18 shows how the temperature in the middle point of each component of the window changed according to the outside temperature. It was observed that the temperature of the surfaces in contact with the indoor environment was not considerably affected, especially, in the inner frames. However, the temperature in the interior glass pane was better suited to the tendency of the outside temperature. For instance, the temperature on the inner glass surface raised up to 1.1°C when the outdoor temperature increased by 5°C overtime, this is, the surface temperature changed by 0.22°C per degree of temperature changed outdoors. On the other side, the temperatures of the surfaces in contact with the outdoor environment, followed the trend of the outdoor temperature, both in the frame and the exterior glass pane. In other words, if the outdoor temperature increased the temperature of these surfaces rise too; on the contrary, if the outdoor temperature decreased, the temperature on these surfaces was lower too. In this case, increasing the outdoor temperature by 5°C overtime, the temperature on the outer glass surface increased up to 3.56°C, this is, the surface temperature changed by 0.71°C per degree of temperature changed outdoors.

![Figure 18. The temperature of the window components with changes in outside temperatures during 5 days.](image)
Interior surfaces required larger temperature difference to notice any temperature change on them. Thus, changes on the outside temperature mainly affected the outdoor surfaces by increasing or decreasing the temperature difference across each component.

Nevertheless, the temperature did not change immediately on the surfaces together with the outdoor environment. For instance, if the trend was a rise in temperature, and suddenly the temperature dropped for a few minutes, it did not affect the results because it needed time to react. Besides, due to the reaction time:

- As for the rise in outdoor temperature, outdoor and indoor surfaces began to rise in temperature when the outdoor temperature rose 0.25°C for 20 minutes.
- Regarding the drop in outdoor temperature, from 0:12 on December 20th onwards, the outdoor temperature tended to fall, although with ups and downs of 0.1°C. Even so, the outer surfaces temperature continued to rise in temperature for 4 hours; while the temperature on the inner surface kept going up in the glass and in the frames for 4 and 16 hours respectively.

In terms of the reaction time, the results show that the window section gained heat quickly, however, when the temperatures started to drop, the window took more time to cool down.

4.2.1.2 Insulation

As for the insulation, Figure 19 shows the temperature evolution of some points on both sides of the insulation. The temperature of the insulation part in contact with the indoor part varied ± 0.02°C which may be due to changes in the interior temperature. The outside temperature only affected a small area behind the insulation, the wall side closest to the outdoor (component 9, Figure 8), where its temperature varied on average 11.65 ± 0.21°C. The changes were noticeable one day later due to its great thermal mass. However, in the rest of the length behind the insulation the temperatures dropped, it had no relation to the outside temperature. The temperatures of that side of the wall were converging into a fairly stationary temperature even after 5 days.
4.2.2 Heat flux

4.2.2.1 Window

The figure below (Figure 20) indicates the average heat flux through the window components throughout time.

![Heat flux through the window and hot box components as well as the indoor-outdoor temperature difference throughout 5 days.](image)

The heat flux followed the same trend as the temperature difference between outside and inside. The heat flux was around $42.29 \pm 4.64$ W/m$^2$ through the window with a change of 10%.
Nonetheless, the heat flux was not the same if the outdoor temperature went up (Figure 21) or down (Figure 22):

- When the difference between the indoor and outdoor temperature was decreasing by each degree, the average heat flux on the following components decreased by: 2.19 W/m² through the glass and 1.82 W/m² through the whole window. The heat flux evolution on the frames was not linear and regarding the correlation number $R^2$ it was better suited to a logarithmic function.

\[
\begin{align*}
\text{Glass: } & y = 2.1946x \\
& R^2 = 0.976 \\
\text{Total window: } & y = 1.8221x \\
& R^2 = 0.944 \\
\end{align*}
\]

\[
\begin{align*}
\text{Frames: } & y = 20.751\ln(x) - 37.941 \\
& R^2 = 0.9894 \\
\end{align*}
\]

- On the other hand, when the difference between the indoor and outdoor temperature was increasing by each degree, the average heat flux on the following components decreased by: 2.17 W/m² through the glass and 1.80 W/m² through the whole window. Again the heat flux evolution on the frames was not linear and regarding the correlation number $R^2$ it was better suited to a logarithmic function.

\[
\begin{align*}
\text{Glass: } & y = 2.1745x \\
& R^2 = 0.9432 \\
\text{Total window: } & y = 1.8x \\
& R^2 = 0.9449 \\
\end{align*}
\]

\[
\begin{align*}
\text{Frames: } & y = 26.559\ln(x) - 56.854 \\
& R^2 = 0.9407 \\
& y = 9.7733\ln(x) + 6.6851 \\
& R^2 = 0.9912 \\
\end{align*}
\]
Hence, the results showed that the heat loss decreased more when the temperature difference decreased, causing the heating of the surfaces; and the heat loss did not increase in the same way when the temperature difference increased, delaying the cooling of the surfaces.

4.2.2.2 Insulation

The total heat flux through the insulation could not be accurately estimated because the temperature of the indoor part of the wall was not stable yet. The temperature was still decreasing and the heat loss amount would increase more over the insulation. According to the latest simulation step, the heat transfer would be around 1.78 W/m². However, bearing in mind the greatest heat loss were in the smallest part of the insulation (component 9, Figure 8), and that the outdoor temperature already influenced that part, the total heat transfer in that length varied around 5%, from 0.57 W up to 0.6 W. Heat flux changes were not in the instant that the temperature changed, in the same way as the temperature variations in that area. The heat flux fluctuation was 5% lower than in the window, but both variations were not at the same instant.

4.2.3 U-value

The window heat flux varied between 37.65 and 46.93 W/m². The U-value was the slope of the regression line (Figure 23). At the end, the U-value of the window was 1.81 W/m²-K with 0.94 of correlation degree (R²). The U-value decreased by 2% compared to the stationary case but it was still reasonable.

Figure 23. Heat loss through the window in function of the indoor-outdoor temperature difference.
4.2.4 Simulation vs measurements

The comparison between the simulation and the hot box measurements was made in terms of the temperatures obtained at the same points (Figure 10). Overall, the average temperature difference in absolute terms between the measurements and the simulation was of 0.71 (SD 0.17) °C. The temperatures still varied in the same way as in the stationary case, but the difference was reduced by 26%.

In addition, regarding the window, the temperature difference remained almost constant overtime and the difference was minimum above all in the right frame. The window was the exception since the deviations sometimes went up to 0.5°C. According to the measurements, from time to time there were some peaks caused by some factors that the simulation did not take into account (Appendix C). Thereby, window temperatures of the simulations followed the same trend as the sensor measurements, but the simulation values were not approaching the sensor values.

As for the insulation, Figure 24 shows the comparison between the sensor measurements and simulation results in the components 9, 10 and 11 of Figure 8. In the areas furthest away from the exterior, the simulation temperatures gradually converged, but not to the temperature measured by the sensor. This could be because the k-value was set somewhat higher in the insulation than the true values. Otherwise, in the insulation part closest to the wall, the same values were obtained, so the temperature and heat flux analysis in that area was done with great precision.

As an outcome, even if there is still a difference between the two methods, it can be said that the simulation succeeded in demonstrating what actually happened.
4.3 Hot box validation

Transient simulation was better adjusted to reality than the stationary state. When the hot box worked with outdoor stationary temperatures, the real geometry was still under the effect of the previous days and stationary conditions could not be achieved within the real geometry. Even so, the study helped to see that heat losses were predominant though the window, and that the insulation heat losses were mainly in the section closer to exterior with a 45º cut.

On the other side, the input of the transient study depended on the solution of the previous stage, so it allowed to see whether it was possible to calculate the U-value under transient conditions. Although a cold chamber was missing, the results of the warm chamber did not undergo much change. The interior surfaces were hardly affected by the outside temperature because the temperature of the warm chamber was kept constant. There were slight changes in the interior surfaces of the window components, but the temperatures remained quite stable through the insulation. The wall in which the insulation is at is of great thickness and subsequently, the outdoor temperature only affected in the first 400 mm of the external wall at a 5.3°C steady outdoor temperature change. On the other hand, temperature changes were observed all over the outside surfaces. However, the outside temperature needed time to change the temperature along the geometry which varied according to each component. This could involve errors when working with this type of hot box since the actual temperature distribution of the geometry might not correspond exactly to the outdoor temperature used to calculate the U-value. Moreover, the outdoor temperature affected primarily the heat flux through the window with few interferences with the insulation. The heat loss ratio of the two components was not kept constant, but with few variations. All the same, the heat losses through the window were still prevailing.

Even so, as far as the assessment of the U-value is concerned, the U-value is still more accurate when working with stationary conditions, even though for this thesis comparative measurements for a very long and steady period were not available.
5 Discussion

Heat transfer of a window with a hot box was evaluated using COMSOL Multiphysics 5.3. The simulation model used to evaluate the heat transfer of the window section with the hotbox resemble reality as in previous studies conducted by Martin et al. [17] and Prata et al [18]; but still with some numerical difference due to certain factors that were not taken into consideration and certain simplifications.

The results could differ because the model created was in 2D instead of in 3D, in particular, in corners and in changes of materials and shapes. The properties of some materials were guessed for educational purpose, they were isotropic and did not undergo any change with temperature variations. The study time taken into account might not have been sufficient. The more data taken into account, however, the longer the simulation were and the time was limited. In addition, one type of mesh was only used which was the finer discretization. COMSOL still allowed more precise mesh such as extra finer or extremely finer discretization. This should have been verified as well.

Furthermore, only heat transfer by conduction was taken into account within the geometry. Regarding the boundary conditions, convection and radiation heat transfer were mainly taken as boundary conditions even if some surfaces already had preset or adiabatic temperatures. The h or the combined heat transfer coefficient, which took into account the convection and radiation heat transfer, could not be exactly calculated for all scenarios. The h coefficient was found using average temperatures of the surfaces, wind velocities and empirical formulas. As a result, in the wall, it was possible to obtain approximate values to reality even if there might be some pores or infiltrations. Heat transfer is mainly due to conduction through the wall, while convection and radiation are important on the internal and external side of the wall.

On the contrary, although the window had a replacement to simulate the behavior of the air cavity and low-e plastic films, the results could vary. According to Arasteh et al. and Bakonyi et al., heat transfer mechanisms through the window differs according to the part of the window but in the simulations it was the same [4],[5].

Nonetheless, the estimated U-value of the window was around 1.81-1.86 W/m²·K which was quite realistic for a low-e window in terms of previous studies carried out by the staff at Högskolan i Gävle² and Rosencratz et al. [11]. Thus, the heat transfer of the window was fairly well represented. Moreover, the window components gained heat easily with the rise in the outdoor temperatures and lost heat with difficulties when lowering the outdoor temperature. The behaviour of the window components coincided with the mechanism of low-e plastic films seen in [3].
The heat losses would be considerably reduced in winter, but overheating could still be a problem in summer for the windows facing south in Rådhuset. Even so, the difference was rather small.

In spite of the differences with the reality, the simulations were useful to obtain certain results in a simple and complete way in accordance with [27]. All that was needed were: the outdoor and indoor temperatures that had to be measured with sensors and the h coefficients that had to be calculated. The rest was solved by the software. Otherwise, analytical calculations would have been very extensive in order to know the temperature distribution and the heat flux. Apart from numerical results, it was also possible to visualize the behavior of the window with the hot box in two different scenarios, this is, for stationary and time dependent study. In this way, the effect of the external temperature was better seen.

The simulation results were also used to validate the hot box set-up when it was under uncontrolled outside temperatures. The stationary study served as a base case, to guide a little how the heat transfer through the window with the hot box would go under stationary outdoor conditions. Most of the heat losses would go through the window, so the hot box was quite well designed. Besides, the stationary simulations were carried out in a matter of seconds, so any change could be made in case the results differed a lot from reality. The real values were measured by sensors which might not have been properly calibrated. Nevertheless, the stationary simulation solution did not match the temperature at which the geometry actually was. The stationary study was conducted over the course of one day, but the actual geometry still was influenced by the temperatures of the previous days. Therefore, no stationary conditions were reached. The stationary study could not be extended because the outdoor temperature relies on the weather. Prata et al waited 48 hours to reach stationary conditions on a thermal bridge [18].

The results of the transient case were closer to the reality than the stationary case because the solution of the previous step was taken into account. In the wall behind the insulation, the temperatures did not converge in 5 days and the study would have to be extended to know the k value of the wall with more accuracy. Overall, the results showed that the outdoor temperature influenced the temperature of the geometry after few minutes, hours or days. Martin et al also found that there was a difference of 8 hours on a thermal bridge [17]. In other words, the effect was not immediate due to the delay in time, specially, in the most distant areas from the exterior.
The insulation heat loss had few fluctuations throughout the time comparing with the window. The heat loss ratio would have remained constant between the insulation and the window, so that the heat loss of each element could be identified without interfering with each other. In addition, the heat loss percentage of the window should be as high as possible, so that the heat that is lost through the wall does not have to be much calibrated as mentioned by [26]. Many factors must be taken into consideration when using the hot box in transient conditions.

Finally, although the precision of the simulation could be improved, it can be said that all the objectives of the study were fulfilled.
6 Conclusion

6.1 Study results

The results of the study demonstrate that uncertainty persists when applying the hot box technique under transient conditions. The outside temperature does not have the same impact on all parts of the window with the hot box set-up; indeed, the outside temperature affects the window more than the insulation and not simultaneously. When working with transient conditions, it is necessary to be cautious because many factors have to be taken into consideration for the result to be valid. Therefore, the most accurate way to apply this technique would still be under stationary conditions. In Gavle, although the outdoor temperature remained constant for one day, it was not long enough to achieve stationary conditions in the hot box set-up. The temperature of the previous days was still playing an important role. In conclusion, it would be best to apply this technique in places where the outside temperature does not vary so much, as the temperature changes can have a long-lasting effect on the geometry.

6.2 Outlook

The present study could be extended in the future taking into account the following aspects:

- The stationary study could be repeated again, when outdoor temperatures are kept more constant, and see whether it is possible to achieve stationary conditions.

- The transient study could be extended one more week to know the k value of the wall with more precision.

- A 3D model could be performed. The 3D study would allow to assess what happens along the height of the hot box. In addition, different types of mesh could be tested.
6.3 Perspectives

The thermal efficiency of new building components is assessed by laboratory techniques. However, once incorporated into the building, its properties deteriorate gradually, especially after many years. Due to the deterioration of properties, it is often necessary to increase the energy demand in buildings in order to maintain indoor air quality standards. Increasing energy demand increases the CO$_2$ emissions as well. The study carried out in this thesis helps to develop techniques to know the current properties of the window, so that they can be improved in order to reduce the use of energy and ensure thermal comfort indoors. However, these techniques are often expensive, and thus, they have to be subsidized by the government or some other institution. Ultimately, the window being studied had a low-e plastic film attached to the indoor glass pane. In this way, the entire window did not have to be changed. This reduces the life cycle cost of the window and also the waste generated, the manufacture of new materials, the transport and the energy required for it.
References


Appendix A

Appendix A gives more information regarding the dimension, position of the sensors of the hot box, the outside temperature and the mesh selected to perform the simulations.

Figure 1 represents the shape and the dimension of the window.

![Figure 1. Dimensions of the window.](image1)

Figure 2 indicates the location of the sensors at the middle cross section of the hot box set-up.

![Figure 2. Position of the sensors in the hot box set-up.](image2)
The outdoor temperature in the days prior to the study might have affected the results of the stationary and transient study. Figure 3 shows the outdoor temperature 5 days before the study (from December 12th to December 17th 2018) as well as the temperature during the study period (from December 18th to December 22nd 2018).

Figure 3. Outdoor temperature on the days before and after the study.

Figure 4 shows the chosen the mesh to perform the study.

Figure 4. Mesh creation in COMSOL Multiphysics 5.3.
Appendix B

This appendix shows the calculations made to obtain the combined heat transfer coefficients which took into account convection and radiation. Three h coefficients were calculated: two corresponded to the interior and exterior surfaces of the window, and the third one was for the inner part of the wall. The heat transfer coefficient for the window were obtained based on the equations developed by ISO 15099:2003. As for the wall, the equations are those generally used for room surfaces.

- Window-internal side

The combined heat transfer coefficient (h) was achieved for when the average indoor air temperature was about 21.6°C and the average temperature of the inner surfaces was considered 12°C. Besides, the low-e plastic film was in the internal side whose emissivity was considered to be 0.1. The height of the window was 2 m. By entering the requested values in the equations (8), (9) and (10), the convective heat transfer coefficient (h) was estimated to be 8.61 W/m²·K.

\[
Ra_h = \frac{\rho^2 H^3 g C_p (T_{air} - T_{surf})}{(T_{air} + \frac{1}{2}(T_{surf} - T_{air})) \mu k} = \frac{1.2^2 \cdot 2^3 \cdot 9.8 \cdot 1007 \cdot (21.6 - 12)}{273.15 + 21.6 + \frac{1}{4}(12 - 21.6) \cdot 1.78 \cdot 10^{-5} \cdot 0.025} = 9.95 \cdot 10^0 \quad (-)
\]

\[
Nu = 0.13Ra_h^{1/3} = 0.13 \cdot (9.95 \cdot 10^0)^{1/3} = 689.34 \quad (-)
\]

\[
h_c = Nu \frac{k}{H} = 689.34 \cdot \frac{0.025}{2} = 8.61 \quad (W/m²·K)
\]

The radiation heat transfer coefficient (h_r) was calculated using equation (14).

\[
h_r = 4 \varepsilon \sigma (273.15 + T_{surf})^3 = 4 \cdot 0.1 \cdot 5.67 \cdot 10^{-8} \cdot (273.15 + 12)^3 = 0.52 \quad (W/m²·K)
\]

In the end, by summing up the convective (h_c) and radiative (h_r) heat transfer coefficients, the combined heat transfer coefficient (h) for the inner side of the window was obtained which was 9.13 W/m²·K.

- Insulation-internal side

The combined heat transfer coefficient (h) for the internal side of the insulation was calculated when the average indoor air temperature was about 21.6°C (T_m) and the average temperature of the inner insulation was around 20°C (T_int). The emissivity of the insulation was assumed to be 0.95, since it was blacked painted. The height of the insulation was considered to be 2 m like the window.

The convective heat transfer coefficient (h_c) was estimated to be 1.83 W/m²·K by entering the requested values in the equations (12) and (13).

\[
Gr = \frac{\frac{1}{4} \pi T_{int}^2 (T_{int} - T_{surf}) L^3}{v^2} = \frac{9.81 \pi 273.15 + 21.6 \cdot 2^3}{(1.525 \cdot 10^{-5})^2} = 1.84 \cdot 10^9 \quad (-)
\]

\[
Nu = 0.13(GrPr)^{1/3} = 0.13 \cdot (1.84 \cdot 10^9 \cdot 0.73)^{1/3} = 143.44 \quad (-)
\]

\[
h_c = Nu \frac{k}{H} = 143.44 \cdot \frac{0.025}{2} = 1.83 \quad (W/m²·K)
\]
The radiative heat transfer coefficient was calculated in the same way as the previous cases (14).

\[ h_r = 4 \varepsilon \sigma (273.15 + T_{surf})^3 = 4 \cdot 0.95 \cdot 5.67 \cdot 10^{-8} \cdot (273.15 + 20)^3 = 5.42 \text{ (W/m}^2 \cdot \text{K)} \]

The sum of the convective and radiative heat transfer coefficients gave the combined heat transfer coefficient of 7.25 W/m²·K

- Window-external side

The combined heat transfer coefficient \( h \) was calculated when the average outdoor air temperature was about -3.68°C and the average temperature of the outer surfaces was around 1.5°C \( (T_{surf}) \). In addition, the wind with speed was around 4 m/s measured by meteorological stations around. The emissivity of the outer surface was assumed to be 0.85, since there was no low-e plastic film attached to the outer panes.

The convective heat transfer coefficient turned out to be 12.3 W/m²·K regarding equation (11).

\[ h_c = 4.7 + 1.9 \cdot v = 4.7 + 1.9 \cdot 4 = 12.3 \text{ (W/m}^2 \cdot \text{K)} \]

The radiative heat transfer coefficient was calculated in the same way as the previous cases (14).

\[ h_r = 4 \varepsilon \sigma (273.15 + T_{surf})^3 = 4 \cdot 0.85 \cdot 5.67 \cdot 10^{-8} \cdot (273.15 + 1.5)^3 = 4 \text{ (W/m}^2 \cdot \text{K)} \]

As a result, the combined heat transfer coefficient \( h \) for the window was figured out which resulted in 16.3 W/m²·K.
Appendix C

In this appendix, more details about the results are shown.

- Cut lines in the geometry in the stationary study.

Besides, several cuts were made in the geometry to calculate accurately the temperature gradient, note that only conductive heat transfer was considered in the solid geometry. Figure 1 shows the temperature gradients in the vertical cut line on the window panes and the wall, and also gives more information of the effect of the insulation and its edge.

![Vertical cutline of the window](image1)
![Vertical cutline of the wall](image2)
![Cutline of the 45º tilted part of the insulation](image3)
![Cutline behind insulation](image4)

**Figure 1. Geometry cuts in the stationary study.**
In the following graphs, the temperatures obtained by COMSOL Multiphysics 5.3 and the measurements by sensors are shown in different elements of the window during the transient study. C refers to the results obtained with COMSOL and M to the sensors measurements.

**Figure 2. Temperature evolution in the left frame.**

**Figure 3. Temperature evolution in the window panes.**
Figure 4. Temperature evolution in the right frame.