Improved Fire Performance of Windows by Low Emissivity Coatings

Sandra Hedqvist
2016

Master of Science in Engineering Technology
Fire Engineering

Luleå University of Technology
Title: Improved fire performance of windows by low emissivity coatings

Titel: Förbättrat brandmotstånd hos fönster med lågemissivitetsbeläggningar

Author: Sandra Hedqvist

Supervisors: Michael Försth, Luleå University of Technology
            Mikael Ludvigsson, Glafo - Glass Research Institute

Keywords: glass breakage in windows, radiative heat transfer, spectral absorptivity, in depth absorption, emissivity of semi-transparent materials

Nyckelord: glasbrott i fönster, värmeöverföring genom strålning, spektral absorptivitet, absorption på djupet, emissivitet för semitransparenta material
Preface

This master thesis is my completion of the master programme in Fire Engineering at Luleå University of Technology. The thesis has been performed for a period of 20 weeks in Luleå during the autumn of 2015 and winter of 2015 and 2016.

I would like to thank all the people who have helped me in this thesis. My internal supervisor Michael Försth who gave me the idea and have helped me a lot within this project, both with valuable tips regarding the study and report writing but also a lot of help within the area of spectral glass properties, in depth absorption and emission.

An especially thanks to Naveed Iqbal who have helped me with the modelling in Abaqus.

I would also like to thank my external supervisor Mikael Ludvigsson and his colleagues at Glafo whom have enlightened me with information about windows, low emissivity coatings and ongoing research within the area of the project.

Not to forget my fellow students and opponent, you have all been a great asset and support during this project.

Stockholm, 23th August 2016

Sandra Hedqvist
Nomenclature

$q$  heat flux
$h$  heat transfer coefficient, Planck’s constant, height of the glass pane
$T$  temperature
$k$  thermal conductivity
$M$  emissive power
$c_0$  speed of light in vacuum
$k_b$  Boltzmann’s constant
$E$  Irradiance, Young’s modulus
$F_{v.x}$  view factor between two surfaces

$a$  height of the heat source
$b, h$  width of the heat source
$c$  distance to the heat source
$w$  width of the window
$L_f$  Mean flame height
$Q$  heat release rate from a burning object
$D$  diameter of a burning object
$b_w$  Wien’s displacement constant
$\sigma$  stress, characteristic bending strength
$c_p$  specific heat capacity
$L$  Length, cold side of the glass pane
$F$  force
$A$  Area, instrumental amplification factor

\[ x \]  distance into the glass
\[ y \]  distance away from the edge towards the middle of the pane
\[ z \]  distance along the edge
\[ s \]  frame height
\[ H_n, H_c \]  half-length of the exposed glass
\[ \theta \]  hot side of the glass pane
\[ t \]  time
\[ g, f \]  force balance factor/geometry factor
\[ S \]  signal when measuring spectral properties of glass specimens

\[ \Delta \]  difference

\[ \alpha \]  absorptivity
\[ \varepsilon \]  emissivity, strain
\[ \lambda \]  wavelength
\[ \rho, R \]  density and reflectivity
\[ \tau, T \]  transmissivity
\[ \nu \]  Poisson’s Ratio

\[ \beta \]  coefficient of linear thermal expansion

\[ \Delta \]  difference

\[ \text{Superscripts} \]

‘’  per unit area
\[ \cdot \]  per unit time

\[ \text{Subscripts} \]

\[ \text{con, c} \]  convection
\[ g \]  gas
\[ s \]  surface
\[ \infty \]  ambient
\[ f \]  surface film
\[ x \]  dimension into a material
\[ \text{rad} \]  radiation
\[ \text{source} \]  source

\[ \lambda \]  spectral
\[ \text{emi} \]  emitted

\[ \text{inc, i} \]  incident
\[ \text{abs} \]  absorbed
\[ \text{max} \]  maximal
\[ \text{eff} \]  effective
\[ \text{net} \]  net rate
\[ b \]  breakage
\[ \text{exposed} \]  exposed bulk of the glass pane

\[ \text{coldest} \]  coldest spot at the shaded edges
\[ \text{sample} \]  specimen of the glass
\[ \text{ref} \]  reference specimen
Abstract

In a room fire wall openings are playing an important role for how the fire is developed since the size of the fire, the heat release rate, is often limited by the flow of oxygen from these openings. When a window breaks and falls out, this sudden geometric change and increased access of oxygen can lead to backdraft and/or flashover which is not desirable.

Glass breakage in windows mainly occurs due to differential heating of the glass pane. The literature review suggest that it is the temperature difference between the exposed central pane and the shaded edges that is causing critical stresses and breakage. Glass breakage tend to initiate at edge flaws and then propagating to the central of the glass causing fallout of the glass pane.

Temperature rise in materials caused by radiation is depending on the size of absorbed heat flux which is depending on the absorptivity of the material. According to Kirchhoff’s law the spectrally resolved absorptivity is equal to the emissivity for opaque surfaces. But since glass is a semi-transparent material that absorbs and emits energy in depth Kirchhoff’s law is not valid and the in depth absorption and emission has to be taking into account.

Using low emissivity coatings, Low-E coatings, has been discussed for several decades, mainly for energy saving purposes. But what about the positive effects in the fire protection area? Does reducing the absorptivity prevent rapid and early temperature rise and therefore stop or delay windows from breaking? And if this is the case, how effective are low emissivity coatings for this purpose?

In this study the efficiency of Low-E coatings on glass exposed to radiation caused by an enclosure fire has been investigated. Theory and physics about heat transfer, windows in buildings, Low-E coatings, glass breakage and spectral properties of in depth absorptivity and emissivity has been studied. Simplified and more advanced models for calculations of the windows breaking time, with and without low emissivity coatings, has been investigated and calculations has been performed.

Abaqus, an advanced FEM (Finite Element Method) program, was chosen for the thermal analyses and a simplified calculation method presented by Joshi and Pagni was used to evaluate the critical temperature difference. To get accurate input data spectral properties of the glasses was measured.

Two glass types has been studied and compared, one with a Low-E coating (K-glass) and one without (F-glass). The glasses were exposed to two cases, one with an incident radiation from a flame of 23.4 kW/m² and one with an incident radiation from a hot gas layer of 14.3 kW/m². The result showed that reducing the absorptivity is preventing the rapid and early temperature rise and therefore stop or delay windows from breaking. In the case where the glasses was exposed to 23.4 kW/m² the F-glass breaks after 42 seconds and the K-glass after 137 seconds, an increased integrity of 226 %. In the other case the F-glass breaks after 59 seconds while the K-glass is keep intact.

The importance of in depth absorption was also examined and the results show that in depth absorption reduces the early and rapid temperature rise in the glass, the temperature rise is delayed at an early state, compared to surface absorption. This is probably since the glass is more uniformly heated which is believed making the heat flux done by conduction less rapid. The retardation of increased temperature makes the critical temperature difference exceeding later. It was also shown that taking in depth absorption into account gives computational results closer to the experimental result, but whether in depth absorption has to be taking into account or not is hard to tell since only one comparison was made. Further examination of the phenomena has to be performed. Surface absorption is considered to be a good first approximation since it will give conservative results but in depth absorption may be a more accurate boundary regarding absorption for semi-transparent materials.
Sammanfattning


Glas spricker huvudsakligen på grund av att olika delar av glasskivan värms upp olika snabbt. Den studerade litteraturen visar att det är temperaturskillnaden mellan det exponerade mittpartiet och de skuggade kanterna som orsakar kritiska spänningar och sprickor i glasets kanter. Sprickorna tenderar att börja i kanternas ojämnheter för att sedan föröka sig in mot mittpartiet.

Temperaturökning i ett material som utsätts för strålning regleras av den mängden energi som absorberas. Hur mycket av den infallande strålningen som absorberas beror i sin tur på materialets absorptivitet som enligt Kirchhoff’s lag är densamma som ytans emissivitet för ett ogenomskinligt material. Men eftersom glas är ett halvtransparent material som både absorberar och emitterar strålning på djupet måste dessa egenskaper beaktas.

Att använda lågemissivitetsbeläggningar, Low-E beläggningar, har länge diskuterats och används på fönster med det främsta syftet att spara energi. Det eftersom beläggningen isolerar fönstret. Men kan beläggningen även vara bra ur brandsynpunkt? Förhindras den kraftiga temperaturökningen i glaset, och därmed fördjöjer eller förhindrar att glaset spricker, genom att minska ytans absorptivitet? Och hur effektiva är i så fall dessa beläggningar?

I det här arbetet har effektiviteten av Low-E beläggningar på glas som utsätts för strålning från en rumsbrand undersökt. Teori och fysik om värmeströmförförränning, fönster i byggnader, Low-E beläggningar, varför glas går sönder och spektrala egenskaper av absorption och emission på djupet har studerats. Fördenklade och mer avancerade beräkningsmetoder för beräkning av tiden till sprickbildning, med och utan beläggning, har studerats och beräkningar har genomförts.

Ett avancerat FEM program, Abaqus, valdes till temperaturanalysen och en enklare modell presenterad av Joshi och Pagni valdes för att beräkna den kritiska temperaturskillnaden. För att få bra indata mättes de spektrala egenskaperna på de olika glasen.

Två typer av glas har studerats och jämförts, ett med en Low-E beläggning (K-glas) och ett utan beläggning (F-glas). Glasen utsattes för två fall, ett där strålningen kommer från en flammat motsvarande 23.4 kW/m² och ett fall där glasen utsattes för en strålningstvå från ett varmt rökgasklager på 14.3 kW/m². Resultatet visade att reducering av absorptiviteten förhindrar den kraftiga temperaturökningen i glaset, och därmed fördjöjer eller förhindrar att glaset spricker. Vid en infallande strålning på 23.4 kW/m² gick F-glaset sönder efter 42 sekunder och K-glastet efter 137 sekunder, en ökad integritet på 226 %. I det andra fallet behöll K-glastet sin integritet medan F-glastet sprack efter 59 sekunder.

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1 Introduction

1.1 Background and problem formulation

In a room fire wall openings are playing an important role for how the fire is developed since the size of the fire, the heat release rate, is limited by the flow of oxygen from these openings. When a window breaks and falls out, this sudden geometric change and increased access of oxygen can lead to backdraft and flashover which is undesirable. [1]

In case of fire it is of high importance that the evacuation can be performed in a satisfying manner. Critical limits for untenable conditions should not be reached before everyone has evacuated. High temperatures and a high amount of toxic gases are two examples of limits that must not be exceeded. [2] Since rapid and high temperature rise and the amount of toxic gases is depending on the size of the fire, which in its turn is depending on the amount of oxygen, the evacuation time can be elongated by preventing windows from breaking. In another case where the glass is acting as a separating construction between the fire and the evacuating people there are limits for critical conditions with respect to radiation [2]. To manage this requirement the glass must not break during evacuation.

In fire protection engineering fire modelling program is often used to predict the fire growth and temperatures in constructions. When doing this modelling the openings of the room/building must be known. Therefore glass breakage has become of special interest the last decades and has promoted a number of theoretical and simplified studies and a few empirical ones to [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The focus has been to predict the windows breaking time and how to delay or stop the windows from breaking and falling out.

Generally glass breaking occurs due to thermal stress from the differential heating of the central pane and the shaded edges of the window [7]. Heat transfer from a fire to a surface is mediated by convection and radiation where radiation has a more dominating impact on the early, rapid and high temperature rises of the surface [13]. The amount of absorbed energy to the surface by radiation is further depending on the surface absorptivity. The more energy that is absorbed the higher temperatures is obtained.

Using low emissivity coatings have been discussed for several decades, mainly for energy saving purposes. But what about the positive effects in the fire protection area? Does reducing the absorptivity prevent rapid and early temperature rise and therefore stop or delay windows from breaking? And how effective are the coatings?

The aim of this study has been to investigate the efficiency of low emissivity coatings on glass exposed to radiation caused by fire. To do that the theory and physics behind heat transfer, windows in buildings, Low-E coatings, glass breakage, and spectral properties of in depth absorptivity and emissivity has been studied. Simplified and advanced models for calculations of the windows breaking time, with and without low emissivity coatings, has been investigated. And further calculations has been made to evaluate the efficiency of low emissivity coatings on glass in windows.
1.2 Research questions

1. Does reducing the surface absorptivity prevent rapid temperature rise, and steep temperature gradient, and therefore stop or delay windows from breakage?
2. How effective is low emissivity coatings on windows exposed to high temperatures compared to windows without coatings?
3. How well can the breakage time be predicted and is the prediction accuracy affected by low emissivity coatings?

1.3 Purpose of the study

The aim of this study is to investigate the structural integrity effect of low emissivity coatings on glass exposed to high temperatures caused by radiation.

1.4 Limitations

Since radiation is dominating and causes the major impact on the early and rapid temperature rise of a surface heating by convection is not considered in this study.

The analysis are limited to two cases where a one paned soda lime silicate glass with and without a Low-E coating are exposed to a constant heat flux from; 1. a flame and 2. a hot gas layer. The dimensions of the glass pane is limited to the dimensions of 1000 x 1000 x 4 mm³ and with a 10 mm shading frame.

Window breakage due to pressure is not considered.
2 Theory

2.1 Enclosure fires

A fire can occur and develop in many different ways. The development is mainly affected by the amount of combustible material and in addition the oxygen supply is a very decisive factor for the outcome. If the enclosure is sealed there will be a lack of oxygen which will cause the fire intensity to decrease providing lower temperatures. [1]

A window is acting as a wall before breaking and as a vent after breaking. Provided that sufficient amount of combustible gases have accumulated in the hot gas and smoke layer this sudden geometric change can lead to backdraft or flashover [1]. But if the enclosure has no vents the fire growth will be limited by the amount of oxygen, the fire will not grow to a fully developed as illustrated in Figure 1.

Figure 1 illustrates different scenarios for enclosure fires. In our case the desired scenario is that the window keeps its integrity. Provided that the rest of the rooms’ openings are closed this will stop the fire growth due to lack of oxygen providing more time for people to evacuate, more time for firefighters to interfere or it will provide the fire to self-extinguish. If flashover occurs the fire intensities and becomes very hard to extinguish causing great damage on the property and more adverse environment for evacuating people [1]. Another scenario is if the window breaks or a door is opened at a later state, in that case the down going curve (due to lack of oxygen) will turn providing higher temperatures and potentially flashover. In Figure 1 another case is also seen where the curve at an early state of the fire is turning down and self-extinguish which probably is due to lack of oxygen or combustible material.

Before flashover the smoke-gas layer has a temperature around 500-600 °C and at a fully developed fire the temperatures is usually around 700-1200 °C. The flame temperature is varying depending on the burning material and if the flame is laminar or turbulent but 800-1000 °C is typical values of fully evolved flame in compartments. [14]
2.2 General heat transfer

When there is a temperature difference between one physical body and its surroundings heat is transferred from the hot body to the cold one until thermal equilibrium is established. There are generally three modes of heat transfer. Convection, conduction and radiation. [13]

2.2.1 Convection

Convection is the mode of heat transfer that naturally arises in gases and liquids due to temperature differences between a hot surface and the adjacent gas or liquid. This phenomenon is called natural or free convection. If the flow is induced by a fan or similar it is called forced convection. [13]

When a window is exposed by radiation the glass surface will increase in temperature. The temperature difference between the glass surface and the surrounding air will induce natural convection. The heat transfer by convection is directly proportional to the temperature difference described by Eq. (1) derived from Newton’s law of cooling [13].

\[ \dot{q}_{\text{con}} = -h_c(T_g - T_s) \] (1)

Where \( h_c \) is the convection heat transfer coefficient, \( T_g \) is the surrounding gas or liquid temperature and \( T_s \) is the hot surface temperature. For a flow condition of free convection at vertical plates such as windows the mean heat transfer coefficient can be calculated according to Eq. (2). [13]

\[ h_c = 76.0 \cdot T_f^{-0.666} \cdot (T_s - T_\infty)^{1/3} \] (2)

Where \( T_s \) and \( T_\infty \) are the surface and ambient temperatures respectively. \( T_f \) is the surface film temperature described by Eq. (3). [13]

\[ T_f = (T_s + T_\infty) / 2 \] (3)

2.2.2 Conduction

Conductivity is another mode of heat transfer in liquids and solid materials. It is a molecular process where energy is transferred from particles of high energy (high temperature) to particles with lower energy (lower temperature). When a molecule of high energy is e.g. colliding with or vibrating next to a neighbouring molecule heat transfer by conduction occurs from the more to the less energetic molecule. [13]

The Fourier’s law states that the heat flux by conduction is proportional to the heat conductivity, \( k \), for the material times the thermal gradient in the specific section according to Eq. (4).

\[ \dot{q}_{\text{cond}} = -k \cdot \frac{dT}{dx} \] (4)

2.2.3 Radiation

Radiation occurs from all materials such as solids, liquids or gases. Thermal radiation consists of electromagnetic waves and differs from convection and conduction since no matter is needed to be present for radiation to be transferred. Radiative energy can pass through vacuum as well as air. [13]

Between a hot emitting surface and its surrounding air radiation takes not place only in the direction from the hot surface to the air but also in the direction from the air to the surface. The surface gains or loses energy from the surrounding air depending on the temperature differences. Assuming an emissivity equal to 1 for the ambient the net radiation from a surface to the ambient occurs according to Eq. (5) [13].
\[ \dot{q}_{rad} = \sigma (\alpha_s T_\infty^4 - \varepsilon_s T_s^4) \]  

(5)

Where \( T_s \) and \( T_\infty \) is the absolute surface and ambient temperature in Kelvin, \( \alpha_s \) is the absorption coefficient of the surface, \( \sigma \) is the Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \) W/m\(^2\)K\(^4\) and \( \varepsilon_s \) is the emissivity of the surface.

But this is not the typical way of presenting the radiation from a surface since the emissivity and absorptivity is equal according to Kirchoff's law hence Eq. (5) is often written as Eq. (6).

\[ \dot{q}_{rad} = \varepsilon_s \sigma (T_\infty^4 - T_s^4) \]  

(6)

### 2.3 Radiative heat transfer

#### 2.3.1 General

There are generally three modes of heat transfer. Convection, conduction and radiation. In an enclosure fire the dominating mode is very often radiation due to the high temperatures of the flames and hot gas layer [14]. This since the radiation depends on the difference of the body surface temperature to the fourth power (see Eq. (6)) while it for convection is approximately to the first power (see Eq. (1)) [13]. Hence only heat transfer by radiation is considered in this report.

#### 2.3.2 Thermal radiation from a surface

In this chapter the thermal radiation from a heated surfaces such as hot gases and flames is described. Further in chapter 2.3.3 thermal radiation against and trough matter such as a glass pane in a window is described.

The first appropriate description of thermal radiation, i.e. transfer of heat by electromagnetic waves, was done in the early 1900s by Planck’s Law which is described by Eq. (7). It gives the energy emitted per unit area and wavelength of the electromagnetic spectrum. [14, 15]

\[ M_\lambda = \frac{2\pi h c_0^2}{\lambda^5} \left[ e^{\frac{h c_0}{\lambda k_B T_s}} - 1 \right] \]  

(7)

where

- \( M_\lambda \) = spectral emissive power (W/m\(^2\) \( \mu \text{m} \)),
- \( h \) = Planck’s constant, \( 6.626 \times 10^{-34} \) J/s
- \( c_0 \) = speed of light in vacuum, \( 299792458 \) m/s (exact)
- \( k_B \) = Boltzmann’s constant, \( 1.381 \times 10^{-23} \) J/K
- \( T_s \) = the body’s surface temperature (K),
- \( \lambda \) = wavelength of the radiation (\( \mu \text{m} \)).

Adding all of the energy in the spectrum, integrating Eq. (7) from 0 to \( \infty \) with respect to wavelength, gives Eq. (8), the ideal blackbody emissive power. It is the upper limit of energy leaving a blackbody surface by radiation, also called the Stefan Boltzmann law. [14, 13]

\[ \dot{q}_{\text{em}} = \sigma T_s^4 \]  

(8)

Where \( \sigma \) is the Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \) W/m\(^2\)K\(^4\), which is the resulting constant of Planck’s constant, the speed of light, Boltzmann’s constant and the wavelengths in Eq.(7)
But there are however no surface or absorbing media that are ideal radiators such as ideal blackbodies so the emissive power for blackbodies is in reality reduced by the property called emissivity, $\varepsilon$. With values in the interval $0 \leq \varepsilon_{source,\lambda} < 1$ this property is a measure of how efficiently a surface emits energy relatively to a blackbody surface where the subscript “source” refers to the heat source and not to the surface receiving the radiation. The emissivity depends on the medium and it varies with wavelength of the emitted radiation. How to calculate a weighted value of the spectral emissivity for a specific heat source is further described in chapter 2.3.7. The spectral emissive power from a real hot surface is described by Eq. (9). [14, 13]

$$\dot{q}^\varepsilon_{emi,\lambda} = \varepsilon_{source,\lambda} M_\lambda$$

The emitted radiation from a surface depending on the wavelength, $q_{emi,\lambda}$, is further transported to a receiving surface, then denoted by, $q_{inc,\lambda}$, the incident radiation which also often is described by the symbol $E_\lambda$, the irradiance against the receiving surface.

2.3.3 Thermal radiation to a surface

Thermal radiation can either be absorbed, reflected or transmitted through matter which is illustrated by Figure 2. The fractions of incident energy reflected, absorbed or transmitted are represented by the properties of reflectivity ($\rho$), absorptivity ($\alpha$) and transmissivity ($\tau$). These properties depends on the material and the wavelength of the incident energy. [14] A window in a façade can for example transmit desirable wavelengths such as sunlight and (from the inside) reflect wavelengths from the interior, i.e. force the heat to stay inside.

![Figure 2. Incident radiation through matter. Illustration from Karlsson and Quintiere [14].](image)

In a fire scenario it is desirable to avoid windows from breaking i.e. prevent them from heating. In that case low absorptivity glass properties is desirable. With low absorptivity the window absorb less energy and therefore does not increase fast in temperature. Tension will not appear and the window will be kept intact for a longer time.

The amount of spectrally resolved absorbed energy for a specific wavelength in a glass is a fraction of the incident heat flux according to Eq.(10).

$$\dot{q}^\alpha_{abs,\lambda} = \alpha_{\lambda} \cdot \dot{q}^{inc}_{inc,\lambda}$$

The absorptivity for a specific wavelength, $\alpha_{\lambda}$, is depending on the transmittance and reflectance as shown in Eq. (11). [15]

$$\alpha_{\lambda} = 1 - \rho_{\lambda} - \tau_{\lambda}$$
Where both the reflectivity, $\rho_\lambda$, and transmissivity, $\tau_\lambda$, can be measured.

Further Kirchhoff’s Law states that the spectral emissivity and absorptivity for a specific wavelength are equal for opaque mediums at the same temperature, i.e. as Eq. (12) shows. [14]

$$\alpha_\lambda = (\lambda, T) = \varepsilon_\lambda (\lambda, T)$$  \hspace{1cm} (12)

This relation is not strictly valid for glass since glass is a semi-transparent material that absorbs and emits energy in depth which is further described in chapter 2.6.1. How to calculate the spectrally averaged, i.e. not wavelength dependant, absorptivity and emissivity is presented in chapter 2.3.6 and 2.3.7.

**Incident radiation and view factors**

The incident radiation to an exposed surface is depending on the amount emitted energy from the emitting hot surface and its position in relation to the exposed surface. This can be regulated by the concept of view factors, also called configuration factors, shape factors and angle factors. The view factor between two surfaces is describing the fraction of emitted radiation from one surface, 2, arriving at the other, 1, according to Eq. (13). [13]

$$\hat{q}_{\text{inc,2-1}} = F_{1-2} \cdot \hat{q}_{\text{emi,2}} = F_{1-2} \cdot \varepsilon_2 \cdot \sigma \cdot T_2^4$$  \hspace{1cm} (13)

The symbol $F_{1,2}$ is denoting the view factor from surface 1 to surface 2 and is defined by the size, geometry, relative positions and orientation of the two surfaces.

In our case it is of interest to know some approximate amounts of incident radiation arriving at the window in a room fire. In a room fire the window is mainly exposed to emitted radiation from the hot flames, where the size of the flame is depending on the burning object, and smoke-gas layer. Therefore two cases is of interest. Calculation of the view factor for the window in relation to the smoke-gas layer and for the window in relation to the flames. In this report the hot flame is represented by a burning television setup.

Figure 3 describes the two different cases. To the left a plane element $dA_1$, the window, is plane parallel and passes through the corner of the rectangle $A_2$, the flame. To the right there are two infinitely long plates of unequal widths $h$ (corresponding to the smoke-gas layer) and $w$ (corresponding to the window), having one common edge with an angle of 90° to each other.

![Figure 3](image)

*Figure 3. To the left: The window ($dA_1$) in relation to the fire ($A_2$). To the right: The window ($A_3$) in relation to the smoke-gas layer ($A_4$). Illustrated by Wickström [13].*
The view factor for each scenario is calculated according to Eq. (14) and (15). [13]

\[ F_{1-2} = \frac{1}{2\pi} \left[ \frac{X}{\sqrt{1+X^2}} \arctan \left( \frac{Y}{\sqrt{1+X^2}} \right) + \frac{Y}{\sqrt{1+Y^2}} \arctan \left( \frac{X}{\sqrt{1+Y^2}} \right) \right] \]

where

\[ X = \frac{a}{c} \quad \text{and} \quad Y = \frac{b}{c} \]

\[ F_{3-4} = \frac{1}{2} \left[ 1 + H - \sqrt{1+H^2} \right] \]

where

\[ H = \frac{h}{w} \]

Mean flame height

The incident radiation is also depending on the size of the heat source, e.g. the area of the hot smoke gas layer or the area of the flame. A flame is constantly fluctuating with time and the mean height of the flame is the height where the flame most often is presented. To get reasonable values for the flame height the mean flame height can be calculated according to Eq. (16).

\[ L_f = 0.235 \dot{Q}^{(2/5)} - 1.02D \]  

Where \( \dot{Q} \) is the heat release rate in kW from the burning object and \( D \) is the object’s diameter in meters.

2.3.4 Wavelengths and irradiance

Radiation can appear in different shapes, i.e. within different wavelengths. Depending on the source that is emitting energy the radiation appears within different wavelengths, see Figure 4. Wavelengths from the sun, visible light and near infrared radiation, is mainly in the area of \( 0.3-2.5 \) \( \mu m \) while radiation from a fire, in the infrared region, is in the area of \( 1-10 \) \( \mu m \) [14, 16]. Environmental radiation, i.e. radiation from interior inside of a room, is in the range of \( 4-40 \) \( \mu m \) [17]. Note that a part of the radiation from a fire lies in the range of the environmental radiation.

![Figure 4. The electromagnetic spectrum. [18]](image)

When a surface is exposed to radiation it is called irradiation. The definition of irradiance is the radiant flux received by a surface for a specific wavelength per unit area e.g. W/m². Figure 5 shows irradiance from the sun and Figure 6 shows irradiance from blackbodies with different temperatures.
As seen in Figure 6 the spectral blackbody irradiance is changing with the surface temperature where a higher temperature results in a larger maximal irradiance which is in consistence with Stefan Boltzmann’s law, see Eq. (8) in chapter 2.3.2. It can also be seen that the peak is displaced to the left (smaller wavelengths) for higher temperatures. This phenomenon can be described by Wien’s displacement law which states where the blackbody radiation curve peaks for different temperatures. [15] The peak is at the maximal wavelength $\lambda_{\text{max}}$ given by Eq. (17).

$$\lambda_{\text{max}} = \frac{b_w}{T_s}$$  \hspace{1cm} (17)

Where $b_w$ is Wien’s displacement constant equal to $2.8977729 \times 10^{-3}$ m·K $\approx 2900$ μm·K \cite{19} and $T_s$ is the surface absolute temperature in Kelvin. Hence a greater temperature gives a smaller $\lambda_{\text{max}}$. 

---

**Figure 5.** Solar irradiance. Illustration from Karlsson and Quintiere [14].

**Figure 6.** Spectral blackbody irradiance for different fire temperatures. Calculated according to Eq.(7).
As mentioned the emissivity and the absorptivity is varying with different wavelengths. Figure 7 illustrates this phenomenon for the emissivity, i.e. irradiance from surfaces with different emissivities depending on wavelength.

![Figure 7](image)

*Figure 7. Irradiance from surfaces with different emissivity. Illustration from Karlsson and Quintiere [14].*

The total irradiance, \( q_{inc} \), against a surface is obtained by integrating the spectral irradiance, \( q_{inc,\lambda} \), over all wavelengths according to Eq. (18). [15]

\[
q_{inc} = \int_{0}^{\infty} q_{inc,\lambda} d\lambda
\]  

The total radiant heat flux for the whole wavelength spectrum absorbed into a material is given by integrating the spectral absorptivity with the spectral irradiance according to Eq. (19). [15]

\[
q_{abs} = \int_{0}^{\infty} \alpha_{\lambda} q_{inc,\lambda} d\lambda
\]

It is often assumed that \( \alpha_{\lambda} \) is constant for all wavelengths, e.g. \( \alpha = 0.9 \). This assumption is called the grey-body assumption. However, as shown in a study done by Försth and Roos [20], \( \alpha \) vary significantly with wavelength and it is therefore more appropriate to use the spectral absorptivity, \( \alpha_{\lambda} \), especially for certain materials with high reflectance such as metals and certain glass. However most FEM programs can’t handle a spectral dependant property such as the absorptivity. How to calculate a weighted value of the spectral absorptivity for a specific heat source is further described in chapter 2.3.6.

### 2.3.5 Summarization of radiation between to surfaces

Figure 8 summarizes the above described theory of radiation between two surfaces. I.e. energy transportation from a hot emitting surface such as a hot gas layer or a flame to a receiving surface such as a window or a wall.
The emitting energy from a hot surface is described by Eq. (9) where the surface emissivity, $\varepsilon_{\text{source},\lambda}$, depending on the wavelength of the emitted energy and surface temperature, is multiplied with the blackbody energy for the specific wavelength, $M_\lambda$. The amount of emitted blackbody energy, $M_\lambda$, varies with the surface temperature according to Eq. (7). Further the irradiance, $E_\lambda$ (called $q_{\text{inc},\lambda}$ in this report), against the receiving surface is absorbed. The absorbed radiant heat flux, $q_{\text{abs},\lambda}$, is further calculated according to Eq. (10) describing the absorptivity, $\alpha_\lambda$, which is depending on the heat source, multiplied with the incident radiation, $q_{\text{inc},\lambda}$.

2.3.6 Weighted value of the absorptivity

In this chapter theory about how to calculate a weighted value of the absorptivity is presented which is further used in this study to obtain useful input data for the analyses.

Recall that the total irradiance, $q_{\text{inc}}$, impacting on a surface is obtained by integrating the spectral irradiance, $q_{\text{inc},\lambda}$, over all wavelengths according to Eq. (18).

Also recall that the total radiant heat flux, $q_{\text{abs}}$, for all wavelengths into a material is given by integrating the spectral absorptivity, $\alpha_\lambda$, multiplied by the spectral irradiance, $q_{\text{inc},\lambda}$, according to Eq. (19).

If the irradiance arises from a perfect blackbody the totally spectral distribution would be given by Stefan Boltzmann law according to Eq. (8). But as stated real surfaces are not perfect blackbodies. For a real hot body the irradiation is given by the blackbody irradiance multiplied by the sources’ emissivity, $\varepsilon_{\text{source}}$ according to Eq. (9).

In Figure 2 in chapter 2.3.3 a schematic geometry is given that describes the formalism in this report. Assume two infinite surfaces. This entails that angular dependencies can be disregarded and the equations mentioned above describes total hemispherical properties. Combining Eqs. (7), (9) and (19) gives the radiant heat flux absorbed by a surface receiving radiation from a heat source according to Eq. (20).
The effective absorptivity, $\alpha_{\text{eff}}$, can be calculated according to Eq. (21) for a given spectral distribution of the irradiance, i.e. for a given heat source. This is simply the ratio between the actually absorbed radiant heat flux and the maximal possible (ideal) absorbed radiant heat flux for a given temperature of the heat source. If the incident radiant heat flux is identical to the absorbed radiant heat flux the receiver is an ideal absorber with $\alpha_\lambda \equiv 1$.

$$\alpha_{\text{eff}} = \frac{\dot{q}_{\text{abs}}}{\dot{q}_{\text{abs},\text{ideal}}} = \frac{\int_0^\infty \frac{2\pi h c_0^2 \alpha_\lambda \varepsilon_{\text{source}}(\lambda)}{\lambda^5 \left[ \exp \left( \frac{hc_0}{\lambda k_b T} \right) - 1 \right]} \, d\lambda}{\int_0^\infty \frac{2\pi h c_0^2 \varepsilon_{\text{source}}(\lambda)}{\lambda^5 \left[ \exp \left( \frac{hc_0}{\lambda k_b T} \right) - 1 \right]} \, d\lambda}$$  \hspace{1cm} (21)

The dependence of $\varepsilon_{\text{source}}$ on wavelength is not considered in this study where the absorptivity (and emissivity) of the surface receiving heat radiation is in focus. This entails that an assumption that fires emit radiation like blackbodies, or like grey bodies can be made. A grey body is a body emitting radiation with a spectrum with the same shape as one of the curves in Figure 7, se chapter 2.3.4. For a grey body the emissivity is $< 1$ and constant. Depending on how sooty the flames are or how black the smoke layer is the irradiation behaviour changes, i.e. the emissivity changes. In general measurements are needed in order to access the exact existence spectrum for a certain fire. By assuming a constant $\varepsilon_{\text{source}}$ in Eq. (21) this term cancels and by cancelling other common factors gives the expression in Eq. (22).

$$\alpha_{\text{eff}} = \frac{\int_0^\infty \frac{\alpha_\lambda}{\lambda^5 \left[ \exp \left( \frac{hc_0}{\lambda k_b T} \right) - 1 \right]} \, d\lambda}{\int_0^\infty \frac{1}{\lambda^5 \left[ \exp \left( \frac{hc_0}{\lambda k_b T} \right) - 1 \right]} \, d\lambda}$$  \hspace{1cm} (22)

Another way to express the effective absorptivity is shown in Eq. (23) which is identical with Eq. (22). Both showing the weighted average of the spectral absorptivity, where the weight function is the exitance spectrum for the actual heat source.

$$\alpha_{\text{eff}} = \frac{\int_0^\infty \alpha_\lambda M_\lambda \, d\lambda}{\int_0^\infty M_\lambda \, d\lambda}$$  \hspace{1cm} (23)

If the glass spectral absorptivity, $\alpha_\lambda$, is high for large wavelengths (within the infrared region) the weighted value of the absorptivity will decrease with higher blackbody temperature in consistence
with the theory of Wien’s displacement law presented in chapter 2.3.4. The blackbody radiation peaks at lower wavelengths the higher the blackbody temperature is hence the weighted value of the absorptivity will decrease for higher blackbody temperatures.

With an effective absorptivity the amount of spectrally resolved absorbed heat flux for a specific wavelength, described by Eq. (10), can be rewritten according to Eq.(24), i.e. the fraction absorbed energy from the whole spectrum of incident radiation.

\[ \dot{q}_{\text{abs}} = \alpha_{\text{eff}} \cdot \dot{q}_{\text{inc}} \]  

(24)

2.3.7 Weighted value of the emissivity

In this chapter theory about how to calculate a weighted value of the emissivity is presented which is further used in this study to obtain useful input data for the analyses.

Kirchoff’s law states that the absorptivity is equal to the emissivity at the same wavelength and temperature, i.e. \( \alpha(\lambda, T) = \varepsilon(\lambda, T) \) for opaque bodies. Hence Eq. (23) is often rewritten according to Eq. (25). Where the weight function, \( M_\lambda \), in this case is the black body spectra with a temperature equal to the surface temperature of the receiving body, instead of the heat source temperature.

\[ \varepsilon_{\text{eff}} = \frac{\int \varepsilon_\lambda M_\lambda d\lambda}{\int M_\lambda d\lambda} \]  

(25)

This is only an approximation of the exact solution for glass since glass is a semi-transparent material for which Kirchoff’s law is not applicable. According to Gardon [21] the emissivity, \( \varepsilon_\lambda \), of transparent materials should be calculated according to the theory presented in Appendix C. More about the properties of semi-transparent materials is presented in in chapter 2.6.1.

By using Stefan Boltzmann law (Eq. (8)) and the effective emissivity the amount of spectrally resolved emitted heat flux from a body for a specific wavelength, earlier described by Eq. (9), can be rewritten according to Eq.(26), i.e. the fraction emitted energy from the whole spectrum depending on surface temperature of the emitting body.

\[ \dot{q}_{\text{emi}} = \varepsilon_{\text{eff}} \sigma T_s^4 \]  

(26)

2.3.8 In depth absorption

In opaque bodies the absorption takes place only in a very thin layer near the surface but for semi-transparent bodies, such as glass, absorption and emission takes place not just at the surface but in depth, i.e. in depth absorption and emission. The theory about in depth absorption and how to approximately calculate the quantities absorbed in different depths is presented in Appendix B. The theory about the emissivity of semi-transparent materials and how to calculate the emissivity of such materials is presented in Appendix C.

Temperature dependence of the absorption coefficient

The absorption coefficient, \( A \), in Beer’s law is describing in-depth absorption. The absorption coefficient is as mentioned (in Appendix B) depending on the wavelength of the incident radiation and this property is also depending on the surface temperature, e.g. as shown in Figure 9. With higher temperatures the coefficient tends to decrease but for temperatures in the range of 18-200 °C the coefficient is practically equal. Since the glass is expected to break before reaching 200 °C the temperature dependence of the absorption coefficient is not treated in this report.
Figure 9. Spectral absorption coefficient of glass at different temperatures. Illustrated by Gardon R [22].

**Thickness dependence of the absorption coefficient and emissivity for glass**
The emissivity and absorption coefficient is depending in the thickness of the glass. The dependence for the emissivity is illustrated by Figure 10. Hence it is important to measure the spectral properties for the specific thickness of the glass.

Figure 10. Spectral emissivity of glass for different thicknesses. Illustrated by Gardon R. [23].
2.4 The process of heat transfer in the studied case

In an enclosure fire with windows, such as in this study, the heat from the fire to the window surface is recognised mainly to be transferred by radiation since radiation is the dominating mode of heat transfer at high temperature levels as in fires [13]. The radiation imposed on the glass surface is assumed to mainly originate from a hot flame and the hot gas layer. In this report the hot flame is represented by a burning television setup.

At the window surface a certain amount of the incident heat flux will be reflected, some transmitted and some absorbed. The absorbed energy will induce the glass to increase in temperature. With temperature rise natural cooling by convection between the glass surface and the surrounding air will appear. Further the increased surface temperature will also induce the surface to emit energy which amount is depending on the surface emissivity. The increased surface temperature will also provide heat transfer by conduction through the solid glass. This will promote temperature rise at the unexposed surface which also will emit energy and be chilled from the surrounding air by natural convection. At a certain point the temperature difference between the exposed central pane and the shaded edges will induce a stress greater than the critical breaking stress and the glass will crack.

The net rate of heat transferred to the exposed surface, neglecting losses to the frame by conduction, is obtained by subtracting losses by emitted radiation and cooling by convection from the absorbed radiation according to Eq. (27). [13]

\[
\dot{q}_{net} = \dot{q}_{abs} - \dot{q}_{rad} - \dot{q}_{con}
\]  

(27)

With Eq. (24), the absorbed incident radiation, (1) and (5) describing the convective heat flux and the radiation to the ambient respectively, and with the addition of effective emissivity and absorptivity in Eq. (26) and (24), Eq. (27) can be rewritten as Eq. (28).

\[
\dot{q}_{net} = \alpha_{eff} \dot{q}_{inc} - \varepsilon_{eff} \sigma T_s^4 + \alpha_{eff} \varepsilon T_w^4 - h \varepsilon (T_w - T_s)
\]

(28)

Important to note is that \(\alpha_{eff}\) is the effective absorption coefficient and \(\varepsilon_{eff}\) is the effective emissivity which both is weighted values and therefore are not wavelength dependant.

2.5 Windows in buildings

The most ordinary used glass in windows is the soda lime silicate glass which also is called “Floatglas” or “Flachglas” in German and “glace” in French [24, 25]. In this report the term “soda lime glass” or “the glass” is used when referring to the soda lime silicate glass.

2.5.1 Functions

The original purpose with windows is to transfer visible light through the building’s facade but as the community has evolved windows can also provide several other functional requirements. Today windows can provide functions regarding solar control, energy saving, safety, security, fire resistance, environmental protection or practical qualities like self-cleaning, scratch resistance and design aspects. [26]

The properties and features mentioned above are often achieved by coating the glass surface with different types of coatings. Coatings have been available on the market for several years and has mainly been used to regulate the windows insulating properties, which is indicated in terms of the U-value. The lower the U-value, the greater a window’s resistance to heat flow and the better its insulating properties is. [27]
A low emissivity coating, a Low-E coating, is often used on an inner pane unit as shown in Figure 11. This type of coated glass is often called “Low-E glass”. In terms of thermal insulation the Low-E glass with its high reflectivity properties in a specific range is used to reflect the thermal radiation back into the room at the same time as it is allowing the solar radiation to pass through the window yielding light and heat into the building. In the other case when solar control is wanted the Low-E coating is designed to prevent the solar heating from passing through the window, i.e. preventing the sun from heating the interior, and at the same time allowing the entrance of visible light into the building. [26]

2.5.2 Design of the window
There are many different types of windows available today. A window can consist of one to four pane units, often with soda lime glass and with different types of coatings on the middle unit/units and with a gas or liquid in the space between them. Where the coating, gas or liquid is placed depends on the desired properties of the window. A window where the space is filled with a liquid is often used to get desired fire protection properties and the liquid is then seen to be a glass pane itself. A commonly used selective window consists of three soda lime glass with a Low-E coating and gas filling as illustrated in Figure 11. In a three pane window such as the window in Figure 11 there are six possible surfaces to place the coating. Low-E coatings are often sensitive to air and scratches, hence it is mainly surface 2, 3, 4 or 5 that is coated. The numbered surfaces is counted from the sun through the window to the inside of the room. [25] In Figure 11 surface 5 is coated which the most commonly coated surface today for three paned windows. For two paned windows the most commonly coated surface is 3. [25] More about Low-E coatings in chapter 2.5.3.

![Figure 11. Example of a windows structure.](image)

![Figure 12. Example of a frame constructions made of aluminium [28] and wood [29].](image)
Further the pane unit/units is attached to a frame, often made of wood or aluminium as illustrated in Figure 12. The frame is allowing the glass panes to move in the direction of the surface since there is a little space between the glass edges and the frame. This is allowing the phenomenon of thermal expansion caused by the sun. The pane surface is attached to the space bars which is further attached to the frame. There is also some sort of sealer compound between the outer glass surface and the frame so that the window will be well proofed, preventing water and dirt from getting between the frame and glass surface. [25]

2.5.3 Low emissivity coatings
Low emissivity coatings, which are often applied in the gap between two units in a window since they are sensitive to air and scratches, reduces the thermal radiative energy exchange when it is acting as a reflector. [25]

Today Low-E coating is used to reflect wavelengths from the interior, making the heat to stay inside of the building, at the same time as it is allowing visible light from the sun to pass through. A Low-E coating consists of multiple layers, as much as 5-10 thin films. The most ordinary Low-E coating, a soft coating, consists of a simple or double layer of silver together with metal oxides to protect the silver layer in different ways. Typical materials that can be used are Ag, SnO₂, TiO₂ and Si₃N₄. [17]

There are both hard and soft coating available on the market today. The above described Low-E coating is a soft coating and is as mentioned sensitive to air and scratches. But there are also hard coatings which is more attractive since they are resistant to air and scratches and can therefore be used both on the inside and outside of the panes. Though, hard coatings have in general a lower thermal insulation level and lower light transmittance than soft coatings. [17] Both soft and hard coatings are proved to tolerate at least 620 °C during a short time. This since modern Low-E glasses can be hardened which is performed at least 620 °C. [25] In this report a glass sheet with a hard coating is representing the coated glass, called K-glass.

The desirable fire properties of Low-E glasses in buildings is that they are transparent in the visible part of the spectrum (no visible colour), have high transmittance in the field of solar wavelengths and high reflectance in the field of radiative wavelengths from fires as illustrated in Figure 13. Hence you want to be able to see through the glass, get the light from the sun at the same time as the glass does not break in a fire scenario.

This beneficial usage of coatings has been pointed out in the literature [30, 31] where it has been shown that Low-E glasses has a greater resistance against fire heat radiation than glass without Low-E coating. In an experimental study [31] where 20 float glass and 21 Low-E glasses where heated by uniform radiation with a rising rate of 15°C/min the result showed that the Low-E glass had a better heat resistance than the float glass. In the other study [30] it is pointed out that in terms of glass breakage it is clearly beneficial to use coatings since the surface becomes mainly opaque to radiation in the infrared section.
Figure 13. Desirable properties of Low-E coatings.

Three panes is better than two panes in terms of integrity since the one closest to the fire will act as a shield protecting the panes behind. In Figure 13 the Low-E coating is placed on the 6th surface since the beneficial usage of Low-E coating provides this position. Position 4 and 2 is also useful positions in terms of integrity when the glass is exposed to fire but not as good as position 6. This since the radiation will be reflected back from position 2 or 4 to the pane to the right causing temperature rise and breakage faster in that pane. Position of number 1, 3 or 5 will isolated the glass which will cause a more rapid temperatures rise in the glass since the radiation is reflected back into the glass. Maybe a hard coating placed on position 6 (three paned window) is the most advantageous combination in the fire protection area since position 6 is the most advantageous position as described above and hard coatings is resistant to air and scratches which position 6 requires.

**Today’s usage of coatings and criticism**

Low-E coatings are very widely used in today’s society. They are mainly used to reduce energy consumption for heating/cooling in buildings which are built more and more energy efficiently. [25] Unfortunately there have been cases where the houses are “too” energy effective. The houses are so isolated that they shuts out the microwaves to/from our cell phones. [32]

Another disadvantage is that Low-E coatings often reflects some of the sun light, i.e. have lower transmittance than glass without coating. Some Low-E coatings is also soft and is needed to be protected from scratches and air, hence Low-E coatings is mainly suited for two pane windows. [17]

### 2.6 Physical and material properties of glass

Glass is an isotropic, semi-transparent and brittle material. Under this chapter material properties and phenomenon regarding heat transfer in glass is described.

#### 2.6.1 Semi-transparency and in depth absorption

It was in the early 60s stated by Robert Gordon [5] that both the absorption and emission of radiation is depending on the bulk rather than being a surface phenomenon for semi-transparent materials such as glass. In opaque bodies the absorption takes place only in a very thin layer near the surface but for semi-transparent bodies’ absorption and emission takes place not just at the surface but in depth, i.e. in depth absorption and emission.

Depending on the spectral properties of the glass, it reflects and absorbs a certain amount of the incident radiation near the surface while some quantity travels further into the glass and absorbs in
different depths. Some quantity is not absorbed, i.e. is transmitted through the glass. [33] The theory about in depth absorption and how to approximately calculate the quantities absorbed in different depths is presented in Appendix B.

When a glass pane increase in temperature it starts to emit energy like other materials. But for semi-transparent materials such as glass the emissivity is not a surface phenomenon but a bulk phenomenon. This since the radiation penetrates in certain depths heating each layer in the glass. Each layer then starts to emit energy, starting in this certain depth of the glass. [21] The theory about the emissivity of semi-transparent materials and how to calculate the emissivity of such materials is presented in Appendix C.

2.6.2 Transition of glass
Glass can either be solid e.g. glassy at low temperatures or liquid at high temperatures. The transition from the glassy to the liquid state occurs at glass transition temperature which is between 400-600°C for most commercial silicate glasses [34]

Rearrangements that occur in glass material at the glass transition temperature leads to characteristic jumps of thermodynamic parameters such as the coefficient of thermal expansion and the specific heat capacity. [34]

2.6.3 Compositions of soda-lime silicate glass
Soda-lime silicate glass is generally a composition of Silicon dioxide (SiO$_2$), Calcium oxide (CaO) and Sodium oxide (Na$_2$O). Magnesium oxide (MgO), Aluminium oxide (Al$_2$O$_3$) and other substances are also frequently used in the manufacturing where other substances can be suitable materials used to obtain tinted glass. [24] The composition can differ from one soda-lime silicate glass to another. Material properties can be strongly dependant on the glass composition and it is not unusual that some material properties also have a temperature dependence. [34]

In this study material properties according to SS-EN 572-1:2012 is used. The SS-EN 572-1:2012 is a standard covering a great magnitude of compositions as follows:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide (SiO$_2$)</td>
<td>69 % to 74 %</td>
</tr>
<tr>
<td>Calcium oxide (CaO)</td>
<td>5 % to 14 %</td>
</tr>
<tr>
<td>Sodium oxide (Na$_2$O)</td>
<td>10 % to 16 %</td>
</tr>
<tr>
<td>Magnesium oxide (MgO)</td>
<td>0 % to 6 %</td>
</tr>
<tr>
<td>Aluminium oxide (Al$_2$O$_3$)</td>
<td>0 % to 3 %</td>
</tr>
<tr>
<td>Other substances</td>
<td>0 % to 5 %</td>
</tr>
</tbody>
</table>

In Table 1 general characteristic values of soda-lime silicate compositions is presented. They are generally accepted values for use in calculations where a high degree of accuracy is not required [24]. For more accurate results the material properties for the specific specimen and composition could be measured.
Table 1. Material properties for soda-lime silicate glass according to SS-EN 572-1:2012 [24].

<table>
<thead>
<tr>
<th>Material property</th>
<th>Symbol</th>
<th>Numerical value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>ρ</td>
<td>2 500 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>E</td>
<td>70 ∙ 10⁹ N/m²</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>ν</td>
<td>0.2</td>
</tr>
<tr>
<td>Characteristic bending strength (stress)</td>
<td>σ</td>
<td>45 ∙ 10⁶ N/m²</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>cₚ</td>
<td>720 J/kgK</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>k</td>
<td>1 W/mK</td>
</tr>
<tr>
<td>Average coefficient of linear thermal expansion between 20 °C and 300 °C*</td>
<td>β</td>
<td>9 ∙ 10⁻⁶ /K</td>
</tr>
<tr>
<td>Resistance against temperature differential and sudden temperature change</td>
<td></td>
<td>40 K*</td>
</tr>
<tr>
<td>Emissivity</td>
<td>ε</td>
<td>0.837</td>
</tr>
</tbody>
</table>

*Generally accepted value that is influenced by edge quality and glass type and thickness.

The properties in Table 1 corresponds very well with values for soda-lime glass (73 % SiO₂, 15 % Na₂O, 7 % CaO, 4 % MgO and 1 % Al₂O₃) presented in the Handbook of glass properties [34]. Below these properties is further described. When referring to material properties according to the Handbook of glass properties it is a material property for the soda-lime glass composition described within the parentheses above.

2.6.4 Density, ρ
Density describes the materials weight per volume, e.g. kg/m³. The density for silicate glasses is not a strong function of temperature. The density for soda-lime glass is 2 500 kg/m³. [34]

2.6.5 Brittle cracking
Glass is close to an ideal linearly elastic material that fails by brittle cracking without any plastic deformation below the transition temperature, i.e. below 400-600 °C [34]. In Figure 14 the material behaviour of glass and steel is compared. Glass deforms instantaneously under continuous load and the deformation recovers instantaneously when the load is released while the deformation for steel can be permanent if the plastic region is reached.

![Figure 14. Material behavior, stress-strain curve of glass (below transition temperature) and steel.](image_url)
2.6.6 Strain, $\varepsilon$

Strain in the elastic region is described by Hooke’s Law as the fraction between the added length and the total length [35] according to Eq. (29). Tension describes the force obtained when stretching or lengthen a material, i.e. $\Delta L > L$ as shown in Figure 15 below.

$$\varepsilon = \frac{\Delta L}{L}$$ (29)

2.6.7 Breaking stress and tensile stress, $\sigma_b$

Regarding failure due to thermal load it is the tensile stress at the edges that will exceed the critical limit first. [8, 6] Tensile stress is the stress obtained by stretch or lengthening of the material - acts normal to the stressed area [35], as shown in Figure 15. Stress is described by the force that neighbouring particles of a material exert on each other per unit area according to Eq. (30).

$$\sigma = \frac{F}{A}$$ (30)

![Figure 15. Tensile force on a specimen causing stress and lengthening of the material.](image)

The theoretical strength of the glass is very high, $\sim 1.6 \cdot 10^{10} \text{ N/m}^2$ for commercial soda-lime glass but this strength is not appropriate to use in practice because of surface and edge flaws, fatigue, treatment history, handling of the glass, installing procedure and relative humidity [34]. Thus the effective strength is reduced and the maximum design strength for glass pieces exposed to ambient air is $20 \cdot 10^6 \text{ N/m}^2$ or less according to the Handbook of glass properties [34]. According to the SS-EN 572-1:2012 the breaking stress is $45 \cdot 10^6 \text{ N/m}^2$. More about the variety of breaking stress in chapter 2.7.5.

2.6.8 Module of elasticity, $E$

Modulus of elasticity also known as Young’s modulus and elastic modulus, is a mechanical property of linear elastic solid materials described by the relation between stress and strain according to Eq. (31), also shown in Figure 15.

$$E = \frac{\sigma}{\varepsilon}$$ (31)

2.6.9 Poisson’s ratio, $\nu$

When a material is compressed in one direction the material tends to expand in the other two directions, this is called the Poisson effect and Poisson’s ratio is a measure of this effect describing the fraction of expansion divided by the fraction of compression. [34]
According to the *Handbook of glass properties* the Young’s modulus is 72 GPa and Poisson’s ration is 0.25 for soda-lime glass which correspond well to the values in SS-EN 572-1:2012.

### 2.6.10 Thermal conductivity, k

Heat can be transported through glass both by conduction and radiation. Thermal conductivity describes how well a material transfer heat through conduction. Glass is generally a poor conductor and most glasses have a thermal conductivity around 1 W/mK at room temperature [34]. The poor thermal conductivity of glass consequently leads to that a thin sheet of glass is more resistant to a certain amount of incident radiation than a thick sheet (given that the glass pane is uniformly heated without any shaded parts) since a greater temperature gradient through the thickness will appear in the thicker sheet providing greater tension which further causes breakage. More about the thickness dependence of glass fire resistance in chapter 2.7.5

The composition of the glass does not affect the thermal conductivity considerably much but above room temperature the thermal conductivity of silicate glasses increases slowly as the temperature increases, i.e. the thermal conductivity is temperature dependant [34]. As an example from *The Handbook of Glass Properties* the composition for soda-lime glass described earlier has a thermal conductivity of 1.00 W/mK at 0 °C and 1.12 W/mK at 100 °C [34]. In this study the glass is predicted to break at temperatures around 100 °C, a range where the change in thermal conductivity is very small hence the temperature dependence of thermal conductivity is not considered.

### 2.6.11 Specific heat capacity, \( c_p \)

Specific heat capacity describes the quantity of heat (energy) required to raise a specific mass one degree, e.g. J/kgK. Specific heat capacity for glass is slightly temperature dependent. At lower temperatures the specific heat capacity increases sharply but from room temperature to higher temperatures (500 °C) the change is very small [34] hence the temperature dependency of this property is not considered in this report. The specific heat capacity of silicate glasses containing more than about 60 % of silica (SiO\(_2\)) are not much composition dependent, they are all being around 800±100 J/kgK at 25 °C. Other oxide glasses such as borates and phosphates have similar values at 25 °C.

According to the *Handbook of glass properties* the mean heat capacity for soda-lime glass in the range 25-175 °C is 870 J/kgK which corresponds well compared to the SS-EN 572-1:2012 with respect to the variety that can occur for different compositions of the glass.

### 2.6.12 Coefficient of linear thermal expansion, \( \beta \)

Most materials expand when they are heated. Glass is an isotropic material, i.e. a substance that expands at the same rate in every direction. The coefficient of linear thermal expansion describes how much a material expand per unit temperature according to Eq. (32). The coefficient usually depends upon temperature hence it is necessary to specific the temperature range over which \( \Delta L \) is measured. A common range is from 0 to 300 °C or from room temperature to the temperature just below the glass transition range.

\[
\beta = \frac{\Delta L}{L \Delta T}
\]  

(32)

Together with Hooke’s law, Eq.(29), the strain can be described by the coefficient of linear thermal expansion and the temperature rise according to Eq.(33).
For soda-lime glass in the range of 0 to 300 °C the coefficient of linear thermal expansion is $9.2\cdot10^{-6}$ /K [34] which corresponds well with the value given in SS-EN 572-1:2012. It is also important to know that this coefficient is strongly dependent on the glass composition. [34]

### 2.6.13 Compositions with improved thermal material properties

The most common glass is the soda-lime silicate glass since it is cheap. But there are also many minor additions to the basic composition to improve the material properties of the glass available. One example is the addition of borates, borosilicate glass, which have a lower thermal expansion and is therefore more resistant to thermal shocks. As an example has a composition of 39.76 % of $\text{B}_2\text{O}_3$; a coefficient of thermal expansion of $4.75 \cdot 10^{-6}$ /K (0-100 °C) compared to $9 \cdot 10^{-6}$ /K (0-300 °C) for soda-lime glass. Borosilicate glasses is often called “hard” glass because of its higher softening temperature compared to soda-lime glass. [34]

### 2.7 Physics of glass breakage

In this chapter the theory of glass breakage is presented followed by simplifications and reasonable assumptions of the problem. The phenomenological physics behind glass breakage is relatively well known but the mathematical formulas to solve the exact problem of glass breakage are very complex.

#### 2.7.1 History of glass breakage in windows

The problem of window breakage was first acknowledged in the 80s by Emmons [3]. He wrote an article “Needed Fire science” in Fire Safety Science, its first Symposium, where he described the importance of knowing why and when a window breaks in a fire scenario. The main reason for its importance according to Emmons is that in an enclosure fire a sudden new supply of air should not appear before a fireman with a hose stream is ready to apply water through the new vent. Hence this new supply of air can generate backdraft or flashover. Emmons suggested thermally induced tensile stress as the main mechanism of glass breakage.

Later Pagni and Joshi took the research further presented in the second and third Symposium of the Fire Safety Science and other journals [7, 8, 9, 10]. Emmons announcement was also followed by many other different studies in the area of glass breakage, both theoretically and experimental, e.g. [4, 6, 9, 11, 12, 30, 36, 37, 11, 38]. The focus has been to predict the breaking time for a window in a compartment fire. In the literature many different ways to solve the physics mathematically is presented, some of them are simple solutions and some are more advanced. The goal has mainly been to properly calculate the breakage time and then implement the method in a more advanced compartment fire model such as FIRST [11, 38], a zone compartment fire model or a simpler glass breaking program such as BREAK1 [39].

#### 2.7.2 General

Glass breakage in windows according to the literature generally occurs due to temperature differences between the glass exposed to radiation and the glass shaded by the edges. The temperature differences cause thermal stress and tension which induces cracks and eventually total breakage, the glass falls out. The cracks mainly starts where the tension is high, at cold spots around edge imperfections as illustrated in Figure 16. [3, 6, 8] The cracks travels, usually in multiple paths through to central of the pane, forming islands [9, 37, 11, 38] as shown in Figure 17.
Figure 16. Thermal breakage of glass in windows.

Figure 17. Illustration of glass breakage for windows exposed to enclosure corner fires, illustrated by Shields et.al. [11]

Figure 17 shows the crack pattern of a window exposed to an enclosure fire. The figure presents the position of the windows and cracks (width and height), the time for cracking and fallout and also the size of the incident heat flux (the axis to the right) in kW/m².

The above described phenomenon is the most common way to describe glass breakage but there are also another theory about glass breakage when the glass sheet is very thick and is exposed to a thermal shock. When glass is heated thermal gradients through the glass surface and thickness occurs
due to heating of the surface. The temperature rise causes different movements within the pane of the glass due to thermal expansion which in its turn in some cases (when the glass is thick and the thermal exposure is high enough) can cause bowing as shown in Figure 18. The rate of bowing is depending on the frame of the window, if the glass is fixed or allowed to move. [11] The bowing in its turn cause tension in surface flaws inducing glass breakage, similar to the procedure for glass breakage at edge flaws presented in Figure 16 (nr.3).

![Figure 18. Theoretically bowing due to thermal expansion on the exposed side.](image)

This phenomenon, glass breakage due to bowing and surface imperfections, is only discussed to be a reason of glass breakage in the literature, not shown in experimental studies. In an experimental study done by Cheng et al [4] five 8 mm thick glass panes was exposed to the same condition. They concluded that the primary factor for glass cracking is the heat stress along the glass surface rather than along the glass thickness when the glass surface is exposed to uneven radiation.

In two other experimental studies done by Shields et.al. [38, 11] where several windows (all 6 mm thick float glass) was exposed to a corner and a central enclosure fire, providing an uneven heating of the glass surface, the glass breakage occurs at the edges as shown in Figure 17.

What phenomenon that is causing glass breakage is probably depending on the thickness of the glass and the imposed heat flux, how fast/slow the energy is absorbed.

In this study the first mentioned phenomena, glass breakage due to temperature difference at the surface and edge imperfections, is assumed since the studied glass thickness is 3 and 4 mm.

When the breakage occurs depends on the temperature gradients in the glass which in its turn is depending on the rate and spatial distribution of absorbed energy. How much energy glass is absorbing is determined by its optical spectral properties as described in Chapter 2.3.6, and by the spectral irradiance as described in Chapter 2.3.2. How the incident energy is absorbed is described in Chapter 2.6.1. Notice that only radiative heat transfer is considered in this report as explained in Chapter 2.3.1.

### 2.7.3 Window breakage according to P.J. Pagni and A.A Joshi

From Emmons suggested theory of glass breakage P.J Pagni and A.A. Joshi [8, 7, 10] quantified the theory based on the temperature rise required to break window glass in an enclosure fire. The model was first presented by Eq. (34) below and is based on the following scenario:

"The window is surrounded by an opaque frame, the glass is a relatively poor thermal conductor, the central part of the window is heated by infrared radiation and by hot gas convection while the frame remains near its initial temperature. When heated the
thermal expansion of the central portion places the covered edges in tension until the edge cracks. The cracks will then quickly propagate which causes the window to break and become a vent.”

In Figure 19 the window’s geometry is presented where \( x \) is the depth, \( y \) is along the vertical shading, \( z \) is along the horizontal shading, \( s \) is the width of the shading, \( H_y \) and \( H_z \) are the exposed pane half-length and \( L \) is the glass thickness.

![Diagram of window geometry](image)

Figure 19. Window geometry according to the method. Illustrated by Patrick J. Pagni [7].

\[
\beta \cdot \Delta T_b = \frac{\sigma_b}{E} = \varepsilon_b \tag{34}
\]

Eq. (34) follows directly from Hooke’s law where \( \Delta T_b \) is the temperature difference between the glass edge and central pane given by Eq. (35), \( \beta \) is the thermal coefficient of linear expansion, \( \sigma_b \) is the breaking stress, \( E \) is the Young’s modulus and \( \varepsilon_b \) is the breaking strain. The point of crack will be at the edges coldest spot which will have the largest stress concentration.

\[
\Delta T_b = T_{exposed} - T_{coldest} \tag{35}
\]

The exposed temperature, \( T_{exposed} \), is the average temperature of the central spot given by Eq.(36) and \( T_{coldest} \) is the coldest, i.e. the outmost edge temperature.

\[
T_{exposed}(t_b) = \int_0^L T(x,H,t_b)dx / L \tag{36}
\]

Eq. (35)-(36) simply says that it is the integrated bulk temperature over the central pane and the colder temperature at the outmost edge that is causing the temperature difference inducing thermal stress at the edges.

Further Eq. (34) was improved by include a factor \( g \), the force balance factor (also called geometrical factor or edge coefficient), on the right side of the equation to account for the compression from the unshaded glass. The central pane will not expand without any resistance from the shaded edges, this
resistance will make the expansion smaller which consequently will decrease the tension at the edges. This improvement is presented in Eq. (37).

\[ \Delta T_b = g \sigma_n / E \beta \]  

Values of \( g \) is depending on the glass thickness and the size of the shaded area and can be obtained from Fig. 2 in the BREAK1 User’s Guide [39] or Fig. 6 in [10] which shows \( g \sim 1 + s / H_y \).

**Validation of the theory presented by P.J. Pagni and A.A Joshi**

The theory has been validated by Keski-Rahkonen [6] who did an analysis on the stress fields induced in window glass by heating which confirms the theory that maximum stresses are located at the coldest spots. The analysis was based on a specific case hence Keski-Rahkonen’s conclusions confirms Eq. (34) only for small-scale experiments with a constant radiative heat flux [7]. In the analysis the assumption that there are no temperature gradients through the glass thickness, i.e. \( \Delta T_b \) is the surface temperature difference between the glass edge and central pane, was made.

The reliability of Eq. (34) was also confirmed in another experimental study done by Frederick W. Mowrer [40]. The result from 72 small-scale experiments and 19 large-scale experiment with a constant heat flux showed that the breakage of ordinary glass in windows with frames is generally consistent with the theory presented by Emmons and developed by Pagni and Joshi.

Skelly et al [12] did an experimental study of glass breakage in a compartment fire. This experimental study also indicates that Eq. (34) is a reasonable first approximation for the glass temperature breakage.

In a similar experimental study done by Harada et al [41] 50 experiments was carried out to measure time to initial crack and fallout for 30 float glass and 20 wired glass with and without lateral restrain. The imposed heat flux was varied between each test and constant during each test. The study suggests a value of the geometrical factor, \( f ( = 1 / g ) \), to be in the range 0.6-0.73 for float glass, i.e. \( g = 1.37 - 1.67 \). This experimental study is of interest since the model in the FEM-software Abaqus can be validated against the results from the experiment. Hence the experiment and its set up is presented later in chapter 4.1.

Shields et al [11, 38] has also performed two experimental studies where the performance of single glazing assembly exposed to: 1. Enclosure corner fires of increasing severity and 2. Fire in the centre of an enclosure was examined. These experimental studies also show good agreement with the theory of Eq.(34) but suggests that the geometrical factor, \( f = 1 / g \), should be in the order of 0.2-0.3, i.e. \( g = 3.3 - 5.0 \).

The presented values of the force balance factor, \( g \), in the experiments described above is evaluated by using Eq. (34) and the measured temperatures and stresses/strains from the experimental results. Hence the different opinions of the force balance factor, \( g \), is directly proportional to the measured temperatures and stresses in the experiment hence \( g \) it is a very uncertain parameter. In this study the critical breakage temperature is calculated with and without the force balance factor using the definition, \( g \sim 1 + s / H_y \), presented by Joshi and Pagni.

**2.7.4 BREAK1**

With the theory presented by Pagni and Joshi a glass breaking program, BREAK1, the “Berkeley Algorithm for Breaking Window Glass in a Compartment Fire” was developed. BREAK1 have good agreement with experiments. [9, 40, 7] The glass breaking model is also implemented in the zone compartment fire model, FIRST [7].
BREAK1 is an algorithm and is based on the approach that treats the glass as a distributed mass that absorbs radiation through its thickness with nonlinear radiative boundary conditions.

With Eq. (37), for a given breaking stress, geometry and material properties, the critical temperature $T_b$ is calculated with the assumption that the shaded part stays at its initial temperature, $T_i$. Further the temperatures on the exposed and unexposed side is calculated and when the average temperature between theses sides exceeds the critical temperature the calculations stops, i.e. the window breaks and the breaking time is presented. For a more detailed calculation methodology see articles of Joshi and Pagni [8, 7, 10].

**Criticism of BREAK1**

In a study done by Robert Larsson [42] the program BREAK1 was investigated and evaluated. The conclusions of the study was that BREAK1 should only be used when comparison with experimental studies are available. Calculations without comparison is to be considered as very unreliable results. The reason to this conclusion lies in the uncertainty of the input data. Glass is a very special material which material properties is hard to determine. The cutting of the glass edges is mentioned to be one of the greatest uncertainties. Also the uncertainties and variation of the fire properties is discussed.

**Investigation of BREAK1**

In this study BREAK1 was investigated to evaluate the possibilities to use the program to evaluate the efficiency of Low-E coatings. To do that a computer that supports a 32-bit system has to be used.

Two simulations was made one with an emissivity equal to 1 and the other with an emissivity equal to 0.5. The results showed that a lower emissivity gave a shorter breaking time, which it should not, see input- and output-file in Appendix A. Since no contact with the developer was obtained other approaches such as Abaqus was investigated.

2.7.5 **Important affecting parameters and knowledge**

In this chapter information and guidance from the literature is presented. This information is further considered and used in the study.

**Cracking vs fallout**

The theory behind the time for the first crack to occur is relatively well understood while the time to actually fallout remains to be solved [40, 7]. Fallout is not treated in this report.

**Angle of the irradiation**

The direction of the irradiance against a surface is a phenomenon depending on the interior; what kind of material is burning, its geometry and its distance to the surface. The irradiation levels presented in this report are assumed to impinge perpendicularly on the glass.

**Frame dependence**

In an experimental study done by Skelly et al [12] they examined the breaking of window glass in an compartment fire where data was collected for two groups: protected edges (isolated frame) and unprotected edges (uniformly heating of the pane). The result of the edge-protected window indicated that breakage occurred due to the critical temperature difference between the centre of the pane and shaded edges. This critical temperature difference was measured to approximately 90 °C. For the edge-unprotected window the test result showed that breakage did initiate at a temperature of 197 °C. [12]

It is a statement that glass breaking occurs due to thermal stress caused by uneven temperature rise of the glass in a fire scenario. If there are temperature differences within the glass (shaded parts) the
breakage occurs at a lower temperature than if the whole pane is heated uniformly. In this study the frame is assumed to be totally isolating the shaded parts.

**Breaking temperature difference**

Many studies have been carried out where the breaking temperature difference of window glass is presented [37, 4, 12, 6, 11]. Temperature differences ranging from 50-110 °C has been presented (for shaded edges). They probably differ since the conditions for each specimen is varying. Even when the experimental setup is similar the results are varying due to the complex nature of glass and probably because of different edge imperfection.

The above presented temperature differences is higher than 40 °C which is presented in SS-EN-572-1:2012 [24]. This may depend on a certain safety margin in the SS-EN standard.

In this study the critical temperature difference is calculated according to the theory presented by Pagni and Joshi in chapter 2.7.3.

**Breaking stress and imperfections**

The breaking stress depends on the material properties and imperfections at the surface and edges. In an experimental study done by Joshi and Pagni [9] they determined that a reasonable value for the breaking stress, $\sigma_b$, at the edges is 40 MPa for ordinary windows. They also stated that there is a large variation between the breaking stresses of nearly identical specimens and that the fractures initiated at edge imperfections rather than at surface flaws.

In another experimental study done by T.J. Shields et al [11] they measured the stresses in single pane glass exposed to an enclosure fire. The measured breaking stress during these experiments ranged from 8.4 MPa to 16.1 MPa.

In the experiment done by Harada et al [41] they conclude that the tensile stress at breakage was in order of 25 MPa for float glass.

Further the SS-EN-572-1:2012 [24] standard recommend a value of 45 MPa for the characteristic bending strength which is also used in this report.

The great difference between the above presented studies is probably due to different edge imperfections (caused by different cutting methods or installation procedure) and maybe different measuring equipment.

**Imperfections in the glass**

In a few experimental studies [11, 9] edge imperfections is investigated and in many other studies this affecting parameter is often discussed. Edge imperfections appear to be a significant factor that affects the performance of the glass exposed to fire conditions. The cutting of glass and edge treatment afterwards can be done in different ways, hence there are a variety in edge imperfections. How the window is installed is also stated to be an affecting factor.

**Thickness of the glass**

According to the theory of Joshi and Pagni [8] a uniform approximation for glass temperature distribution with depth is not valid due to large temperature differences between the inner and outer surface.

In the *Handbook of glass properties* [34] thermal shock resistance for different thicknesses of soda-lime glass is presented, i.e. at which temperature differences between the exposed and unexposed side the probability of glass breakage will be significant. A 3.2 mm thick glass has a resistance of
$\Delta T=60$ °C, for $6.4$ mm $\Delta T=50$ °C and for $12.6$ mm $\Delta T=35$ °C. Hence thicker glass panes is more sensitive to temperature differences.

Cheng et al [4] did an experimental study where they exposed five 8 mm thick float glasses to the same conditions. The result showed that the temperature difference between the exposed and shaded part of the surface reached 80 °C at the time of glass cracking. They also stated that the primary factor for glass cracking is the heat stress along the glass surface rather than along the glass thickness.

What phenomenon that is causing glass breakage, stress along the surface (because of bowing) or stress at the edges (due to compression between the shaded and exposed part), seem to be dependent on the thickness of the glass. It may also depend on the imposed heat flux, if the heating is fast or slow. This since the thickness of the glass and how rapid the heating is will determine the size of temperature difference trough the thickness.

In this study glass breakage due to temperature difference at the surface and edge imperfections causing is assumed to be the mechanism of glass breakage.

**Fixed or not fixed edges**

Using Hooke’s law for typical values of the breaking stress, $10 \leq \sigma_b \leq 50$ MPa and $E \sim 72$ GPa, gives small breaking strains, $1.5 \times 10^{-4} \leq \varepsilon_b \leq 7 \times 10^{-4}$; i.e. $0.015$ % to $0.07$ % thermal expansion to induce cracks in the glass. Since the maximum expansion, $\leq 1$ mm, is less than the normal gap of several distances between the frame and the pane, the frame is not restraining the glass. [7] During a mechanical analysis in a FEM program there must be some restraining boundary condition in the glass to obtain tension and stress. In this study only the thermal analysis is performed in Abaqus since the restraining boundary condition has to be investigated which is further explained in chapter 2.8.4.

**Pressure forces**

In a study done by Pagni [7] he pointed out that pressure forces (i.e. forces created by the increased pressure in the room which is a consequence of the fire) may play an important role when glass falls out in real growing fires. Pressure forces is not considered in this study.

**Size of the shaded frame and energy loss into the shaded edges**

The heat diffusing into the shaded edge is quite small according to Joshi and Pagni [8], this because the cross-section area of the glass is small. However, in the same article Joshi and Pagni states that the breaking time decreases with a large shading. This since with large shadings the outer edge temperature stays at lower temperatures causing temperature difference between the shade and central part earlier.
2.8 FEM and Abaqus

The finite element method, FEM, is a numerical technique for finding approximate solutions for partial differential equations using computers. Subdivisions of the whole problem domain is made creating smaller parts called finite elements. Further the many simple element equations are connected, approximating a more complex equation over the large domain. [43]

Abaqus is a simulation program based on the finite element method that can solve problems ranging from relatively simple linear analyses to more challenging nonlinear analyses. Abaqus is often used for structural stress/displacement problems but can also be used in several other cases where heat transfer analysis is one application. Thermal and mechanical analysis can be done parallel (directly depending on each other) or separated. [44]

Elements and nodes define the basic geometry of the physical structure in Abaqus. Figure 20 shows an example of a modelled glass pane of 500x500x3 mm³. Each element in the model represents a discrete portion of the physical structure which in its turn is represented by many interconnected elements. Elements are connected to one another by shared nodes. The collection of all the elements and nodes in a model is called the mesh. [44]

Figure 20. Example of a mesh with elements and nodes in Abaqus.

The element type, shape, and location, as well as the overall number of elements used in the mesh, affect the results obtained from a simulation. The greater the mesh density is (i.e., the greater the number of elements in the mesh), the more accurate the results generally become. But as the mesh density increases the required computer simulation time and the size of the output-file increases thus it is important to find a mesh that works in all aspects. [44]

The solutions obtained from Abaqus are generally an approximation to the exact solution of a physical problem. How well the numerical simulation matches the physical problem depends on the extent of approximations made in the input data such as the model’s geometry, material behavior, boundary conditions, and loading. [44]
Regarding heat transfer nodes are used to measure the temperature at the exact position of the node while elements can measure the centroid temperature of the part. [44]

### 2.8.1 Thermal analysis

The thermal analysis can either be performed under steady-state conditions or under transient conditions. Steady-state analyses are used in order to find the equilibrium status of an object exposed to a heat flow under constant conditions (constant heat flux, boundary conditions, geometry and material) while transient analyses are used to determine the variation in temperature as a function of time. [45]

### 2.8.2 Assumptions made by Abaqus regarding thermal analyses

Abaqus is programmed with some preprogrammed assumptions regarding radiative heat transfer. In this chapter the assumptions concerning this study is presented.

**Grey-body assumption**
A grey body has an emissivity that is independent of wavelength for all levels of radiation. [45] An average value of the emissivity for the electromagnetic spectrum is therefore needed to be used.

**Absorption**
An important thing to notice is that the grey-body assumption is only considered for surfaces emitting energy, not surfaces absorbing energy. Abaqus has no approach or function that can handle absorption depending on the surface absorptivity.

**Opaque surfaces**
In Abaqus surfaces are considered opaque, i.e. no wavelengths is allowed to pass through. Thermal radiation is assumed to be a surface phenomenon rather than a volumetric phenomenon. [45] This assumption entails that in depth absorption is not considered and radiation cannot be transmitted through a surface or a body.

**Diffuse surfaces**
Incident radiation, reflected radiation and emitted radiation at the surface are assumed to have no directional tendencies; they are diffuse. [45]

### 2.8.3 Boundary conditions available in Abaqus regarding heat transfer

When modelling in Abaqus different boundary conditions can be used. In this chapter boundary conditions regarding heat transfer is presented.

**Conduction**
When assigning thermal elements in a heat transfer analysis the thermal conductivity is always required. This since the heat flow by conduction is calculated according to Eq.(38) in Abaqus.

\[ \dot{q} = -k \frac{dT}{dx} \quad (38) \]

Where \( k \) is the thermal conductivity in W/mK. [45] Note that Eq. (38) is consistent with the theory of conduction described in chapter 2.2.2

**Emitted radiation**
The “Radiation to the ambient” function in Abaqus is a surface boundary condition taking heat transfer by radiation from a grey body into account where heat is transferred from a body by radiative energy exchange with the environment according to Eq.(39).
\[ \dot{q}^r = -\varepsilon_{\text{source}} \sigma (T_s^4 - T_\infty^4) \]  

(39)

Where \( T_s \) and \( T_\infty \) is the absolute surface and ambient temperature in Kelvin. [45] Note that Eq. (39) is in consistent with the theory of radiation described in chapter 2.2.3 for opaque surfaces and not for semi-transparent surfaces since the absorptivity, \( \alpha \), is assumed to be equal to the emissivity, \( \varepsilon \), according to Kirchhoff’s law.

**Film for convection**

A common type of boundary condition in heat transfer is a surface being heated or cooled by an adjacent fluid or gas. In Abaqus different film conditions can be used where a film boundary loses or gains heat according to Eq. (40)

\[ \dot{q} = -h_c (T_s - T_\infty) \]  

(40)

Where \( T_s \) is the surface temperature, \( T_\infty \) is the fluid or gas temperature and \( h_c \) is the, in Abaqus called, film coefficient with the unit of W/m\(^2\)°C. In terms of thermal analysis and convection the film coefficient is the same as heat transfer coefficient for convection. The film coefficient can be defined as a surface temperature dependent coefficient. [45] Note that Eq. (40) is consistent with the theory of convection described in chapter 2.2.1.

**Surfaces without any boundary condition**

Surfaces that are not assigned any boundary condition are adiabatic in Abaqus, no heat transfer occurs at the surface, i.e. the surface is totally isolated. [46]

### 2.8.4 Why the mechanical analysis was not simulated in Abaqus

The extent and distribution of stresses induced in the glass are largely dependent on how the glass is secured, is the glass allowed to move or is it fixed? The boundary conditions at the edges can then either be chosen to be free to movement with only rigid body motion prevented, be fully clamped or to have fixed edge lines (one or two) as illustrated in Figure 21.

![Figure 21. Boundary conditions that could be chosen: a) only rigid body motion prevented, b) fully clamped edge surface, c) one simply supported edge and d) two simply supported edges. Illustrated by Karin Lundstedth [47].](image)

The conditions for movement in the structure is varying depending on the type of window and its installation. The glass in most windows is mounted so that its edges cannot move perpendicular to the surface, but is free to move in the plane of the glass. There is also a distance between the frame and the glass edges being sufficiently large to permit unrestricted thermal expansion of the glass. In the scenario where the edges is shaded and stays at lower temperatures the shaded frame will itself start to restrain the unshaded part from expanding. What boundary condition that is best suited for the scenario has to be investigated.

A study with the purpose to investigating what boundary condition at the edges is resulting in the most accurate stress/strain distribution is needed to be made. Due to lack of time another approach to
calculate the breaking time was identified and made. Hand calculations according to the theory presented by Pagni and Joshi. was made. By using Eq.(37) the critical breaking temperature was determined and further a separate thermal analysis in Abaqus was done.

2.9 The studied specimens

In this study two simple plane glasses has been studied, Pilkington K-glass and Pilkington Optifloat, with and without coating respectively.

Pilkington’s Optifloat, called F-glass, is an ordinary plane glass without coating that is used in Pilkington’s window constructions. Other manufacturers have similar products. [25]

Pilkington’s K-glass, called K-glass, consist of an F-glass with a Low-E coating of fluorine-doped (~1 %) tin oxide. This coating is a hard coating which has a higher resistance compared to soft coatings. In comparison to other silver based soft coatings this coating can be used in atmospheric air hence it can be used in one paned windows. [25]

The glasses spectral properties has been measured at SP, Technical Research Institute of Sweden according to the theory presented in chapter 2.9.1. The measured spectral properties is presented in Appendix D and has been used to evaluate the glasses effective absorptivity and absorption coefficient for absorption in the depth.

The spectral properties was measured on 4 mm F- and K-glass. For validation purpose the spectral properties of a 3 mm F-glass was also measured.

Other options such as thinner glass was considered but since soda lime silicate glass of 4 mm thickness is the most commonly used in today’s society it was chosen for the analysis.

2.9.1 Measurement equipment for spectral properties

Direct absorptivity measurements are difficult to perform and instead the reflectivity, \( R_{\lambda, \text{sample}} \) (R is earlier described by \( \rho \)), and the transmittance, \( T_{\lambda, \text{sample}} \) (T is earlier described by \( \tau \)), are measured. The spectral absorptivity, \( \alpha_{\lambda} \), is then calculated according to Eq. (11) in chapter 2.3.3, i.e. Eq.(41).

\[
\alpha_{\lambda} = 1 - R_{\lambda, \text{sample}} - T_{\lambda, \text{sample}}
\]  

Spectra of the reflectance with wavelengths in the interval of 0.3 – 17 \( \mu \)m was recorded with an integrating sphere is shown in Figure 22.

In the interval of 0.3 – 2.5 \( \mu \)m the spectral properties was measured by using a Perkin Elmer Lambda 900 double beam spectrophotometer equipped with a Spectralon integrating sphere. In the thermal infrared wavelength range, with wavelengths in the interval 1.7 – 17 \( \mu \)m, a Bruker FTIR single beam spectrophotometer equipped with a gold coated integrating sphere was used. [15]
Figure 22 shows a cross-section of an integrating sphere with the incident beam entering the sphere through the entry port to the left and hitting the sample (or reference) covering the sample port to the right. The light reflected from the sample surface is trapped inside the sphere and illuminates the inside wall of the sphere. This illumination intensity is seen by the detector, which then records a signal, $S_{\text{ref, } \lambda}$, proportional to all the reflected light, including both the specular and diffuse parts.

To get accurate results two measurements are performed. First one with a reference scan (calibration) followed by a sample scan. The scans are taken immediately after one another to avoid instrument drift.

The reference reading with a reference standard covering the sample port gives the detected signal according to Eq. (42).

$$S_{\text{ref, } \lambda} = A R_{\text{ref, } \lambda}$$  \hspace{1cm} (42)

Where $R_{\text{ref, } \lambda}$ is the reflectance of the reference standard and $A$ is an instrument amplification factor. Further the sample is measured and the reference standard is replaced by the sample according to Eq. (43).

$$S_{\text{sample, } \lambda} = A R_{\text{sample, } \lambda}$$  \hspace{1cm} (43)

By merging Eq. (42) and (43) the reflectance of the sample is then obtained from the ratio in Eq. (44) if $R_{\text{ref, } \lambda}$ is known. [15]

$$R_{\text{sample, } \lambda} = \frac{R_{\text{ref, } \lambda} S_{\text{sample, } \lambda}}{S_{\text{ref, } \lambda}}$$  \hspace{1cm} (44)

The reflected light can be separated into a specular and diffuse (scattered) component. The specular part is strictly defined as light being reflected as from a perfectly smooth and flat mirror. In an integrating sphere this definition is approximated by the light leaving the sphere when the cover is removed from the specular exit port. [15] In this study this separation was not regarded as being relevant and the reflectance was only measured as the total hemispherical value using a diffusion 8° integrating sphere. The reflectance measurements had an accuracy of +/-3%.

Transmittance measurements are performed in a similar manner to the reflectance measurements described above, but with the sample positioned across the beam entry port. All measurements were performed at an ambient temperature of $\sim 23^\circ C$. 

$$R_{\text{tot}} = R_{\text{diff}} + R_{\text{spec}}$$
All reflectance and transmittance measurements were performed at near normal incidence and the reflected and transmitted radiation were detected hemispherically. This means that the calculated absorptivity value is the near normal value.

Only a few of the tested products had any measurable transmittance.

Note that the reflectance and transmittance was measured with an angle almost perpendicular to the surface. The reflectance will be greater with a greater/smaller angle hence the measured properties is the minimum reflected from the surface.

More details about the measurements can be found in the report written by Försth and Roos [15].
3 Method

The approach of the study is schematically illustrated by Figure 23, a flow chart of the study procedure.

Figure 23. Flow chart of the study procedure.

A field study and a literature review was followed by an investigation leading to hand and FEM calculations. From the results the efficiency of Low-E coatings was estimated and conclusions was made followed by recommendations about continuous work.
3.1 Field study

The field study was done at Glafo, a glass research institute in Sweden. Glafo works internationally with glass research, development, education and technical support. For instance they carry out research on flat float glass in windows [48].

The purpose with the visit was to get an insight of how the glass industry and research works and to establish contact with experts within the area of the study.

3.2 Literature review

The theory and physics behind heat transfer, windows in buildings, glass breakage, spectral absorptivity, low emissivity coatings and material properties of glass has been studied. Simplified and advanced models for calculations of the windows breaking time, with and without low emissivity coatings, has been investigated and presented.

3.3 Spectral properties

To get more accurate input data regarding the spectral behaviour of the glass their spectral properties was measured at SP Technical Research Institute of Sweden. In Appendix D the measured spectral properties of 3 mm F-glass and 4 mm F- and K-glass is presented.

3.4 Investigation

Initial BREAK1 was investigated but since calculations, see input- and output-file in Appendix A, showed that a lower emissivity gave a shorter breaking time, which it should not, and since no contact with the developer was obtained after some effort other approaches such as Abaqus was investigated. Abaqus was chosen for the analyses.

First a Validation Model was created which results were compared with an experimental study. The Validation Model was also used to evaluate the difference between in depth absorption and surface absorption. Further another model, The Model, was created which was used to evaluate the efficiency of Low-E coatings. Unfortunately, due to lack of time only the thermal analysis was performed. To perform a mechanical analysis of glass exposed to fire conditions in Abaqus an investigation of the edge constrains must be done as explained in chapter 2.8.4. Thereafter hand calculations of the critical breaking temperature according Eq.(37) and the presented theory in chapter 2.7.3 was made. Other hand calculations was also made to get input data for the model in Abaqus.

3.4.1 Hand calculations

The critical temperature difference, weighted value of the absorptivity and emissivity, the in depth absorptivity, the incident heat flux and convective heat transfer coefficient was calculated using spread sheets in Excel.

The theoretically calculated critical temperature difference for the Validation Model was compared with the actual critical temperature difference in the experiment to validate the reliability of the theory.

3.4.2 FEM calculations

Since the efficiency of Low-E coating is to be estimated a comparison between a window with and without coating exposed to fire conditions is required. Calculations regarding heat transfer and stress analysis in structures are very complex thus only hand calculations is not suitable. The finite element method can handle these kinds of calculation very effectively and with good results hence Abaqus
was selected for the analyses. It was later found that there was not enough time to perform the mechanical analyses in Abaqus (as explained in chapter 2.8.4) hence a simpler hand calculation was replacing the stress analysis.

The commercial ABAQUS CAE 6.13-2 finite element program was used for the modelling. The standard model database was used to simulate heat transfer.

Two FEM-models was created. One equal to an experimental setup, referred as the Validation Model, and one equal to an ordinary window used in today’s society, with and without coating, referred as The Model.

The temperature distribution in the glass was calculated in Abaqus and with the calculated value of the critical temperature difference, $\Delta T_b$, between the central pane and the shade edge the critical breaking time was determined.

### 3.4.3 Validation Model

The Validation Model is a model equal to the experimental setup presented in chapter 4 used to validate both the theory presented by Pagni and Joshi, i.e. Eq. (37) and the temperature calculations done in Abaqus. The Validation Model was also used to investigate the importance of taking the in depth absorption into account compared to surface absorption.

### 3.4.4 The Model

The Model is used to investigate the efficiency of Low-E coatings hence both the F- and K-glass is simulated with this model. The different glass types is further exposed to two different cases of heat sources. One where the impact of radiation is from a flame and another where the impact of radiation is from a hot gas layer.

A mesh analysis was carried out for both the Validation model and The model to investigate the results mesh dependency.
4 Validation experiment

To validate the results from a modelling program such as Abaqus is often of interest and can be made by comparing the results with some experimental study. When doing that it is of high importance that the conditions in the experiment is equal to the model in the program. In this chapter an experimental study used to validate the results from Abaqus is presented.

4.1 “An Experimental Study on Glass Cracking and Fallout by Radiant Heat Exposure”

Harada et al [41] carried out 50 experiments where both float and wired glass, with and without lateral restrain, was exposed to different radiant heat fluxes from a radiant panel. Temperatures at the edges, central pane (both exposed and unexposed side) and strains at the edges were measured. In mail correspondence [42] information regarding the temperature of the propane burner and exact positions of the thermocouples and strain gauge were obtained.

The experimental setup is shown in Figure 24-Figure 26.

![Experimental setup](image)

*Figure 24. Experimental setup. Illustrated by Harada et al [41].*

The incident heat flux was varied in the range of 5.31-9.23 kW/m² by changing the distance between the specimen and the radiant panel. The incident heat flux was measured by a heat flux gauge 100 mm below the specimen. [41] The temperature of the radiant panel was not measured. However, as the panel was fired by propane gas, the surface temperature could be close to normal open fires, i.e. 800 °C [49].

A radiation shield was put in front of the specimen until the radiant panel was heated up. When starting the test the shield was removed resulting in a transient heating of the specimen at constant incident heat fluxes. [41]
As shown in Figure 26 the geometry of the window was 500x500x3 mm with a 15 mm shading length. Temperature and strain was measures at all four edges. The thermocouples position was at the middle of the shaded part, i.e. 7.5 mm from the outer edge, and the strain gauges position was at the outmost edge of the glass [49]. Two infrared thermometers measured the pane temperature on the exposed and unexposed side. [41]

The specimen of float glass was called “non-heated ordinary float glass”. The specimens without lateral restrain was supported by two rubber blocks at the bottom edge.

Since only float glass without lateral restrain is of interest in this study these are the only results from the experiment presented in this report, see Table 2. The marked tests are the randomly chosen tests used for the validation model simulated in Abaqus. The pane temperature is the temperature on the central pane’s unexposed side and the edge temperature is a mean temperature of all four edges measured 7.5 mm from the outmost edge.
Table 2. Summary of the experimental result for 3 mm float glass without lateral restrain.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Imposed heat flux [kW/m²]</th>
<th>Time to crack [s]</th>
<th>Pane* temp. [°C]</th>
<th>Edge** temp. [°C]</th>
<th>Edge strain [x 10⁶]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.31</td>
<td>218</td>
<td>87.8</td>
<td>44.6</td>
<td>427</td>
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<tr>
<td>2</td>
<td>5.41</td>
<td>272</td>
<td>88.0</td>
<td>45.7</td>
<td>404</td>
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<tr>
<td>3</td>
<td>5.62</td>
<td>204</td>
<td>100.7</td>
<td>56.5</td>
<td>422</td>
</tr>
<tr>
<td>4</td>
<td>5.72</td>
<td>376</td>
<td>104.8</td>
<td>48.9</td>
<td>399</td>
</tr>
<tr>
<td>5</td>
<td>6.83</td>
<td>106</td>
<td>76.0</td>
<td>32.4</td>
<td>371</td>
</tr>
<tr>
<td>6</td>
<td>7.03</td>
<td>160</td>
<td>93.7</td>
<td>37.9</td>
<td>503</td>
</tr>
<tr>
<td>7</td>
<td>7.16</td>
<td>156</td>
<td>94.3</td>
<td>37.5</td>
<td>510</td>
</tr>
<tr>
<td>8</td>
<td>7.18</td>
<td>144</td>
<td>90.0</td>
<td>35.8</td>
<td>482</td>
</tr>
<tr>
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<td>498</td>
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<td>673</td>
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<tr>
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<tr>
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<tr>
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<td>78</td>
<td>89.3</td>
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<td>443</td>
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<td>9.23</td>
<td>96</td>
<td>99.0</td>
<td>40.7</td>
<td>524</td>
</tr>
</tbody>
</table>

*Unexposed side. At time of breakage. [49]

** 7.5 mm from the outer edge. Mean value of all four positions. At time of breakage. [49]

In the article an example of the strain and temperature rise from one sample, called number 6 in this report, is presented. It shows, as seen in Figure 27, that the glass pane temperatures rises rapidly at an early state while the edge temperature rise is slow. At 160 seconds the initial crack took place. The strain increases with time until initial crack where a sudden decrease in strain took place.

Figure 27. Results of test number 6. Float glass without lateral restrain exposed to 7.03kW/m². Illustrated by Harada et al [41]
4.2 Processed experimental results

To get input values for the Validation Model the measured experimental results was processed. By using the measured result from the experiment in Table 2 mean values for the pane temperature, edge temperature, edge strain and temperature difference was calculated by summarizing the values and dividing them by the number of tests as shown in Table 3. The breaking stress was calculated by using the relation between the Young’s modulus, stress and strain according to Eq. (31). With values of the stain measured in the experiment and by assuming a Young’s modulus according to the SS-EN572-1.2012 in Table 1 of 70 GPa the breaking stress was obtained.

Table 3. Summary of the experimental result with the addition of calculated mean values and critical temperature difference.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>2.95</td>
<td>44.2</td>
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<td>2.79</td>
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</tr>
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<td>37.9</td>
<td>503</td>
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<td>55.8</td>
</tr>
<tr>
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<td>37.5</td>
<td>510</td>
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<td>482</td>
<td>3.37</td>
<td>54.2</td>
</tr>
<tr>
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<td>49.3</td>
</tr>
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<td>59.3</td>
</tr>
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<td>68</td>
<td>77.3</td>
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<td>418</td>
<td>2.93</td>
<td>48.0</td>
</tr>
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<td>3.10</td>
<td>49.5</td>
</tr>
<tr>
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<td>99.0</td>
<td>40.7</td>
<td>524</td>
<td>3.67</td>
<td>58.3</td>
</tr>
</tbody>
</table>

(ΣX)/quantity - - 91.4 39.3 468 3.28 52.1

*Unexposed side. At time of breakage.

** 7.5 mm from the outer edge. At time of breakage.
5 The FEM-modelling

Two FEM-models was created in Abaqus, the Validation Model and The Model. The Validation Model is equal to the experimental setup presented in the previous chapter 4 and The Model is similar to ordinary plane glasses used in windows today.

The thermal analyses have been carried out under transient conditions since glass breakage occurs due to thermal stress caused by temperature raise before steady state is obtained.

5.1 Material properties and geometry

In this study material properties according to the SS-EN 572-1:2012 is used except for the critical breaking stress for the validation model.

The critical breaking stress for the Validation Model was calculated by using the measured strains in the experiment and the relation between the Young’s modulus, breaking stress and strain according to Eq.(31). By using the mean value of the measured edge strains of \(468 \cdot 10^6\), see Table 3 in chapter 4.2, and the Young’s modulus according to SS-EN 572-1:2012 calculations entails in a critical breaking stress of \(32.8 \cdot 10^6\) N/m².

In Table 4 the material properties and geometry used in the Validation Model and The Model is presented.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Numerical value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>(\rho)</td>
<td>Validation Model: 2 500 kg/m³, The Model: 2 500 kg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>(E)</td>
<td>Validation Model: (70 \cdot 10^9) N/m², The Model: (70 \cdot 10^9) N/m²</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td></td>
<td>Validation Model: 0.2, The Model: 0.2</td>
</tr>
<tr>
<td>Breaking stress</td>
<td>(\sigma_b)</td>
<td>Validation Model: (32.8 \cdot 10^6) N/m², The Model: (45 \cdot 10^6) N/m²</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>(c_p)</td>
<td>Validation Model: 720 J/kgK, The Model: 720 J/kgK</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(k)</td>
<td>Validation Model: 1 W/mK, The Model: 1 W/mK</td>
</tr>
<tr>
<td>Average coefficient of linear thermal expansion between 20 °C and 300 °C*</td>
<td>(\beta)</td>
<td>Validation Model: (9 \cdot 10^6)/K, The Model: (9 \cdot 10^6)/K</td>
</tr>
<tr>
<td>Height</td>
<td>(h)</td>
<td>Validation Model: 0.5 m, The Model: 1 m</td>
</tr>
<tr>
<td>Width</td>
<td>(w)</td>
<td>Validation Model: 0.5 m, The Model: 1 m</td>
</tr>
<tr>
<td>Thickness of the glass</td>
<td>(L)</td>
<td>Validation Model: 0.003 m, The Model: 0.004 m</td>
</tr>
<tr>
<td>Frame height</td>
<td>(s)</td>
<td>Validation Model: 0.015 m, The Model: 0.01 m</td>
</tr>
</tbody>
</table>

5.2 Thermal boundary conditions

The thermal boundary conditions for the models is presented in Figure 28 and is based on the reasoning in chapter 2.4. The glass is absorbing a certain amount on the incident radiation causing temperature rise in the glass. Energy loses at both sides is due to cooling by convection and emitted radiation (note that the amount of losses isn’t necessary equal at both sides). An isolating frame is attached, shading the panes edges. Only the exposed sides’ edges were isolated with a frame for the
Validation Model in consistency with the experimental setup and for The Model the edges is isolated by a frame on both sides.

Figure 28. Boundary conditions used in the models.

When investigating the importance of in depth absorption the above described boundary conditions was used with the addition that fractions of the incident radiation was absorbed in different layers, i.e. in different depths of the glass. The thickness was divided into 3 layers of 1 mm each as shown in Figure 29. Further a sensitivity analysis was performed where the thickness was divided into 6 layers of 0.50 mm each and 9 layers of 0.33 mm each.

Figure 29. Boundary conditions for in depth absorption.

5.3 Element properties

Type of FEM-element and element size are important choices to make since they can be decisive for the results, and affects not only accuracy but also the calculation time.

There are several different categories of elements in Abaqus, such as plates-, shell and solid elements and in order to produce reliable results it is important to select the right type of element. Since heat transfer through the thickness is of interest a solid heat transfer element is used in this study.
The Validation Model has one element in thickness (except for the model investigating the in depth absorption that has the number of elements in thickness corresponding to the number of layers) and an element size of 7.5x7.5 mm$^2$ at the surface.

The Model has one element in thickness and an element size of 5x5 mm$^2$ at the surface.

# 5.4 Assumptions and simplifications

In this chapter assumptions and simplifications made in the models are presented.

## 5.4.1 Absorbed energy

Since Abaqus can’t handle a surface that absorbs a certain amount of the incident heat flux it has to be handled manually. For energy absorption at the surface the weighted value of the absorptivity is multiplied with the incident heat flux according to Eq. (45), i.e. the incident heat flux is reduced according to the effective absorptivity. E.g. if you want to simulate a surface with an absorptivity of 0.2 exposed to a radiation of 20 kW/m$^2$ the input of the radiative heat flux in Abaqus is set to the product of these to values, i.e. 4 kW/m$^2$.

\[
q_{\text{abs}} = q_{\text{inc}} \cdot \alpha_{\text{eff}}
\]  

(45)

For in depth absorption the weighted value of the absorptivity is replaced by the calculated fraction at each depth. These fractions and the weighted values of the absorptivity’s is presented in chapter 5.5.5. and 5.5.3 respectively. Further the input data for the incident radiation, i.e. the absorbed heat flux is presented in chapter 5.5.6.

## 5.4.2 Emitted energy

The emitted energy from the glass surface is handled in Abaqus by using the Radiation to the ambient function presented in chapter 2.8.3 where the ambient temperature is set to 20 °C. Note that the Radiation to the ambient function in Abaqus is not in consistent with Eq. (5) in chapter 2.2.3 for semi-transparent materials since Kirchhoff’s law is used. This will provide a smaller emitted heat fluxes at the surface (providing larger temperatures) since the effective emissivity is larger than the effective absorptivity presented in chapter 5.5.3 and 5.5.4. The difference is given by Eq. (46), the fraction that should have been emitted if Abaqus could handle the difference between the emissivity and absorptivity.

\[
\Delta q = \sigma T_x^4 (\varepsilon_{\text{eff}} - \alpha_{\text{eff}})
\]

(46)

With the calculated values for the effective emissivity and absorptivity the difference lays in the range of ~70-377 W/m$^2$ which is relatively small compared to the incident heat fluxes.

## 5.4.3 Frame

Considering the previous science the frame is assumed to be totally isolated, i.e. adiabatic. Any heat transfer by conduction through the frame is considered to be negligible since the glass is expected to break fast, before any significant heating of the shaded glass is obtained. The exposed area of the incident heat flux in Abaqus is therefore limited to the central pane of the glass, as illustrated in Figure 28.

## 5.4.4 Temperatures of the heat sources and the ambient

Since the weighted value of the absorptivity, the fractions of in depth absorption and the incident heat fluxes is depending on the heat source temperature these temperatures must be determined. The radiation sources for The Model, the flame and the hot gas layer, is assumed to be blackbody surfaces.
(with an surface emissivity equal to 1) and to have temperatures according to the theory presented in chapter 2.1, i.e. 900 °C and 600 °C respectively. For the Validation model the heat source, the radiant panel, has a temperature of 800 °C [49]. The radiant panel is also assumed to be a blackbody surface.

The ambient temperature during the experiment is unknown hence an ambient temperature of 20 °C is assumed.

## 5.5 Calculated input data

### 5.5.1 Convective heat transfer coefficient

The convective heat transfer coefficient was calculated according to the theory presented in chapter 2.2.1. By using Eq. (3) and (2) and that \( T_{air} \) is equal to 20 °C the heat transfer coefficient for free convection is depending on the surface temperature, \( T_s \), according to Figure 30.

![Heat transfer coefficient for free convection](image)

*Figure 30. The heat transfer coefficient for free convection depending on the surface temperature.*

The values in Figure 30 are used both on the exposed and unexposed side of the glass pane.

### 5.5.2 The incident heat flux

The incident heat fluxes for the Validation model correspond to the heat fluxes measured in the validation experiment, see Table 2 in chapter 4.

The incident heat flux for The Model consist of two different cases, the heat flux from a flame and the heat flux from a hot gas layer. These incident heat fluxes are calculated according to the theory of view factors in chapter 2.3.3.

**Incident heat flux from a flame**

In this scenario it is assumed that a truck with LNG overturns outside the window and creates a pool fire 18 m wide, 7 m high and with a depth enough to yield an emissivity of one. This corresponds to the the case to the left in Figure 3 If the flame front is 10 m from the window and if the flame temperature is assumed to be 900 °C this results in an incident heat flux of 23.4 kW/m² from the flame.

**Incident heat flux from the hot gas layer**

Assuming a relation between the hot gas layer and the window as two infinitely long plates with specified widths \( h \) and \( w \) according the right pictures in Figure 3. Further the width of the window,
w, is 1 m and the width of the smoke gas layer, h, is assumed to be 10 m. Using Eq. (13) and (15) results in an incident heat flux of 14.3 kW/m² from the hot gas layer.

5.5.3 Weighted value of the absorptivity
Using the spectral properties in Appendix D a weighted value of the absorptivity for the glasses was calculated according to the theory presented in chapter 2.3.6. By using Eq. (7) the emitted radiation from a blackbody was obtained for the different heat sources. The blackbody spectra for the different heat sources are illustrated in Figure 6, chapter 2.3.4. Further Eq. (23) was used to calculate the weighted value of the absorptivity for the different glass types and heat sources.

The calculated weighted value of the absorptivity for the F-glass (3 and 4 mm) and K-glass (4 mm) is presented in Table 5.

Table 5. Weighted value of the absorptivity for the different glasses and fire cases.

<table>
<thead>
<tr>
<th>The model</th>
<th>Heat source</th>
<th>F-glass 3mm</th>
<th>F-glass 4 mm</th>
<th>K-glass 4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flames (900 °C)</td>
<td>-</td>
<td>0.622</td>
<td>0.270</td>
<td></td>
</tr>
<tr>
<td>Hot gas layer (600 °C)</td>
<td>-</td>
<td>0.775</td>
<td>0.230</td>
<td></td>
</tr>
<tr>
<td>Validation model</td>
<td>Radiation pane in the experiment (800 °C)</td>
<td>0.622 (0.6216)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In Appendix D, Figure 53, is can be seen that the spectral absorptivity for the F-glass is large for higher wavelengths (in the IR region) while the absorptivity for the K-glass is small. Hence the weighted value of the absorptivity for 4 mm F-glass is smaller for heat sources with a higher temperature which is in consistence with the theory of Wien’s displacement law presented in chapter 2.3.4. The blackbody radiation peaks at lower wavelengths the higher the blackbody temperature is hence the weighted value of the absorptivity will decrease for higher blackbody temperatures given that the spectral absorptivity is large for wavelengths within the IR region, which is longer wavelengths. This consistency check is not applicable to the K-glass since the absorptivity is small for large wavelengths.

5.5.4 Weighted value of the emissivity
Using the spectral properties in Appendix D the value of the emissivity for the glasses was calculated according to the theory of Gardon [21] presented in Appendix C. The absorption coefficient A_λ (not the absorptivity) was calculated as explained in chapter 5.5.5 and is presented in Figure 32.

The theory of Gardon is not applicable for coated surfaces since they can be considered to be opaque surface, the reflectance is high. See the reflectance for the K-glass in Figure 52, Appendix D. The emissivity for the coated side of the K-glass was therefore calculated in the same way as for opaque bodies by using Eq. (25), see chapter 2.3.6 and 2.3.7.

Since only the spectral properties of the coated side of the K-glass was measured the uncoated side is assumed to have the same emissivity as the 4 mm thick F-glass.

The calculated values of the emissivity for the F-glass (3 and 4 mm) and K-glass (4 mm) is presented in Table 5.

Table 6. Value of the emissivity for the different glasses at 100 °C.

<table>
<thead>
<tr>
<th>Side of the glass</th>
<th>F-glass 3mm</th>
<th>F-glass 4 mm</th>
<th>K-glass 4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>0.900</td>
<td>0.903</td>
<td>0.906*</td>
</tr>
<tr>
<td>Coated</td>
<td>-</td>
<td>-</td>
<td>0.171</td>
</tr>
</tbody>
</table>

*Assumed to be equal to the 4 mm F-glass since only the spectral properties of the coated side was measured for the K-glass.
The assumption that the emissivity of the uncoated side of the 4 mm K-glass is equal to the emissivity of the 4 mm F-glass is considered to be a reasonable assumption. The emissivity of a 1 m thick glass pane is 0.91 according to the theory of Gardon, almost the same as for the 4 mm thick F-glass, which indicates that the emissivity on that side is independent of the thickness and the other sides properties. Hence the coated side of the K-glass will have no or negligible little impact on the emissivity of the uncoated side.

5.5.5 In depth absorption
The fraction absorbed energy at a certain depth in the glass has been calculated according to the theory presented in Appendix B for 3 mm F-glass.

By using the spectral properties of the 3 mm F-glass, see Figure 50 and Figure 51 in Appendix D, and Eq. (B19), (B21), and (B23) the surface reflectance, \( R_\lambda \), the surface transmittance, \( T_\lambda \), and the absorption coefficient, \( A_\lambda \), was calculated. The consistency checks 1, 2 and 3 in Appendix B was performed with good agreement.

As shown in Figure 50 in Appendix D the transmittance signal is almost zero and sometimes negative for wavelengths higher than 4600 \( \mu \)m. This means that there are no transmitted radiation for these wavelengths since no signal is measured. The measured values can be seen as instrumental errors which entails in strange values of \( A \) hence \( A \) is assumed to be equal to 2000 m\(^{-1}\) for wavelengths greater than 4600 \( \mu \)m. This is the value of \( A \) right before the transmittance signal is lost.

The calculated values of \( R_\lambda \), \( T_\lambda \) and \( A_\lambda \) is presented in Figure 31 and Figure 32.

![Calculated R\( _\lambda \) and T\( _\lambda \)](image)

*Figure 31. Calculated value of the surface reflectance \( R_\lambda \) and surface transmittance \( T_\lambda \).*
Further the fractions absorbed radiation in different depths was calculated according to Eq. (B10) and (B12). The incoming irradiation, \( I_{\lambda,0} \), used in Eq. (B10) was calculated for a blackbody with a temperature of 800 °C according to Eq.(7). The defined layers and calculated fractions is presented in Table 7.

Table 7. Absorbed fraction (rounded values) in depth with a source temperature of 800 °C.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Absorbed fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 layer á 1.0 mm</td>
</tr>
<tr>
<td>1</td>
<td>43.3</td>
</tr>
<tr>
<td>2</td>
<td>12.4</td>
</tr>
<tr>
<td>3</td>
<td>6.10</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>Totally absorbed fraction (0-3 mm):</td>
<td>61.7 % (0.6174) ≈ 62 %</td>
</tr>
</tbody>
</table>

The totally absorbed fractions of 61.74 % corresponds well to the weighted value of the absorptivity of 62.16 % (see Table 5, the 3 mm F-glass for the validation model). They differ 0.42 % which will give a slight difference in totally absorbed irradiation for the in depth absorption compared to surface absorption.

5.5.6 Calculated absorbed irradiation

In this chapter the input values for the absorbed heat fluxes is presented. The absorbed energy was calculated according to Eq.(45) presented in chapter 5.4.1.
Validation model

In Table 8 - Table 11 the calculated absorbed energy is presented for the Validation Model. The incident radiation corresponds to the measured imposed heat fluxed in the experiment presented in Table 2 in chapter 4.1 and the weighted value of the absorptivity and fractions of in depth absorption (exact values) corresponds to the calculated values presented in Table 5 and Table 7, se chapter 5.5.3 and 5.5.5 respectively.

Table 8. Calculated input values for the absorbed radiation (rounded values) for surface absorption.

<table>
<thead>
<tr>
<th>Corresponding Test No.</th>
<th>Incident radiation, $q_{inc}$ [kW/m²]</th>
<th>The weighted value of the absorptivity, $\alpha_{eff}$</th>
<th>The absorbed irradiation, $q_{abs}$ [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5.62</td>
<td>0.622</td>
<td>3.49</td>
</tr>
<tr>
<td>6</td>
<td>7.03</td>
<td>0.622</td>
<td>4.37</td>
</tr>
<tr>
<td>9</td>
<td>7.24</td>
<td>0.622</td>
<td>4.50</td>
</tr>
<tr>
<td>12</td>
<td>8.22</td>
<td>0.622</td>
<td>5.11</td>
</tr>
<tr>
<td>15</td>
<td>9.23</td>
<td>0.622</td>
<td>5.74</td>
</tr>
</tbody>
</table>

Table 9. Calculated input values for the absorbed radiation (rounded values) in different depths for 1 mm thick layers.

<table>
<thead>
<tr>
<th>Incident radiation, $q_{inc}$ [kW/m²]</th>
<th>Layer (each layer is 1 mm)</th>
<th>Layer fraction</th>
<th>The absorbed irradiation $q_{abs,x}$ [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.62</td>
<td>1</td>
<td>0.433</td>
<td>2.43</td>
</tr>
<tr>
<td>5.62</td>
<td>2</td>
<td>0.124</td>
<td>0.696</td>
</tr>
<tr>
<td>5.62</td>
<td>3</td>
<td>0.061</td>
<td>0.340</td>
</tr>
<tr>
<td><strong>Totally absorbed energy</strong></td>
<td></td>
<td></td>
<td>3.47</td>
</tr>
<tr>
<td>7.24</td>
<td>1</td>
<td>0.433</td>
<td>3.14</td>
</tr>
<tr>
<td>7.24</td>
<td>2</td>
<td>0.124</td>
<td>0.896</td>
</tr>
<tr>
<td>7.24</td>
<td>3</td>
<td>0.061</td>
<td>0.439</td>
</tr>
<tr>
<td><strong>Totally absorbed energy</strong></td>
<td></td>
<td></td>
<td>4.47</td>
</tr>
<tr>
<td>9.23</td>
<td>1</td>
<td>0.433</td>
<td>4.00</td>
</tr>
<tr>
<td>9.23</td>
<td>2</td>
<td>0.124</td>
<td>1.14</td>
</tr>
<tr>
<td>9.23</td>
<td>3</td>
<td>0.061</td>
<td>0.559</td>
</tr>
<tr>
<td><strong>Totally absorbed energy</strong></td>
<td></td>
<td></td>
<td>5.70 (exact 5.698)</td>
</tr>
</tbody>
</table>

Table 10. Calculated input values for the absorbed radiation (rounded values) in different depths for 0.5 mm thick layers.

<table>
<thead>
<tr>
<th>Incident radiation, $q_{inc}$ [kW/m²]</th>
<th>Layer (each layer is 0.5 mm)</th>
<th>Layer fraction</th>
<th>The absorbed irradiation $q_{abs,x}$ [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.23</td>
<td>1</td>
<td>0.294</td>
<td>2.72</td>
</tr>
<tr>
<td>9.23</td>
<td>2</td>
<td>0.139</td>
<td>1.28</td>
</tr>
<tr>
<td>9.23</td>
<td>3</td>
<td>0.0758</td>
<td>0.699</td>
</tr>
<tr>
<td>9.23</td>
<td>4</td>
<td>0.0480</td>
<td>0.443</td>
</tr>
<tr>
<td>9.23</td>
<td>5</td>
<td>0.0343</td>
<td>0.316</td>
</tr>
<tr>
<td>9.23</td>
<td>6</td>
<td>0.0263</td>
<td>0.243</td>
</tr>
<tr>
<td><strong>Totally absorbed energy</strong></td>
<td></td>
<td></td>
<td>5.70 (exact 5.698)</td>
</tr>
</tbody>
</table>
Table 11. Calculated input values for the absorbed radiation (rounded values) in different depths for 0.33 mm thick layers.

<table>
<thead>
<tr>
<th>Incident radiation, $q_{inc}$ [kW/m$^2$]</th>
<th>Layer (each layer is 0.33 mm)</th>
<th>Layer fraction</th>
<th>The absorbed irradiation, $q_{abs,x}$ [kW/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.23</td>
<td>1</td>
<td>0.221</td>
<td>2.04</td>
</tr>
<tr>
<td>9.23</td>
<td>2</td>
<td>0.130</td>
<td>1.20</td>
</tr>
<tr>
<td>9.23</td>
<td>3</td>
<td>0.0817</td>
<td>0.754</td>
</tr>
<tr>
<td>9.23</td>
<td>4</td>
<td>0.0547</td>
<td>0.505</td>
</tr>
<tr>
<td>9.23</td>
<td>5</td>
<td>0.0392</td>
<td>0.362</td>
</tr>
<tr>
<td>9.23</td>
<td>6</td>
<td>0.0299</td>
<td>0.276</td>
</tr>
<tr>
<td>9.23</td>
<td>7</td>
<td>0.0239</td>
<td>0.221</td>
</tr>
<tr>
<td>9.23</td>
<td>8</td>
<td>0.0198</td>
<td>0.183</td>
</tr>
<tr>
<td>9.23</td>
<td>9</td>
<td>0.0168</td>
<td>0.155</td>
</tr>
<tr>
<td><strong>Totally absorbed energy</strong></td>
<td></td>
<td></td>
<td>5.70 (exact 5.698)</td>
</tr>
</tbody>
</table>

The absorbed irradiation is absorbed at the surface at the certain layer.

The totally absorbed energy for the in depth absorption is marginally lower than the absorbed irradiation for the surface absorption, 40 W/m$^2$ lower. This is due to the difference between the weighted value of the absorptivity and the totally absorbed fraction of 0.42 % as stated in chapter 5.5.5.

The Model

The incident radiation in Table 12 corresponds to calculated values for the incident radiation of the flame and hot gas layer presented in chapter 5.5.2. The weighted value of the absorptivity (exact values) corresponds to the calculated values presented in Table 5, chapter 5.5.3.

Table 12. Calculated input values for the absorbed energy in for the model.

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Glass type</th>
<th>Incident radiation, $q_{inc}$ [kW/m$^2$]</th>
<th>The weighted value of the absorptivity, $a_{eff}$</th>
<th>The absorbed irradiation, $q_{abs}$ [kW/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot gas layer</td>
<td>F-glass 4mm</td>
<td>14.3</td>
<td>0.775</td>
<td>11.1</td>
</tr>
<tr>
<td>Flame</td>
<td></td>
<td>23.4</td>
<td>0.621</td>
<td>14.5</td>
</tr>
<tr>
<td>Hot gas layer</td>
<td>K-glass 4mm</td>
<td>14.3</td>
<td>0.230</td>
<td>3.29</td>
</tr>
<tr>
<td>Flame</td>
<td></td>
<td>23.4</td>
<td>0.270</td>
<td>6.31</td>
</tr>
</tbody>
</table>

5.6 Output data

5.6.1 Simulation time

The Abaqus simulation time was set to 600 seconds for all models except for the K-glass exposed to the hot gas layer where the time was set to 1200 seconds since the critical temperature difference was not reached after 600 seconds and is was of interest to see if it was to be reached after 600 seconds. Hence the output data is showing the temperatures changing with the specified times.
5.6.2 Measured temperature positions

For the Validation Model the positions for the output data was chosen in consistency with the measured positions in the experiment, i.e. the edge temperature was measured 7.5 mm from the outer edge at the exposed side and the central pane temperature was measured at the exact middle of the glass panes unexposed side. These positions was used both when comparing the FEM model with the experiment and also when evaluating the dependency of in depth absorption. Nodal temperatures was used at all desired positions. Further for the in depth absorption the output data was supplemented at two positions, the middle (in thickness) central pane temperature and the temperature on the exposed side. For 3 and 9 layers in thickness the mid central pane temperature was measured using centroid at the middle layer and for 6 layers in thickness the mid central pane temperature was measured at the node between the two middle layers. For 3 and 9 layers in thickness the mid central pane temperature is presented by the mean temperature in the middle layer and for 6 layers in thickness the mid central pane temperature is presented by the nodal temperature between the two middle layers.

The positions of the output data for The Model was chosen in consistency with the theory of Pagni and Joshi, i.e. the edge and central pane temperature was measured as a mean value between the exposed and unexposed side. The edge temperature was measures at the outmost edge (the coldest spot) and the central pane temperature was measured at the exact middle of the glass pane. Nodal temperatures was used at the edge and centroid temperature was used at the central pane. To obtain a mean value of the edge temperature the nodal temperature at both the exposed and unexposed side was extracted.

5.7 Critical breakage temperature

The critical temperature difference, $\Delta T_b$, was determined according to the theory presented by Pagni and Joshi in chapter 2.7.3 with and without the force balance factor $g$. By using Eq.(37) and material properties in Table 4 in chapter 5.1 the critical temperature difference for both the Validation Model and The Model was obtained. The measured critical temperature difference in the experiment was calculated and is presented in Table 3, chapter 4.2.
6 Results

6.1 Mesh analyses

The results from the mesh analysis is presented in Appendix E.

6.2 The validation model

6.2.1 Critical temperature difference

The theoretically critical temperature difference for the Validation Model was calculated to 55.4 °C (52.0 °C with g=1).

The mean critical temperature difference at when initial crack occur according to the results from the experiment was 52.1 °C as seen in Table 3, chapter 4.2.

6.2.2 Temperature analyses in Abaqus

Figure 33 shows how the temperature is changing with time on the exposed side, visualization from Abaqus at 0, 100, 300 and 600 seconds. From 20 °C (blue) to warmer (green) to warmer (orange) to the warmest around 150 °C (red).

Figure 34 presents No. 6 nodal temperatures changing with time for the central pane, exposed and unexposed side and at the edge (7.5 mm from the outer edge, exposed side). The axis is modified to resemble Figure 27 in chapter 4.1, the measured temperatures from the corresponding experiment specimen.

Figure 33. Visualization in Abaqus. From 20 °C (blue) to warmer (green) to warmer (orange) to the warmest around 150 °C (red).

Figure 34. Temperature vs. time for the FEM-model exposed to 7.03 kW/m².
In Appendix F all of the results from the Validation Model is presented. Graphs are showing temperature vs. time for the pane and edge temperatures.

Table 13 presents the results from the FEM-model compared with the experiment. The comparison is made between the FEM-model in relation to the experiment, e.g. a temperature difference of -5 °C means that the FEM-model showed 5 °C lower temperature at the time of initial crack according to the experiment, than the corresponding temperature according the experiment.

Table 13. Comparison between experiment and Abaqus.

<table>
<thead>
<tr>
<th>Imposed heat flux [kW/m²]</th>
<th>Time to initial crack [s]</th>
<th>Central pane* [°C]</th>
<th>Edge** [°C]</th>
<th>Central pane* [°C]</th>
<th>Edge** [°C]</th>
<th>Central pane [°C]</th>
<th>Edge [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.62</td>
<td>204</td>
<td>101</td>
<td>56.5</td>
<td>99.4</td>
<td>42.4</td>
<td>-1.6</td>
<td>-14.1</td>
</tr>
<tr>
<td>7.03</td>
<td>160</td>
<td>93.7</td>
<td>37.9</td>
<td>105</td>
<td>40.5</td>
<td>11.3</td>
<td>2.6</td>
</tr>
<tr>
<td>7.24</td>
<td>142</td>
<td>91.8</td>
<td>39.4</td>
<td>101</td>
<td>38.0</td>
<td>9.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>8.22</td>
<td>104</td>
<td>98.8</td>
<td>39.5</td>
<td>93.3</td>
<td>33.1</td>
<td>-5.5</td>
<td>-6.4</td>
</tr>
<tr>
<td>9.23</td>
<td>96</td>
<td>99.0</td>
<td>40.7</td>
<td>96.8</td>
<td>33.0</td>
<td>-2.2</td>
<td>-7.7</td>
</tr>
</tbody>
</table>

*Unexposed side.

**7.5 mm from the outer edge.

Table 13 shows that the central pane temperature in the FEM-model differs with +11.3 to -5.5 °C compared to the experiment. The edge temperature on the other hand shows more often lower temperatures in the FEM-model with differences from -1.4 to -14.1 °C except from one which showed a difference of +2.6 °C.

6.2.3 In depth absorption

Figure 35 and Figure 36 show results for in depth absorption for 3 layers compared with surface absorption.

![Pane temperature graph](image-url)

Figure 35. Pane temperature on the unexposed side vs time for the surface and in depth absorption.
In Figure 36 - Figure 40 the results for surface absorption and in depth absorption for 3, 6 and 9 layers is presented and compared.

Figure 36. Edge (7.5 mm from outer edge) temperature vs time for the surface and in depth absorption.

Figure 37. Pane temperature on the exposed side vs time for the surface and in depth absorption.
Figure 38. Pane temperature on the unexposed side vs time for the surface and in depth absorption.

Figure 39. The central pane centroid temperature vs time for the surface and in depth absorption.
In Table 14 the results from Figure 38 and Figure 40 is summarized where the pane temperature, edge temperature and time presented is where the critical temperature difference of 58.3 °C is exceeded.

**Table 14. Summarized results for the comparison of the breakage time and temperatures for surface and in depth absorption.**

<table>
<thead>
<tr>
<th>Absorption mode</th>
<th>Pane* temperature [°C]</th>
<th>Edge** temperature [°C]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>99.0</td>
<td>40.7</td>
<td>96</td>
</tr>
<tr>
<td>Surface</td>
<td>88.5</td>
<td>30.1</td>
<td>82</td>
</tr>
<tr>
<td>3 layers</td>
<td>88.5</td>
<td>30.0</td>
<td>82</td>
</tr>
<tr>
<td>6 layers</td>
<td>90.2</td>
<td>31.8</td>
<td>98</td>
</tr>
<tr>
<td>9 layers</td>
<td>91.0</td>
<td>32.4</td>
<td>103</td>
</tr>
</tbody>
</table>

*Unexposed side.

** 7.5 mm from the outer edge.

6.3 The Model

6.3.1 Critical temperature difference

The critical temperature difference for *The Model* was calculated to 72.9 °C (71.5 °C with g=1) as explained in chapter 5.7.

6.3.2 Temperature analyses in Abaqus

In Figure 41 - Figure 44 the results for both F- and K-glass is presented and compared. Figure 41 and Figure 42 show the pane temperature and edge temperature for an incident heat flux of 23.4 kW/m². Figure 43 - Figure 44 show the same temperatures for an incident heat flux of 14.3 kW/m². When the critical temperature difference is exceeded this is marked as the breakage point.
Figure 41. Comparison of pane temperatures with an incident radiation of 23.4 kW/m².

Figure 42. Comparison of edge temperatures with an incident radiation of 23.4 kW/m².
At steady-state the K-glass reaches a temperature of 143 °C at the central pane as seen in Figure 43.

**6.3.3 Summarized results of The Model**

Figure 45 shows how the temperature differences for the different cases changes with time and where the critical temperature difference exceeds.
Figure 45. Comparison of temperature difference for the F- and K-glass exposed to different heat sources.

In Table 15 the results of the breakage time and temperatures at the breakage point is summarized and compared.

Table 15. Comparison of the breakage time and temperatures for F- and K-glass at the critical temperature difference of 72.9 °C.

<table>
<thead>
<tr>
<th>Incident heat flux [kW/m²]</th>
<th>Glass type</th>
<th>Pane temperature [°C]</th>
<th>Edge temperature [°C]</th>
<th>Time [s]</th>
<th>Increase in time to breakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.4</td>
<td>F-glass</td>
<td>98.5</td>
<td>25.1</td>
<td>42</td>
<td>+226 %</td>
</tr>
<tr>
<td></td>
<td>K-glass</td>
<td>119</td>
<td>45.9</td>
<td>137</td>
<td></td>
</tr>
<tr>
<td>14.3</td>
<td>F-glass</td>
<td>102</td>
<td>29.2</td>
<td>59</td>
<td>∞</td>
</tr>
<tr>
<td></td>
<td>K-glass</td>
<td>105</td>
<td>58.0</td>
<td>(maximal ΔT is 47.0 at t=272 s)</td>
<td>∞</td>
</tr>
</tbody>
</table>

*Time where maximal temperature difference appears.

The K-glass exposed to 14.3 kW/m² did not reach the critical temperature difference, i.e. did not break. After 272 seconds the greatest temperature difference was recorded followed by a slowly decrease of the temperature difference as can be seen in Figure 45.

Comparison between the F- and K-glass for an incident heat flux of 23.4 kW/m² gives an increased integrity of 226 %. 


7 Discussion

7.1 Mesh analysis

As seen in Figure 54 - Figure 65 (in Appendix E) the result from the mesh analyses indicated that the results in the previous chapter for both the Validation Model and The Model is mesh independent since the chosen surface element sizes and number of elements in thickness shows approximately the same results as the bigger and/or smaller surface element sizes and greater and/or less number of elements in thickness.

The mesh analysis for The Model where the surface element size was varied the edge temperature is depending on the surface element size as shown in Figure 65. This phenomenon is also slightly seen in Figure 59, the corresponding mesh analysis for the Validation Model. As the incident heat flux is greater for The Model in comparison to the Validation Model the phenomenon may be shown more significantly for greater heat fluxes and it is therefore more important to take the size of the surface element into account for greater heat fluxes.

That the temperature becomes higher at the edges with a surface element size of 15x15 mm$^2$ and 10x10 mm$^2$ compared to 5x5 mm$^2$ for The Model and higher for 10x10 mm$^2$ compared to 7.5x7.5 mm$^2$ and 5x5 mm$^2$ for the Validation Model is probably because of the elements position which lays both in the shaded region and in the exposed region which may lead to higher temperatures within the element and therefore also at the edges.

These observations indicates that the surface element size may be modelled with smaller elements at the edges while the central pane element could be coarser (saving simulation time). The number of elements in thickness is shown not to affect the results which probably is due to the thin thickness of the glass sheet.

7.2 The validation model

7.2.1 Critical temperature difference

As seen in chapter 6.2.1 the mean critical temperature difference at when initial crack occur according to the results from the experiment, 52.1 °C, corresponds well to the theoretically calculated temperature difference of 55.4 °C.

The slightly difference of 3.3 °C is probably due to the positions of thermocouples in the experiment. The edge temperature was measured ~7.5 mm from the outer edge and the pane temperature was measured at the unexposed side. According to the theory presented by Joshi and Pagni the edge temperature is the temperature at the outmost edge and the pane temperature is the mean temperature through the central panes thickness. If the edge temperature had been measured at the outer edge it would probably have shown lower edge temperatures and therefore also given a higher temperature difference at initial crack. And if the pane temperature had been measured at the centroid of the glass the pane temperature would probably be slightly higher which also would give a higher temperature difference at initial crack.

The force balance factor $g$ may also cause some uncertainties. Without this factor $g$ the calculated temperature difference became 52.0 °C which is closer to the experimental results. There could also be some uncertainties in the theoretical model presented by Joshi and Pagni.
7.2.2 Temperature analyses in Abaqus

When comparing Figure 34 with Figure 27 where the temperatures vs time for test number 6 is presented the comparison indicates that the temperature rise in the FEM and experiment is acting similar. The edge temperature rise is slow and both the exposed and unexposed central pane temperature rises fast. But there are a slightly difference in the early state of the exposure. After a few seconds the temperature at the exposed and unexposed side for the FEM model rises in parallel to each other but in the experiment there is a delay where the temperature difference is greater in the beginning and smaller at the end.

Table 13 shows that the central pane temperature in the FEM-model differs with +11.3 to -5.5 °C compared to the experiment which is considered to be a good agreement since it is both higher and lower temperatures. The difference could depend on uncertainties in the experimental equipment, more particular the imposed heat flux which probably was not ideal and constant as in the FEM-model.

The edge temperature on the other hand shows more often lower temperatures in the FEM-model with differences from -1.4 to -14.1 °C except from one which showed a difference of +2.6 °C. That the FEM-model shows lower temperatures at the edges compared to the experiment can depend on the assumption of a totally isolated (adiabatic) frame in Abaqus. The isolation used in the experiment is probably not perfectly insulating leading to higher temperatures at the edges. It can also be seen in Figure 25, chapter 4.1, that the thickness, s, of the isolation may not consequently be 15 mm around the edge since the insolation is not cut straight round the edges. When studying the edge temperatures from the experiment in Figure 27, which was measured at all four edges, it shows that the edge temperatures was not exactly the same at all positions which also indicates that the isolation may have some imperfections compared to the perfectly isolating frame in Abaqus. It could also depend on the measure equipment which could have some uncertainties when measuring the temperature.

But the lower temperatures in the FEM-model may also depend on the boundary condition on the unexposed sides’ edges. In the FEM-model the edges are losing heat by convection and emission but in the experimental setup there are a steel sash at the edges on the unexposed side as seen in Figure 26. This steel sash prevents the edges to lose heat by convection and emission, the energy losses are instead done by conduction through the steel sash. But since steel has a high thermal conductivity the difference is probably very small but could be a reason why the temperature in the FEM-model is smaller.

7.2.3 In depth absorption

The totally absorbed fraction of 61.74 % when in depth absorption is accounted for corresponds well to the weighted value of the absorptivity of 62.16 % for surface absorption. The slight difference of 0.42 % may depend on the assumption of $1 \gg R^2 e^{-2Ad}$ when calculation the values of $T_i$ of in depth absorption, see chapter B 2.1 in Appendix B. Another potential affecting parameter is the assumption of that $A_\lambda=2000$ for wavelengths greater than 4600 μm. An $A_\lambda>2000$ for these wavelengths would, according to Eq. (B10) and (B12) , give a higher rate of absorbed energy.

As seen in Figure 35 and Figure 36 the in depth absorption with 3 layers does not differ significantly from the surface absorption. But when expanding the in depth absorption to 6 and 9 layers the results differs from the surface absorption where in depth at all measuring points shows lower temperatures in the span of 50-500 seconds as seen in Figure 37 - Figure 40. Hence the effect of in depth absorption is significant shown for finer partitioning of the thickness. Further it can be seen in Table
that the lower temperatures causes a critical temperature difference exceeding later for 6 and 9 layers compared to surface absorption.

The temperature rise at all measuring points for in depth absorption seem to be delayed in the beginning and at a certain point the temperature rises faster and the temperature becomes equal to the surface absorption at steady-state, see Figure 37 and Figure 38 around 500 seconds. This phenomenon, a phenomenon of in depth absorption, is believed to depend on the heat flux distribution in depth. The imposed heat flux is absorbed deeper which increases the temperatures in the different layers leading to smaller temperature differences between each layer, i.e. a more uniform heating of the glass sheet in thickness. Smaller temperature differences will make the effect of conduction less rapid since the heat flux by conduction is stated by the temperature difference according Fourier’s law, Eq. (38). Hence the temperature rise will be less rapid for the in depth absorption at the beginning compared to surface absorption where the temperature differences through the glass is bigger. This effect is also found to be greater between the layers nearest the exposed side since the phenomenon seem to be greater at the exposed side, see Figure 37, compared to the unexposed side and the central pane centroid temperature, see Figure 38 and Figure 39. This is probably due to the amount of absorbed energy near the exposed side which is greater compared to the other layers.

This theory of delayed temperature rise due to a less rapid effect of conduction is especially reasonable for the temperature on the exposed side since the imposed heat flux is smaller there for the in depth absorption compared to surface absorption. But on the unexposed side the increased imposed heat flux in depth should lead to higher temperatures itself and therefore higher temperature difference in the last layer and further led to a reverse effect, that the temperature rise for the in depth absorption should be faster compared to the surface absorption on the unexposed side. Further a thought is that this delay in temperature rise may depend on a computational error. But since the mesh analyses for the Validation model that was used to evaluate the in depth absorption didn’t show any computational errors due to the choice of mesh size in thickness, see Figure 54 - Figure 56 in Appendix E (testing 1 to 8 elements in thickness) the probability is small. Whether this phenomenon is a computational error or an effect due to a less rapid effect of conduction is unsure and has to be examined further.

That the totally absorbed heat flux for in depth absorption is 40 W/m² lower compared to the surface absorption is not considered to be the reason for the lower temperatures, the reason is rather believed to be the in depth absorption itself. This since using 3 layers shows equal temperatures on the exposed and unexposed surface at steady-state (around 500 seconds) as when the surface absorption is assumed even though the difference between the totally absorbed heat fluxes is 40 W/m².

As can be seen in Table 14 for the studied cases the in depth absorption gives results closer to the experiment regarding the breakage time. Whether in depth absorption has to be taking into account is hard to tell based on the results since only one comparison with experimental results has been made. More comparisons to experimental results have to be made to get a statistically supported conclusion. Surface absorption is considered to be a good first approximation since it will give conservative results but in depth absorption may be more accurate regarding absorption in semi-transparent materials.
7.3 The model

7.3.1 F-glass vs K-glass
In Figure 41 - Figure 44, showing results from both heat sources, it can be seen that the temperature rise in the K-glass, both at the central pane and at the shaded edges, is less rapid compared to the F-glass. Hence coatings is preventing rapid temperature rise in the glass. The lower temperatures are directly depending on the fraction absorption heat flux that is reduced using a coating. The surface absorption in its turn is reduced because of the spectral properties of the glass since the reflectance is high and the absorption is low in the range of the emission spectrum of a fire (1500-6000 nm) as can be seen in Figure 52 and Figure 53, Appendix D.

The reduction of temperature increase at the central pane gives the edges “time” to get heated through conduction, i.e. uniformly heating of the whole glass pane is obtained by using a coating. Hence the temperature difference for the K-glass becomes smaller as seen in Figure 45. This gives a better integrity of the glass since the breakage is delayed and even stopped for one case.

Table 15 shows that the integrity increases 226 % for an incident heat flux of 23.4 kW/m$^2$ when using the K-glass instead of the F-glass. In the other case where the glasses was exposed to 14.3kW/m$^2$ the F-glass breaks after 59 seconds while the K-glass stays intact.

The increase in integrity by using Low-E coatings require a position where the coating is placed on the exposed side, see position 6, 4 or 2 in Figure 13. This since the coating otherwise only would isolate the glass pane and probably cause breakage at an earlier state.

It is also important to notice that a window consisting of three panes will have a greater resistance against breakage than a window consisting of one pane since the two inner panes will act as two shields that protects the outer pane until they break. How much this will delayed the breakage time is remained to be solved.

Another question to be solved is how the coating will react in reality exposed to high temperatures, will it melt, evaporates or stay intact?

7.4 Input data
High quality material data for glass is difficult to obtain since the literature review shows that decisive material properties such as the breaking stress is strongly dependent on the edge imperfections. The variety of imperfections at the edges will entail different breaking stresses and therefore also different breakage times for different sheets of glass. This variety will not affect the result since the purpose with the study was not to estimate the exact time to breakage but only to estimate the efficiency of Low-E coatings in comparison to a glass without coating. The shown increasing integrity is independent of the breaking stress since the breaking stress is assumed to be exactly the same for the F- and K-glass. But it is important to notice that the critical breaking time estimated in this study can vary from the reality since the material property of the breaking stress can differ.

For the Validation Model the in depth absorption was investigated. This phenomenon was not considered when evaluating the efficiency of the Low-E coating. This will neither effect the result based on the same reason described above for the breaking stress and edge imperfections.

Absorptivity and its temperature dependence, as shown in Figure 9, was neglected since the glass breakage was expected to occur before 200 °C and only small variations is reported in the range 20-200 °C. It has been shown that coatings provide a more uniform heating of the glass pane which may allow temperatures higher than 200 °C before breakage. In that case this property dependence has to
be considered. In the studied cases the K-glass reaches a maximum temperature of 143 °C at steady-state when exposed to the heat flux of 14.3 kW/m² and a temperature of 115 °C at the central pane when breakage occurs for the imposing heat flux of 23.4 kW/m², as shown in Table 15. The pane temperatures for the F-glass at breakage is 98 °C and 102 °C which also is shown is Table 15. These temperatures are not exceeding 200 °C where the absorptivity becomes temperature dependent and the assumption is therefore considered to be decent.

7.5 Assumptions made

The greatest assumption made is that glass breakage occurs due to temperature differences within the pane according to the theory presented by Joshis and Pagnis Eq. (34). This assumption is considered to be reasonable since Eq. (34) has been validated with the Validation Model in this study and other studies as well with good agreement.

Since Eq. (34) follows directly from Hooke’s law where \( \Delta T_b \) is the critical temperature difference between the glass edge and central pane depending on the breaking stress, thermal expansion and Young’s modulus the equation is considered to be accurate as long as the strength of the glass, the breaking stress, is constant, i.e. before the glass transition temperature.

It has been shown that coatings provide a more uniform heating of the glass pane which may allow higher temperatures in the glass. In the studied cases the K-glass reaches a maximum temperature of 143 °C and 115 °C at the central pane and the F-glass reaches 98 °C and 102 °C at the central pane at breakage. These temperatures is not near the transition temperature and the accuracy of the breakage time is therefore considered to be accurate.

The theory presented by Pagni and Joshi of glass breakage is probably not accurate for great pane thicknesses and when the incident heat flux is high and momentary, i.e. for fast heating. In that case the breakage phenomenon may be that the breaking stress exceeds at surface flaws because of bowing, the question is for what thicknesses and speed of heating will bowing be the main mechanism causing breakage? Another interesting thought, relevant in countries with cold winter climate, will the cold climate outside during the winter promote the phenomenon of glass breakage at surface flaws due to bowing since it will promote higher temperature differences between the exposed and unexposed surface?

It is important to notice that the breakage time is the time for the first crack to appear. The actual fallout time remains to be solved. In a room fire the pressure will probably have some impact on the actual fallout, probably will the pressure decrease the time between first crack and actual fallout.

Another affecting assumption is the assumption of a totally isolating frame. In reality the frame is not totally isolating and the edges will probably be heated by conduction at the interface between the frame and glass surface. This will give a more uniform heating of the glass pane promoting smaller temperatures difference between the shaded edge and central pane. The integrity of the glass will increase.

The irradiation levels presented in this report are assumed to impinge perpendicularly on the glass. The reflectance and transmittance was also measure with an impinge irradiation perpendicular to the surface. Angles not perpendicular to the surface will give higher reflectance and therefore a smaller absorption which will promote smaller temperature rise in the glass hence this assumption is considered to be conservative.
8 Conclusions

In this study it has been shown that reducing the surface absorptivity will reduce the rapid temperature rise and steep temperature gradient in the glass. For the K-glass the reduced absorptivity in case of fire appears since the spectral properties of the coating, the reflectance and absorptivity, is high respectively low in the range of the emission spectrum from an enclosure fire. The reduction does not only reduce the pane temperature, the slow heating of the central pane also allows the edges to increase in temperature before the critical temperature difference is exceeded. For the case where the glasses was exposed to 23.4 kW/m² the F-glass breaks after 42 seconds and the K-glass after 137 seconds, an increased integrity of 226 %. In the other case the F-glass breaks after 59 seconds while the K-glass is kept intact.

The increase in integrity by using Low-E coatings require a position where the coating is placed on the exposed side in relation to the fire, see position 2, 4 and 6 in Figure 13, where position 6 is the most advantageous position.

It is important to notice that the breakage time is the time for the first crack to appear. The actual fallout time remains to be solved. The prediction of the first crack to appear is well understood. The theory of Pagni and Joshi as well as the thermal analysis in Abaqus has been validated with the Validation Model with good agreement.

It has been shown that coatings is providing a more uniform heating of the glass pane which may allow temperatures exceeding the transition temperature. But since the temperature in the studied cases is not near transition temperature the prediction according to Pagni and Joshi is considered to be accurate.

The in depth absorption was closer to the experimental result but whether in depth absorption has to be taking into account is hard to tell. Further examination of the in depth absorption has to be performed. Surface absorption is considered to be a good first approximation since it will give conservative results but in depth absorption may be a more accurate boundary regarding absorption in semi-transparent materials.
9 Continuous work and recommendations

In this study it has been shown that Low-E coatings improves the integrity of a window exposed to a constant radiant heat flux. The following future studies with recommendations are suggested.

Carry out the mechanical analyses in Abaqus
To carry out the mechanical analyses in Abaqus where the edge constrains is evaluated as explained in chapter 2.8.4 is of interest since the it can be used to evaluate where the stress exceeds first, at the edges or surface flaws, depending on the thickness and imposing heat flux.

As a suggestion Abaqus could be used where a recommendation is to use the brittle material option in Abaqus when performing the stress analysis.

Examine the integrity of Low-E glasses exposed to a varying heat flux
In this study the windows has been exposed to a momentarily and constant heat flux which often is not the case in a real growing enclosure fire. Hence it is of interest to investigate the integrity of Low-E glasses exposed to a varying heat flux. As a suggestion FDS or similar program could be used to get a more realistic input for the incident heat flux in an enclosure fire. Further Abaqus or similar FEM program could be used to examine the Low-E glass integrity equally to the methodology in this study or by perform the mechanical analyze in the FEM program to.

A study like this could preferably be validated against a full-scale test such as the two performed by Shields et al [11, 38].

The tricky question for this suggested study is how to properly calculate the weighted value of the absorptivity for a heat source with a varying temperature.

Examine the integrity in a two or three pane window
Examine a more realistically case where two or three glass panes is attached to a frame made of wood or aluminum. As a suggestion in Abaqus or similar FEM program.

Small- or full-scale test with Low-E glasses
Firstly the reaction of the coating exposed to a real fire is of interest to examine. Further the integrity of Low-E glasses compared to ordinary float glasses exposed to a small- or full-scale test could be examined, both in one, two, three and four paned windows.

In experiments like this it is important to measure not only the temperatures but also the imposed heat flux and strains, both at the central pane and at the edges.

Other recommendations
It is hard to find proper material properties for glass. If it is possible to measure the material properties of the critical breaking stress, thermal conductivity and specific heat capacity with more precision than to use material properties found in the literature or in standards it is of interest since it will give more accurate results.

When using Abaqus or similar FEM program the surface element size could preferably be chosen with a courser size at the central pane and with a finer size at the edges. It is important that the surface element size at the edge do not exceed the thickness of the shaded edge since it will affect the temperature at the edge resulting in greater temperatures than it should.
References


Appendix A - Results from BREAK1

Two cases were simulated in BREAK1. Case 1 with an emissivity equal to 1 and Case 2 with an emissivity equal to 0.5. The gas temperature was reduced to 300 K so that the glass mainly would be heated by radiation. The result from the different cases results in a shorter breakage time for Case 2 which according to the theory of emissivity and absorptivity should not, the result is summarized in Table 16. Input and output file for the cases is presented below.

Table 16. Summary of the result from BREAK1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Emissivity</th>
<th>Breakage time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>201</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>199</td>
</tr>
</tbody>
</table>

Case 1

INPUT

PHYSICAL AND MECHANICAL PROPERTIES OF GLASS
1. Thermal conductivity [W/mK] = .7600E+00
2. Thermal diffusivity [m^2/s] = .3600E-06
3. Absorption length [m] = .1000E-02
4. Breaking stress [N/m^2] = .4700E+08
5. Young’s modulus [N/m^2] = .7000E+11
6. Linear coefficient of expansion [/deg C] = .9500E-05

GEOMETRY
1. Glass thickness [m] = .0064
2. Shading thickness [m] = .0150
3. Half-width [m] = .5000

COEFFICIENTS
1. Heat transfer coeff, unexposed [W/m^2-K] = 10.00
2. Ambient temp, unexposed [K] = 300.0
3. Emissivity of glass = 1.00
4. Emissivity of ambient (unexposed) = 1.00

FLAME RADIATION
Number of points used for flux input: 2

<table>
<thead>
<tr>
<th>point #</th>
<th>time [s]</th>
<th>flux [W/m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>2</td>
<td>1000.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

GAS TEMPERATURE
Number of points used for temperature input: 17

<table>
<thead>
<tr>
<th>point #</th>
<th>time [s]</th>
<th>temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>300.00</td>
</tr>
<tr>
<td>2</td>
<td>10.00</td>
<td>303.30</td>
</tr>
<tr>
<td>3</td>
<td>20.00</td>
<td>303.96</td>
</tr>
</tbody>
</table>
HEAT TRANSFER COEFF. ON HOT LAYER SIDE
Number of points used for heat transfer coeff input: 2
point # time [s] h2 [W/m²-K]
1 .00 50.00
2 1000.00 50.00

EMISSIVITY OF HOT LAYER
Number of points used for emissivity input: 2
point # time [s] emissivity
1 .00 1.00
2 1000.00 1.00

NUMERICAL PARAMETERS
1. Maximum fractional error in soln= .000100
2. Size of time step [s] = 1.000
3. Maximum run time [s] = 250.00
4. Time interval for output [s] = 10.00

OUTPUT
TEMPERATURE HISTORY
-----------------------
Time     Exposed     Unexposed     Theta     Tau
(s)   T(K)   T(K)       (Average)
.0    300.0    300.0    .000    .000
10.0   300.3    300.0    .001    .089
20.0   300.6    300.0    .002    .179
30.0   300.8    300.1    .004    .268
40.0   301.1    300.2    .006    .357
50.0   301.4    300.4    .008    .446
60.0   301.8    300.5    .012    .536
70.0   302.3    300.7    .016    .625
80.0   302.9    301.0    .021    .714
<p>| | | | | |</p>
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<tbody>
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<td>303.7</td>
<td>301.2</td>
<td>.028</td>
<td>.804</td>
</tr>
<tr>
<td>100.0</td>
<td>304.6</td>
<td>301.6</td>
<td>.036</td>
<td>.893</td>
</tr>
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<td>110.0</td>
<td>305.9</td>
<td>302.0</td>
<td>.047</td>
<td>.982</td>
</tr>
<tr>
<td>120.0</td>
<td>307.5</td>
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<td>1.071</td>
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<td>309.7</td>
<td>303.3</td>
<td>.080</td>
<td>1.161</td>
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<tr>
<td>140.0</td>
<td>312.6</td>
<td>304.2</td>
<td>.105</td>
<td>1.250</td>
</tr>
<tr>
<td>150.0</td>
<td>316.4</td>
<td>305.4</td>
<td>.138</td>
<td>1.339</td>
</tr>
<tr>
<td>160.0</td>
<td>321.1</td>
<td>307.0</td>
<td>.180</td>
<td>1.428</td>
</tr>
<tr>
<td>170.0</td>
<td>327.2</td>
<td>309.0</td>
<td>.235</td>
<td>1.518</td>
</tr>
<tr>
<td>180.0</td>
<td>334.7</td>
<td>311.6</td>
<td>.304</td>
<td>1.607</td>
</tr>
<tr>
<td>190.0</td>
<td>366.5</td>
<td>314.6</td>
<td>.536</td>
<td>1.696</td>
</tr>
<tr>
<td>200.0</td>
<td>434.9</td>
<td>320.3</td>
<td>1.033</td>
<td>1.786</td>
</tr>
<tr>
<td>201.0</td>
<td>442.7</td>
<td>321.2</td>
<td>1.092</td>
<td>1.795</td>
</tr>
</tbody>
</table>

**Window breaks at time = 201.00 [s]**

\[ \tau = \frac{t}{t_c}, \quad t_c = 112.0 \text{ s}, \quad \text{Avg. } \theta = \frac{(T_{av} - T_i)}{T_c}, \quad T_c = 70.7 \text{ K} \]

\[ g = 1.039 \]

Avg. \( T_{init} = 300.0 \text{ K}, \) Avg. \( \Delta T = 77.2 \text{ K}, \) Avg. \( T_{break} = 377.2 \text{ K} \)

**Case 2**

**INPUT**

**PHYSICAL AND MECHANICAL PROPERTIES OF GLASS**

1. Thermal conductivity [W/mK] = .7600E+00
2. Thermal diffusivity [m^2/s] = .3600E-06
3. Absorption length [m] = .1000E-02
4. Breaking stress [N/m^2] = .4700E+08
5. Youngs modulus [N/m^2] = .7000E+11
6. Linear coefficient of expansion [/deg C] = .9500E-05

**GEOMETRY**

1. Glass thickness [m] = .0064
2. Shading thickness [m] = .0150
3. Half-width [m] = .5000

**COEFFICIENTS**

1. Heat transfer coeff, unexposed [W/m^2-K] = 10.00
2. Ambient temp, unexposed [K] = 300.0
3. **Emissivity of glass = .50**
4. Emissivity of ambient (unexposed) = 1.00

**FLAME RADIATION**

Number of points used for flux input: 2
point # | time [s] | flux [W/m^2]
1    | 0.00    | 0.00
2    | 1000.00 | 0.00

GAS TEMPERATURE

Number of points used for temperature input: 17

point # | time [s] | temperature [K]
1    | 0.00    | 300.00
2    | 10.00   | 303.30
3    | 20.00   | 303.96
4    | 30.00   | 304.60
5    | 40.00   | 305.57
6    | 50.00   | 306.85
7    | 60.00   | 308.20
8    | 70.00   | 310.09
9    | 80.00   | 312.64
10   | 90.00   | 315.50
11   | 100.00  | 319.56
12   | 110.00  | 325.19
13   | 120.00  | 331.73
14   | 140.00  | 353.71
15   | 160.00  | 388.29
16   | 180.00  | 437.97
17   | 200.00  | 831.07

HEAT TRANSFER COEFF. ON HOT LAYER SIDE

Number of points used for heat transfer coeff input: 2

point # | time [s] | h2 [W/m^2-K]
1    | 0.00    | 50.00
2    | 1000.00 | 50.00

EMISSIVITY OF HOT LAYER

Number of points used for emissivity input: 2

point # | time [s] | emissivity
1    | 0.00    | 1.00
2    | 1000.00 | 1.00

NUMERICAL PARAMETERS

1. Maximum fractional error in soln= 0.000100
2. Size of time step [s] = 1.000
3. Maximum run time [s] = 250.00
4. Time interval for output [s] = 10.00

OUTPUT
## TEMPERATURE HISTORY

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<th>Time (s)</th>
<th>Exposed T(K)</th>
<th>Unexposed T(K)</th>
<th>Theta (Average)</th>
<th>Tau (Average)</th>
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</tr>
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</table>

Window breaks at time = 199.00 [s]

tau = t/tc, tc = 112.0 s, Avg. theta = (Tav-Ti)/Tc, Tc = 70.7 K

g = 1.039

Avg. T init = 300.0 K, Avg. Delta T = 73.6 K, Avg. T break = 373.6 K
Appendix B – Theory about in depth absorption

Depending on the spectral properties of the glass, it reflects and absorbs a certain amount of the incident radiation near the surface while some quantity travels further into the glass and absorbs in different depths. Some quantity is not absorbed, i.e. is transmitted through the glass. [33]

The following chapter is written by Michael Försth [33] and covers the theory about in depth absorption in semi-transparent material such as glass followed by a simplified calculation methodology of the problem. The theory and calculation methodology is used in this study to evaluate the dependence of in depth absorption.

B 1 In depth absorption

The decay of irradiation in a homogeneous absorbing sample is given by the Beer-Lambert law [B1]

\[ I(x) = I(0)e^{-Ax} \]  \hspace{1cm} (B1)

where:

\( I(x) \) is the irradiation at depth \( x \) into the sample [Wm\(^{-2}\)], and

\( A \) is the absorption coefficient describing in-depth absorption [m\(^{-1}\)]

B 1.1 Spatially dependent irradiation in a thick slab

When an irradiation \( I_0 \) impinges perpendicularly on a semi-transparent symmetric glass sample multiple reflections will occur inside the glass. Each time the radiation hits a surface parts of the energy will be reflected and parts will be transmitted. This is illustrated in Figure 46 where \( x=0 \) is the front surface where the \( I_0 \) is impinging and \( x=d \) corresponds to the rear side of the glass. For thin films, where the coherence length\[B1] of the radiation is on the order of the thickness of the sample, interference effects will appear. This means that the complex electromagnetic fields must be considered instead of the real-valued irradiation. The coherence length, \( l_c \), of blackbody radiation has been estimated as\[B2]

\[ l_c = \frac{3.6 \cdot 10^{-3}}{T} \]  \hspace{1cm} (B2)

where \( l_c \) is given in meters. Thermal radiation from fires typically correspond to blackbody radiation corresponding to temperatures of at least 600°C, that is 873 K. This gives a coherence length \( l_c \leq 4 \) μm. Therefore, for glass samples, which typically are much thicker than 4 μm, interference effects will not occur and the irradiations from multiple reflections and transmissions should be added, instead of adding the electromagnetic fields.
The following abbreviations are used:

- \( I_0 \) incoming irradiation [Wm\(^{-2}\)]
- \( R \) reflectance at a glass/air or air/glass interface [ ]
- \( T \) transmittance through a glass/air or air/glass interface [ ]
- \( A \) absorption coefficient describing in-depth absorption, see Eq. (B1) [m\(^{-1}\)]
- \( d \) thickness of glass sample [m]

where \( R, T, \) and \( A \) are intrinsic material properties of the glass. These properties are in general spectrally dependent, see Section B 1.2. It should be noted that \( I_0 \) differs from \( I(0) \) in Eq. (B1). \( I_0 \) is the irradiation impinging onto the surface of the samples, whereas \( I(0) \) is the irradiation inside the sample, infinitesimally close to the front surface.

The irradiation will be calculated at five positions:

a. the irradiation reflected from the glass sample
b. the irradiation at an infinitesimal depth below the front surface where the original irradiation \( I_0 \) impinges
c. the irradiation at an arbitrary depth \( x \) into the glass
d. the irradiation at an infinitesimal small distance from the rear edge of the glass
e. the irradiation transmitted through the glass sample, that is the irradiation in the air on the rear side of the glass.
The irradiation at infinitesimally small distances from the front and rear surface can also be calculated from the equation for an arbitrary depth \( x \), Eq. (B6), but with \( x = 0 \) (front surface) or \( x = d \) (rear surface). These two positions are only considered in order to perform a consistency check of the results.

Inside the glass the radiation travels in two opposite directions. In order to understand the importance of the two directions they will be color-coded in green, for radiation in the original direction of \( I_0 \), and red for radiation in the opposite direction.

Figure 47. Color-coding of the different reflected and transmitted parts. Green corresponds to the original direction of the impinging \( I_0 \) and red corresponds to the opposite direction. The vertical dashed line shows the x-axis. The letters indicating the positions listed above are also displayed.

In the derivation below the value of a geometric series will repeatedly be used. This is given by [B3]:

\[
\sum_{i=0}^{\infty} a^i = \frac{1}{1 - a} \quad |a| < 1
\]  

(B3)

B 1.1.1 a. Reflected radiation

The sum of the reflected parts is given by

\[
RI_0 + RTI_0e^{-2Ad} + R^2TI_0e^{-2Ad} + \cdots = RI_0\left(1 + T^2e^{-2Ad} + T^2R^2e^{-2Ad} + \cdots\right)
= RI_0\left(1 + \frac{T^2e^{-2Ad}}{1 - R^2e^{-2Ad}}\right) \quad (B4)
\]

B 1.1.2 b. Irradiation in glass near front surface

The sum of the transmitted part and reflected parts are given by
\[ T_0 + RT_0 e^{-2Ad} + R^2 T_0 e^{-2Ad} + R^3 T_0 e^{-4Ad} + \ldots \]
\[ = T_0 \left( 1 + R^2 e^{-2Ad} + \ldots + Re^{-2Ad} + R^3 e^{-4Ad} + \ldots \right) \]
\[ = T_0 \left( \sum_{i=0}^{\infty} (R^2 e^{-2Ad})^i + Re^{-2Ad} \cdot \sum_{i=0}^{\infty} (R^2 e^{-2Ad})^i \right) \]
\[ = T_0 \sum_{i=0}^{\infty} (R^2 e^{-2Ad})^i \left( 1 + Re^{-2Ad} \right) = \frac{T_0 \left( 1 + Re^{-2Ad} \right)}{1 - R^2 e^{-2Ad}} \]  

**B 1.1.3 c. Irradiation at an arbitrary depth x**

The sum of the transmitted part and reflected parts are given by
\[ T_0 e^{-Ax} + RT_0 e^{-A(d+x)} + R^2 T_0 e^{-A(2d+x)} + R^3 T_0 e^{-A(3d+x)} + \ldots \]
\[ = T_0 \left( e^{-Ax} + R^2 e^{-A(2d+x)} + \ldots + Re^{-A(2d-x)} + R^3 e^{-A(4d-x)} + \ldots \right) \]
\[ = T_0 \left( e^{-Ax} \cdot \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i + Re^{-A(2d-x)} \cdot \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i \right) \]
\[ = T_0 e^{-Ax} \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i \left( 1 + Re^{-2Ad(d-x)} \right) \]
\[ = \frac{T_0 e^{-Ax} \left( 1 + Re^{-2Ad(d-x)} \right)}{1 - R^2 e^{-2Ad(d-x)}} \]

**B 1.1.4 d. Irradiation in glass near rear surface**

The sum of the transmitted part and reflected parts are given by
\[ T_0 e^{-Ad} + RT_0 e^{-Ad} + R^2 T_0 e^{-3Ad} + R^3 T_0 e^{-4Ad} + \ldots \]
\[ = T_0 \left( e^{-Ad} + R^2 e^{-3Ad} + \ldots + Re^{-Ad} + R^3 e^{-3Ad} + \ldots \right) \]
\[ = T_0 e^{-Ad} \left( 1 + R^2 e^{-2Ad} + \ldots + R + R^3 e^{-2Ad} + \ldots \right) \]
\[ = T_0 e^{-Ad} \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i \]
\[ = T_0 e^{-Ad} \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i (1 + R) = \frac{T_0 e^{-Ad} (1 + R)}{1 - R^2 e^{-2Ad}} \]  

**B 1.1.5 e. Transmitted irradiation**

The sum of the transmitted parts are given by
\[ T^2 I_0 e^{-Ad} + R^2 T^2 I_0 e^{-3Ad} + \ldots = T^2 I_0 e^{-Ad} \left( 1 + R^2 e^{-2Ad} + \ldots \right) \]
\[ = T^2 I_0 e^{-Ad} \sum_{i=0}^{\infty} \left( R^2 e^{-2Ad} \right)^i = \frac{T^2 I_0 e^{-Ad}}{1 - R^2 e^{-2Ad}} \]  

**B 1.1.6 Summary**
Equations (B4) and (B8) describe the total reflected and transmitted radiation through the glass sample, respectively [B4]. Recall Equation (B6) that gives the irradiation $I(x)$ at an arbitrary depth $x$ into the glass:

$$I(x) = \frac{T I_0 e^{-A x} \left(1 + R e^{-2A(d-x)}\right)}{1 - R^2 e^{-2A d}} \quad (B6)$$

For consistency checks it can be seen that with $x = 0$ mm Eq. (B6) gives $I(0) = T I_0 (1 + R e^{-2A d})/(1 - R^2 e^{-2A d})$, in agreement with Eq.(B5). Furthermore, with $x = d$ Eq. (B6) gives $I(d) = T I_0 e^{-A d} (1 + R)/(1 - R^2 e^{-2A d})$, in agreement with Eq. (B7).

The results are summarized in Figure 48.

**Figure 48. Summary of Eqs. (B4)-(B8).**

### B 1.2 Spectrally resolved absorption in defined layers

In Section B 1.1 no consideration was given to the spectral properties of the irradiation $I$ or of the material properties of the glass; $A$, $R$, and $T$. In reality these four parameters vary with wavelength, they have a spectral dependence. Section B 1.2.1 describes the absorbed power per unit area in a layer of the glass if there are no spectral characteristics of the irradiation or of the glass. This is called the gray assumption and is in general not a realistic assumption. Section B 1.2.2 describes the realistic case where the irradiation and the material have spectrally dependent properties.

#### B 1.2.1 Without spectral properties - Gray assumption

The absorption rate, in units Wm$^{-2}$/m, at depth $x$ is given by $-dI/dx$ and the total absorption $\Delta I$ between two depths $x_1$ and $x_2$ is given by

$$\Delta I = - \int_{x_1}^{x_2} \frac{dI}{dx} dx = I(x_1) - I(x_2) \quad (B9)$$

#### B 1.2.2 With spectral properties


Equation (B6) should strictly be written as, taking the spectral characteristics into account:

\[
I_\lambda(x) = \frac{T_\lambda I_{\lambda,0} e^{-A_\lambda x}(1 + R_\lambda e^{-2A_\lambda(d-x)})}{1 - R_\lambda^2 e^{-2A_\lambda d}} \tag{B10}
\]

The absorption rate, in units Wm\(^{-2}\)μm\(^{-1}\)/m, at depth \(x\) is given by \(-dI_\lambda/dx\) and the total spectrally resolved absorption \(\Delta I_\lambda\) between two depths \(x_1\) and \(x_2\) is given by

\[
\Delta I_\lambda = - \int_{x_1}^{x_2} \frac{dI_\lambda}{dx} dx = I_\lambda(x_1) - I_\lambda(x_2) \tag{B11}
\]

The total absorption, not spectrally resolved, that is in units Wm\(^{-2}\), is given by:

\[
\Delta I = \int_0^\infty \Delta I_\lambda d\lambda = \int_0^\infty I_\lambda(x_1) d\lambda - \int_0^\infty I_\lambda(x_2) d\lambda \tag{B12}
\]

Radiation from fires is typically relatively concentrated to the spectral range 1 – 10 μm which therefore can replace the integration limits 0 and \(\infty\). In practice there is also a spectral limitation of the UV/vis/NIR spectrometer(s) used. This limitation could typically be a spectral interval of 0.3 – 17 μm.

**B 2 Optical properties**

In this section the surface reflectance \(R\), surface transmittance \(T\), and absorption coefficient \(A\) are calculated based on experimental measurements of the reflectance and transmittance of the entire slab. These properties are in general wavelength dependent, which is not indicated here.

The following abbreviations are used:

- \(R\) reflectance at a glass/air or air/glass interface [ ]
- \(R_{\text{sample}}\) total reflectance from a glass sample [%] (can be measured)
- \(T\) transmittance through a glass/air or air/glass interface [ ]
- \(T_{\text{sample}}\) total transmittance through a glass slab [%] (can be measured)
- \(A\) absorption coefficient describing in-depth absorption according to the Beer-Lambert law, see Eq. (B1) [m\(^{-1}\)]
- \(d\) thickness of glass sample [m] (can be measured)

**B 2.1 Approximatively calculation of \(R\), \(T\), and \(A\)**

When measuring the optical properties \(R_{\text{sample}}\) and \(T_{\text{sample}}\) the percentage reflected or transmitted radiation in relation to the incoming radiation is measured, i.e.

\[
X_{\text{sample}} = \frac{I_X}{I_0} \tag{B13}
\]

Where \(I_X\) is the totally reflected or transmitted irradiation for the specific wavelength described by Eq. (B4) and (B8) which gives

\[
R_{\text{sample}} = R \left(1 + \frac{T^2 e^{-2Ad}}{1 - R^2 e^{-2Ad}}\right) \tag{B14}
\]
\[ T_{\text{sample}} = \frac{T^2 e^{-Ad}}{1 - R^2 e^{-2Ad}} \]  \hspace{1cm} (B15)

Approximation:

\[ 1 \gg R^2 e^{-2Ad} \]  \hspace{1cm} (B16)

This approximation is reasonable since in general \( R^2 \) is on the order 0.04\(^2=0.0016 \) for glass with refractive index \( n \approx 1.5 \) [C1]. The approximation becomes even more reasonable for thicker and more absorbing materials. It can be seen in the measured reflectance’s in Figure 50 and Figure 52 (in Appendix D) that the reflectance \( R < 0.1 \) for all wavelength under 8000 nm where the reflectance peaks up to 0.25 and then is lower than 0.1 again. An \( R=0.1 \) gives an \( R^2=0.01 \). The approximation above is therefore considered to be a good approximation.

Equations (B14) and (B16) give:

\[ R_{\text{sample}} \approx R \left( 1 + T^2 e^{-2Ad} \right) \]  \hspace{1cm} (B17)

or

\[ R \approx \frac{R_{\text{sample}}}{1 + T^2 e^{-2Ad}} \]  \hspace{1cm} (B18)

which, using Eqs. (B15) and (B16) gives:

\[ R \approx \frac{R_{\text{sample}}}{1 + T_{\text{sample}}} \]  \hspace{1cm} (B19)

Energy is conserved at the (infinitely thin) surface, where the radiation is either reflected or transmitted (the radiation can only be absorbed inside the finite sample, not at the infinitely thin surface):

\[ R + T = 1 \]  \hspace{1cm} (B20)

Equations (B19) and (B20) give:

\[ T = 1 - R \approx \frac{1 + T_{\text{sample}} - R_{\text{sample}}}{1 + T_{\text{sample}}} \]  \hspace{1cm} (B21)

Equations (B15) and (B16) give:

\[ T_{\text{sample}} \approx T^2 e^{-Ad} \]  \hspace{1cm} (B22)

Solving Eq. (B22) for \( A \) and inserting Eq. (B21) give:

\[ A \approx -\frac{1}{d} \ln \left( \frac{T_{\text{sample}}}{T^2} \right) = \frac{1}{d} \ln \left( \frac{1 + T_{\text{sample}} - R_{\text{sample}}}{1 + T_{\text{sample}}} \right)^2 \]  \hspace{1cm} (B23)

\[ = \frac{2}{d} \ln \left( \frac{1 + T_{\text{sample}} - R_{\text{sample}}}{(1 + T_{\text{sample}}) \sqrt{T_{\text{sample}}}} \right) \]
Equations (B19), (B21), and (B23) give R, T, and A based on the measured values of R_{sample}, T_{sample}, and d.

Several consistency checks can be carried out in order to confirm that accuracy of the calculations.

**B 2.1.1 Consistency check 1**

R and T according to Eqs. (B19) and (B21) can be calculated for both thicknesses. The results should be consistent (that is approximately the same) in order to verify the calculations.

**B 2.1.2 Consistency check 2**

Equations (B15) and (B16) give:

\[ T_{\text{sample}} \approx T^2 e^{-Ad} \]  

(B24)

T is a material property and independent of sample thickness d. Measuring T_{slab} for two different thicknesses d_1 and d_2, and dividing Eq. (B24) for the two thicknesses gives:

\[ \frac{T_{\text{sample},1}}{T_{\text{sample},2}} = e^{-A(d_1-d_2)} \]  

(B25)

or

\[ A \approx \frac{\ln \left( \frac{T_{\text{sample},1}}{T_{\text{sample},2}} \right)}{d_2 - d_1} \]  

(B26)

The calculated values of A from Eq. (B26) should be consistent (that is approximately the same) with Eq. (B23) in order to verify the calculations.

**B 2.1.3 Consistency check 3**

Equations (B24) and (B26) give:

\[ T \approx \sqrt{T_{\text{sample}} \cdot e^{-A(d_2-d_1)}} \]  

(B27)

Where T_{slab} and d can correspond to thickness 1 or 2. The results should be consistent (that is approximately the same) with Eq. (B21) in order to verify the calculations.

**References for Appendix B**


Appendix C – Emissivity of semi-transparent materials

When a glass pane increases in temperature it starts to emit energy like other materials. But for semi-transparent materials such as glass the emissivity is not a surface phenomenon but a bulk phenomenon. This since the radiation penetrates in certain depths heating each layer in the glass. Each layer then starts to emit energy, starting in this certain depth of the glass. [21]

In the article “The Emissivity of Transparent Materials” by Robert Gardon [21] he describes how to properly calculate the spectral emissivity of transparent materials such as glass. Figure 49 is an extraction from the article where an example of how the emissivity of a window pane at 1000°C varies with thickness and wavelength is presented, calculated according to the following method.

\[
\varepsilon_{\lambda X} = \frac{W_{\lambda X}}{W_{\lambda}} = 2 \int_0^{\pi/2} \left(1 - e^{-AX\sec^2 \alpha} \right) Y' \sin \beta \cos \beta \, d\beta
\]  

(XI)

Where \( A \) is the surface absorption coefficient, \( \alpha \) is the incident angle inside the glass, \( \beta \) is the exiting angle in air, \( X \) is the thickness of the sheet and the effective directional transmissivity, \( Y' \), is described by Eq. (X2).

Figure 49. Emissivity of glass sheets with different thicknesses at 1000°C. Illustrated by Gardon [21].
\[ Y' = \frac{1}{2} \left[ \frac{\tau'_\perp}{1 - (\rho'_\perp) e^{-\gamma \lambda x \sec \alpha}} + \frac{\tau'_\parallel}{1 - (\rho'_\parallel) e^{-\gamma \lambda x \sec \alpha}} \right] \] (X2)

Where the \( \gamma \) is the absorption coefficient (\( \alpha \)), \( \sec \) is the multiplicative inverse of \( \cos \) (i.e., \( 1/\cos \)) and the perpendicular and parallel polarization reflectance (\( \rho \)) and transmittance (\( \tau \)) is calculated according to Eq. (X3)-(X6) [50]. The sum of the perpendicular and parallel reflectance/transmittance equals 1 for each angle.

\[ \rho'_\perp = \left( \frac{n_i \cos \alpha - n_t \cos \beta}{n_i \cos \alpha + n_t \cos \beta} \right)^2 \] (X3)

\[ \tau'_\perp = \frac{n_t \cos \alpha}{n_i \cos \beta} \left( \frac{2n_i \cos \alpha}{n_i \cos \alpha + n_t \cos \beta} \right)^2 \] (X4)

\[ \rho'_\parallel = \left( \frac{n_t \cos \alpha - n_i \cos \beta}{n_t \cos \beta + n_i \cos \alpha} \right)^2 \] (X5)

\[ \tau'_\parallel = \frac{n_t \cos \alpha}{n_i \cos \beta} \left( \frac{2n_i \cos \alpha}{n_i \cos \beta + n_t \cos \alpha} \right)^2 \] (X6)

Where \( n_i \) and \( n_t \) is the spectral refractive index of glass and air respectively.

\( \alpha \) and \( \beta \) is related by Snell’s law which describes the relationship between the angles of incidence and refraction when electromagnetic wavelengths is passing through a boundary, in our case between the air and the glass. [50] The exiting angle in air, \( \beta \), is assigned to a span, \( \beta = 0 - 90 \,^\circ \). Further is the incident angle inside the glass, \( \alpha \), calculated according to Snell’s law presented in Eq. (X7).

\[ \alpha = \sin^{-1} \left( \frac{\sin \beta}{n_i} \right) \] (X7)

The refractive indexes for air is 1 and 1.5 for glass [50] and is here assumed to be independent of wavelength.

Table 17 shows a comparison between the calculations made according to the theory presented above compared to the presented results of Gardon in Figure 49.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The emissivity at 1000°C for different thicknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gardon, Figure 49</td>
</tr>
<tr>
<td>1mm</td>
<td>0.4</td>
</tr>
<tr>
<td>3mm</td>
<td>0.57</td>
</tr>
<tr>
<td>10mm</td>
<td>0.63</td>
</tr>
<tr>
<td>30mm</td>
<td>0.71</td>
</tr>
<tr>
<td>100mm</td>
<td>0.82</td>
</tr>
<tr>
<td>1000-( \infty )mm</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Appendix D – Measured spectral properties

The following spectral properties was measured at SP, Technical Research Institute of Sweden, using the equipment described in chapter 2.9.1.

3 mm F-glass

![Graph showing spectral properties of 3 mm F-glass](image1)

*Figure 50 Spectral properties of reflectance and transmittance for 3 mm F-glass.*

![Graph showing spectral properties of absorptivity for 3 mm F-glass](image2)

*Figure 51. Spectral properties of absorptivity for 3 mm F-glass.*
4 mm F- and K-glass

Figure 52. Spectral properties of reflectance and transmittance for 4 mm F- and K-glass.

Figure 53. Spectral properties of absorptivity for 4 mm F- and K-glass.
Appendix E – Mesh analyses

The Validation Model

The mesh analysis was done at the Validation Model number 15. It consists of a 3 mm F-glass with an absorptivity of 0.62 and emissivity of 0.9. The incident radiation, \( q_{\text{inc}} = 9230 \text{ W/m}^2 \) and the absorbed radiation, \( q_{\text{abs}} = 5738 \text{ W/m}^2 \).

Elements in thickness

When changing the elements in thickness the surface element size is 7.5x7.5 mm. The measured edge temperature is at 7.5 mm from the outer edge in consistence with the experimental setup. The exposed and unexposed side is the pane temperatures at the exact middle of the pane surface.

![Exposed side graph](image1)

*Figure 54. Central pane temperatures vs time on the exposed side for varying elements in thickness.*

![Unexposed side graph](image2)

*Figure 55. Central pane temperatures vs time on the unexposed side for varying elements in thickness.*
Element size at the surface

When changing the surface element size there is 1 element in thickness. The measured edge temperature is the outer edge temperature on the exposed side to get comparable values. The exposed and unexposed side is the pane temperatures at the exact middle of the pane surface.
At 100 seconds 15x15 and 7.5x7.5 differs ~1.7°C, 7.5x7.5 and 5x5 differs ~1.1°C and 5x5 and 2.5x2.5 differs ~0.4°C.

At 600 seconds 15x15 and 7.5x7.5 differs ~2.7°C, 7.5x7.5 and 5x5 differs ~1.3°C and 5x5 and 2.5x2.5 differs ~0.3°C.
The Model

The mesh analysis for The Model was done at the F-glass exposed to an incident radiation corresponding to a flame. It consists of a 4 mm F-glass with an absorptivity of 0.62 and emissivity of 0.9. The incident radiation, $q_{inc} = 23414 \text{ W/m}^2$, and the absorbed radiation, $q_{abs} = 14549.9 \text{ W/m}^2$.

Elements in thickness

When changing the elements in thickness the surface element size is 5x5 mm. The outer edge temperature is the mean temperature between the exposed and unexposed side. The exposed and unexposed side is the pane temperatures at the exact middle of the pane surface.

![Exposed side](image)

*Figure 60. Central pane temperatures vs time on the exposed side for varying elements in thickness.*

![Unexposed side](image)

*Figure 61. Central pane temperatures vs time on the unexposed side for varying elements in thickness.*
Element size at the surface

When changing the surface element size there is one element in thickness. The outer edge temperature is the mean temperature between the exposed and unexposed side. The exposed and unexposed side is the pane temperatures at the exact middle of the pane surface. Since a surface element size of 2.5x2.5 resulted in too big output files that could not be handled this surface element size is not presented.
Figure 64. Central pane temperatures vs time on the unexposed side for varying element sizes at the surface.

Figure 65. Outer edge temperatures 2 mm in depth of the glass vs time for varying element sizes at the surface.

At 100 seconds 15x15 and 10x10 differs ~10.5°C and 10x10 and 5x5 differs ~3°C.

At 600 seconds 15x15 and 10x10 differs ~10°C and 10x10 and 5x5 differs ~3°C.
Appendix F – Results from the Validation Model

Figure 66. Pane temperature (unexposed side) vs. time for all simulated test numbers.

Figure 67. Mid edge (7.5 mm from outer edge) temperature vs. time for all simulated test numbers.