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Characteristics of Temperature changes and Stress of Float Glass under Heat Radiation

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ABSTRACT

This study aims to evaluate results of radiant heat transfer on float glass surface, where radiant heat and convection rate are distributed from initial glass heating to the maximum or final temperature of the float glass using varied temperature and thickness by means of Mecway FEA simulation. This research also seeks to measure thermal stress on float glass with thickness of 4-19mm. To calculate the rates of heat transfer occurring by conduction, it is assumed that with exposure to heat of 200-600°C for 20 minutes and temperature of about 32°C, the simulation distributes radiation temperature with maximums of 160.2-395.5°C. Results show overprediction of thermal change based on validation from prior experiments. In this study an initial crack took place around the edge of the glass frame, where the float glass underwent heat stress to maximums of 34.69-33.10 MPa. The focus of this study is to identify the characteristics of the float glass used in this and previous research under heat treatment with varied thickness and temperature.

Key words : Heat transfer, Radiation, Simulation, Float glass, Thermal stress.

1. INTRODUCTION

In countries with advanced and developed industries, glass is generally found in use at homes, offices and other buildings. Glass serves to subdue heat from exposure to sunrays and to maintain indoor temperature so as to not release or hold heat. Glass is also utilized for other purposes, such as in glass material, civil, manufacture and automotive industries [1].

One common type of glass used for windows, tables, doors, cabinets, etc. is float glass. Meanwhile, the automotive world typically employs laminated and tempered glass, both of which help minimize injuries in the event of an accident as they offer higher levels of protection than usual float glass [2][3].

According to Kenny, damage by heat radiation may expose glass structure to concentrated thermal spikes with higher glass composition and atomic ratio [4]. As glass is thermodynamically unstable, it will continue to absorb heat to cool down and stabilize its temperature [5]. Heating and radiation affect the stability and structure of glass in a closed system, and radiation from yielding glass could alter the mechanical properties and structure of the glass [6]. Irregular dispersion is observable for two hours in film glass layers subjected to forced heat treatment of up to 500°C [7].

Heat treatment is a common practice to improve the quality of clarity of glass or glass-like gemstones after melting [8]. Glass damage on buildings stems from increasing glass stress prompted by rising heat in fire situations. Therefore, it is necessary to calculate the temperature distribution and stress of glass during fires [9] [10].

Experiments conducted by Zhang et al. [11] revealed that initial damage on glass with thicknesses of 4mm, 6mm, 10mm and 12mm takes similar time, while that on 19mm-thick glass takes longer. Temperature difference rises in line with increase in glass thickness. Resulting maximum time and temperature gap are used as reference by engineering applications to predict the first fracture [11]. However, research simulations regarding radiation heat on float glass with five thicknesses are still limited, while the dimensions and temperatures of glass in prior studies apply GB11614 standards by using float glass with sizes of 4-19mm x 600mm x 600 mm and heat of up to 600°C.

This study undertook a continuous approach to simulate heat transfer on glass with distributed radiant heat reaching ±600°C at thicknesses of 4 mm to 19 mm according to the national standard (SNI 15-0047-2005) and same sizes as used by Zhang et al. [11] This research focuses on running thermal transient, thermal steady state and thermal stress simulations using Mecway 10 FEA to obtain rates of heat flow on glass surface and yield stress in accordance with standards. The gathered outcomes are then compared with data reference from past research.

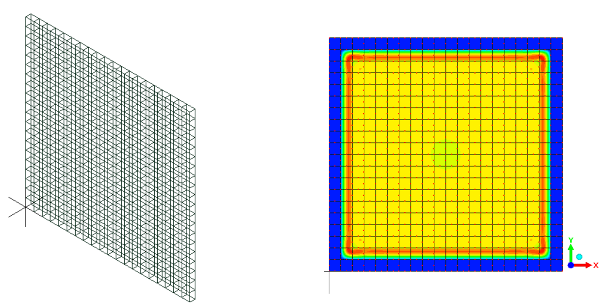
2. METHODOLOGY

2.1 Geometry and meshing

Dimensional modeling of the glass used variations in thickness and heat. The following are specifications of dimensions and thickness of the float glass:

Glass type	: Float glass
Glass dimensions (p x t)	: 600mm x 600mm
Glass thickness	: 4, 6, 10, 12, 19mm
Ambient temperature	: 32°C
Radiation temperature	: 200, 300, 400, 500, 600°C
Nodes and elements	: 3003 and 400

The dimensional glass structure was designed according to the type of glass employed, namely float glass, and the Indonesian National Standard (SNI 15-0047-2005) from the National Standardization Agency (BSN) [12]. The meshing of the glass structure is illustrated in Figure 1.



a.Glass meshing 3003 nodes b. Glass and frames 400 elements

Figure 1: Glass and structure meshing

2.2 Material characteristics

Data for the used glass material were collected from composition testing results of existing float glass specimens. Table 1 presents the physical traits of the float glass [1], [12].

Table 1: Physical and Mechanical Properties of Float Glass

No.	Property	Value	Unit
1	Refractive Index	1.52	.-
2	Specific Heat	0-50	°C
3	Softening Point	720-730	°C
4	Thermal Conductivity	0.68	kcal/h°C
5	Coefficient of Linear Expansion	8.5-9 x 10^{-6}	°C
6	Density	2,500	kg/cm^3
7	Young Modulus	720,000	kg/cms²
8	Poisson's Ratio	0.25	-
9	Breaking Stress	350-500	kg/cm²

2.3 Simulation steps

The flow of heat transfer analysis on float glass sheets from start to finish is described as follows:

a. The glass surface is exposed to radiant heat ranging from 200°C to 600°C for 20 minutes at an ambient temperature of 32°C.
b. From outcomes of thermal transient and thermal steady state analyses on glass with varied thickness and temperature, comparison is made with thermal stress analysis on radiation heat values and inward and outward heat flow rates until the glass cracks. At this stage comparison results are discussed in relation to the limit of exposure to radiant heat at which point the glass cracks.

2.4 Transient Heat Transfer

In the study by Zhang et al. [11], heat was distributed for one minute up to 20 minutes until maximum temperature of 600°C was attained and the glass was fractured. The gap between the temperature directly integrated on the glass center and the lowest temperature at the edge of the glass panel produced stress that led to glass damage. [11].

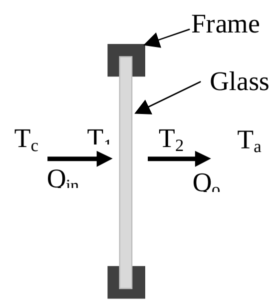


Figure 2: Inward and outward heat

The illustration of the temperature difference is shown in Figure 2. The equation for the rate of heat transfer from the heat source to the glass wall is:

$$Q_{rad} = \varepsilon . \sigma . A . (T_c - T_1) \quad (1)$$

where ε denotes surface emissivity, σ is an independent constant against the surface, and T represents absolute temperature.

For the rate of heat transfer from the glass wall to the ambient temperature, the equation is:

$$Q_{conv} = h . A . (T_2 - T_a) \quad (2)$$

in which h signifies the coefficient of convection heat transfer and A the surface area.

2.5 Thermal Stress Formula

The risk of glass breaking is determined by several variables, including stress, edge strength, area under pressure, stress duration, and the presence of edge flaws [13].
Calculation of thermal stress on the material uses the following formula:

$$S_c = \frac{P}{A} \quad (3)$$

where P represents outward heat pressure and A the glass surface area.
Principal stresses can be calculated by equivalent von Mises stress on float glass using this formula:

$$\sigma_{VM} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (4)$$

In which σ_1 , σ_2 and σ_3 denote principal stresses that are perpendicular to the principle plain or surface.

3.RESULTS AND DISCUSSION

3.1 Temperature Change

Figure 3 shows simulation and experimental results of temperature change ΔT and temperature change at the center ΔTc.

The temperature difference ΔT with thickness variation of from 4 mm to 19 mm showing ΔT respectively: 2.6, 10.9, 41.6, 94.6 and 276.1°C, while the green line shows experiment outcomes that differ from those of the simulation namely ΔT = 136, 125.5, 155.5, 161.1 and 223.8°C.

When the glass is thin experimental cannot capture the difference temperature since the high environmental temperature involved to the measurement gauges. This problem did not occur in simulation since the unexpected parameters are not involved to the solution.

Temperature change from the glass wall center to the inside of the isolated frame is represented by the blue line with ΔTc = 137.6, 186.2, 256.4, 323.6 and 336.2°C, whereas experiments revealed that ΔTc = 105, 116.3, 125.6, 140.6 and 205°C.

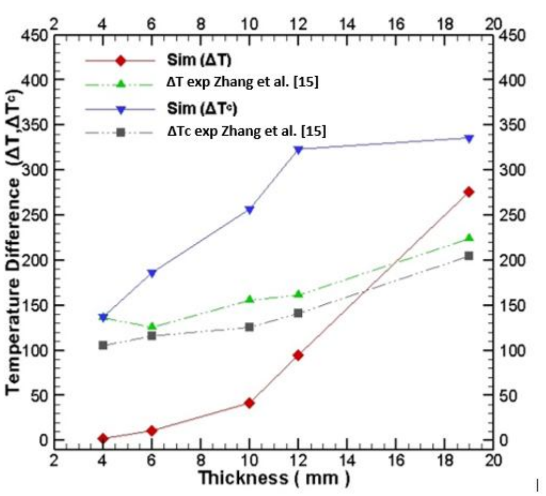


Figure 3: Temperature difference against glass thickness

3.2 Temperature Distribution against Time and Thickness

For maximum results of the thermal transient simulation, the maximum temperature is determined as in Figure 4, which is at node 1487 at the center of the 19 mm-thick float glass dimension. The location of the maximum temperature is located at the center (Figure 4).

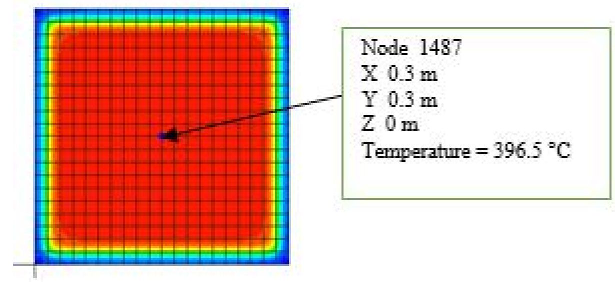


Figure 4: Coordinate of maximum temperature

It is also situated at the same node on glass with 4-12 mm thickness at the peak time of 20 minutes, but with a different final temperature. As seen in Figure 5, temperature from the 15th to 16th minute rose from 336.3 to 356.8°C, and from the 16th to 20th minute elevated from 356.8°C to the maximum temperature of 362.2°C.

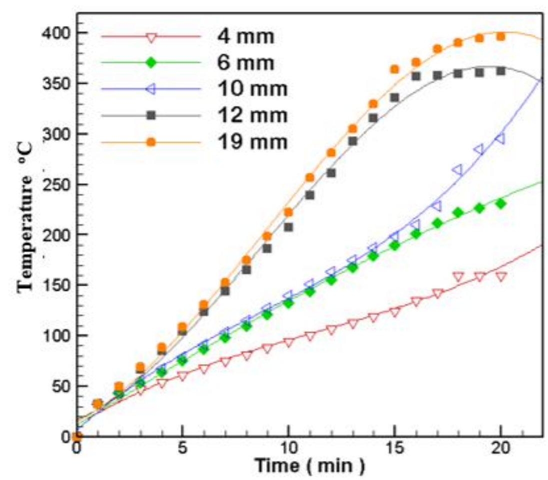


Figure 5: Temperature against time

On 19 mm glass with a minimum temperature of 32.33°C, temperature leapt between the 14th, 15th, and 16th minute from 330.1 to 364.5 and 370.7°C, whereas from the 17th to 20th minute the temperature steadily grew until reaching a maximum of 396.5°C.

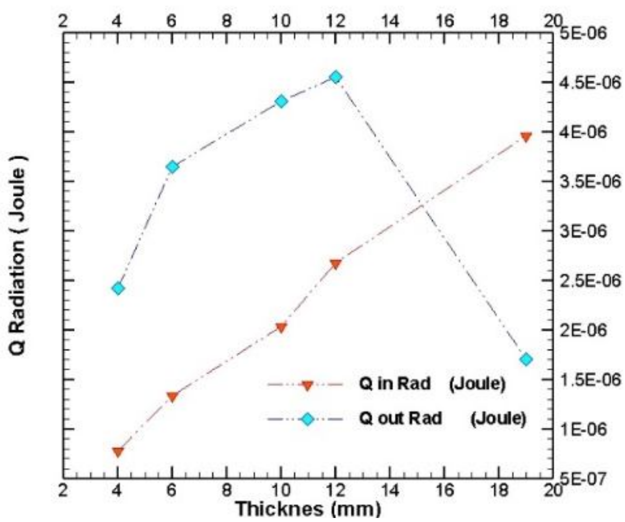
3.3 Temperature Distribution in Steady State

Figure 5 shows the results of heat transfer on the glass due to ambient temperature. The increase in heat flux magnitude from the thinnest thickness of 4 mm to the thickest 19 mm. This results indicates that there is heat discharged due to a large internal heat flow spreading outside the glass back or back.

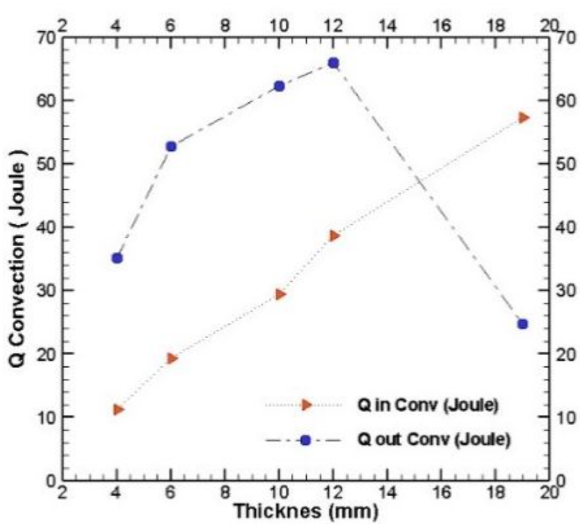
When the radiation time maximum, a steady state heat transfer simulation was conducted. The results are compared and presented in Table 2. The steady state simulation transferred all temperature results from the transient maximum time then applied steady state heat transfer analysis. The maximum temperature results are comparable with that from transient analysis.

Table 2: Glass Dimension Variations with Transient and Steady State Simulation

Time (min)	Thickness (mm)	Transient (°C)	Steady (°C)	Heat flux (W/m²)
20	4	160.2	160	5892
20	6	231.4	231.2	8210
20	10	295.8	294.2	11489
20	12	362.2	361	16185
20	19	396.5	394.2	21778



a. Q_{rad}



b. Q_{conv}

Figure 6 :. Heat transfer rate

3.4 Change in Heat Flow Rate

The flow rate from the heat source to the glass and out toward the ambient temperature is determined through the flow rate of inward radiation ($Q_{in\ rad}$) and convection ($Q_{in\ conv}$) and the rate of outward flow to the ambient temperature ($Q_{in\ rad}$, $Q_{out\ conv}$), or the ambient temperature and thermal conductivity in the properties of the simulation as basis for calculation with the end result in joule (J).

Radiation and convection heating against time can be seen in Figure 6, which depicts that from the 1st to the 20th minute $Q_{in\ rad}$ changed from 7.76E-07 J at 4 mm thickness to 3.96E-06 J at 19 mm, whilst $Q_{in\ conv}$ was 11.232 J at 4 mm and became 57.2832 J at 19 mm. Meanwhile, $Q_{out\ rad}$ at 4 mm thickness started at 2.42E-06 J and attained 1.71E-06 J at 19 mm, whereas $Q_{out\ conv}$ began at 35.1 J at 4 mm and reached 24.7104 J at 19 mm.

3.5 Thermal Stress

Table 3 shows outcomes of calculation from the thermal stress simulation, where ΔT = 2.6°C at 4mm thickness with P = 0.5948 N and Sc = 1.6522 MPa, while at 6mm, ΔT = 10.9°C, P = 2.493 N and Sc = 6.9266 MPa. At thickness of 10mm, ΔT = 41.6°C, P = 9.5168 N and Sc = 26.43 MPa, whereas ΔT = 94.6°C, nilai P = 21.641 N and Sc = 60.11 MPa at 12 mm. Due to the significant gap in thickness from 4-12mm, results from 19mm glass are far different, among which ΔT = 276.1°C, P = 63.163 N and Sc = 175.4 MPa.

Table 3: Thermal Stress Analysis Results

No	Thickness (mm)	ΔT (°C)	P (N)	Sc (MPa)	Sc Steady (MPa)
1	4	2.6	0.594	1.652	16.30
2	6	10.9	2.493	6.926	43.11
3	10	41.6	9.516	26.430	80.47
4	12	94.6	21.641	60.110	115.70
5	19	276.1	63.163	175.400	176.80

Based on data analysis, Figure 7 below points out that in terms of von Mises stress, float glass with the least thickness of 4mm and different heat stress indicates a greater yield stress value at 34.69 MPa than the thickest 19mm variant with 33.1 MPa. This is because smaller or thinner material has greater yield stress, as evidenced by past research [14].

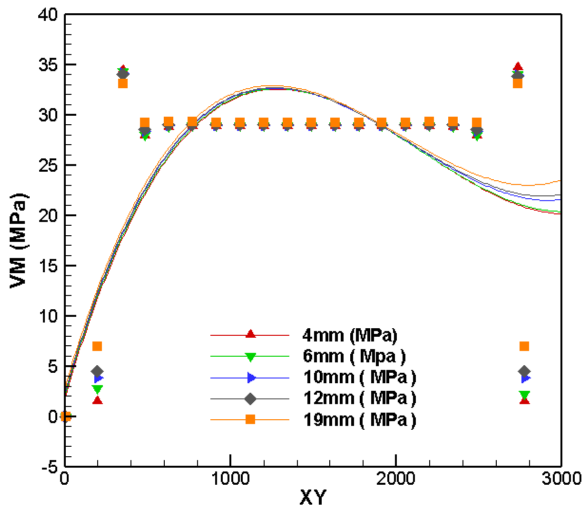
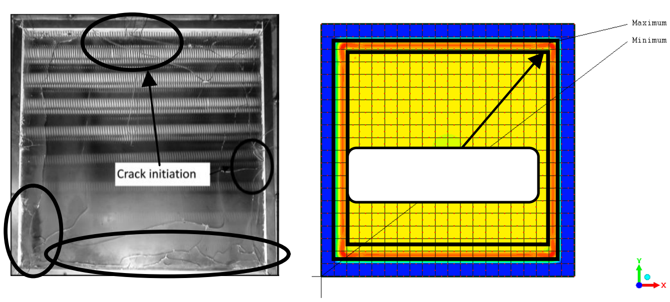


Figure 7: Von Mises stress on XY-axes and nodes

Experimental data in literature on heated glass mostly concern time until initial crack occurs and temperature on glass surface [15]. The simulation found that float glass can break even without cover when thermal load is quite high [10].



(a) Experiment by Zhang et al. [11] (b) Simulation results

Figure 8: Validation of glass fracture in simulation and experiment

It can be observed in Figure 8(a) that in the prior experiment performed by Zhang et al. [11] fracture took place on the edge of the glass frame and spread to all of the glass edges. This is validated by simulation as in Figure 8(b) in which fracture emerges at the element and node with maximum stress at the top corner or the line in red gradient color.

At the back of the glass temperature escalation is controlled by the rate of heat radiation from the front and heat convection to the surroundings. Difference in temperature between the shaded and open parts, or between the back and front sides, builds heat stress within the glass due to its expansion [16].

The simulation results are thus consistent with those of Zhang et al. [11], in that crack transpires on the glass edge at the yield stress of SNI 15-0047-2005 [12].

The implementation of software for development further can be considered in more interactive manner as explained n [17].

4. CONCLUSION

It can be concluded from outcomes of this study that with varied thickness against the radiant heat source and physical properties of float glass, exposure to radiation of 160.2-395.5°C from a heat source of 200-600°C causes glass to change shape or fracture. The ΔT resulting from this research and from the prior experiment are inconsistent with the used data reference, in that overprediction occurred at every thickness, while the ΔT_c from this study is also greater than that of the referred experiment.

However, in terms of thermal stress, 4-19mm-thick float glass receives maximum stresses of 34.69, 34.34, 34.15, 33.99 and 33.10 MPa, thus conforming to SNI. Findings of the cited experiment also revealed fracture on the edge of the glass that is similar to or consistent with that shown by computer simulation.

Overall, the conducted simulation on heat transfer and stress distribution of float glass sheets provides accurate and accountable data.

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