Experimentální Analýza Napětí 2010
Experimental Stress Analysis

Numerical modelling of the glass shaping forms cooling

Martina Havelková,[1] Petr Schovánek[2]

Abstract: The purpose of heat treatment of semi finished glass pieces in shaping forms is not only to fit their shape but also to reduce internal stresses. Thermal differences are unwanted and have to be eliminated in the cooling procedure of the glass pieces. Simulations of different types and sizes of shaping forms and complex model cooling were accomplished. The aim of these simulations was to optimise geometrical parameters, clamping conditions and material of the form, so that thermal differences at glass or glass – form interface are minimized during the cooling.

Keywords: Numerical simulation, Finite element method (FEM), Heat treatment

1. Introduction

Joint Laboratory of Optics of Palacky University and Institute of Physics of the Academy of Sciences of the Czech Republic is an important producer of mirror systems for detectors of weak optical signals [1-3]. In addition to the participation in the research and the development of these detectors, the production technology of used mirror segments is developed and improved concurrently.

The glass segments of these mirror systems - for example with the diameter 630mm and the thickness 15mm of the mirror segment - produced for the Pierre Auger Observatory belong to the category of the nonimaging ultralight mirrors. The term no imaging mirror segment means that the mirror is used for transport of incident optical signal to detector. The optical system doesn't create an image, but focuses optical signal with maximal efficiency on the surface of light detector.

The Simax glass is generally used as the mirror segments material supplied by Kavalier a.s. Sázava. The segments are manufactured by common optical abrasive processes applied on basic material – moulded piece of glass. Shape parameters and internal stress suitability of this basic material are tested previously. Due to high cost of material the elimination of unsuitable pieces is economically unacceptable, so these pieces are fitted in an electric-powered glass bending furnace instead.

The glass pieces undergoing carefully controlled treatment are heated above the critical temperature limit to reach a plastic state. Then, thanks to the gravitation

---

[1] *Mgr. Martina Havelková; Joint Laboratory of Optics, Institute of Physics of the Academy of Sciences of the Czech Republic; tř. 17. listopadu 50a, 77207 Olomouc, Czech Republic; martina.havelkova@upol.cz*

[2] *RNDr. Petr Schovánek; Joint Laboratory of Optics, Institute of Physics of the Academy of Sciences of the Czech Republic; tř. 17. listopadu 50a, 77207 Olomouc, Czech Republic; petr.schovanek@upol.cz*

Experimentální analýza napětí 2010, Petr Šmíd, Pavel Horváth, Miroslav Hrabovský, eds.,
May 31 - June 3 2010, Velké Losiny, Czech Republic (Palacky University, Olomouc; Olomouc; 2010).

glass piece fits the template form. This process is called slumping. After following steady stage above critical temperature, the piece is regularly and slowly cooled. Acquired material has an ideal shape, minimized internal stress and is prepared for the next manufacturing without shape change liability in result of following surface abrasion. The minimization of internal material stress decreases its influence on the shape changes of mirrors segments in the final technological operations.

The series of simulations described in this article serves to optimisation or at least to improvement of the size and the shape parameters, the clamping conditions and the material of the form. This way we minimize the thermal differences at the glass or at the system glass – form interface during the cooling.

2. Simulation method

The commercial program SYSWORLD – FEM software, simulates various heat treatment and welding processes - was used for all simulated cooling processes.

For accurate finite element prediction of the temperature field of involved material evolution during heat treatment, the formulation has to take into account following facts.

2.1. Geometrical meshed 3D model

Sysworld [7,8] allows various ways to implement geometry or meshed geometry into the model, as for instance IGES or VDA imported files. 3D description of the whole shape for FEM calculation purposes has to be meshed, it means that a continuous 3D workpiece is substituted by a variety of simpler solid shapes which are often called brick, wedge (hexahedral) or tetrahedral elements. The element formulation involves no simplification of the geometry other then those imposed by the limits of the shapes that can be defined. Only high time period of solution may restrict the number of elements used in a model.

In our simulations Sysworld *Preprocessing GeoMesh* for generation of one half 2D section of the simulated object (some of them are shown in Fig.2) was always used. Due to the rotational shape of all forms using the extrusion-rotation utility *(Preprocessing)* was advantageous for extruding 2D meshed section into solid meshed 3D model. Number of elements in particular simulations is changed due to different thickness of the form. But the part coinciding with glass in the model keeps the same discretization parameters in the course of all simulations. The particular numbers of elements are noticed in the end of section 3. Table 1.

2.2. Physical properties of involved materials

The heart of Sysworld is a coupling between thermal analysis and phase (in metallurgical meaning) transformation computation, two physical effects that have a strong influence on each other. In these simulations no phase transformations are involved, because the maximal temperature in our simulations doesn't get over initial 680°C so any temperature limit for phase transformation of used materials isn't exceeded.

Thermal analysis requires input of subsequent physical quantities of used material: The thermal conductivity (k), the density (ρ), the specific heat (c), each of them in dependence on the temperature, as accurate as it's possible to obtain. Our data were obtained in the case of the cast iron from [4], glass parameters from [5] and parameters of material Monalite M1A from [6].

2.3. Initial and boundary conditions of the model

Sysworld takes into account even externally computed or another way obtained temperature field as an initial conditions of the system. In the next computations initial condition was set as constant temperature **680°C** for every element.

In Sysworld, any kind of heat transfer is taken into the account as a function of space, time and temperature. The heat transfer to the surroundings takes into the account radiation and convection. At higher temperature, radiation plays the major role. The cooling of the part due to radiation and convection to the surroundings has main role in the next simulations. The Sysworld function *Convective and radiative losses* is applied to part of prepared geometry (2D elements group *Surface*), describing surface of the model bordering with the surrounding air. Required cooling rate is achieved by gradual decreasing of the temperature (function AirSimTemp in Fig. 8) imposed to the air in consecutive simulation restarts. This method is justified by the fact that unaffected, not controlled cooling rate is higher than simulated one, so that in real cooling process additional heating is necessary to keep low cooling rate required for glass.

3. Simulations

The prediction of the temperature field during the cooling for different **sizes and shapes of cooling form** was done in the first stage of simulations. The temperature differences of the form surface part matching with glass are monitored and assessed. The most suitable shape and size of the form corresponding to the minimal simulated temperature differences were chosen.

In the second stage glass component was implemented into the model. Then, complete model temperature field distribution during the cooling was analyzed. Two different types of **form constraints** were simulated.

The last stage of simulations involved the best shape and constraints of the form and was done for comparison two possible **materials** of future form with the view of the temperature differences in the cooled glass.

3.1. Convex and concave forms

Theses series of simulations were focused on

1. convex forms with cylindrical (r_{bottom}= 325 mm) shape and spherical (R = 3400 mm) convex upper base which matches the front side of the concave piece of glass. Simulations were done for three different heights (v) of the cylinder (the values from the interval of possible heights of the cylinder in future form weight terms). In simulation Convex11

v = 11 mm, Convex40 v = 40 mm, Convex80 v = 80 mm. The geometries are shown in Fig. 1.

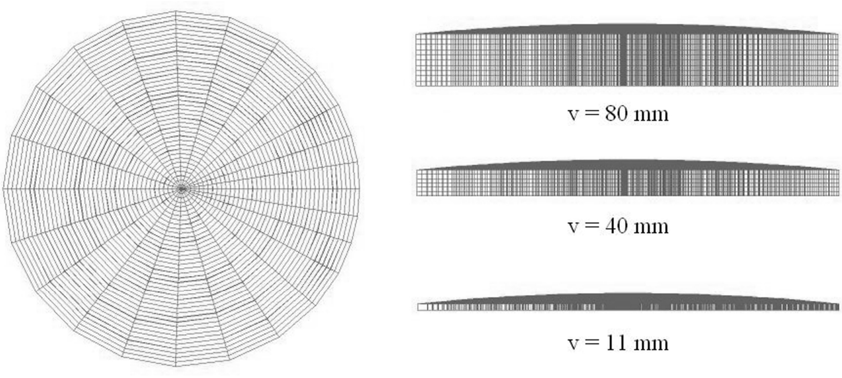

Fig. 1. Upper and side view of geometries of simulations Convex11, Convex40, Convex80.

2. concave forms with cylindrical (r_{bottom}= 335 mm) shape and spherical (R = 3400 mm) concave upper base which matches the rear side of concave piece of glass. Simulations were done for two different heights (v) of the cylinders (thickness of form in its thinnest place – in the centre). In Concave10 v=10mm, Concave20 v=20mm. These sizes were chosen from possible weight of the future form again. One half of the 2D section of Concave20 and Concave10 geometry is shown in (Fig. 2., part 2,3).

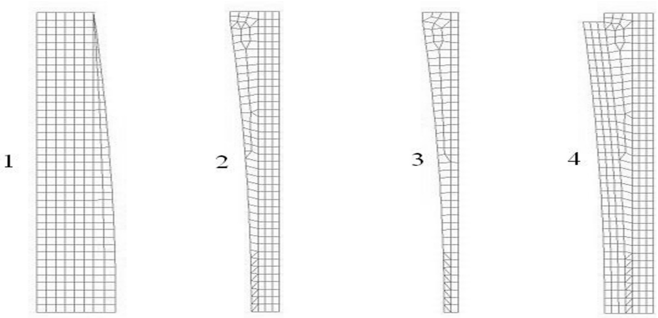

Fig. 2. View of ½ 2D section of geometries of simulations Convex40, Concave20, Concave10, Concave20+glass.

Every simulated object had material data of the cast iron [4] and the cooling was defined by means of function *Convective and radiative losses* with cooling rate of surrounding air 1°C/min. This function was defined on all 2D surface elements of the model **except** the disc (r = 250 mm) in the centre of the form bottom, where the trunk shaped lagged constraint of the real form is situated. So any heat exchange was omitted here (for instance Fig. 4 shows group SURFACE of Convex40 simulation with this type of constraint). From obtained temperature field thermal differences on spherical part of the surface (matching with glass) were monitored and are shown in Fig. 3. Simulation was stopped when value of thermal difference became stable.

From Graph in Fig. 3 appears that concave shape is more suitable then convex in thermal differences terms. Simulations furthermore imply the less thickness of the concave form the better (lower) thermal difference is. Despite this fact the Concave20 shape was chosen for next simulations and scrutiny because thickness 20 mm was found as minimal possible in the shape stability terms.

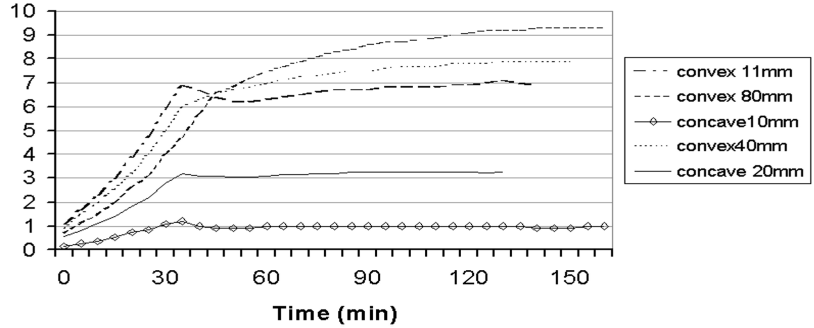

Fig. 3. Thermal differences (central and periphery temperature) on form-glass interface in dependence of time. Simulations Convex11, Convex40, Convex80, Concave 10, Concave20

3.2. Disc and ring shaped constraints to base stall

The glass piece was implemented into the above mentioned model Concave20 (Fig. 2, 4.part). Glass part of the model had material data of the Simax glass [5] and rest (the form) had material data of the cast iron [4], the cooling was defined by means of function *Convective and radiative losses* with the cooling rate of the surrounding air 0,1°C/min., this value is maximal permitted for glass heated above 600°C.

The purpose was to compare two types of constraint, one of them original described in paragraph above (disc shape). The second one was circular, ring shaped (between circles r1 = 284.75 mm, r2 = 318.25 mm) (Fig. 5). So heat exchange – cooling is defined on whole 2D surface of joined (form and glass) piece **except** this lagged place where the heat exchange with surrounding air is omitted.

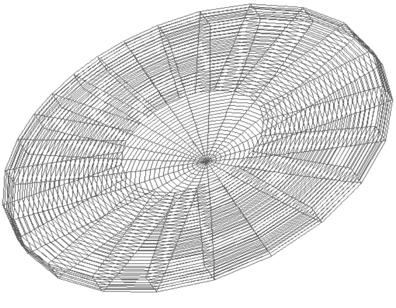

Fig. 4. Mesh of group SURFACE of the simulation Convex40 without central disc.

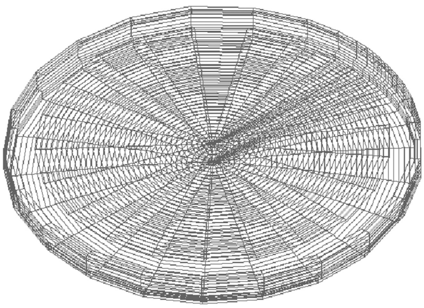

Fig. 5. Mesh of group SURFACE –bottom view-of the simulation Concave20+glass-ring without the ring.

The simulations Concave20+glass-disc and Concave20+glass-ring were done. From the obtained temperature field thermal differences in glass part of the model were monitored and are shown in Fig. 6. and in Fig. 7. The simulation was stopped when value of thermal difference became stable.

The graphs (Fig. 6. and Fig. 7.) show that ring shaped constraint to base stall is more suitable then the disc shaped one in thermal differences terms.

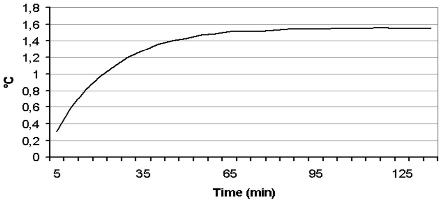

Fig. 6. Temperature differences in Concave20+glass-disc

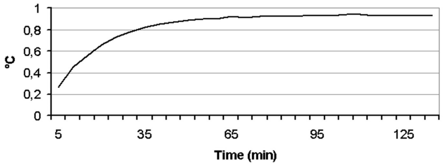

Fig. 7. Temperature differences in Concave20+glass-ring

3.3. Material comparison

This stage of simulations involved the best shape and constraints of the form, it means the Concave20+glass-ring model and was done for comparison of two possible materials of future form – original cast iron and Monalite M1A (the calciumsilicate plate supplied by the PROMAT) firm. New geometrical model Concave50+glass-ring-Monalite had to be created because of unified thickness 50mm of plates of this material. So the maximal thickness of the model (rim part) was 50mm. The upper side stayed the same, again concave - with removed spherical central part.

The purpose of this stage was to find if replacing original cast iron material by the offered calciumsilicate one has any negative effect on thermal differences in system. Glass part of the model had again material data of the Simax glass [5] and rest (the form) had material data of the Monalite M1A [6], cooling was defined by means of function *Convective and radiative losses* with cooling rate of surrounding air 0,1°C/min.

Cooling diagram with maximal and minimal temperature in glass and simulated air temperatures in dependence on time is shown in Fig. 8., overview of the temperature differences in the cooled glass in Fig. 9.

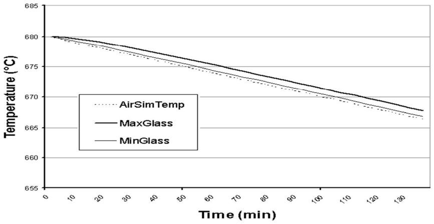

Fig. 8. Graph of cooling for model Concave50+glass-ring-Monalite

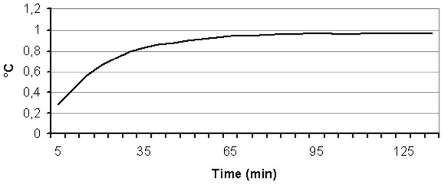

Fig. 9. Temperature differences in glass in Concave50+glass-ring-Monalite model

Thermal difference became stable approximately after 90 min. of cooling and the value 0.97°C was not significantly different from the value 0.93°C achieved in Concave20+glass-ring model. Temperature gradient was oriented vertically. It means that maximal temperature was achieved on the bottom surface of the glass touching the form and minimal temperature occurs on the surface where thermal exchange with the air is.

Following table (Table 1) presents the number of elements in meshed geometry for each simulation.

Table 1. Numbers of elements for computed simulations

Model	Number of elements
Convex11	9624
Convex40	10004
Convex80	13368
Concave10	5766
Concave20	8370
Concave20+glass-disc	11997
Concave20+glass-ring	12338
Concave50+glass-ring-Monalite	16151

4. Conclusion

Set of simulations with variable shape, size, constraint and material parameters was realised. These new geometrical, constraint and material parameters were used in new improved design of the shaping form. The result of the simulations is the model where the thermal differences in the glass material during the cooling of the mirror's segment are minimized.

Acknowledgements

The Academy of Sciences of the Czech Republic supports this work under project no. KAN301370701. This work is also supported by the project of the Ministry of Education of the Czech Republic – INGO no. LA08016.

References

[1] Barrau A., et al., “The CAT imaging telescope for very-high-energy gamma ray astronomy”, *Nuclear Instruments & Methods In Physics Research A,* **416**(2-3), pp. 278-292 (1998). ISSN 0168-9002.

[2] Pare E., et al., “CELESTE: an atmospheric Cerenkov telescope for high energy gamma astrophysics”, *Nuclear Instruments & Methods In Physics Research A,* **490**(1-2), pp. 71-89 (2002). ISSN 0168-9002.

[3] Schovánek P., et al., ”Thin glass mirrors for the Pierre Auger project”, in *Proceedings of 13th POLISH-CZECH-SLOVAK CONFERENCE OF WAVE AND QUANTUM ASPECTS OF CONTEMPORARY OPTICS*, Nowak, J., Zajac, M., Masajada, J., eds., Proc. SPIE **5259**, pp. 215-214 (2003). ISBN 0-8194-5146-0, ISSN 0277-786X

[4] ČSN 422420 (422420). *Litina 42 2420 s lupínkovým grafitem* (ČNI, Praha, 1989).

[5] ČSN ISO 3585. *Sklo boritokřemičité 3,3* (ČNI, Praha, 1999).

[6] MONALITE®–M1A, Technické údaje, *Available from* www.promatpraha.cz, *Accessed:* 2009-09-17.

[7] SYSWORLD 2006, “Heat Treatment,” Release notes, pp. 38-42 (2006).

[8] SYSWELD Toolbox CD-ROM (ESI Group, February 2009).