SIMULATION EFFECT OF BRICK MATERIALS ON THE MICRO THERMO MECHANICS BEHAVIOR OF ELECTRICAL FURNACE

Dheya N. Abdulamer
Energy and Renewable Energies Technology Center, University Of Technology
Email: diaa_diaa197@yahoo.com

ABSTRACT :-

During this research, simulation of the candidate materials done as insulted brick for the furnace wall. Results were obtained through the use of simulation by COMSOL multiphysics program. Showed results obtained from this program, Al_2O_3 brick has high deformation value 2.34 $*10^{-4}$ m and the maximum vonmises stress value 267 Mpa focused at the edges of the fifth slice. Vonmises stresses various along the slices of bricks of Al_2O_3-MgO, Al_2O_3-ZrO_2 and MgO-ZrO_2. Zirconia brick has 486 Mpa the maximum value of the vonmises stress.

ZrO_2 brick has low value 1.486 * 10^4 w/m^2 of the total heat flux, while maximum value of the total heat flux occur in the Magnesia brick which has 2.267 * 10^5 w/m^2. Structural brick of Al_2O_3-MgO has low total deformation value 7.987 * 10^{-5} m and low value of the maximum vonmises stress 133 Mpa. These data supporting use this brick of Al_2O_3-MgO as best candidate for the furnace wall without failure during the service.

KEY WORDS : Finite element method, COMSOL multiphysics, Total heat flux, Deformation Vonmises stress.

الخلاصة :-

تم خلال هذا البحث ، اجراء محاكاة للمواد المرشحة كطابوق عازل لجدار الفرن. تم الحصول على نتائج المحاكاة من خلال استخدام برنامج (*COMSOL* multiphysics) وأظهرت النتائج المستحصلة من هذا البرنامج ان طابوق الالومينا يحصل فيه قيمة تشوه عالي m $2.34 * 10^{-4}$، والقيمة القصوى لاجهاد فون مسيس 267 Mpa تتركز عند حافات الشريحة الخامسة. اجهادات فون مسيس تتغير على طول شرائح طابوق الومينا – مغنيسيا، الومينا – زركونيا، ومغنيسيا – زركونيا. اقصى اجهاد فون مسيس 486 Mpa يحصل في طابوق الزركونيا.

طابوق الزركونيا يحصل فيه قيمة منخفضة $1.486 * 10^4$ w/m^2 من قيمة الفيض الحراري الكلي بينما اقصى قيمة للفيض الحراري الكلي $2.267 * 10^5$ w/m^2 يحدث في طابوق المغنسايتي. الطابوق المركب من الومينا – مغنيسيا يمتلك $7.987 * 10^{-5}$ m اقل تشويه كلي و قيمة منخفضة 133 Mpa لاقصى اجهاد فون مسيس. هذه البيانات تدعم وتشجع على استخدام هذا النوع من الطابوق المركب الومينا – مغنيسيا كافضل مرشح لجدار الفرن بدون حصول فشل.

ABBREVIATIONS :-

c	Concentration of the diffusing material per unit volume	mol/m^3
Z	Gradient direction	
Q	Activation energy	KJ/mol
R	Universal gas constant	$J/mol\ K$
T	Absolute temperature	K
ν	Poisson's ratio	
α_{th}	Coefficient of thermal expansion	$1/k$
ΔL	Deformation	mm
l	Original length	mm
P	Load applied	N
E	Modulus of elasticity	GPa
A	Cross sectional area	mm^2
σ_{res}	Residual thermal stress.	MPa

1. INTRODUCTION :-

In the past various authors reported on modeling the thermo-mechanical behavior of refractory materials based on damage mechanics. Headrick et al. model combined thermo-mechanical and chemical damage in an alumina silicate refractory lining of a gassifier. Separate damage variables are used for compressive and tensile failure. Liang and Headrick. Model filling of an alumina refractory cup using separate damage variables for compressive and tensile damage. The total damage is found via a multiplicative combination of the damage variables. Prompt et al. analyze the wear of a blast furnace duct. Based on the observed fracture pattern of micro- and macro cracks due to high transient thermal gradients, a continuum damage approach was adopted. A single damage variable was satisfactorily used to describe damage originating from a compressive stress state at the hot face and from a tensile stress state inside the refractory lining [Frederik Damhof, 2010].

Refractory materials are capable of withstanding high temperature in different industrial processes. A refractory should be able to resist the chemical action of the material being heated and withstand the mechanical load. They have high dimensional stability and do not lose their physical shape and chemical composition. Refractories confine the heat and prevent the heat loss to the atmosphere from the outside walls of furnaces [S. K. Duggal, 2008]. Refractory ceramic linings of high temperature furnaces are often built with bricks. Chemical composition and geometry are selected regarding the service conditions and the lining structure. Raw materials used for the production of refractory materials are typically alumina (Al_2O_3), silica (SiO_2) and magnesia (MgO) [K. Andreev, 2012]. Alumina refractory is one of the most chemically stable oxides known, which offers excellent hardness, strength and spalling resistance. Magnesite refractories are chemically basic materials. The physical properties of this class of brick are generally poor. Zirconium dioxide (ZrO_2) is a polymorphic material. There are certain difficulties in its usage and fabrication as a refractory material. It is essential to stabilize it before application as a refractory. The thermal conductivity of zirconium dioxide is found to be much lower than that of most other refractories and the material is therefore used as a high temperature insulating refractory [*A. Bhatia*, 2011].

Thermal conduction through electrically insulating solids depends on the vibration of atoms in their lattice sites. Steady state heat transfer refers to the condition where the rate of heat flowing into one face of an object is equal to that flowing out of the other [Robert F. Speyer, 1994]. When two miscible materials are in contact across an interface, the quantity of diffusing material which passes through the interface is proportional to the concentration gradient. The atomic flux J is given by Fick's First Law:

$$J = -D\frac{dc}{dZ} \tag{1}$$

Where J is measured per unit time and per unit area. The proportionality factor D, the diffusion coefficient, is measured in units of m^2/s, and are generally written by Arrhenius relationship:

$$D = D_o \exp(\frac{-Q}{RT}) \tag{2}$$

Where D_0 the diffusion pre-exponential factor which is generally assumed to be independent of temperature while diffusion coefficients depend exponentially on temperature [Robert E. Newnham, 2005]. Thermal stresses, which are introduced in a body as a consequence of temperature changes, may lead to fracture or undesirable plastic deformation. The two prime sources of thermal stresses are restrained thermal expansion (or contraction) and temperature gradients established during heating or cooling. Thermal shock is the fracture of a body resulting from thermal stresses induced by rapid temperature changes. Because ceramic materials are brittle, they are especially susceptible to this type of failure [D. G.Rethwisch. et al, 2007]. The entire refractory lining is subjected to thermal stress which plays a dominant role in selection. Thermo-mechanical FEM analysis is a reliable tool to investigate thermal stresses and develop ways on improving the lining behavior [*A. Bhatia*, 2011].

The aim of this work was to get thermo- mechanics data of various refractory materials used as furnace wall, Interpret of these data and comparing it's to select a better of them. COMSOL multiphysics program, is a package of FEM computer analysis have been used to obtain total heat flux, total deformation and vonmises stresses which it's generated in the lining of furnace wall when assuming steady-state service conditions, i.e; one-dimension heat flow through the furnace wall by supposed that the model was symmetry insulated with constant properties.

2. THEORETICAL BACKGROUND :-

The major cause leading to early failure of refractory materials is the wear due to fatal thermal stresses. The generation of such stresses is generally referred to as thermal shock. The resistance of a refractory material against thermal shock fracture initiation is represented by the first Hasselman parameter R defined as:

$$R = \frac{\sigma(1-\nu)}{\alpha_{th}\,\mathrm{E}} \tag{3}$$

The parameter R represents the maximum allowable temperature difference in a material subject to infinitely fast heating-up [Frederik Damhof, 2010]. The thermal shock resistance of crystals depends on the thermal expansion. The thermal expansion of solids is a basic physical property representing the dimensional changes in a solid induced by a change in temperature. It is of technical importance as it determines the thermal stability of a crystal. The average linear strain e represents the ratio of the change in length to the original length [D.B. Sirdeshmukh. et al, 2006]. Residual stresses generated after cooling system involve contributions from the stresses due to contraction and the stresses due to the internal moment generated from the asymmetric stress distribution [S.P. Timoshenko. et al, 1970]. By adding the stresses due to these two effects, the total residual stress can be given as [K.S. Ravichandran, 1995]:

$$\sigma_{res} = \frac{P*l}{A*\Delta l}\alpha \ \Delta T \qquad (4)$$

For micro thermo - mechanical stresses that generated along *x*- axis of furnace wall which has 2*x* thickness as shown during figure 1. which it is represents three dimension of the model; equation. (4) can be rewritten as follows: [Satyam S. Sahay. et al, 1996].

$$\sigma_{res} = E(x)\left[\alpha(x) - \frac{A_1}{E_1} - \frac{\left\{A_2 - \frac{A_1}{E_1}E_2\right\}\left\{xE_1 - E_2\right\}}{\left\{E_1E_3 - E_2^2\right\}}\right]\Delta T \qquad (5)$$

In which

$$A_1 = \int_{-x}^{x} \alpha(x)E(x)dx \qquad (6)$$

$$A_2 = \int_{-x}^{x} \alpha(x)E(x)xdx \qquad (7)$$

$$E_1 = \int_{-x}^{x} E(x)dx \qquad (8)$$

$$E_2 = \int_{-x}^{x} E(x)xdx \qquad (9)$$

$$E_3 = \int_{-x}^{x} E(x)x^2dx \qquad (10)$$

3. DESIGN THE MODEL

COMSOL package is a program of finite element method used to analyses multi-physics problems. Simulations of thermo mechanics problems require the collection of analyzes for the different physical fields and interact together. Thermo mechanics elements are required to report the thermal mechanical analysis such as thermal gradient and the stresses generated in the model. So all cases must be built separately, by constructed a thermal model where is applied in the first case then switched and used together with the mechanical model. The five steps of procedures have been used of analyses of thermo mechanics problem using version of 3.5a COMSOL software are as follows:

3.1. Drawing the model

Geometry of a 2D model using static analysis under plane stress with thermal expansion of thermal structural interaction in structural mechanics module then input dimensions of model into rectangle window under the draw menu. Three types of refractory materials have been used as brick insulator of electric furnace wall and dimensions of these bricks mentioned in the table (1). Three dimension of the model have been drawn and illustrated in the figure. 1.

3.2. Input properties

The table 2 below shows the required constants of the materials properties of the furnace wall needs to be introduced under the physics menu using subdomain settings option. Inserted values of thermal conductivity and density at the first case of thermal field, then switch into structural field to insert values of modulus of elasticity and thermal coefficient of expansion.

3.3. Input boundary conditions

Under the option physics – boundary setting – general heat transfer, the models suppose it's an symmetrically isolated, just the outer surface of the furnace wall and the other side of the inner surface of the furnace wall shall be subject to the heat difference. Do not apply loads on the model, only gets thermal changed of 375 °C along the model. According to these considerations as mentioned in the table 3 , so the temperature flow in one dimension from the inner surface of the brick towards the outer surface and the heat flux is off. The model constrained by switch to plane stress then fixed the model from the outer surface.

3.4. Meshing the model

Refine mesh under mesh option have been used to divide boundaries and subdomains settings of the model into elements.

3.5. Solving

Partial differential equations of the model were collected in the meshed model. Under the main toolbar menu – solve – solve problem have been used to solve the meshed model. Repeated all the five states mentioned during table.1 respectively.

4. RESULTS AND DISCUSSION :-

The schematic image of the total heat flux of Al_2O_3 brick shown in the figure. 2, which composed of tertiary dimensions contour and the strip values with graded color. The maximum and the minimum values of the total heat flux was bookmark in this strip. The red color in the strip refereed into the maximum value, while the blue color refereed to the minimum value. The red color in the strip referred into the maximum value, while the blue color referred to the minimum value, and the graded color referred to the graded values. Figures. 3-7 shows of the total heat flux for bricks of MgO, ZrO_2, Al_2O_3-MgO, Al_2O_3- ZrO_2 and MgO-ZrO_2 respectively. the maximum values in these figures, denoted that the magnesia brick has 2.267 * 10^5 w/m^2 the maximum value of the total heat flux as compared with the other types of bricks. In contrast, ZrO_2 brick has 1.486 * 104 w/m^2 low value of the maximum total heat transfer which is focus on the inner surface of the furnace wall as displayed with red color during figure. 4.

The total deformation of the Al_2O_3 brick as a result to change in temperature offered in the figure. 8. In this figure, the original shape of the Al_2O_3 brick drawing with black cubic shape while graded colors concerned with the deformed cubic shape. The minimum values of the deformation equal to zero for all kinds of bricks as mentioned in figures. 8-13. As comparison with other types of bricks, Al_2O_3 brick has high deformation value 2.34 *10^{-4} m, in this context, brick of Al_2O_3-Mgo has low deformation value 7.987 * 10^{-5} m. This behavior related to the thermal conductivity of alumina brick, so dissipate high thermal energy at the alumina-magnesia interface and this lead to disappearing of deformation at the magnesia side as illustrated in the figure. 11.

Slices of vonmises stress of Al_2O_3 brick shown in the figure. 14, and during this slices, the stresses increased from the first slice at the left side to the fifth slice at the right side. At the fifth slice which is close to outer surface of Al_2O_3 brick of the furnace wall, the stress moved as circular waves from the edge of slice to the center. The maximum stress focused at the edge of the fifth slice and it is value 267 Mpa. According to the considerations of the model design, the deformation occurred will be impeded and the generated stresses in the brick as a result to reaction against applied the thermal load.

Slices of vonmises stresses of MgO and ZrO_2 shown in the figures. 15 and 16 respectively. The behavior of these stresses similar to that appear on the alumina brick, but difference from that shown in the figures. 17-19 for bricks of Al_2O_3-MgO, Al_2O_3-ZrO_2 and Al_2O_3-ZrO_2 respectively. In these bricks, the amplitude stresses various alternating along the slices from the inner surface of brick of furnace wall to the outer surface.

However, Zirconia brick has 486 Mpa the maximum value of vonmises stress, in contrast, brick of Al_2O_3-MgO has 133 Mpa the low value of the maximum vonmises stress as comparison with other types of bricks. The data for the total heat flux, total deformation and vonmises stress obtained from COMSOL multiphysics mentioned in the table. 4.

5. CONCLUSION :-

The materials proposed for the furnace wall simulated using multiphysics computer program. Magnesia brick has $2.267 * 10^5$ w/m^2 the maximum value of the total heat flux as compared with the other types of bricks while ZrO_2 brick has 1.486 * 104 w/m^2 low value of the maximum total heat transfer which is focus on the inner surface of the furnace wall. The minimum values of the deformation equal to zero for all kinds of bricks. As comparison with other types of bricks, Al_2O_3 brick has high deformation value $2.34 *10^{-4}$ m and brick of Al_2O_3-Mgo has low deformation value $7.987 * 10^{-5}$ m. Slices of vonmises stress of Al_2O_3 brick increased from the first slice to the fifth slice, the maximum stress focused at the edge of the fifth slice and it is value 267 Mpa. The amplitude of vonmises stresses alternating various along the slices of bricks of Al_2O_3-MgO, Al_2O_3-ZrO_2 and MgO-ZrO_2. Zirconia brick has the maximum value of vonmises stress 486 Mpa and brick of Al_2O_3-MgO has low value of the maximum vonmises stress 133 Mpa.

Table 1. Refractory materials and dimensions of the brick

State	Brick materials	Dimensions of the model *X, y, Z* (*mm*)
1	***Al_2O_3***	**50**
2	***MgO***	**50**
3	***ZrO_2***	**50**
4	***Al_2O_3- MgO***	**50**
5	***Al_2O_3 - ZrO_2***	**50**
6	***MgO - ZrO_2***	**50**

Table 2. Subdomain settings of the required properties [matweb].

Meaning	Symbol, unit	Al_2O_3	MgO	ZrO_2
Thermal conductivity	*K (W/m.K)*	30	53	1.675
Thermal coefficient of expansion	α $(10^{-6}/K)$	10.5	14	7
Density	ρ (kg/m^3)	3960	3480	5680
Modulus of elasticity	*E (Gpa)*	370	306	220
Poisson's ratio	v	0.22	0.36	0.27

Table 3. Initial boundary conditions

Setting	**Initial conditions**	**Symbol**	Value
Boundary 1	The temperature of the inner furnace wall	T_{in} (K)	**673**
Boundary 2	Insulation symmetry	-	**-**
Boundary 3	Insulation symmetry	-	**-**
Boundary 4	The temperature of the outer furnace wall	T_{out} (K)	**298**
Boundary 5	Constraint of the outer furnace wall	-	**fixed**

Table 4. Characteristics comparison of bricks

Type of brick	**Total heat flux [KW/m^2]**		**Total deformation [mm]**		**Vonmises stress [Mpa]**	
	Max	**min**	**max**	**min**	**max**	**min**
Al_2O_3	**176.8**	**155.7**	**0.234**	**0**	**267.1**	**14.68**
MgO	**226.7**	**196.4**	**0.1644**	**0**	**428.2**	**19.13**
ZrO_2	**14.86**	**14.77**	**0.174**	**0**	**486.1**	**0.9731**
Al_2O_3-MgO	**196.9**	**172.7**	**0.07987**	**0**	**133.1**	**4.595**
Al_2O_3-ZrO_2	**26.22**	**25.68**	**0.1352**	**0**	**470.9**	**2.556**
MgO-ZrO_2	**26.85**	**26.34**	**0.1787**	**0**	**271.4**	**4.667**

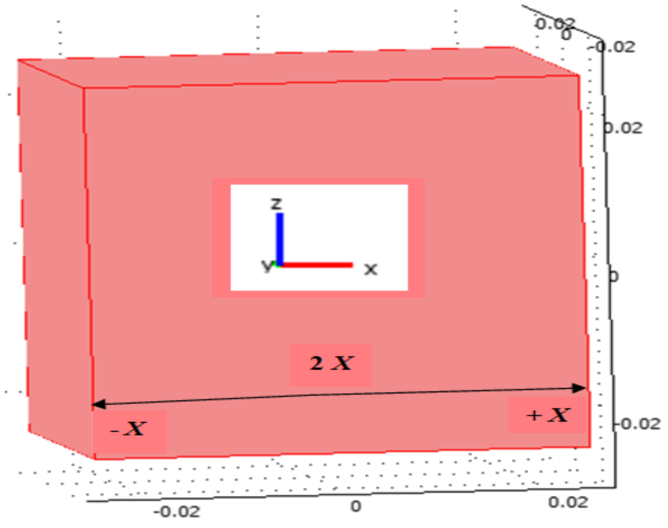

Figure 1. Three dimension of the model

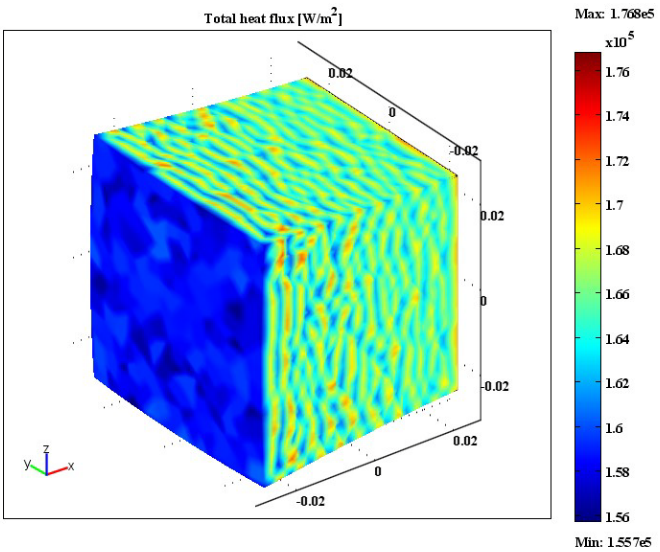

Figure 2. Total heat flux of Al_2O_3 brick

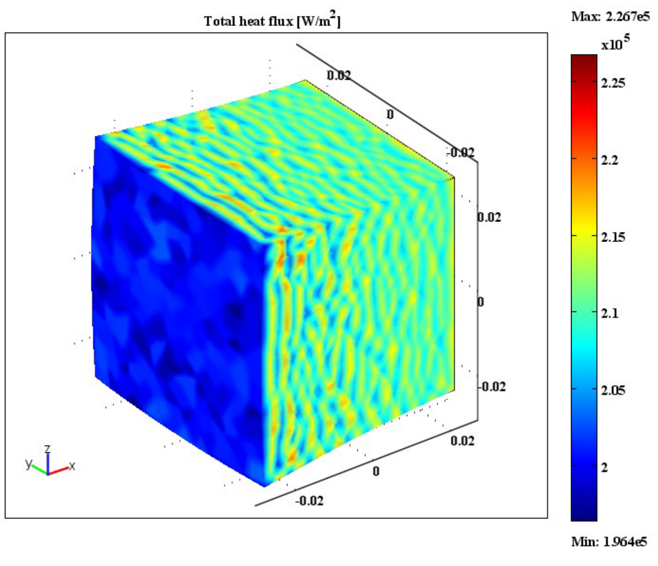

Figure 3. Total heat flux of MgO brick

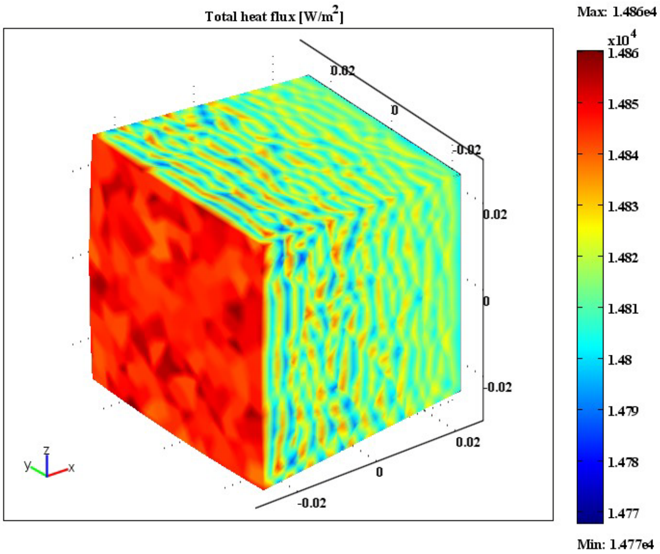

Figure 4. Total heat flux of ZrO_2 brick

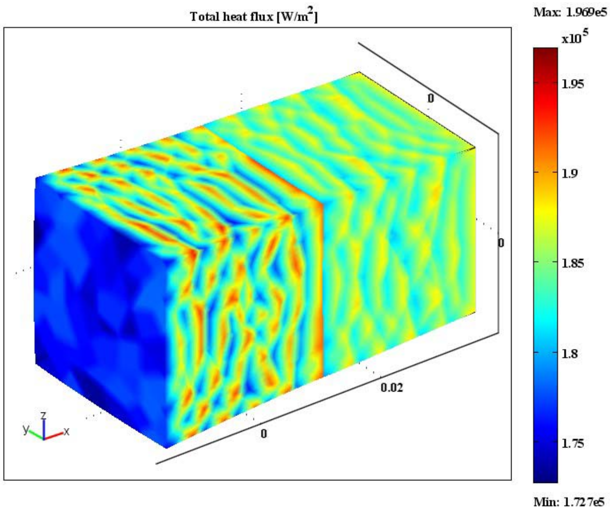

Figure 5. Total heat flux of Al_2O_3-MgO brick

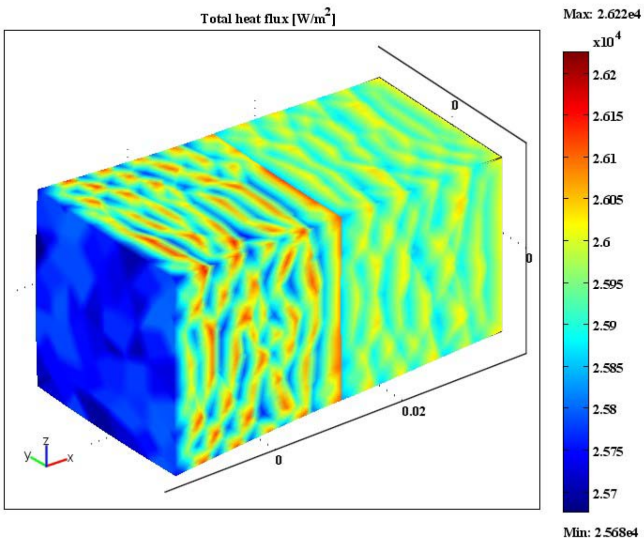

Figure 6. Total heat flux of Al_2O_3-ZrO_2 brick

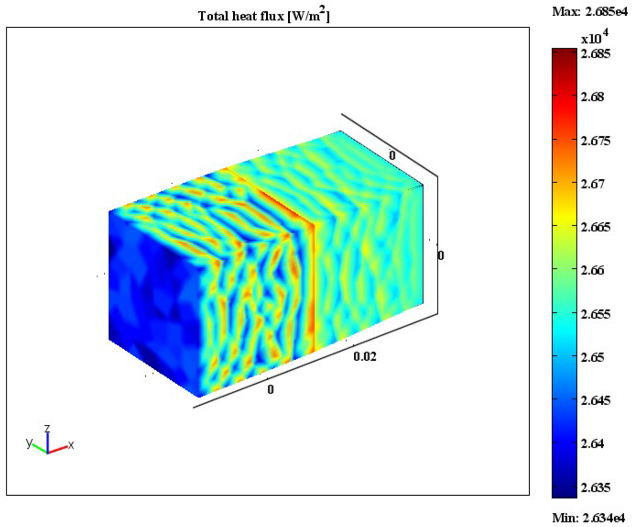

Figure 7. Total heat flux of MgO-ZrO_2 brick

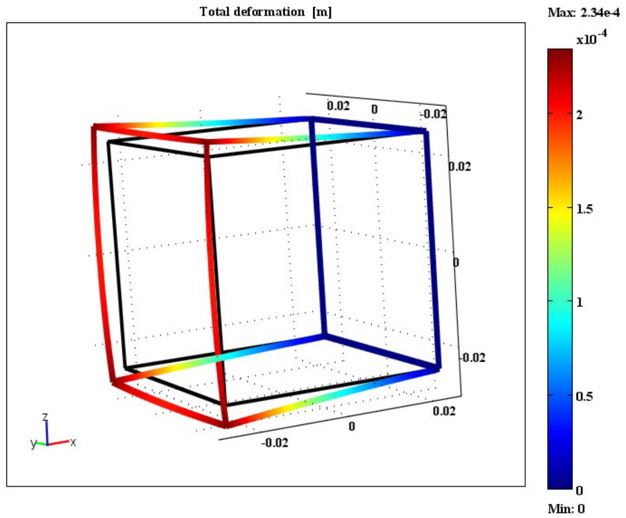

Figure 8. Total deformation of Al_2O_3 brick

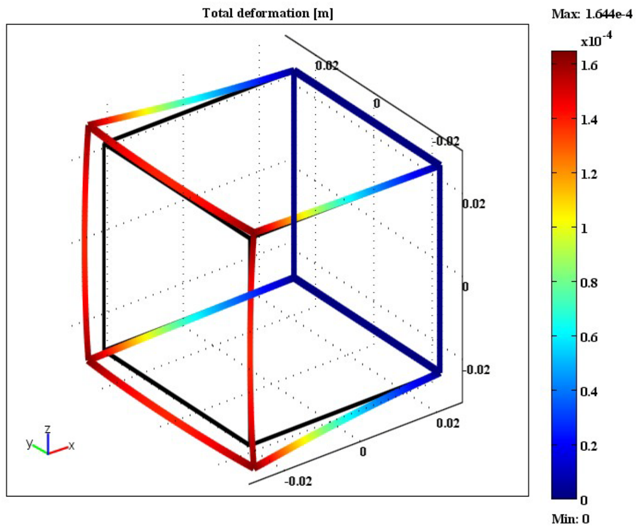

Figure 9. Total deformation of MgO brick

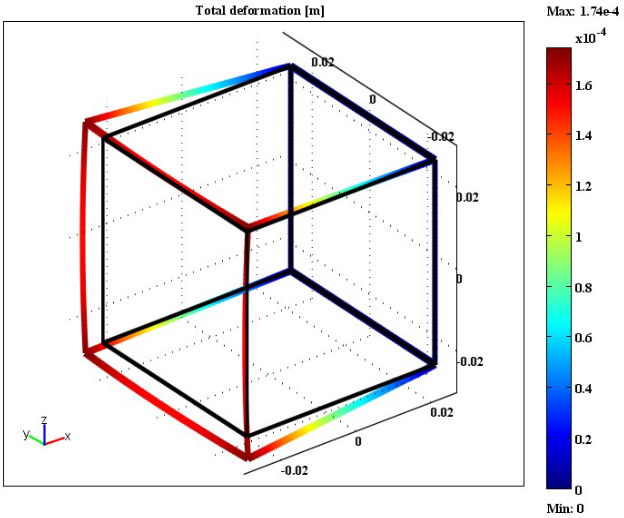

Figure 10. Total deformation of ZrO_2 brick

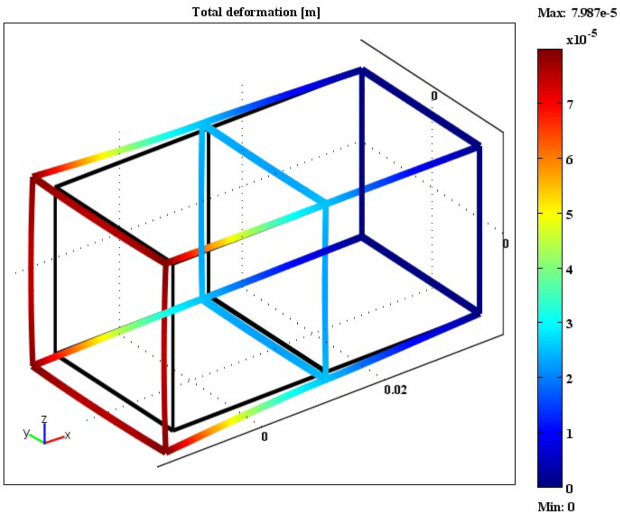

Figure 11. Total deformation of Al_2O_3-MgO brick

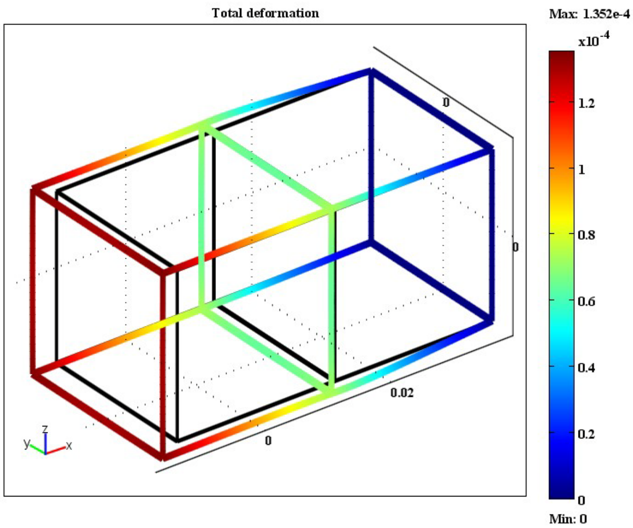

Figure 12. Total deformation of Al_2O_3- ZrO_2 brick

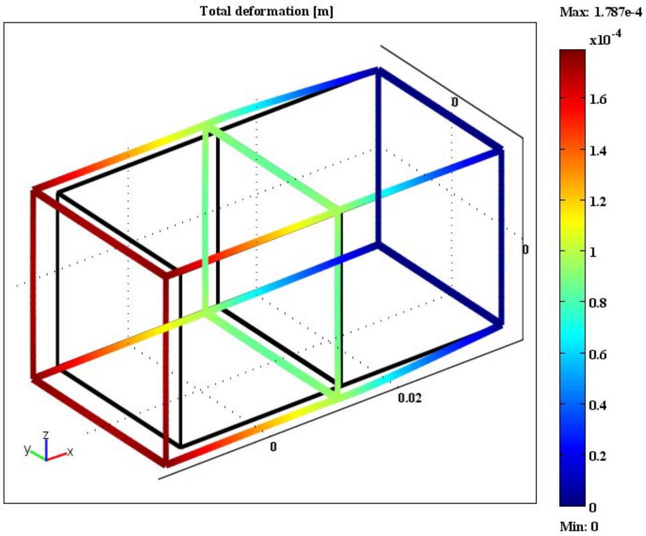

Figure 13. Total deformation of MgO-ZrO_2brick

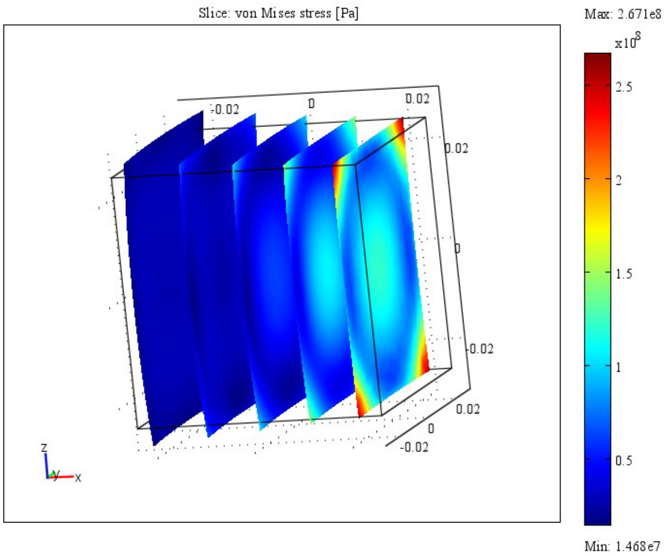

Figure 14. Slices of vonmises stresses in Al_2O_3 brick

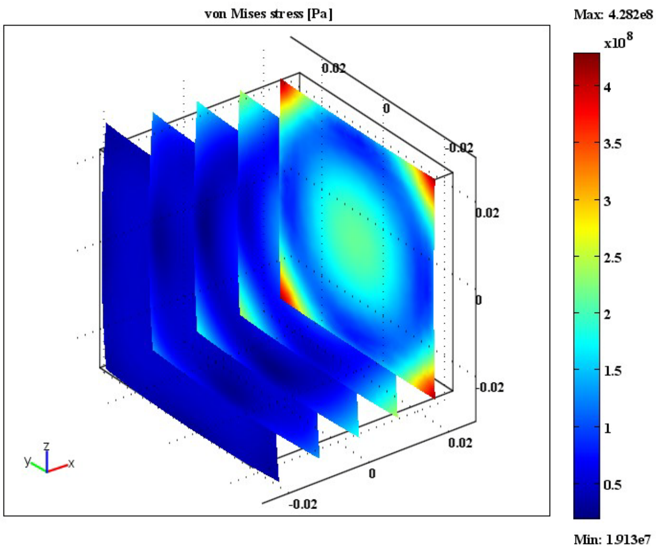

Figure 15. Slices of vonmises stresses in MgO brick

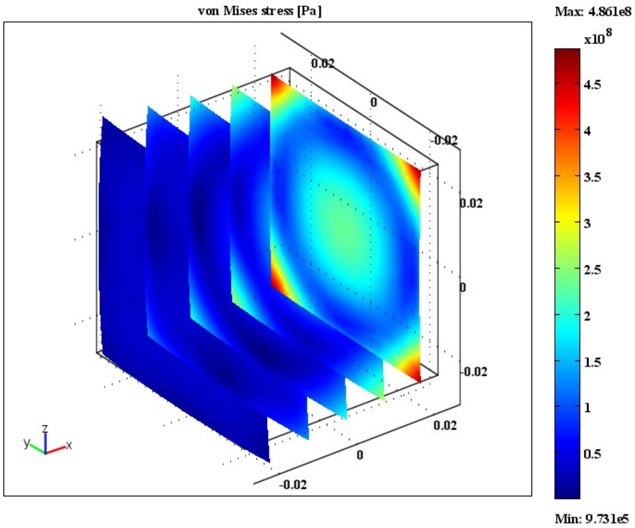

Figure 16. Slices of vonmises stresses in ZrO_2 brick

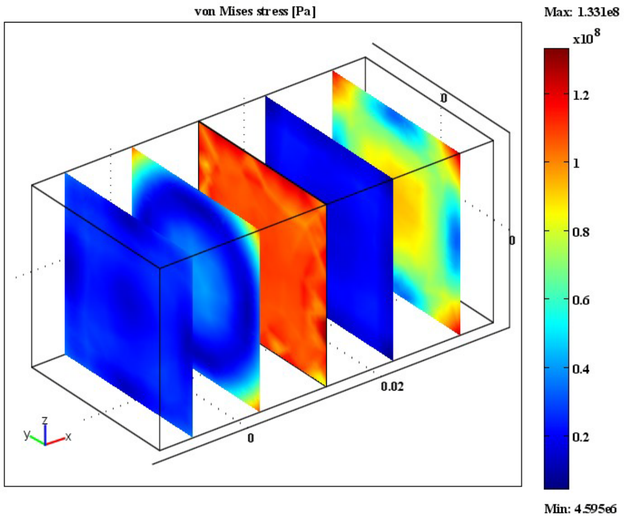

Figure 17. Slices of von mises stresses in Al_2O_3-MgO brick

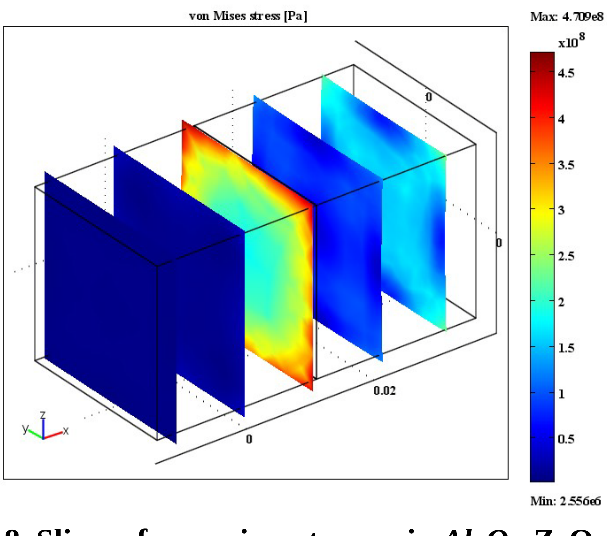

Figure 18. Slices of von mises stresses in Al_2O_3-ZrO_2 brick

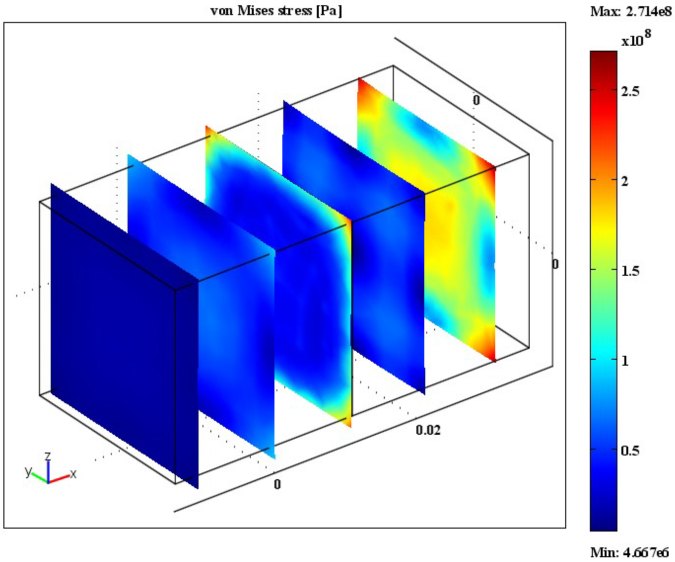

Figure 19. Slices of von mises stresses in *MgO*-ZrO_2 brick

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