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Impact of using FGM Materials for Improving the Efficiency of an Internal Combustion Engine

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Abstract: The biggest problem facing internal combustion engine is the decrease of energy efficiency due to thermal losses, which causes an increase in fuel consumption and operating cost, as well as a large amount of burned gas released with major environmental problems resulting. In this context, we will focus in this work about improving the efficiency to minimize all these problems, for this we propose to minimize thermal losses through the use of FGM materials. In this context, a steady state heat conduction analysis of functionally graded cylinder is conducted to present the advantages of using of functionally graded materials over the metallic materials in structures that subject to thermal loads, the study is based on the comparison of temperature distribution along the radial direction of the cylinder between a pure metallic and two different functionally graded models, the geometric parameters and boundary conditions of the studied cylinder are considered similar to four-cylinder engine liners. The materials properties gradation is modelled using the power law distribution and the governing equation of heat conduction are solved analytically, the thermal dependency of the properties is supposed to be neglected, the presented results are obtained by a developed Matlab code and using Ansys software.

Keywords: Functionally graded material; steady state; heat conduction; energy efficiency; combustion engine;

1. Introduction

One of the biggest challenges facing internal combustion engine manufacturers is their low efficiency. which means that these engines will consume a lot of fuel, therefore having a high operating cost. Without forgetting the increase in the amount of burned gases emitted, which has an increasing impact on the severity of problems resulting from environmental pollution such as global warming and other disasters. As we know, one of the reasons that leads to low engine performance is thermal loss. In this context, we will focus in this work on a proposal to reduce heat loss by using (FGM) materials.

Due to their mechanical and thermal properties, functionally graded materials (FGM); new generation of composites; are preferred and favored for structures under severe thermal loads; compared to laminated composites materials, the physical properties (Young's modulus, density, heat conductivity, specific heat, etc.) of functionally graded materials constituents varied continuously in spatial coordinates.

Due to their thermal properties, the behavior of FGM with heat conduction is widely studied by researchers using different numerical approaches; such as the finite element method (FEM), the finite difference method (FDM); and different theories, and different functions that used to describe the gradation of material properties such as the exponential and power law distributions.

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Markworth A. J. et al [1] presented a review contains a description of modeling studies relative to functionally graded materials (FGM). In their paper, two topics are covered: models for microstructure-dependent thermo-physical properties and models for the design, processing, and performance of FGM. V. Birman et al [2] present a review of the principal developments in functionally graded materials with an emphasis on the recent work published since 2000. Diverse areas relevant to various aspects of theory and applications of FGM are reflected in their paper. They include homogenization of particulate FGM, heat transfer issues, stress, stability and dynamic analyses, testing, manufacturing and design, applications, and fracture. Sharma R. et al [3] also presented a review on the application of finite element methods for Investigating the effect of heat conduction, variation of temperature and other parameters in the functionally graded materials; the use of FEM for steady state heat transfer has been addressed in this work.

Javaheri R. et al [4] derived the equilibrium and stability equations of a FGM rectangular plate under thermal loads, based on the higher order shear deformation plate theory, the material properties are assumed to be varying through the thickness coordinate and expressed using power law. B. Chen, et al [5] presented a sensitivity analysis for the steady-state and transient heat conduction of functionally graded materials (FGMs) based on the finite element method providing detailed formulations. In the solution of transient problem, the precise time integration (PTI) is employed. L. Marin, [6] investigates the steady-state heat conduction in two-dimensional functionally graded materials (FGMs) by the application the method of fundamental solutions to the Cauchy problem. T. Sadowski, [7] evaluated the transient heat conduction problem in the layered FG circular plates subjected to sudden cooling process at the upper side; their work is focused on the comparison of two numerical methods; the first one is a finite difference (FDM) numerical code based on a generalized alternating direction implicit (ADI) method, in second method, the considered problem was solved with the finite element method (FEM) with ABAQUS code. E. Buyukkaya, [8] investigates the thermal behavior of FG piston coatings on AlSi and steel materials using ANSYS simulator, it has been concluded that the using of FGM coating for the AlSi and steel pistons increases the temperature of the combustion chamber of the engine, and the thermal strength of the base metal. M. Jabbari, et al [9] developed the exact solution of steady-state two-dimensional axisymmetric mechanical and thermal stresses for a short hollow FG cylinder. The temperature distribution, as functions of radial and longitudinal directions, is solved analytically.

A. O. Olatunji-Ojo, et al [10] analysed the thermal conduction on layered functionally graded materials (FGMs) based on three different mixing laws: linear, quadratic, and half-order. In their research the functionally graded material considered is a composite of five layers. R. Pourhamid, et al [11] conducted a thermal analysis of functionally graded materials in cylinders and pistons based on super element method (SEM), the obtained results show that the accuracy of the SEM is the same as the FEM. Arefi, M. [12] studied the temperature behavior in a hollow FG cylinder with temperature-dependent thermal conductivity. The nonlinear differential equation of the second order is solved by using the Adomian decomposition and the method of successive approximations. The temperature dependency is employed for the thermal conductivity and the power law distribution is used for simulation the gradation of materials. W. Qu, et al [13] developed a hybrid numerical method for 3D heat conduction in functionally graded materials by integrating the advantages of the generalized finite difference method (GFDM) and Krylov deferred correction (KDC) technique; the obtained results demonstrate that the method has a great potential for 3D transient heat conduction in FGMs especially for those in a long-time simulation. A. A. Delouei, et al [14] developed an exact analytical solution of steady-state heat conduction of a bidirectional FG cylinder sector using the Fourier theory. The material properties according to the power-law function are considered to vary in radial and circumferential directions and in both directions. G. Koutsakis, et al [15] provide an improved analytical solution to the transient heat conduction problem of thermal barrier coatings in reciprocating internal combustion engines. The heat conduction in multilayer walls was investigated analytically under the assumption of one-dimensional heat flow. Time-varying heat flux and temperature boundary conditions were applied to the domain.

In this study, we analyze the temperature profile along the radius of FG hollow cylinder in order to measure their thermal insulating capacity; our study is based on the comparison of temperature distribution between a metallic liner cylinder of four-stroke engine and two models of FG liners. The materials properties gradation is modeled using the power law distribution and the differential equation of heat conduction are solved analytically, the thermal dependency of the material's properties is supposed to be neglected, the results are obtained by a developed Matlab code and using Ansys software and show a good agreement.

2. Material gradation and temperature distribution laws

The present study is based on the analysis of temperature distribution for three models of cylinder, the first model is made by metal, the second and third models are made by functionally graded materials. For FG models, the material's properties vary across the radius of the cylinder as shown in Figure 1. For the first FG model, the ceramic material constitutes the inner core of the cylinder while metal constitutes the outer core, the volume fraction of ceramic decreases along the radial direction from the inner to the outer radius. In the second FG model, the metal constitutes the inner and the outer core of the cylinder while ceramic constitutes the middle area in the mean radius of the cylinder, the volume fraction of ceramic decreases along the radial direction from the mean to the inner and outer radius.

For the FG models, the mechanical and thermal material properties P(r) such as the modulus of elasticity, thermal conductivity and density are determined from the volume fraction of the material constituents:

$$P(r) = P_c V_c + P_m V_m \tag{1}$$

$$V_c + V_m = 1 \tag{2}$$

Where P_c and P_m represent the material properties of the ceramic and metal constituents, V_c and V_m represents the volume fraction of each constituent.

– *For the metallic model, V_c is equal to zero.*

$$V_c = 0; \quad V_m = 1 \tag{3}$$

– *For the first FG model, the expression of volume fraction of the ceramic constituent is defined by:*

$$V_c = \left(\frac{R_o - r}{R_o - R_i} \right)^n \tag{4}$$

R_i and R_o are respectively the inner and outer radius of the cylinder, r is the radial coordinate, n is the power index of volume fraction.

From Eq (4), we deduce several cases such as:

» *n= 0 (Vc = 1): means that the cylinder is made only by ceramic material.*

» *n = ∞ (Vc = 0): means a pure metallic cylinder (metallic model).*

» *n = 1: denotes a linear gradation of materials properties.*

Figure 2 represents the variation curve of volume fraction of the ceramic constituent for different value of power index.

For the second FG model, the volume fraction of the ceramic constituent is defined by:

$$V_c = \left(\frac{(r - R_i)(R_o - r)}{(R_m - R_i)(R_o - R_m)} \right)^n \tag{5}$$

R_m is the mean radius of the cylinder.

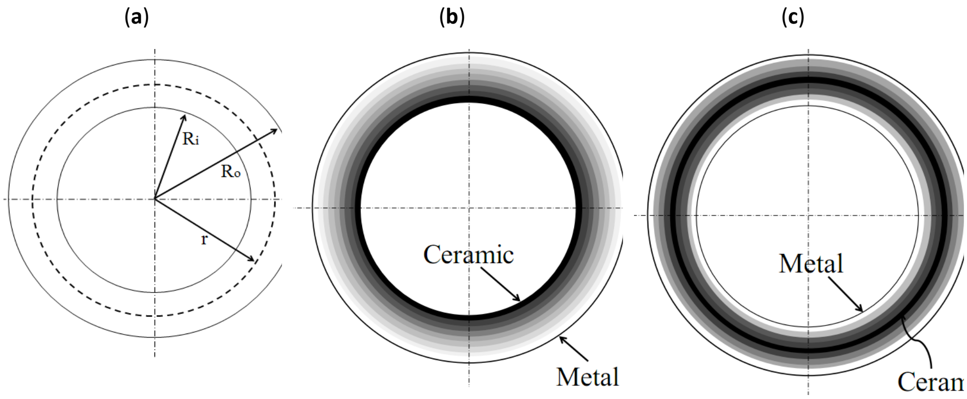

Figure 1: Schematic of studied models. (a) Metallic model. (b) FG model 1. (c) FG model 2.

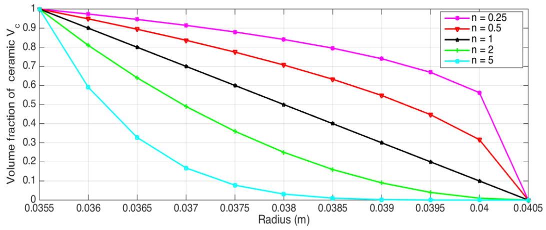

Figure 2: Variation curve of the volume fraction of ceramic for the first FG model.

$$R_m = \frac{R_o + R_i}{2} \tag{6}$$

From Eq (5), we can also deduce several cases, such as:

» *n = 0 (Vc = 1): means a pure ceramic cylinder.*
» *n = ∞ (Vc = 0): means a pure metallic cylinder.*

Figure 3 represents the variation curve of volume fraction of the ceramic constituent for different value of power index.

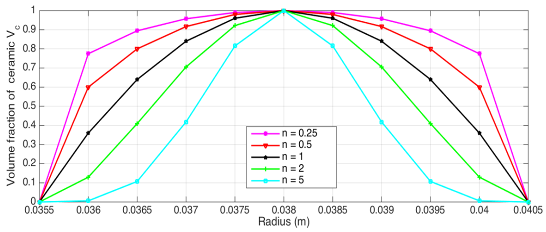

Figure 3: Variation curve of the volume fraction of ceramic for the second FG model.

3. Governing equation of heat transfer

The differential equation that describes the steady state heat conduction for the studied models is given as [9-12-16]:

$$\frac{\partial}{\partial r}\left(r\,K(r)\frac{\partial T}{\partial r}\right) = 0 \tag{7}$$

Where T is the temperature and $K(r)$ is the thermal conductivity, according to the equation (1), $K(r)$ is given as:

$$K(r) = K_c V_c + K_m V_m \tag{8}$$

K_c and K_m are the thermal conductivity of the ceramic and metallic constituents.

The solution of the differential equation of the heat conduction is given as:

$$T(r) = T_i + \frac{(T_o - T_i)}{\int_{R_i}^{R_o}\left(\frac{1}{r\,K(r)}\right)dr}\int_{R_i}^{r}\left(\frac{1}{r\,K(r)}\right)dr \tag{9}$$

To and *Ti* are the boundary conditions or the temperatures of the outer and inner surface of the cylinder.

3. Model description

The configuration considered in the present paper is based on the geometry of four-stroke engine liners that presented by [11]. The cylinder liner is of length 83,6 mm, inner diameter 71 mm and outer diameter 81 mm, Figure 4. The thermal conductivity of metal and ceramic constituents are respectively K_m=13.72 W/m.K, K_c=1.21 W/m.K.

For boundary conditions, the inner wall of the liner cylinder (hot wall) is exposed to the combustion temperature of the engine which is assumed to be equal to T_i = 400°C, and the outer side (cold wall) takes the temperature of the water that is used for cooling T_o = 100°C.

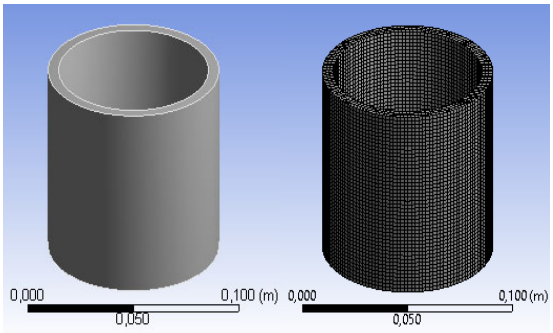

Figure 4: Finite element model using ANSYS.

4. Results and Discussion

In this section, in order to improve engine performance and increase engine life, a comparison of the temperature distribution for the three proposed cylinder liners is presented to determine the appropriate insulation model; the results are obtained using MATLAB code and ANSYS software.

Before comparing the FG models, the temperature distribution for the metallic model is shown in Figure 5 and plotted as contour in Figure 6. These figures show the temperature distribution over the radius of the cylinder. It can clearly see the decrease in temperature from the inner wall to the outer wall due to the cooling flow used outside the cylinder. In addition, metals contribute to heat flow when an external temperature gradient is imposed on the structure. From these figures, a good agreement is observed between the results obtained by the simulation (ANSYS) and the modeling (MATLAB).

Figure 7 shows the temperature distribution along the radial thickness for the metallic liner cylinder comparing with the first FG liner cylinder considering the effect of power index (n), the most noticeable is the temperature drop when using a FG liner, which conveys the heat transfer from a high temperature to a low temperature. It is observed that, for $n \geq 1$, the temperature decreases after a certain distance from the inner wall compared to the results obtained for $n \leq 1$, we can also see that the temperature values for n=1 (linear gradation) are the most remote from the values for the metallic liner.

The temperature distribution of the first FG liner is plotted as contour in Figures 8-10, the red indicates the highest cylinder liner temperature (due to combustion) and blue indicates the lowest cylinder liner temperature (due to cooling). Using a FG liner yield a smaller hot zone than metallic liner. The effect of power law index for FG model 1 is very clear, the cold zone for $n=0.25$ and $n=1.0$ is bigger compared to $n=5.0$ while the hottest zone for $n=1.0$ is smaller than $n=0.25$.

Figure 11 illustrate the temperature distribution for FG model 2 with different (n) comparing with metallic model. The graphs of model 2 look the

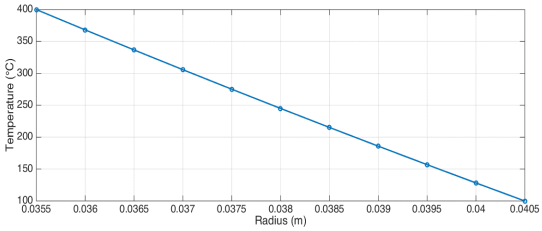

Figure 5: Temperature distributions across the radius of the cylinder for the metallic model.

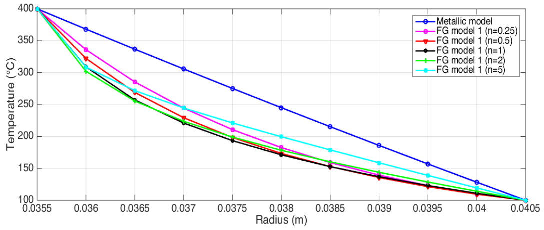

Figure 7: Temperature distributions across the radius of the liner cylinder for the first FG model 1.

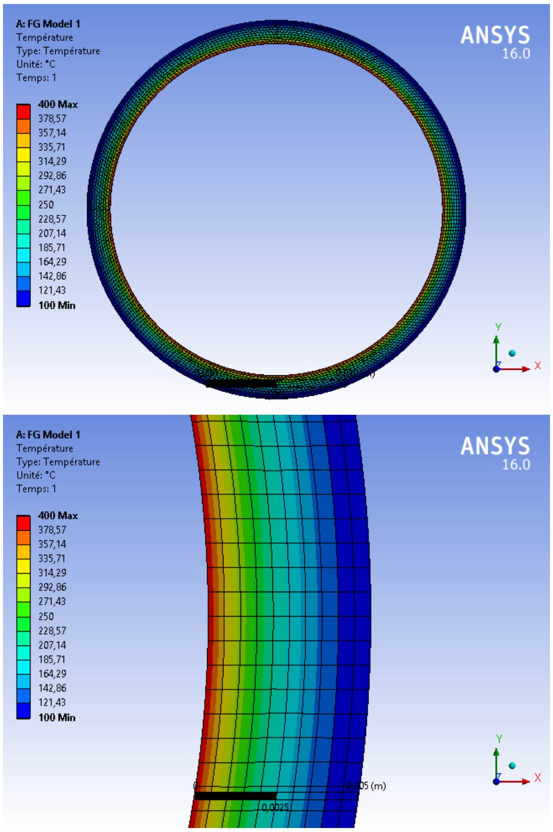

Figure 8: Temperature contours across the radius of the cylinder for the first FG model where n=0.25.

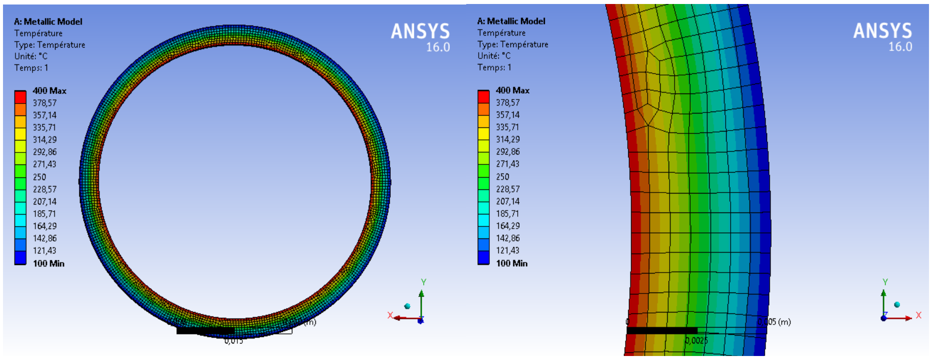

Figure 6: Temperature contours across the radius of the cylinder for the metallic model.

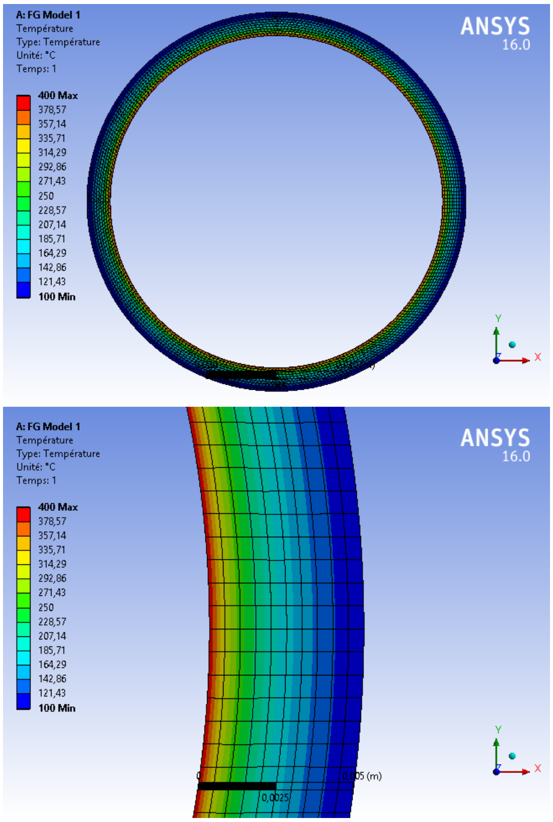

Figure 9: Temperature contours across the radius of the cylinder for the first FG model where n=1.

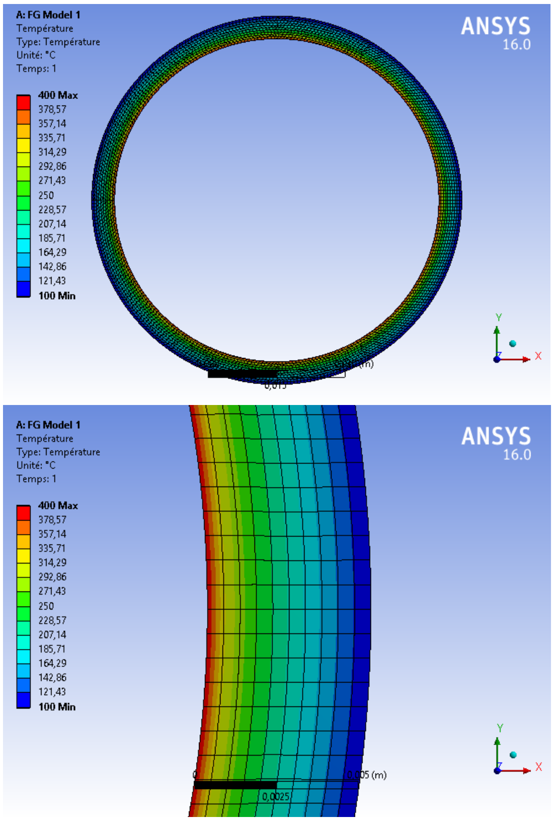

Figure 10: Temperature contours across the radius of the cylinder for the first FG model where n=5.

same pace and are divided into two areas, in the first zone [0.0355-0.038] the temperature is higher than the metallic liner but in the second area the temperature decreases, this phenomenon is attributed to the materials gradation.

Figures 12-14 present the cross-sectional temperature contour for different power law index. The colours of the hot and cold zones make the difference between the metallic liner and the second FG liner. It is very clear that the red (hottest) area for the FG model is larger than the metallic model; this does not mean that the metallic liner is more insulator than the second FG liner; because we can also see that blue area (cooled) for the FG model is also larger than the metallic model that mean this model can absorb heat from the chamber combustion and does not transfer it to the engine block.

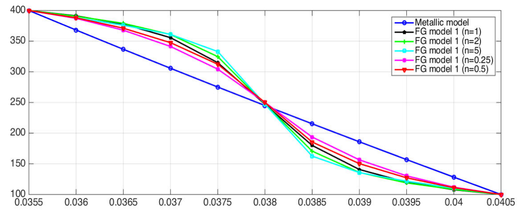

Figure 11: Temperature distributions across the radius of the cylinder for the second FG model 2.

4. Conclusions

The aim of this work is to test the ability of fgm materials to improve the efficiency of the internal combustion engine; in this context we try to exploit the low thermal conductivity of these materials compared to metallic materials to minimize heat losses during combustion. This study is based on the comparison of temperature distribution between a metallic liner cylinder of four-stroke engine and two models of FG liners. From the obtained numerical and analytical results, we can conclude:

– *The temperature decreases along the radius of cylinder liner from the inner side (hottest wall) to the outer side (cooled wall) for all*

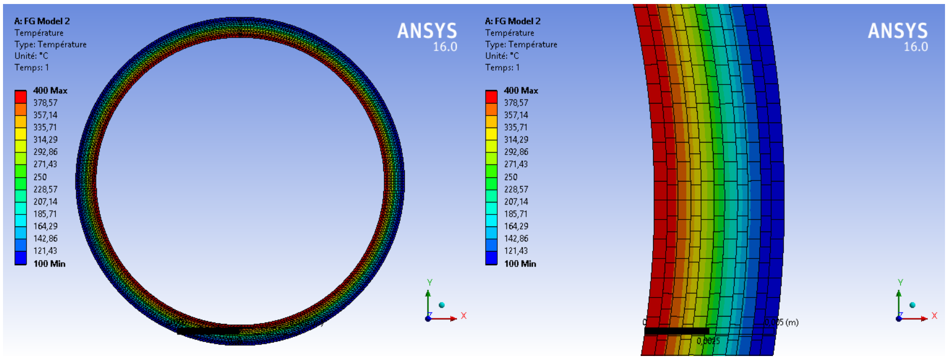

Figure 12: Temperature contours across the radius of the cylinder for the second FG model where n=0.25.

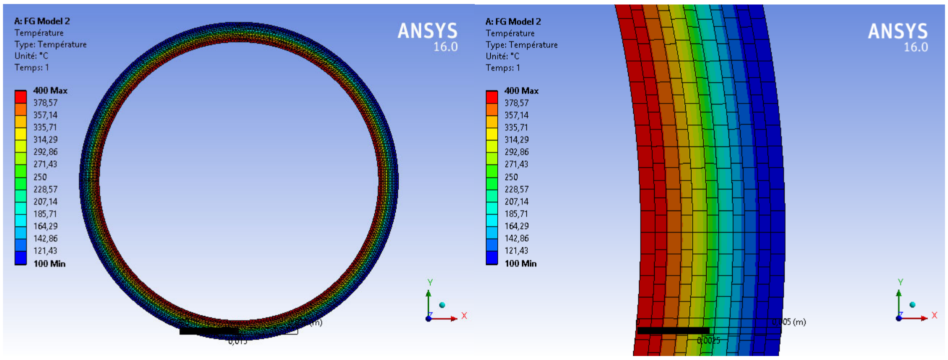

Figure 13: Temperature contours across the radius of the cylinder for the second FG model where n=1.

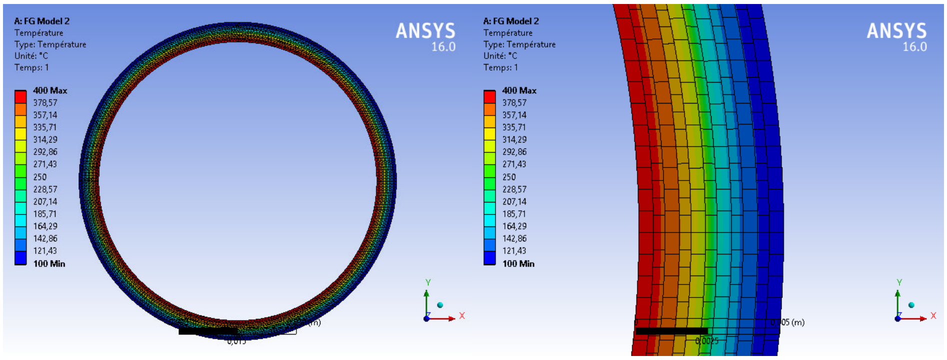

Figure 14: Temperature contours across the radius of the cylinder for the second FG model where n=5.

studied models.

– For the first proposed FG model, the temperature drops quickly along the radius compared to the metallic model, especially for linear material's gradation (n = 1); this decrease is due to the ceramic constituent which forms the inner wall; face to the temperature of combustion; and acting as good thermal insulator due to its lower thermal conductivity. In addition to its good mechanical properties (lower density, higher stiffness); this model is a good thermal insulator than the metallic model.

– For the second FG model, the temperature profile can be devised into three zones; hot, mean and cold; this is due to the variation of thermal conductivity from the value of ceramic constituent at the mean radius to the value of metallic constituent at the inner and outer radius; the hot and cold zone for this model are larger than in the metallic and the first FG models; we can say that this model is a conductor and heat insulator at the same time. Compared to the first FG model and the metallic model, this model has the best mechanical properties.

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