Abstract

The current study considers the theoretical transient treatment of pressurized thick-walled hollow spheres while they are subjected to arbitrary boundary and initial conditions. Under generalized assumptions and using the basic thermoelasticity theory, the thermoelastic problem is solved. By utilizing the Eigen function method, generalized Bessel function and separation of variables, an attempt is made to analyze the transient temperature in the one-dimensional state. In this paper, the resultant relations of the present study are capable of being applied to any arbitrary boundary and initial conditions. Temperature, displacement and thermal stresses are plotted in some figures. In this study, the values are arbitrarily chosen.

Keywords: Arbitrary Boundary, Arbitrary Initial Conditions, Thermoelastic, Thick Sphere, Transient

1. Introduction

Shell structures are used in such engineering applications as military, shuttle, marine, automotive, oil, water, and major manufacturing industries. Different types of shells commonly used in the industry are pipes, vessels, fuselages, wings, rockets, car hoods, dome roofs, projectiles, nuclear reactor vessels, silos, bow dams, parachute aircrafts and many more. Stress problems for hollow cylinders and spheres subjected to transient thermoelastic loads are theoretically and practically important. Thus, many research have been carried out in this subject. In solved, the problem of elastic thermal stresses in the transient condition in an elastic solid. In\textsuperscript{2} studied transient thermal stress in the spherical shell. In the other study, in\textsuperscript{3} investigated the dynamic thermoelastic problem in thick spheres. In\textsuperscript{4} studied the thermo-elastic stresses in a non-homogeneous orthotropic solid continuum having a cavity with spherical form. In\textsuperscript{5} investigated the dynamic thermoelastic displacement and stresses distribution in spherical thick shells having fixed boundaries. In\textsuperscript{6} scrutinized the thermo-elastic waves in a FG sphere applying the Green-Lindsa theory. In\textsuperscript{7} came up with a new approach which could be applied for the purpose of stress analysis of pressurized FGM cylinders, disks or spheres. In\textsuperscript{8} studied thermo-elastic analysis in the transient condition for a multilayered thick-walled sphere. In a study by\textsuperscript{9}, thermo-elastic response in the transient condition of rotating thick-walled cylinder subjected general boundary conditions was obtained. In\textsuperscript{10} provided the transient thermoelastic analysis of pressurized rotating disks under arbitrary boundary and initial conditions. Among other things, they obtained transient thermoelastic stresses of homogeneous and isotropic thick spheres under general boundary and initial conditions.

2. Transient Heat Conduction Analysis

In an isotropic hollow sphere with inner and outer radii a and b, respectively in spherical coordinate, the one-dimensional transient heat conduction equation, without heat source, for isotropic bodies is:
in which the temperature distribution and thermal diffusivity are represented by \( T(r,t) \). Moreover, specific heat capacity, mass density and thermal conductivity are represented by \( c \), \( \rho \) and \( k \) respectively.

The boundary and initial conditions are as:

\[
\begin{align*}
\text{Boundary Condition :} & \quad \left[ C_n T(a,t) + C_{n_2} \frac{\partial T}{\partial r} \right]_{r=a} = g_i, \\
\text{Initial Condition :} & \quad T(r,t) \big|_{t=0} = T_i(r)
\end{align*}
\]

Here \( T_i(r) \) is the given initial condition and \( g_m \) \((m = 1,2)\) and \( C_{mn} \) \((m,n = 1,2)\) are constants.

The Equation (3) can be solved applying the separation of variables method, Eigen-function method, and generalized Bessel function

\[
T(r,t) = T_h(r,t) + T_s(r)
\]

\[
\begin{align*}
1 \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) = 0 \tag{4}
\end{align*}
\]

The boundary conditions for Equation (4) may be defined as follows:

\[
\begin{align*}
\text{B.C. :} & \quad \left[ C_n T(a,t) + C_{n_2} \frac{\partial T}{\partial r} \right]_{r=a} = g_i \tag{6}, \\
& \quad \left[ C_n T(b,t) + C_{n_2} \frac{\partial T}{\partial r} \right]_{r=b} = g_i
\end{align*}
\]

With Integrating Equation (4):

\[
T_i = \frac{C_i}{r} + C_{i_2} \tag{7}
\]

The integral constants in Equation (7) are applied as follows:

\[
\begin{align*}
C_{i_1} &= \frac{g_i}{C_{i_1}}, \\
C_{i_2} &= \frac{g_i}{C_{i_2}}, \\
\frac{C_{i_1} g_i - C_{i_2} g_2}{a^2 \left( a C_{i_1} - C_{i_2} \right)} - \frac{C_{i_1} g_i - C_{i_2} g_2}{b^2 \left( b C_{i_1} - C_{i_2} \right)}
\end{align*}
\]

or:

\[
C_i = \frac{g_i}{C_{i_1}} \left( C_{n_1} g_i - C_{n_2} g_2 \right) \tag{10}
\]

\[
\frac{1}{b^2} \left( b C_{i_1} - C_{i_2} \right) - \frac{1}{a^2} \left( a C_{i_1} - C_{i_2} \right)
\]

The boundary conditions for Equation (5) may be defined as follows:

\[
\begin{align*}
\text{B.C. :} & \quad \left[ C_n T(a,t) + C_{n_2} \frac{\partial T}{\partial r} \right]_{r=a} = 0 \tag{11}, \\
& \quad \left[ C_n T(b,t) + C_{n_2} \frac{\partial T}{\partial r} \right]_{r=b} = 0 \\
\text{I.C. :} & \quad T_i(r,0) = T_i(r) - T_i(r)
\end{align*}
\]

The integral constants in Equation (7) are as follows:

\[
\begin{align*}
C_i &= \frac{1}{\|f(r,\lambda_r)\|} \int_0^r T_i(r) f(r,\lambda_r) dr \\
&= \frac{1}{\|f(r,\lambda_r)\|} \left[ \frac{2\sqrt{\frac{a}{a'} \lambda_r^2}}{2} \right]
\end{align*}
\]

\[
\begin{align*}
&+ \frac{2a \lambda_r^2}{2} \left[ J_{\frac{3}{2}}(\lambda_r b) \left( A a \lambda_r^2 - B b \lambda_r \right) \right] \\
&+ \frac{2a \lambda_r^2}{2} \left[ J_{\frac{3}{2}}(\lambda_r a) \left( A a \lambda_r^2 - B b \lambda_r \right) \right] \\
&+ \frac{2a \lambda_r^2}{2} \left[ J_{\frac{3}{2}}(\lambda_r a) \left( A a \lambda_r^2 - B b \lambda_r \right) \right]
\end{align*}
\]

\[
f(r,\lambda_r) \quad \text{(Eigen-function)} \text{ is as follows:}
\]

\[
f(r,\lambda_r) = \frac{2}{2} \left( A J_{\frac{3}{2}}(\lambda_r a) + B J_{\frac{3}{2}}(\lambda_r b) \right)
\]

Where, \( J_{\frac{3}{2}} \) and \( J_{\frac{3}{2}} \) are Bessel functions of the first-kind and of order \( \left( \frac{1}{2} \right) \), respectively.

In addition, \( \lambda_r \) (eigenvalues) are positive roots of the Equation (15).
Finally, the temperature distribution is obtained as follows:

\[ T(r,t) = T_0 + \sum_{n=1}^{\infty} C_n f(r,\lambda_n) e^{-\alpha_n t} \quad (19) \]

3. Transient Thermoelastic Formulation

In the spherical symmetry condition, the strain-displacement equations are:

\[
\begin{align*}
\varepsilon_{rr} &= \frac{u_r}{r} \\
\varepsilon_\theta &= \frac{\partial u_\theta}{\partial r} \\
\end{align*}
\]

and the stress-strain equations are:

\[
\sigma_r = \frac{E}{(1+\nu)(1-2\nu)} \left( (1-\nu) \frac{\partial u_r}{\partial r} + 2\nu \frac{u_r}{r} \right) - (1+\nu)\alpha T \\
\sigma_\theta = \frac{E}{(1+\nu)(1-2\nu)} \left( \frac{u_r}{r^2} + \frac{\partial u_\theta}{\partial r} \right) - (1+\nu)\alpha T \\
T &= T(r,t) - T_0
\]

Where, E, \( \alpha \), \( \nu \) are young modulus, coefficient of linear thermal expansion, and Poisson’s ratio, respectively. In addition, \( \sigma_r \) and \( \sigma_\theta \) are radial and circumferential stresses components, and \( T_0 \) is reference temperature which in this study is assumed having zero value.

The equilibrium equation is as follows:

\[ \frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \quad (23) \]

Using Equations (20),(21) and (23):

\[ \frac{\partial}{\partial r} \left( \frac{1}{r^2} \frac{\partial (u_r r^2)}{\partial r} \right) = \frac{1+\nu}{1-\nu} \frac{\partial T}{\partial r} \quad (24) \]

With integrating Equation (24):

\[ u_r(r,t) = Ar + B + \frac{1+\nu}{1-\nu} \int_a^r T(r,t) dr \quad (25) \]

\( \sigma_r \) and \( \sigma_\theta \) are obtained with substituting Equation (25) into Equation (20),(21):

\[ \sigma_r = C_r - \frac{2C_r'}{r^3} \quad (26) \]
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\[ \sigma_{ao} = \sigma_{w} = C_{1} + C_{2} + \frac{C_{3}}{r} \]

\[ + \frac{\alpha E}{1 - \nu} \int_{r}^{a} r \frac{dT(r,t)}{dr} dr - T(r,t) \]  \hspace{1cm} (27)

Where,

\[ C_{1} = \frac{AE}{1 - 2\nu} \]

\[ C_{2} = \frac{BE}{1 + \nu} \]  \hspace{1cm} (28)

In this paper, the hollow sphere is subjected to pressures \( P_{a} \) and \( P_{b} \) at the inner and external surfaces, respectively:

\[ \sigma_{a}(r = a) = -P_{a} \]

\[ \sigma_{b}(r = b) = -P_{b} \]  \hspace{1cm} (29)

With substituting boundary conditions (Equation (29)) into Equation (26), \( C_{1} \) and \( C_{2} \) are obtained as follows:

\[ C_{1} = \frac{1}{b^{2} - a^{2}} \left( P_{a} a^{2} - P_{b} b^{2} \right) \]

\[ + \frac{2\alpha E}{1 - \nu} \int_{a}^{b} \frac{1}{r^{2}} r^{2} T(r,t) dr \]  \hspace{1cm} (30)

\[ C_{2} = \frac{a^{2} b^{2}}{2(b^{2} - a^{2})} \left( P_{a} - P_{b} \right) \]

\[ + \frac{2\alpha E}{1 - \nu} \int_{a}^{b} \frac{1}{r^{2}} r^{2} T(r,t) dr \]  \hspace{1cm} (31)

Where,

\[ \int_{a}^{b} r^{2} T(r,t) dr = C_{1} r^{2} + C_{2} \frac{r^{3}}{3} \]

\[ + \sum_{n=1}^{\infty} C_{n} e^{-\lambda_{n}t} \]

\[ \frac{\sqrt{r}}{\lambda_{n}^{2}} \left[ A \left( J_{1} (r \lambda_{n}) - r \lambda_{n} J_{1} (r \lambda_{n}) \right) \right. \]

\[ + B \left( J_{1} (r \lambda_{n}) + r \lambda_{n} J_{1} (r \lambda_{n}) \right) \]

\[ \left. - \frac{\sqrt{a}}{\lambda_{n}^{2}} \left[ A \left( J_{1} (a \lambda_{n}) - a \lambda_{n} J_{1} (a \lambda_{n}) \right) \right. \right. \]

\[ + B \left( J_{1} (a \lambda_{n}) + a \lambda_{n} J_{1} (a \lambda_{n}) \right) \]  \hspace{1cm} (32)

4. Results and Discussion

Consider a sphere with properties as follows

\[ a = 0.4 \text{ m}, \ b = 0.6 \text{ m}, \ E = 200 \text{ GPa}, \ \nu = 0.3 \]

\[ P_{a} = 70 \text{ MPa}, \ P_{b} = 70 \text{ MPa}, \ \rho = 7854 \text{ Kg/m}^{3} \]

\[ \alpha = 1.17 \times 10^{-5} \ 1/\text{C}, \ k = 60.5 \text{ W/m.K} \]

and \( C_{e} = 434 \text{ J/Kg.K} \)

Assume that the internal and external surfaces of the shell are under heat flux and convection, respectively. In addition the initial condition is also as a linear function in terms of the radius. Therefore:

\[ \left. \begin{array}{l}
- k \frac{\partial T}{\partial r} = q \\
- k \frac{\partial T}{\partial r} = h(T(b,t) - T_{\infty}) \\
T(r,0) = T_{i}(r) 
\end{array} \right\} \text{B.C.} \]

Using Equation (6)-(9) and Equation (33) the temperature distribution is obtained as follows:

\[ T_{i}(r) = T_{\infty} + \frac{aq}{k} \left( \frac{1}{r} - \frac{1}{b} + \frac{k}{b^{2}h} \right) \]

and:

\[ A = \frac{k}{a} J_{1} (\lambda_{a}) + k\lambda_{a} J_{1} (\lambda_{a}) \]

\[ B = -k\lambda_{a} J_{2} (\lambda_{a}) \]

Here \( \lambda_{a} \) are positive roots of the following equation:

\[ hJ_{1} (\lambda_{b}) - k\lambda_{b} J_{2} (\lambda_{b}) \]

\[ \times \left[ \frac{k}{a} J_{1} (\lambda_{a}) + k\lambda_{a} J_{1} (\lambda_{a}) \right. \]

\[ \left. - \left( h - \frac{k}{b} \right) J_{1} (\lambda_{b}) - k\lambda_{b} J_{2} (\lambda_{b}) \right] \times k\lambda_{b} J_{2} (\lambda_{b}) = 0 \]

The numerical parameters are presented as follows:

\[ q = 500 \text{ W/m}^{2} , \ T_{i}(r) = \frac{1}{r} \]

\[ T_{\infty} = 15^\circ \text{C} , \ h = 25 \text{ W/m}^{2}.\text{K} \]

Figure 1 shows temperature distribution for the course of 3600 seconds. The distribution of temperature at \( t = 3600 \text{sec} \) is shown in Figure 2. The temperature distribution for different radii versus time is indicated
in Figure 3. The temperature decreases whereas radius increases. The temperature distribution for different times versus radius is indicated in Figure 4. This Figure show that temperature increases as time increases.

![Figure 1. Distribution of temperature versus time for r = 0.45 m.](image1)

![Figure 2. Distribution of temperature versus radius at t = 3600sec.](image2)

![Figure 3. Distribution of temperature for various radii versus time.](image3)

![Figure 4. Distribution of temperature for various times versus radius.](image4)

Figures 5 to 7 provide an illustration of the distributions of radial displacement, radial and circumferential stresses vs. radial direction. Moreover, Figure 8 to 10 shows the distributions of radial displacement, radial and circumferential stresses vs. time. As could be seen in Figure 8, the radial displacement increases when time increases. Figure 9 shows that at first, radial stresses decreases and then it increases as time increases whereas in Figure 10 for circumferential stress this situation is reversed.

![Figure 5. Distribution of radial displacement versus radius at t = 3600 sec.](image5)
Figure 6. Distribution of radial stress versus radius at $t = 3600$ sec.

Figure 7. Circumferential distribution of stress versus radius at $t = 3600$ sec.

Figure 8. Distribution of radial displacement versus time in $r = 0.45$ m.

Figure 9. Distribution of radial stress versus time in $r = 0.45$ m.

Figure 10. Distribution of circumferential stress versus time in $r = 0.45$ m.

The comparison distribution of radial displacement and stress for various time and radii are shown in Figures 11 to 14. In these Figures, radial displacement, radial and circumferential stresses decrease in as radius increases whereas this situation for different times is reversed. Figures 15 and 16 show that values change of radial and circumferential stresses are very small while the time increases.
Figure 11. The compare of distribution of radial displacement for various radii versus time.

Figure 12. The compare of distribution of radial displacement for various times versus radius.

Figure 13. The compare of distribution of radial stress for various radii versus time.

Figure 14. The compare of distribution of circumferential stress for various radii versus time.

Figure 15. The compare of distribution of circumferential stress for various times versus radius.

Figure 16. The compare of distribution of circumferential stress for various times versus radius.
5. Conclusions

In this paper, using the infinitesimal theory of elasticity, thermo-elastic analysis in the transient condition of a thick pressurized sphere under general boundary conditions is presented. The material properties are isotropic and homogeneous. The temperature distribution is versus time and radius. The numerical results show that time and temperature has a significant effect on displacement and stresses.

6. References

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