Thermal stress assessment for a hollow cylinder under asymmetrical thermal loading

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Abstract : A thermo elastic analysis has been carried out for a thin hollow cylinder under asymmetric thermal loading. The cases study includes variation of temperature in azimutal direction and in radial direction. A FEM model of the cylinder developed with the help software ANSYS has been used for the analysis. The temperature variation has been used as boundary condition to the problem. The analyses show that maximum membrane stresses from thermal loads is experienced by the cylinder at maximum temperature gradient locations and they are found to be well within the allowable stress limits.

Key words: Thermo elastic behavior, thin hollow cylinder, thermal stress, FEM analysis

INTRODUCTION

Evaluation of thermal stress for various kinds of heat transfer equipments, storage vessel and pipes carrying high temperature fluid like steam are a part of a regular design assessment. For hollow cylinders like large diameter pipes are subjected to symmetric as well as asymmetric thermal loading based on the situation. These loading are primarily in radial and axial directions. A special care has been taken in design for asymmetrical loading cases as they result high thermal stress which can lead to failure of the piping. For superheated steam carrying pipes of larger wall thickness (thickness greater than $1/10^{th}$ of radius) is supposed to be much hotter from inside as compared to it's outer surface. This large temperature gradient across the thickness leads to an appreciable thermal stress. An axial temperature gradient can arise where a part of steam carrying section may not be insulated as compared to rest section with insulation due to some practical requirement or variation in pipe diameter leading to expansion/contraction of steam resulting different steam temperature. As various situation of thermal loading arise in the industries hence evaluation of thermal stress has become an essential design check and to decide the supports and anchors. Currently several commercial software like ANSYS, COMSOL, ABAQUAS etc. are in use for design evaluation for thermal stress in conjunction with other kinds of loading like pressure, sloshing etc.

Several authors have studied analytically the asymmetric loading of hollow cylinders with composite material as well as for isotropic and orthotropic material. Zibdeh et al. [1] carried out stress analysis in composite hollow cylinders due to an asymmetric temperature distribution. A solution is presented by Zibdeh et al. for the stresses and displacements in an orthotropic, hollow, circular cylinder subjected to asymmetric temperature distribution at the outer surface and heat convection into a medium at zero reference temperature at the inner surface. Assuming temperature-independent material properties, the heat conduction equation in cylindrical coordinates is solved for single and multilayer cylinders. Results of temperature analysis along with linear elasticity theory are used to obtain the required thermal stresses and displacements. Numerical results are given for a typical fiber-reinforced composite material where fibers in each layer are oriented axially or circumferentially. The results show that the response of the cylinder is sensitive to changes in thickness, orientation of fibers in each layer, number of layers, and stacking sequence.

In continuation to thermal stress evaluation Akbari et al. [2] evolved quadrature method for a rotating cylinder. The study details asymmetric deformation and stress analysis of a functionally graded hollow cylindrical shell under the effect of thermo-mechanical loads using the differential quadrature Method. Without losing the generality, material properties of the cylindrical shell are assumed to be graded in the radial direction obeying a power law, while the Poisson ratio is assumed to be constant in this study. The governing partial differential equations are expressed in terms of displacement and thermal fields in series forms with the help of two versions of differential quadrature methods, namely the polynomial and Fourier quadrature methods. The cylindrical shell is considered under both axisymmetric and asymmetric loading conditions. Numerical results for the axisymmetric loading condition of the cylindrical shell graded according to a power law function are obtained and compared with exact solutions which are found to be in very good agreement. Asymmetric thermo-elastic analysis presented by the authors for the shell rotating at a constant angular velocity causing the effect of the grading parameter, angular velocity, temperature difference and geometry on stresses, radial displacement and temperature fields.

The transient thermal loading needs more design evaluation assessment as the transient cyclic loads results to fatigue failures. A transient cyclic thermal loading is studied by Ning et al. [3] studied thermo elasticity problem in a Coke Drum where cladding failure is a design issue. Cracking and clad disbonding typically occur in cladding due to thermo mechanical cycling and high property mismatch between dissimilar materials in a coke drum. The thermoelasticity problem in a coke drum with cladding is assumed quasi-static and solved analytically by the authors. The transient temperature distribution in both radial and axial directions is derived analytically based on the two-dimensional heat conduction theory. The iteration technique is being used in the study to simulate the dynamic thermal boundary conditions caused by a fluid surface level rising continuously during both heated feed filling and water quench steps. Additionally, the classical laminated thin shell theory is applied to solve the quasi-static structural problem. The analytical results of the quasi-static thermo-elasticity problem are compared in the study with the finite element analysis. It is demonstrated analytically that during the water quench step, the maximum axial thermal gradient occurs at the inner surface of the clad, close to the water surface. The tension stresses occur in the clad due to its coefficient of thermal expansion smaller than that of the base metal material. Both the maximal axial stress and hoop stress occur at the cladding surface. These results derived by the authors is found to be helpful in explaining the formation mechanism of the clad disbonding and the shallow surface cracks at the inner surface of cladding.

Literature survey shows a number of investigations carried out for thick cylindrical vessel. Study carried out for thick vessel by A. E. Segall [4] investigates thermo-elastic stress assessment under thermal transients via the inverse route. A common threat to thick-walled vessels and pipes is thermal shock from operational steady state or transient thermo-elastic stresses. As such, boundary conditions must be known or determined in order to reveal the underlying thermal state. For direct problems where all boundary conditions (temperature or flux) are known, the procedure is relatively straightforward and mathematically tractable as shown by many studies. Although more practical from a measurement standpoint, the inverse problem where the boundary conditions must be determined from remotely determined temperature and/or flux data is ill-posed and inherently sensitive to errors in the data. As a result, the inverse route is rarely used to determine thermal stresses. Moreover, most analytical solutions to the inverse problem rely on a host of assumptions that usually restrict their utility to time frames before the thermal wave reaches the natural boundaries of the structure. To help offset these limitations and at the same time solve for the useful case of a thick-walled cylinder exposed to thermal loading on the internal surface, the inverse problem was solved by the authors using a least-squares determination of polynomial coefficients based on a generalized direct solution to the heat equation. Once the inverse problem was solved in this fashion and the unknown boundary condition on the internal surface determined, the resulting polynomial was used with the generalized direct solution to determine the internal temperature and stress distributions as a function of time and radial position. For a thick-walled cylinder under an internal transient with external convection, excellent agreement was found by the authors with known temperature histories. Given the versatility of the polynomial solutions advocated, the method appears well suited for many thermal scenarios provided the analysis is restricted to the time interval used to determine the polynomial and the thermo-physical properties that do not vary with temperature.

The effect of thermal stress on the failure of beryllium oxide hollow cylinder was studied by Swindeman [5] by assessing the thermal stress across the thickness with different boundary conditions. The theoretical treatment considered internal cooling, external cooling, internal heating with external cooling and external cooling with quenching. The author concluded that quenching either internal or external surface leads to failure of BeO thick cylinders.

The above mentioned studies are carried out for symmetric/asymmetric temperature variation in radial and axial direction. Very few literatures are available for evaluation of thermal stresses arising from temperature variation in azimuthal direction. An issue of pressuriser surge line integrity is discussed by Shah et al. [6]. The issue is relevant to the nuclear industry where the surge lines of pressuriser is subjected to hot and cold water stratified flow during start up and shutdown condition. A cyclic asymmetric thermal loading may cause a fatigue failure of such surge lines as reported by Figure 1 shows the typical surge line connecting pressiuriser and Figure 2 shows the cross section of the pipe containing thermal stratified flow.

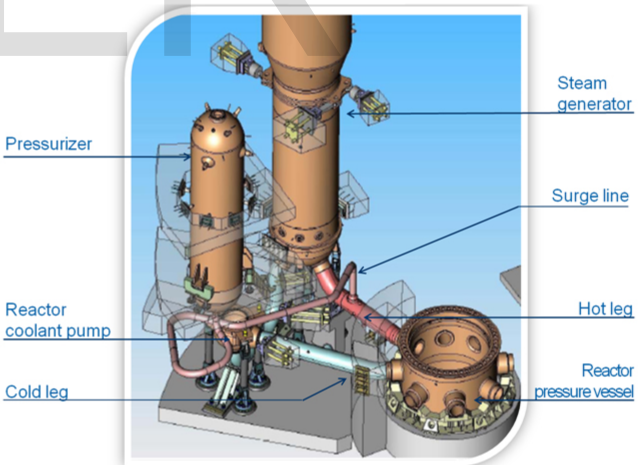

Figure 1: Schematic showing surge line

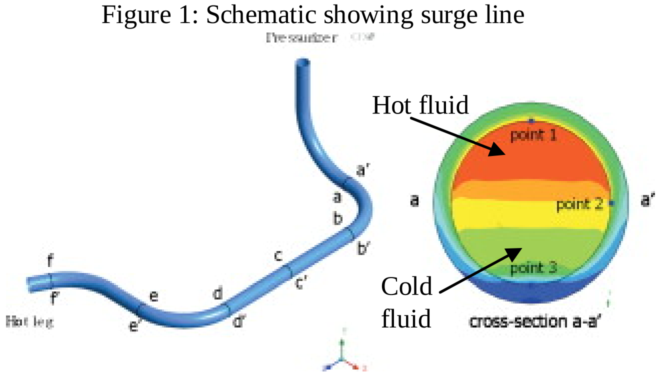

Figure 2: Schematic showing surge line and temperature field of stratified flow

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The issue has been investigated by Hag-ki-Yum [7] and Jhung et al. [8] analytically using CFX and ANSYS software. Temperature and displacement measurements are carrid out at plant also. The estimated stresses are used as guideline to limit the heat and cool down rates during startup and shutdown of the plant to minimize thermal stratification of fluid in the Pressuriser surge line.

The paper discusses estimation of thermal stresses for a SS vessel (6 m dia. and 0.5 m thk.) containing molten salt (m. p. 400^{o}C) filling up at different elevations of the vessel. Cases of 3/4th, ½ and 1/4th filled are studied. A FEM model has been developed and a azimuthal temperature gradient has been imposed on the vessel wall to estimate the stresses.

THEORY

Pipe will experience membrane stresses under a thermal stratified conditions as shown in Figure 1 (cold fluid at bottom and hot fluid at top). The stresses are found to be a function of angle between top and the interface of thermally stratified layer (Ø), the temperature difference (ΔT), thermal expansion coefficient of the pipe material (β) and Young's modulus. Membrane stresses for cold and hot regions for pipe with rigid supports are as follows,

$$\sigma_h = \left(\frac{\emptyset}{180°}\right)\Delta TE \quad (1)$$

$$\sigma_c = -\left(1 - \frac{\emptyset}{180°}\right)\beta\Delta TE \quad (2)$$

Pipe with flexible support will have additional bending stress as given below,

$$\sigma_c = 2\sin\left(\frac{\emptyset}{\pi}\right)\beta\Delta TE\,cos\Theta \quad (3)$$

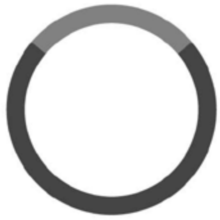
Maximum thermal stress is the summation of membrane and bending stress for the pipe, however for large diameter vessel only membrane stresses are applicable to evaluate thermal stress for a thermally stratified condition.

FEM MODEL

A FEM model of the vessel has been developed with different temperature conditions as per the filling up of the molten salt at upto different heights, This is illustrated in Figure 3,

Lower half hot

Lower quarter hot



Lower 3/4th quarter hot

Fig. 3: FEM model for the vessel with different temperature conditions

The FEM model has been developed using 3-D structural solid elements SOLID45. This element is defined by eight nodes having three degrees of freedom at each node. The finite element model using the solid element has three element layers in the radial direction and therefore has a total of 24336 nodes and 18252 elements. Different azimuthal temperature boundary conditions are imposed as shown in Figure 3. A 400^{o}C and 100^{o}C temperature conditions are imposed at hot and cold zones respectively.

CONCLUSION

The set of analyses show that the maximum membrane stresses are found to be at the interface of hot and cold zones where azimuthal thermal gradient is maximum.
All the stress values are found to be well within the allowable stress limits.

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