THERMO-ELASTIC STRESS ANALYSIS OF
CONTAINMENT WALL PENETRATIONS
USING IMPROVED FINITE ELEMENT FORMULATION

D. T. RAMANI, A. DIMOPOULOS
Sargent & Lundy Engineers, Inc.,
55 East Monroe Street, Chicago, Illinois 60603, U.S.A.

B. M. HEGLIN
Beratung für Statik, Dynamik und Energie, CH-8632 Dürrn, Switzerland

SUMMARY

An increased application of finite element techniques, particularly in evaluating structural integrity of nuclear containment walls around penetration points, has aroused considerable interest. Due to extreme thermal effects in the vicinity of penetrations, the concrete containment wall is subject to unwarranted cracking effects, which must be controlled in accordance with ASME-III Code. This paper essentially deals with a unique finite element method of analysis in which non-linear heat transfer problem across the penetration assembly in the nuclear containment drywell wall, is formulated. Using this technique, thermal analysis, dealing with an evaluation of temperature distribution around axisymmetric penetration assembly accommodating main steam lines or other vital piping at 600°F, is carried out. The method of analysis considers steady-state heat transfer energy balance across the process-pipe, insulation layer, guard-pipe sleeve, two intermediate air layers and an axisymmetric opening in the concrete containment wall, the outer faces of which are maintained at ambient temperature of 120°F. The finite element method of formulation accounts for an axisymmetric three-dimensional formulation for heat conduction through the process-pipe wall, an insulation layer, guard-pipe assembly and containment wall, which is assumed extended to infinity. Similarly, a finite element formulation is obtained for radiation and natural convection through the interposed air layers. Beckmann's technique, based on Grashof's numbers simulating natural convection of axisymmetric trapped layers into equivalent conductivity of air at high temperature, is adopted and applied to finite-element formulation.

The heat-flux at 600°F emitted by the process-pipe, passing through the penetration assembly and through the concrete wall, is ultimately dissipated through the thin film (based on film coefficient) across the outside faces of drywell wall. The method of analysis describes an exact procedure involving refined and realistic 3D-axisymmetric finite-element idealization of the entire penetration assembly for an exact evaluation of temperature distribution and thermal stresses in various regions including in the vicinity of opening in the concrete wall. Should the temperatures in concrete exceed 150°F, necessary cooling will be provided. The method of analysis also considers cooling-coil effects in an overall system and determines the revised concrete temperature distribution and stresses at nodal points.

The method of heat transfer problem formulation, technique of finite-element idealization for conduction, convection and radiation processes as well as corresponding solution to determine temperature distribution, are explained. The thermal stresses are evaluated in different regions of penetration assembly. The numerical results are compared with those of classical analytical methods and advantages of finite element method are explained. With this method, a number of intermediate air-gaps can be introduced and an overall steady-state heat balance across the system evaluated. The method is completely general with respect to geometry and material properties as well as explicitly stable to include temperature-varying material properties and radiation boundary conditions.
1. Introduction

The increased application of finite element method (FEM), particularly in analyzing two- and three-dimensional problems in nuclear safety-related structural components, is well-known (1) and has recently prompted a considerable research. This technique is applied herein to the containment wall penetration assemblies to evaluate the amount of heat energy being transmitted from the source to the cylindrical wall. The penetrations are openings in the containment or drywell wall of a BWR nuclear plant, designed to convey vital feedwater and mainsteam lines as well as electrical conduits. The penetration assemblies which are embedded in the concrete wall, exert three-dimensional mechanical and thermal loads from the piping system. The insulated piping (see Fig. 1), conveying fluids at excessively high temperature (usually in the range of 300°F to 650°F) and supported by the assembly, can overheat the surrounding concrete and cause unwanted cracking. As per recommendations of ASME Code Section III, it is intended due to safety considerations to prevent thermal cracking by providing a cooling-coil system to maintain the temperatures in the concrete at an allowable range of around 150°F to 200°F. Moreover the analysis and design of these penetrations must be performed in accordance with the provisions of the code to ensure that combined effects of thermal and mechanical loads are not exceeded.

It is the purpose of this paper to outline different types of critical thermo-elastic loads acting on the penetration assembly as well as to generate a unified method of analysis. It is intended to develop an exact method of heat-transfer analysis both due to steady-state and non-linear transient thermal gradients using FEM. The complete computer analysis is carried out in several stages to evaluate the maximum temperature distribution in all the subcompartments of the assembly as well as in the finite portion of the wall. While the available computer codes such as ANSYS, NASTRAN, KALSHHELL, MARC-CDC and SAP may be used in the complete mechanical and thermal analyses, a prior evaluation of thermal boundaries conditions must be made using classical methods. The present system developed however deals with what may be termed as a "mixed finite element formulation" of the heat transfer problem, in which classical heat balance equations are first considered around the penetration assembly for thermal boundary conditions, to be input to the existing NONHET Code (2), for yielding complete temperature and stress distributions of the structural subcomponents and the surrounding wall.

The classical analysis of heat-transfer problems dealing with steady-state conduction, convection and radiation processes in coaxial tubes with interposed air-gaps have been investigated earlier by Jakob (3), Beckmann (4) and Holman (5). This methodology was extended by Ramani et. al (6) to evaluate steady-state heat transfer across penetration assembly of the drywell-wall. Similar technique is extended to the fluid head penetration assembly (see Figs. 1 & 2) in conjunction with the finite element technique. The overall coordinated analysis and design using NONHET computer code is to ensure prediction of mechanical and thermal stress gradients in the wall as well as likelihood of possible cracks that might develop in the highly-stressed
regions. Then, in accordance with the ASME code, the principle consideration of incorporating relative magnitudes of thermal and mechanical stress levels in the flued-head sleeve is estimated. It must also be mentioned that problem of this nature where different materials are in contact with each other, certain discontinuity criteria make the classical analysis very complicated. To overcome this, a mixed formulation of classical and finite element methods is a only possibility. Besides, the classical problem alone is rendered highly complex due to geometry, different materials, nature of loading and perturbations caused by local constraints.

2. Problem Formulation, Assumptions & Method of Analysis

The typical mainsteam line passing thru the penetration consists of an insulated piping system and conveys fluid (heat flux) at a very high temperature \( T_0 \). As illustrated in Figs. 1 & 2, the assembly system carries an axisymmetric flued-head sleeve which is embedded in the surrounding concrete wall. The sleeve conducts the heat-energy \( Q_s \) from the heat source to the wall which at the same time receives additional amount of heat by way of radiation and convection through the air-gaps \( G \). The extent of the shell surface around the opening (see Fig. 3) to be included in the FE modeling is indeed a function of the diameter of the opening and its proximity to the boundary constraints. Candelines are established based on available literature and numerical errors. The pertinent ambient temperatures at the inside and outside faces of containment shell are 150\(^\circ\)F and 120\(^\circ\)F respectively. The heat-transfer coefficients, material properties of insulation, concrete, steel and air-medium are the basic input required to perform the mixed F.E. formulation with heat-transfer analysis. The penetration assembly is subjected to thermal gradients under normal steady-state, abnormal and severe transients.

2.1 Steady-State Mathematical Modeling

This analysis investigates the local thermal, mechanical and discontinuity stresses due to steady-state heat conduction thru the pipe wall, insulation layer and flued-head, as well as convection and radiation thru the air-gaps reaching the shell wall. The pipe heat-flux temperature \( T_0 \) gradually dissipates to \( T_w \) in the insulation layer, \( T_g \) in the air-gaps, \( T_s \) in the sleeve and finally to \( T_c \) in the concrete interface as shown in Figs. 2 & 3. The heat-energy \( Q_c \) conducted thru concrete similarly dissipates into the atmosphere thru the film coefficients \( h_L \) and \( h_R \) at the ambient temperatures \( T_{aL} \) and \( T_{aR} \) respectively. Depending upon the mean temperature \( T_g \) in the coaxial air gap, the equivalent conducting property \( K_{Eq} \) can easily be evaluated as explained by Jakob (3) and Beckmann (4). Defining the steady-state amount of conduction thru the insulation layer as \( Q_w \), the amounts of radiation and conduction thru air-medium as \( Q_R \) and \( Q_G \) respectively, the equilibrium equation of the system can be established as:

\[
\{ Q_s + (Q_R + Q_G) \} = Q_c \quad (1)
\]

\[
Q_w = \gamma_e (T_0 - T_w) \quad (2)
\]
FIG:1 TYPICAL LAYOUT OF MAINSTREAM LINE BETWEEN CONTAINMENT AND DRYWELL WALLS

FIG:2 SCHEMATIC DETAILS OF PENETRATION ASSEMBLY AT THE CONTAINMENT WALL

FIG:3 FINITE ELEMENT IDEALIZATION OF THE PENETRATION ASSEMBLY
in which equivalent conductivity $\gamma_e$ is known from the properties of piping and insulation and may be given as:

$$
\gamma_e = \ln \left( \frac{1}{2 \pi K_s L_D} \right) + \ln \left( \frac{1}{2 \pi K_w L_D} \right)
$$

(3)

Where: $R_i$ = inside pipe radius, $t$ = pipe-wall thickness, $W$ = insulation layer thickness, $K_s$ = conductivity of steel, $K_w$ = conductivity of insulation and $L_D$ = sleeve length.

Since part of heat energy is conducted by the sleeve directly to the wall, the equation (1) may be considered as dual in nature and may be expressed as:

$$
\left\{ Q_s + (Q_R + Q_G) \right\} = \left\{ Q_{cs} + Q_{CG} \right\}
$$

(4)

in which $Q_{cs} = \text{heat conducted to concrete wall via sleeve}$ and $Q_{CG} = \text{corresponding heat transmitted thru the air-gap}$. Due to linearity of heat-transfer problem, above equation may be rewritten as:

$$
Q_s = Q_{cs}
$$

(5)

$$
(Q_R + Q_G) = Q_{CG}
$$

(6)

Equation (5), which is essentially a conduction problem, can be easily formulated in the finite element form. It may be shown (3, 5) that net radiation flow of heat across the air gap 'G' follows the Stefan-Boltzman law and can be expressed as:

$$
Q_R = \frac{1}{4} (T_G^4 - T_s^4)
$$

(7)

Where: $\frac{1}{4}$ = coefficient of radiation thru air and 'T_G' and 'T_s' are absolute temperatures at the boundaries of the gap. The above equation can also be readily converted into the finite element formulation (1, 2). The free convection of air (usually termed as an equivalent conduction of air at high temperatures) enclosed in an annular gap of horizontal coaxial cylindrical tube was experimentally investigated by Beckmann (4) and corresponding results are summarized by Jakob (3). With this method, the quantity of heat convected thru the air-gap may be expressed as:

$$
Q_{CG} = \frac{2 \ K_{ea} \ \Phi \ L_D \ (T_G - T_s)}{\ln \ (R_o/R_i)}
$$

(8)

Where: $K_{ea}$ = equivalent conduction of air-layer, the heat flux $\Phi = \Phi (R_o/R_i, N_{GR})$, $R_o$ and $R_i$ = outer and inner radii respectively and $N_{GR}$ = Grashof's number, which can be used to evaluate $\Phi$. If all the finite element nodes are considered, the heat-energy equilibrium for the entire system can be written in the matrix form as:

$$
[K(T)] \ [T] = \ [Q]
$$

(9)

in which $[K(T)]$ = the system conductivity matrix for the process-pipe, the insulation layer, the flue-head sleeve and the air-layer. The vector $[T]$ = nodal point temperatures and $[Q]$ = vector of heat flows within the elements of process-pipe at temperature 'T_G'. The above matrix equation has been solved for unknown temperatures throughout the system by using modified NONHEAT Code (2).
2.2 Transient Analysis

The finite element method of analysis has also been successfully applied using to the penetration assembly under external thermal transient loads from the process-pipe. An explicit method (2, 7) has been applied to solve the non-linear formulation for the entire assembly system in which nodal temperatures, conductivity matrix and external thermal heats are all time-dependent. The differential equation representing the conduction, convection and radiation processes of the system, may be expressed as:

\[
[C(\rho)] \{\dot{T}(t)\} + [K(T)] \{T(t)\} = \{Q(t)\}
\]

(10)
in which, \([C(\rho)]\) = heat capacity matrix of the materials of density \(\rho\) and all other quantities are defined earlier. The vector \(\{Q(t)\}\) represents thermal transients applied to the process-pipe as an external load vector to the system.

3. Application to the Numerical Problems

To illustrate the solution technique as applied to practical numerical problems, the proposed method of analysis was applied to typical penetration assemblies in which mainsteam conveys fluid at high temperatures. Table-1, given below, illustrates the steady-state heat transfer across the penetration with thermal gradients in various components and quantities of heat that must be extracted by the cooling coils as per ASME Code criteria. Figures 4, 6 & 7 show the distributions of thermal gradients in the wall around the opening as well as stresses \(\sigma_{zz}\) and \(\sigma_{\theta}\) developed in the concrete wall if cooling was not provided. Table-2 illustrates the comparison of primary and secondary stress intensities for the normal and upset conditions in fluid-head at the junction with the pipe.

Table-1: Applications to Penetration Problems

<table>
<thead>
<tr>
<th>No:</th>
<th>Pipe O.D. (inch)</th>
<th>Fluid Temp. (T_o) (°F)</th>
<th>Insulation Thickness (inch)</th>
<th>Flued-Head Sleeve O.D. (inch)</th>
<th>Sleeve Thickness (inch)</th>
<th>Quantity of Heat Removal Btu/Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>24.0</td>
<td>620</td>
<td>3.0</td>
<td>48.0</td>
<td>0.50</td>
<td>11,280</td>
</tr>
<tr>
<td>(2)</td>
<td>20.0</td>
<td>550</td>
<td>3.0</td>
<td>50.0</td>
<td>0.50</td>
<td>6,870</td>
</tr>
<tr>
<td>(3)</td>
<td>18.0</td>
<td>555</td>
<td>3.0</td>
<td>48.0</td>
<td>0.50</td>
<td>4,650</td>
</tr>
<tr>
<td>(4)</td>
<td>12.0</td>
<td>500</td>
<td>3.0</td>
<td>36.0</td>
<td>0.50</td>
<td>3,900</td>
</tr>
</tbody>
</table>

Table-2 Comparison of Primary Plus Secondary Stress Intensities for Normal & Upset Conditions (ksi)

<table>
<thead>
<tr>
<th>Location (FIG: 2)</th>
<th>Flued-Head Sleeve Configuration</th>
<th>Mechanical Loads</th>
<th>Thermal Loads</th>
<th>Mechanical Plus Thermal</th>
<th>Code Allowable (3 S_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>As shown</td>
<td>18,200</td>
<td>40,400</td>
<td>40,300</td>
<td>43,000</td>
</tr>
<tr>
<td>(2)</td>
<td>As shown</td>
<td>11,900</td>
<td>25,700</td>
<td>19,400</td>
<td>45,000</td>
</tr>
</tbody>
</table>
FIG: 4 DISTRIBUTION OF THERMAL GRADIENTS THRU WALL THICKNESS

FIG: 5 SIGN CONVENTION OF TRACTION-STRESSES ON THE WALL ELEMENT

FIG: 6 AXIAL COMPRRESSIVE STRESSES IN THE WALL ALONG Z-AXIS

FIG: 7 TANGENTIAL & RADIAL STRESSES IN THE WALL ALONG R & Ø-AXIS
4. Conclusions & Discussions

An improved finite-element method of analysis has been developed for the heat-transfer analysis of penetration assemblies embedded in the containment or drywell wall. The method of analysis capability utilizes exact heat-transfer processes in conduction in solids and convection as well as radiation thru air-gap. By implementing equivalent conduction capability thru air-gap, NONHEAT computer code has been modified to include such effects based on Craschof's numbers and Beckmann's techniques. The improved method is efficient and reliable in evaluating accurately the amount of heat transmitted to the surrounding concrete wall. Using this technique, an optimal cooling capacity of the coils can be suitably designed to ensure protection of the assemblies. Besides, an inclusion of such refinements as in the present technique, has resulted in simulating accurate temperature and stress distributions in all the subcomponents of the assembly as well as in the concrete wall around the opening. By including the effects of heat conduction thru air-gap, an accurate thermal behavior of subcomponents can be predicted under complicated thermal transients.

By using the present finite-element technique and incorporating the present refinements, very complicated geometries of penetration assemblies have been analyzed. The present method is economically incorporated in the NONHEAT computer code and can handle a large segment of the wall around the opening for an accurate stress distribution. An accurate evaluation of discontinuity stresses at interface between dissimilar materials has been obtained.

5. References