New algorithm for simulating heat transfer in a complex CPFS (Cable Penetration Fire Stop)

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Abstract: In this work the dynamic heat transfer occurring in a cable penetration fire stop system built in the firewall of nuclear power plants is three-dimensionally investigated to develop a test-simulator that can be used to verify effectiveness of the sealants. The dynamic heat transfer can be described by a partial differential equation (PDE) and its initial and boundary conditions. For the shake of simplicity PDE is divided into two parts; one corresponding to the heat transfer in the axial direction and the other corresponding to the heat transfer on the vertical layers. Two numerical methods, SOR (Sequential Over-Relaxation) and FEM (Finite Element Method), are implemented to solve these equations respectively. The axial line is discretized, and SOR is applied. Similarly, all the layers are separated into finite elements, where the time and spatial functions are assumed to be of orthogonal collocation state at each element. The heat fluxes on the layers are calculated by FEM. It is shown that the penetration cable influences the temperature distribution of the fire stop system very significantly. The simulation results are shown in the three-dimensional graphics for the understanding of the transient temperature distribution in the fire stop system.

Keywords: Dynamic heat transfer, Finite element method, Sequential over-relaxation, Partial differential equation, Cable penetrated fire stop system.

1. INTRODUCTION

For a few decades a great number of nuclear power plants have been constructed and are operating worldwide to supply the industrial and household electricity. Now, 14 nuclear power plants are operating night and day in the republic of Korea, and 6 nuclear power plants are newly under construction. According to the long-term policy, about 20 additional nuclear power plants will be constructed in South Korea until 2020. Due to the so rapid increase of the number of nuclear power plants, a great deal of social concern has been concentrated on the accidents risk of the nuclear power plant in recent times. The accidents risk is well known previously, and fires among the accidents are especially dangerous. Fires can critically affect the control systems of the nuclear power plant because of their quick spread. The fire penetration seal systems that prevent the passage of the fire, gas and heat between compartments so as to reduce the damage and to save lives are deeply associated with the products assembled in the field or pre-manufactured. Silicone and Latex sealant fire stop systems are usually employed in sealing around metal pipes, joints and gaps. All fire stop systems are tested under the same ASTM standard to ensure repeatability and suitability for the specific application. The Tennessee Valley Authority Browns Ferry nuclear power plant accident that was on March 22 in 1975 resulted in the change of ASTM E-119 to ASTM E-814 or UL-1479, as a standard for testing the performance of fire penetration seal systems. According to the new testing method, previous fire stop systems were revaluated and safety was improved. The fire stop systems have a major responsibility in defense-in-depth.

In this work a simplified fire stop system is considered, shown in Fig. I. The cable penetration fire stop systems built in a nuclear power plant is from 3,000 to 10,000 in number. Because of the great number of the fire stop systems constructed under the old standard of ASTM E-119, safety of all the systems did not verify with the new test method of ASTM E-814 up to now. Corresponding to ASTM E-814, not only the F-rating test but also the T-rating test should be carried out to verify the fire stop system. For that purpose the complementary use of a test-simulator is suitable. Especially, the unsteady-state heat conduction in the fire stop system should be investigated in order to develop the test-simulator that the T-rating test of the fire stop system can be carried out with.

The dynamic heat transfer phenomenon occurring in the fire penetration seal system is formulated in a parabolic partial differential equation subjected to a set of boundary conditions. First, the PDE model is divided into two parts; one corresponding to the heat transfer in the axial direction and the other corresponding to the heat transfer on the vertical faces. The first partial differential equation is converted to a series of ordinary differential equations at finite discrete axial points for applying the numerical method of sequential over-relaxation (SOR) to the problem. After that, we can solve the ordinary differential equations by using an integrator, such as an ODE (ordinary differential equation) solver. In such manner the axial heat flux can be calculated at least at the finite discrete points. For the shake of simplicity a few assumptions are given in this work. There is no heat transfer between the fire stop system and the firewall. The surface of fire site of the fire stop system is always at the temperature of the standard curve of ASTM-119, and the penetration cable is also at the same temperature of the surface. These assumptions are summarized as the boundary condition equations. According to the standard method of ASTM E-814, the fire stop system is exposed to a standard temperature-time fire, and to a subsequent application of cable streams for testing the cable penetration fire stop system. Ratings are established on the basis of the period of resistance to the fire exposure, prior to the first development of through openings, flaming on the unexposed surface, limiting thermal transmission criterion, and acceptable performance under application of the cable stream. This test method specifies that pressure in the furnace chamber with respect to the unexposed surface shall be that pressure which will be applicable to evaluate the fire stop system with respect to its field installation. This pressure shall be determined by a specific code requirement, by the special pressures in the building, in which the fire stop system is to be installed, or by the test sponsor requesting a special environment to evaluate the fire stop specimen (ASTM, 1993). The fire test is performed with the standard temperature-time curve, as shown in Fig. I.

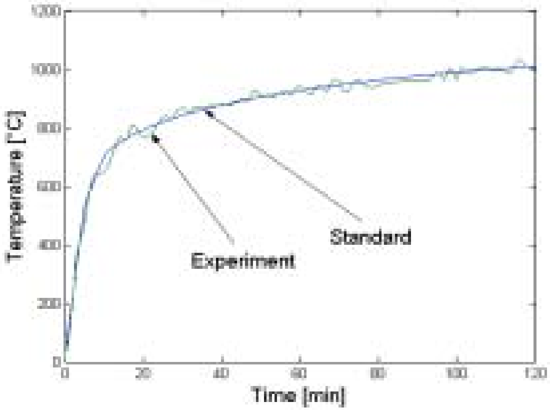


Fig. I: The standard temperature-time curve of ASTM E-119 and the experimental time-temperature curve.

2. MATHEMATICAL MODEL

It is assumed that heat transfer is constant against the change of temperature and pressure, and there is no additional heat generation in the cable penetration fire stop system. In this case the unsteady-state heat transfer in the fire stop system can be described by the parabolic partial differential equation, as follows:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (1)$$

The thermal diffusivity α represents the physical property of a sealing material of the fire stop system. The cable penetration fire stop system can be simplified as a cubic, in which several cables are through-passed, at Cartesian coordinate, as shown in Fig. II.

For the shake of simplicity we assumed that the initial temperature of the cable penetration fire stop system and its surface are constant at the temperature of T_0, and the temperature of the inner faces and the whole cables are constant at the temperature of T_h.

$$T(x, y, z, 0) = T_0 \qquad (2)$$

$$T(x, y, 0) = T_h \qquad (3)$$

for $0 \le x \le X$, $0 \le y \le Y$.

$$T(x, y) = T_h \qquad (4)$$

for $(x - x_i)^2 + (y - y_i)^2 \le r_i^2$, $i = 1, 2, ...$

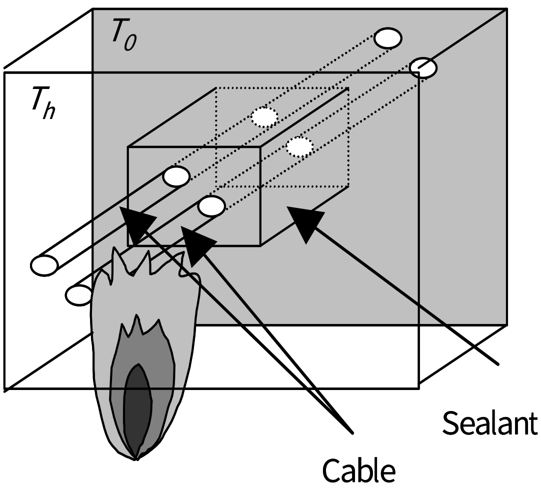


Fig. II: Simplified cable penetration fire stop system.

In addition it is assumed that there is no thermal exchange between the fire stop system and the firewall through the four interfaces – the bottom, up, left and right sides surrounding the sealant cubic, i.e. they are under the adiabatic condition. As a result, it can be described by following equations.

$$-k\frac{\partial T}{\partial x}\Big|_{x=0} = -k\frac{\partial T}{\partial x}\Big|_{x=X} = -k\frac{\partial T}{\partial y}\Big|_{y=0} = -k\frac{\partial T}{\partial y}\Big|_{y=Y} = 0 \qquad (5)$$

The last assumption is that the opposite surface (z=Z) is at a constant temperature of T_Z, and the heat flux, which spreads from the solid surface, is proportional to the temperature difference between the solid surface and the bulk of air, as follows.

$$-k\frac{\partial T}{\partial z}\Big|_{z=Z} = h(T - T_0) \qquad (6)$$

The unsteady-state heat transfer phenomena in the fire stop system can be modelled by a parabolic partial differential equation *Eq.* (1) subjected to an initial condition *Eq.* (2) and a series of boundary conditions *Eqs.* (3), (4), (5) and (6).

3. NUMERICAL CALCULATION

To solve the complex three-dimensional initial value partial differential equation, we used two numerical methods SOR (Sequential Over-Relaxation) and FEM (Finite Element Method) in turn. In this algorithm we calculated the z-axis components derived from the initial value partial differential equation at Cartesian coordinate, and several two-dimensional rectangular systems can be calculated with the results of the z-axis components iteratively. The heat transferred in the z-axis can be calculated by the numerical method of SOR, and the heat transfer on the x-y-layers can be estimated with the numerical method of FEM. Originally, the SOR method is developed as a very sophisticated hand computation technique for solving large sets of simultaneous linear equations iteratively. The overall approach is not well suited to digital computer use because of the extensive logic required, but the original concepts are embodied in the simple but powerful computer-oriented method. Basically, SOR works by using an initial guess of the solution and then progressively improving guesses until an acceptable level of accuracy is reached (Southwell, 1940; Monte, 2002).

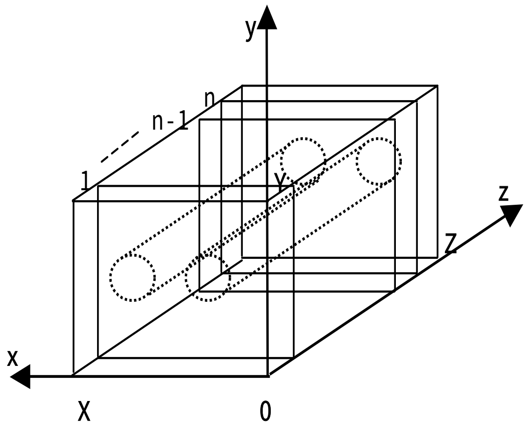


Fig. III: Schematic figure of the fire stop system.

Consider n+1 parallel layers in the fire stop system, as shown in Fig. III. First of all, One-dimensional (z-axis) heat conduction in the fire stop system is described as follows:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial z^2}\right) \qquad (7)$$

By using the numerical method of SOR the partial differential equation Eq.(7) is discretized to *n* ordinary differential equations.

$$\begin{aligned}
\frac{\partial T_1}{dt} &= \alpha\left(\frac{T_2 - 2T_1 + T(0,t)}{\Delta z^2}\right)\\
\frac{\partial T_2}{dt} &= \alpha\left(\frac{T_3 - 2T_2 + T_1}{\Delta z^2}\right)\\
&\vdots\\
\frac{\partial T_n}{dt} &= \alpha\left(\frac{T_z - 2T_n + T_{n-1}}{\Delta z^2}\right)
\end{aligned} \qquad (8)$$

For the first calculation the initial temperature is constant at the temperature of T_0 for every finite element, but the next step temperature of finite element T_P's can be calculated by FEM (Finite Element Method). Often in the finite element approach, the partial differential equation describing the desired quantity (such as displacement) in the continuum is not dealt directly. Instead, the continuum is divided into a number of finite elements, which assumed to be joined at a discrete number of points along their boundaries. A functional form is then chosen to represent the variation of the desired quantity over each element in terms of the values of this quantity at the discrete boundary points of the element (Becker, *et al*., 1981; Feirweather, 1978). By using the physical properties of the continuum and the appropriate physical laws, a set of simultaneous equations in the unknown quantities at the element boundary points can be obtained. The temperature of the front surface is constant at the hottest temperature T_h.

$$\begin{aligned} T(z,0) &= T_0 \\ T(z,t) &= T_P \\ T(0,t) &= T_h \end{aligned} \tag{9}$$

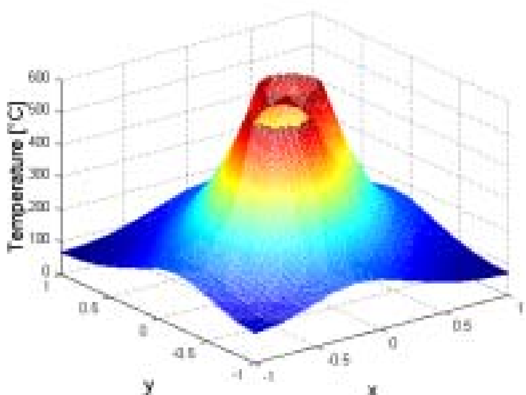
On the assumption that the temperature of the back surface is constant at the initial temperature of T_0, the initial temperature, the heat flux that passes through a layer is proportional to the temperature difference between the layer ($z = z_i$) and the next layer ($z = z_{i+1}$). Therefore, the equation *Eq.* (6) can be approximated to the following equation by using the forward difference method.

$$T_z = \frac{h \cdot T_0 + \dfrac{k}{2 \cdot \Delta z}(4T_n - T_{n-1})}{h + \dfrac{3k}{2 \cdot \Delta z}} \tag{10}$$

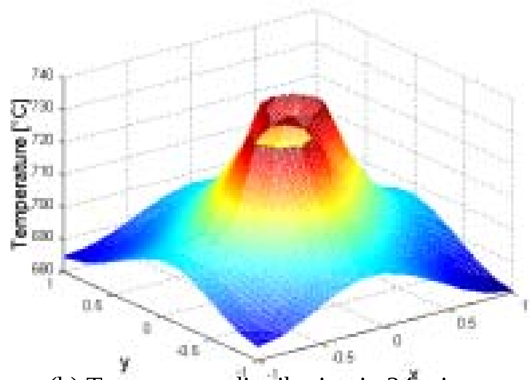
Moreover, the horizontal heat transfer of the back surface can be estimated and can be applied to p finite elements by the partial differential equation *Eq*. (11).

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \tag{11}$$

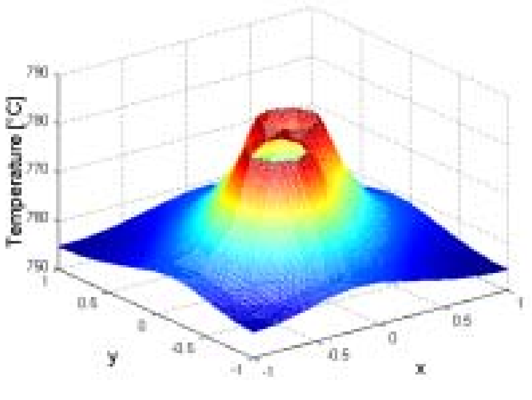
where the specific functions $\{\Phi_j(x) \mid j = 1,\cdots, N_P\}$ and $\{T_j(t) \mid j = 1,\cdots, N_P\}$ are piecewise continuously differentiable (Golebiowski and Kwieckowsk, 2002; Alazmi and Vafai, 2002). The initial condition of each finite element can be obtained from the solution of *Eq*. (8) repeatedly. The whole cable temperature is always assumed to be constant at the temperature of T_h. The temperature $T(x, t)$ as a function of time t and space x can be expressed by the multiplication of the temperature function $T_j(t)$ and the element function $\phi_j(x)$ at the state of orthogonal collation as follows:



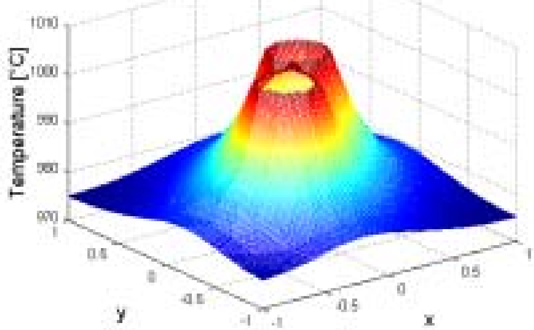
(a) Temperature distribution in 12 minutes.



(b) Temperature distribution in 24 minutes.



(c) Temperature distribution in 36 minutes.



(d) Temperature distribution in 120 minutes.

Fig. IV: Dynamic changes of the temperature distribution on the outer surface of the fire stop system.

$$T(x,t) = \sum_{i=1}^{N_P} T_i(t)\,\phi_i(x) \qquad (12)$$

The partial differential equation *Eq.* (11) subjected to the initial condition and the boundary conditions can be expressed as following ordinary differential equations.

$$M\frac{dT}{dt} + KT = L\,, \qquad (13)$$

where $M = \sum_i \left\{ \int_\Omega (\phi_j \cdot \phi_i) dx \right\}$,

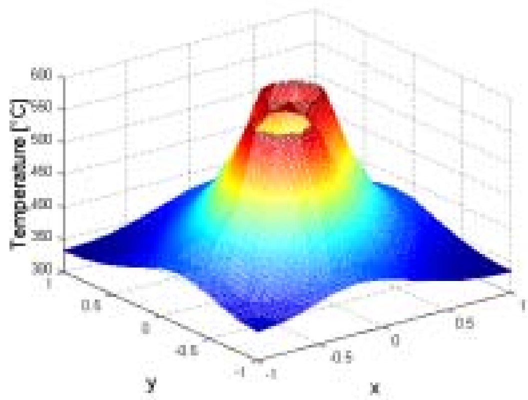
$$K = \sum_i \left\{ \int_\Omega (\nabla\phi_j \cdot \alpha\nabla\phi_i) dx + \int_{\partial\Omega} (\phi_j \cdot \phi_i) ds \right\},$$

$$L = \sum_i \left\{ \int_{\partial\Omega} (l \cdot \phi_i) ds \right\}.$$

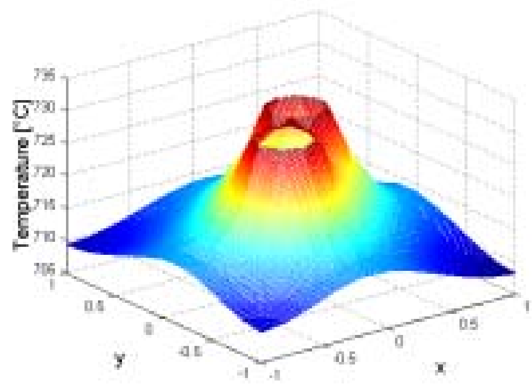
By solving these ordinary differential equations, we can obtain the nodal values as an approximate solution. The computations are performed on the computer Pentium IV-2.0 GHz. The program packet MATLAB is used for realizing the recommended algorithm. The initial temperature of T_0 is fixed at the temperature of 20 ℃, and the fire side wall temperature of T_h follows the ASTM E-119 standard temperature-time curve, changing from the initial temperature of 20 ℃ to the final temperature of 1,200 ℃ for two hours. As a simple geometry, the fire stop system with two penetrated cables is simulated in this work. The temperature values of 2323 elements are estimated simultaneously. The result of the estimation is used as the initial temperature values for calculating the temperature values at the five discrete axial points on each node of the elements. The calculation is carried out by SOR. The result is used again for the initial temperature values of the FEM calculation. In this manner the temperature distribution in the fire stop system is computed repeatedly.

4. RESULTS AND DISCUSSION

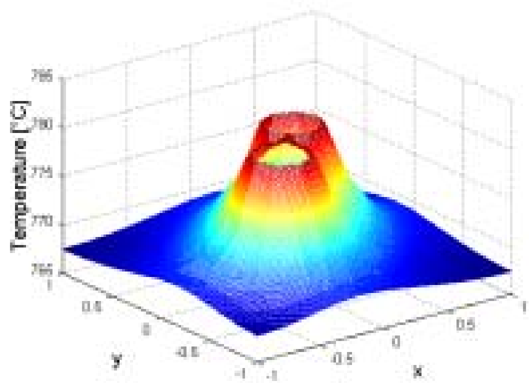
Simulation results are shown in Fig. IV and in Fig. V. The temperature distributions on the surface outer wall of the cable penetration fire stop system, which was built between compartments of the nuclear power plant, were calculated and the simulation results were three-dimensionally presented so as to show the dynamical heat conduction in the fire stop system. As shown in Fig. IV (a), the temperature around the cables reaches about 600 °C in 12 minutes. The temperature values



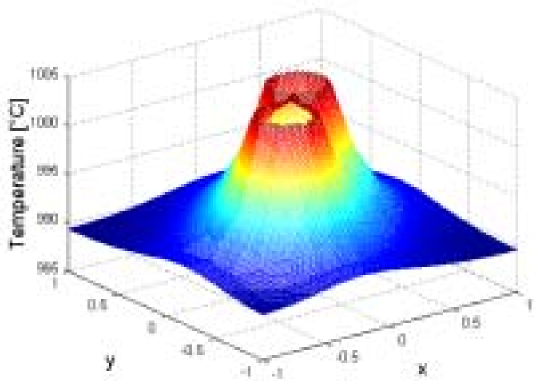
(a) Temperature distribution in 12 minutes.



(b) Temperature distribution in 24 minutes.



(c) Temperature distribution in 36 minutes.



(d) Temperature distribution in 120 minutes.

Fig. V. Dynamical changes of the temperature distribution on the inner face placed in the fire stop system.

near the firewall are under 100 °C. The temperature of the system rises very quickly in keeping with the standard temperature-time curve, as shown in Fig. I. According to the temperature distribution shown in Fig. V (b), the fire heat is transferred along to the cables quickly at the start, while the heat conduction occurs on the layers slowly. On the other hand, it is over the temperature of 700 °C around the cables in 24 minutes, and the temperature near the firewall is over the temperature of 680 °C. That means, the heat transfer on the layer is already progressed very much as well as the heat transfer along the penetrated cables. While the temperature rises in 36 minutes, the temperature difference becomes smaller with time. Furthermore, the temperature distribution in two hours is ranged from the temperature of 675 °C to the temperature of 1,000 °C, as shown in Fig. IV (d).

Similarly, the temperature distribution of the inner site located at a quarter distance of the wall thickness is shown in Fig. V. It consists of four figures. These figures could be compared with each other. By comparing the figures we could get more information for understanding the temperature distribution in the cable penetration fire stop system. The temperature distribution shown in Fig. V (a) is ranged from the temperature of 325 °C to the temperature of 600 °C in 12 minutes. In this case the temperature difference is much less than the case shown in Fig. IV (a). That means that the heat conduction is not working in a steady state, but is working dynamically. Fig. V (b) shows the results as follows. In 24 minutes the temperature variation around the penetrated cables is almost the same to the standard curve, and the difference between the maximum and minimum temperatures is about 20 °C. As shown in Fig. V (c), the temperature difference is decreased with time. The axial temperature difference near the firewall is more than 5 °C, as indicated in Fig. IV (d) and in Fig. V (d). Consequently, we can find the fact that the heat transfer through the cable stream is very significant and the heat conduction is not in a steady state.

5. CONCLSION

This work was aimed to know how the dynamics of heat conduction came about in the cable penetration fire stop system between compartments of nuclear power plants. Furthermore, the interest has focused on the thermal development around the penetration cables. The cable penetration fire stop system was modelled, simulated and analysed. The simulation results were illustrated in three-dimensional graphics. Through the simulations it was shown clearly that the temperature distribution was influenced very much by the number, the position and the temperature of the penetrated cables. Another significant contribution of this work is the development of an efficient numerical algorithm that consists of SOR and PEM for solving special partial differential equations. This numerical algorithm could be applied to the dynamic heat conduction problem successfully. At last, it was found that the dynamic heat transfer through the cable stream was one of the most dominant factors, and the feature of heat conduction could be understood as an unsteady-state and dynamic process.

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