DYNAMIC HEAT CONDUCTION IN A PENETRATION CABLE OF THE FIRE STOP SYSTEM

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Abstract: Fire stop systems prevent the passage of fire, gas and heat between compartments, so that they reduce the damage and save lives, which 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 pipes, cables, joints and gaps. All fire stop systems are tested under the same ASTM standard to ensure repeatability and suitability for the specific application. The fire stop systems have a major responsibility in defense-in-depth. Because of a great number of 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. Ratings are established on account of the resistance time to the fire exposure, the development time of first through opening, flaming on the unexposed surface, limiting thermal transmission criterion, and acceptable performance under application of the cable stream. 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, dynamic heat conduction in a cable through the fire stop system should be investigated to develop the test-simulator that the T-rating test of the fire stop system can be carried out with.

Dynamic heat conduction occurring in the cable through the fire stop system is formulated in a parabolic partial differential equation subjected to a set of initial and boundary conditions. There are a few assumptions given in this work. There is no heat flow from the fire stop system to the tray of penetration cables and to the firewall. Fire tests are performed with the ASTM-119 standard temperature-time curve. The fire-side surface of the fire stop system is always at the temperature of the ASTM-119 standard temperature-time curve, and the fire-side surfaces of the tray and of the cable streams are also assumed to be at the same temperature. These assumptions are summarized as the boundary condition equations. First, the partial differential equation is converted to a series of ordinary differential equations at finite elements, where the time and spatial functions are assumed to be of orthogonal collocation state at each element. The heat fluxes are calculated by the Galerkin finite element method.

This work was aimed to know how dynamic heat conduction came about in the penetration cable of the fire stop system between compartments of nuclear power plants. Therefore, the interest was concentrated on computing the thermal development around the penetration cables. The penetration cable was modeled, simulated and analyzed. Through the simulations it was shown clearly that the temperature distribution was influenced very much by the thickness of the cable and its covering. In addition, it was found that the feature of heat conduction could be understood as an unsteady-state process. These numerical results are useful for making a performance-based design for the cable penetration fire stop system.

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

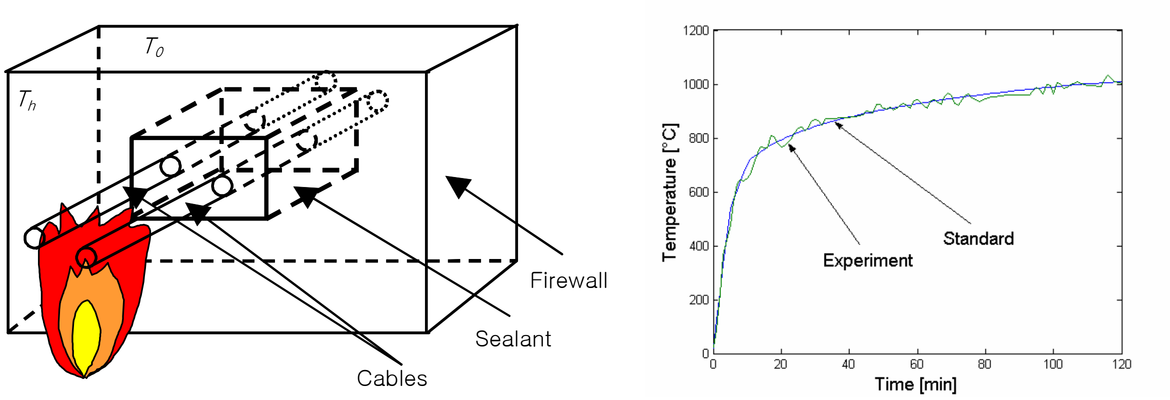
NOMENCLATURE

A, B, C	Constants
C_p	Specific heat
h	Heat transfer cofficient
k	Thermal conductivity
i,j	Indices
N_P	Number of the element
t	Time
T	Temperature
T_0	Initial Temperature
T_f	Surrounding temperature
T_h	ASTM E-119 standard *T-t* curve
T_p	Temperature of the finite element
T_{cable}	Temperature of the cable
T_{tray}	Temperature of the tray

T_{wall}	Temperature of the wall
x, y, z	Coordinates
α	Thermal diffusivity
ρ	Density
$\partial\Omega_{cable}$	Domain of the cable
$\partial\Omega_{tray}$	Domain of the tray
$\partial\Omega_{wall}$	Domain of the wall
Φ_j	Element function

INTRODUCTION

Currently, electricity consumption is drastically increasing in the world. Therefore, a great number of nuclear power plants have been constructed worldwide to supply the industrial and household electricity. In the republic of Korea alone 14 nuclear power plants are operating night and day and 6 nuclear power plants are newly under construction. According to the long-term policy of the Korean government, about 20 additional nuclear power plants will be constructed in South Korea until 2020. Due to such a rapid increase in the number of nuclear power plants, a great deal of social interest has been taken in accidents in the nuclear power plant in recent years. Among a variety of accidents, fires are especially dangerous, and the risk of accidents in the nuclear power plant is well known previously. The control systems of the nuclear power plant can be critically damaged by a quick spread of fires. 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. 1 (a).



(a) The CPFS system (b) ASTM E-119 Standard *T-t* curve

Fig. 1: Simplified cable penetration fire stop system and ASTM E-119 standard temperature-time curve

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. Test-simulators are suitable for such complementary uses. Especially, dynamic 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. Dynamic heat conduction 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 carried out with the ASTM standard temperature-time curve, as shown in Fig. 1 (b).

MATHEMATICAL MODEL

It is assumed that heat conduction 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 dynamic heat conduction in the fire stop system can be described by the parabolic partial differential equation, as follows:

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

The thermal diffusivity α represents the physical property of the material sealing in the fire stop system. The cable penetration fire stop system can be simplified as a cubic block, in which several cables are through-passed, at Cartesian coordinate, as shown in Fig. 1. For the shake of simplicity we assume 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 surface and the whole cables follow the ASTM standard temperature-time curve $T_h(t)$ that is shown in Fig. 1 (b).

$$T(x, y, z, 0) = T_0 \tag{2}$$

$$T(x, y, 0, t) = T_h (t) \tag{3}$$

In addition it is assumed that heat transfer takes place between the fire stop system and the firewall through the four interfaces – the bottom, up, left and right sides surrounding the sealant cubic block, i.e. they are not under the adiabatic condition. Analogously, it is assumed that the sealant is heated with the tray and the cables. As a result, it can be described by following equations.

$$T(x, y, t) = T_{\mathrm{wall}}(z, t) \qquad \text{on } \partial\Omega_{\mathrm{wall}} \tag{4}$$

$$T(x, y, t) = T_{\mathrm{tray}}(z, t) \qquad \text{on } \partial\Omega_{\mathrm{tray}} \tag{5}$$

$$T(x, y, t) = T_{\mathrm{cable}}(z, t) \qquad \text{on } \partial\Omega_{\mathrm{cable}} \tag{6}$$

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

$$-k\frac{\partial T}{\partial z}\Big|_{z=Z} = h(T - T_0) \tag{7}$$

Dynamic heat transfer in the fire stop system can be modelled by a parabolic partial differential equation (1) subjected to an initial condition *Eq*. (2) and a series of boundary conditions from *Eq*. (3) to *Eq*. (7).

NUMERICAL CALCULATION

To solve the complex three-dimensional initial value problem formulated with the partial differential equation, we used two numerical methods, FDM (Finite Difference Method) and FEM (Finite Element Method), alternately. In this hybrid algorithm the amount of heat conduction that flows in parallel with the z-axis is described by an initial value partial differential equation, which can be numerically solved by SOR (Sequential Over-Relaxation). Otherwise, the amount of heat flow on the two-dimensional x-y-layer is described by an initial value partial differential equation, which can be numerically estimated by the Galerkin FEM. This result is used for the initial value of that calculation, and vice versa. In the beginning 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).

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

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial z^2} \right) \tag{8}$$

By using the numerical method of SOR the partial differential equation (8) is discretized to *n* ordinary differential equations (9).

$$\begin{aligned} \frac{\partial T_1}{dt} &= \alpha \left(\frac{T_2 - 2T_1 + T(0,t)}{\Delta z^2} \right) \\ \frac{\partial T_2}{dt} &= \alpha \left(\frac{T_3 - 2T_2 + T_1}{\Delta z^2} \right) \\ &\vdots \\ \frac{\partial T_n}{dt} &= \alpha \left(\frac{T_z - 2T_n + T_{n-1}}{\Delta z^2} \right) \end{aligned} \tag{9}$$

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 the Galerkin FEM. 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.

$$\begin{aligned} T(z,0) &= T_0 \\ T(z,t) &= T_P \\ T(0,t) &= T_h \end{aligned} \tag{10}$$

On the assumption that the temperature of the outside surface is constant at the initial temperature 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 (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 (11).

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

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:

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

The specific functions $\{\Phi_j(x, y) \,|\, j = 1,\cdots, N_P\}$ and $\{T_j(t) \,|\, j = 1,\cdots, N_P\}$ 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 cable, the wall and the tray are assumed to be heated with the temperature of ASTM E-184 temperature-time curve $T_h(t)$. As boundary conditions, their temperatures are always calculated in parallel. In the end the partial differential equation (11) subjected to the initial condition and the boundary conditions can be expressed as a series of ordinary differential equations.

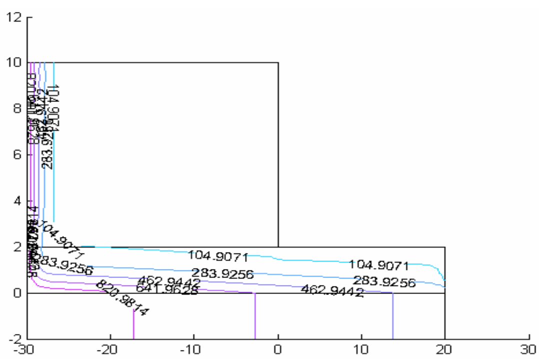
$$A \frac{dT}{dt} + BT = C\,, \tag{13}$$

where $A = \iint \left(\Phi \cdot \Phi^T \right) dx dy$,

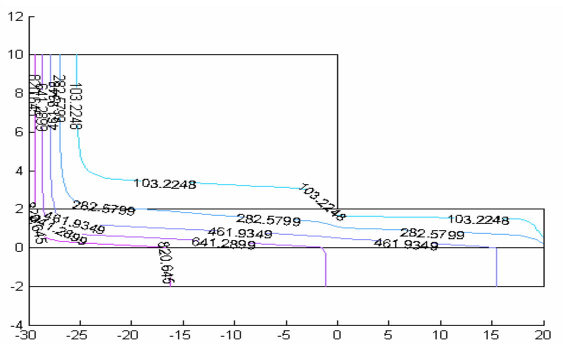
$$B = \alpha \cdot \iint \left(\nabla\Phi \cdot \nabla\Phi^T \right) dx\, dy + \frac{h}{\rho C_p} \cdot \int \left(\Phi \cdot \nabla\Phi^T \right) dx \,,$$

$$C = \frac{hT_f}{\rho C_p} \cdot \int \Phi \, dx \,.$$

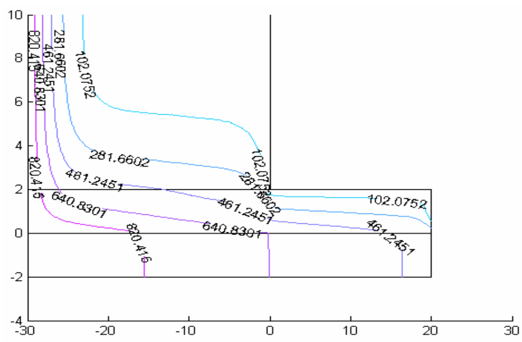
By solving these ordinary differential equations, we can obtain the nodal values as an approximate solution. Computations are carried out on the computer Pentium IV-2.0 GHz. The program packet MATLAB is used for realizing the hybrid algorithm recommended in this study. The initial temperature T_0 is fixed at 20 ℃, and the fire-side wall temperature T_h follows the ASTM E-119 standard temperature-time curve, changing from the initial temperature T_0 to the final temperature of 1,200 ℃ for two hours. As a simple geometry, the fire stop system with two penetrated cables is simulated at first. It is assumed here that the cable and the tray temperatures are the same to the temperature on the ASTM E-119 standard temperature-time curve and 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 block, i.e. they are under the adiabatic condition.



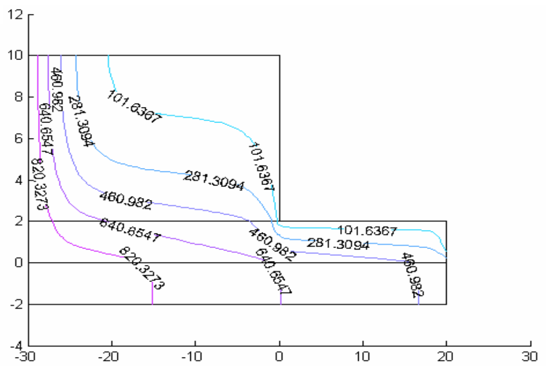
(a) In 20 minutes



(b) In 60 minutes



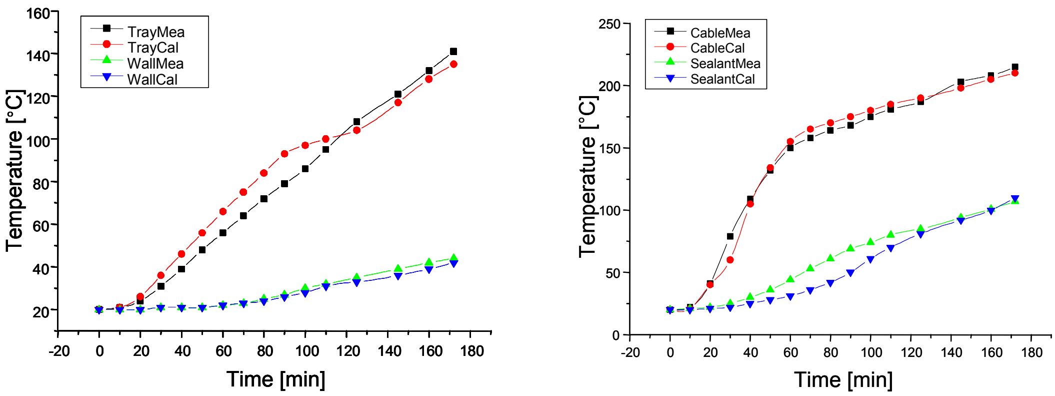
(c) In 90 minutes



(d) In 130 minutes

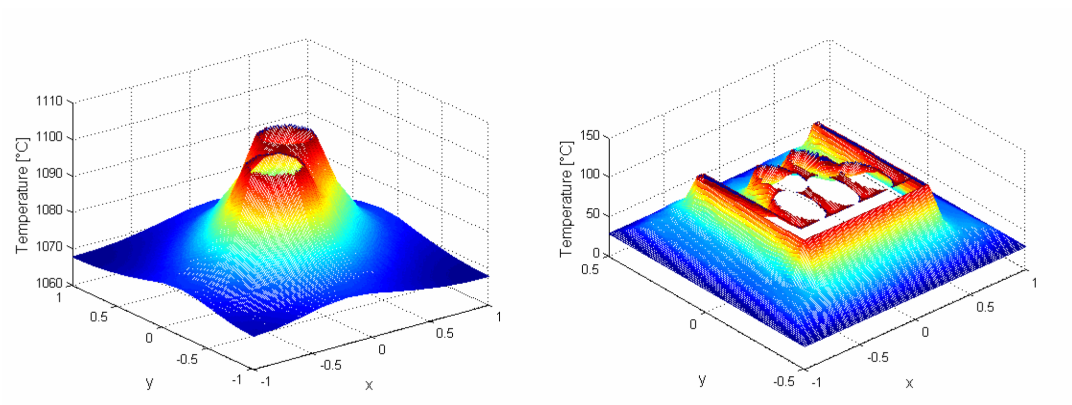
Fig. 2. Temperature profiles in the cable and in its covering in 20, 60, 90, and 130 minutes

The temperatures of 2323 elements are estimated simultaneously. The result of estimation is used as the initial temperatures for calculating the temperatures at five discrete axial points on each node of the elements. The calculation is carried out with the numerical method of SOR. The result is used again for the initial temperature values of the calculation carried out with the numerical method of FEM. In this manner the temperature distribution in the fire stop system is calculated iteratively. In addition the fire stop system penetrated by five cable streams is simulated under the more practical condition. For instance the temperature of cables can be obtained by simplifying the cable structure, as shown in Fig. 2. As a numerical method, the Galerkin FEM is employed to solve the problem about dynamic heat conduction in the cable stream.



(a) About the tray and the wall (b) About the cable and the sealant

Fig. 3. Measured and calculated temperatures on the tray, the wall, the cable and the sealant

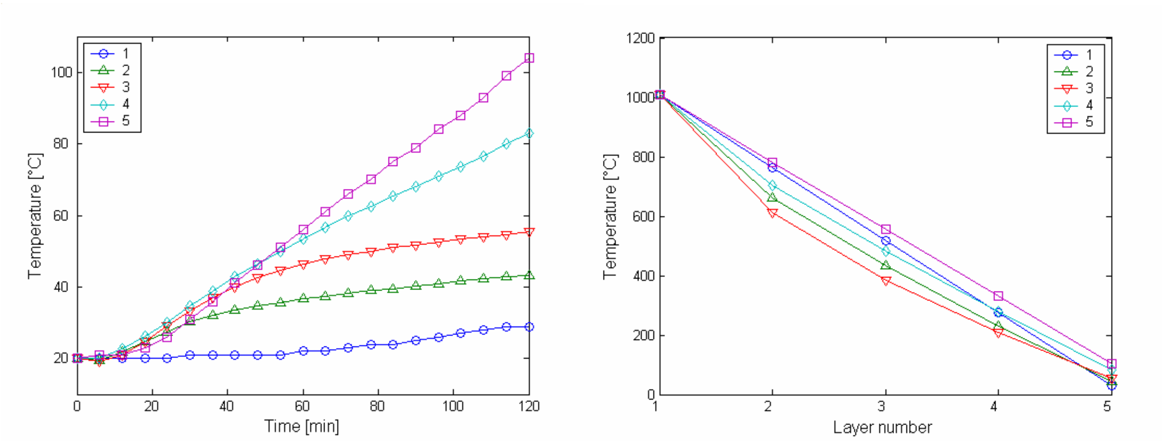


(a) (b)

Fig. 4. Temperature distributions on the sealant (a) under the simplified condition and (b) under the more practical condition

RESULTS AND DISCUSSION

Simulation results are compared to the experimental data about the temperature of the tray, the wall, the cable and the sealant, as shown in Fig. 3. The result does not much deviate from the experimental data. By these comparisons the simulation model can be validated adequately. Simulation is carried out to calculate the temperature distribution on the outside surface of the cable penetration fire stop system built between compartments of the nuclear power plant. The simulation result is three-dimensionally presented in Fig. 4. Fig. 4 (a) is the result of the simplified model having two penetration cables, while Fig. 4 (b) is corresponding to it on the more complicated one having five penetration cables and a tray. Dynamic temperature profiles at five points on the outside surface of the sealant are shown in Fig. 5 (a) to illustrate dynamic heat transfer in the CPFS system. On the contrary temperatures at the point on five layers at a certain time are shown in Fig. 5 (b). As shown in Fig. 5, the temperature on the cable exposed out of the outside surface reaches about 100 °C already in an hour, but the sealant temperature does not rise rapidly. Therefore, the temperature on the outside surface is keeping with the initial temperature. According to the change of temperature profiles shown in Fig. 5, it is apparent that fire heat is transferred along to the cable stream quickly at the start, while the heat conduction occurs on the layers slowly. In two hours it is still about 100 °C around the cables, while the temperature of the sealant rose near the temperature of 100 °C. That means that the heat transfer on the layer is also progressed very much as well as the heat transfer along the penetration cables. Consequently, we can find the fact that heat transfer through the cable stream is very significant and heat conduction is not in a steady-state.



(a) Dynamic temperature profiles (b) Temperature vs. the layer number

Fig. 5. Dynamic temperature profiles at five points on the outside of the sealant (a) and temperatures at the points on the different layers in the sealant (b)

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 modeled, simulated and analyzed. The simulation results were illustrated in three-dimensional graphics. Through the simulations it became evident 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 FDM and FEM for solving special partial differential equations. This hybrid algorithm could be applied to the dynamic heat conduction problem successfully. At last, it was found that 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. These numerical results are useful for making a performance-based design for the cable penetration fire stop system.

ACKNOWLEDGEMENT

We acknowledge the financial support for this research provided by the Ministry of Commerce, Industry and Energy.

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