Numerical Analysis of Gaseous Fluid Flow Around a Nuclear Spent Fuel Shipping Cask

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Abstract

This paper develops the numerical method to evaluate the thermal distribution in the object which is heated by high temperature gaseous fluid in order to provide a tool to show the thermal integrity of shipping casks which is located in flames. This method consists of the calculation of fluid flow and the heat transfer analysis of the object.

Numerical simulations of the fire experiment with model cask were made and the obtained results were compared with experimental data. As results, it was shown that the proposed method produce a reasonable estimate of the temperature distribution in the cask.

1. Introduction

One of the postulated accidents during transportation of nuclear spent fuel shipping casks is a fire. Unusual deformation which lead to the leakage of the contents from a cask or melting of lead which is used to reduce the radioactive rays are not allowed in the fire accidents. In order to assure that the these undesirable states will not occur, it must be demonstrated that the shipping casks have enough thermal integrity to stand the exposure to 800°C atmosphere for 300 minutes for in a fire.

Several numerical analyses are executed to calculate the temperature distribution in casks under thermal condition required in law[1]. Most of those analyses use computer codes which are based on the finite element method, for example MARC, ANSYS etc. However, these codes have no function to calculate the convection of surrounding atmosphere, so they need many assumptions to calculate the heat transfer on the cask-flame boundary.

In this paper, a numerical method was developed that simulate the heat transfer considering the effect of convection of fluid. First, we simulate the fire resistance test of model cask[2] to examine whether the proposed method is effective or not. This led us to the finding that the proposed method can produce results which trace the experimental data successfully. Then, some propaties of heat transfer coefficients at the cask-flame interface were examined by the method.

2. Formulation of the problem

Incompressible fluid assumption is used for flames. The mass and momentum equations of fluid are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \xi \frac{u}{x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \xi \frac{u^2}{x} = -\frac{\partial P}{\partial x} + g_x + \nu_f \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \xi \left(\frac{1}{x} \frac{\partial u}{\partial x} - \frac{u}{x^2} \right) \right), \tag{2}$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \xi \frac{uv}{x} = -\frac{\partial P}{\partial y} + g_y + \nu_f \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\xi}{x} \frac{\partial v}{\partial x} \right), \tag{3}$$

and the energy equation is:

$$\frac{\partial Tf}{\partial t} + u \frac{\partial Tf}{\partial x} + v \frac{\partial Tf}{\partial y} = \frac{\lambda f}{\rho_f C_f} \left(\frac{\partial^2 Tf}{\partial x^2} + \frac{\partial^2 Tf}{\partial y^2} + \frac{\xi}{x} \frac{\partial Tf}{\partial x} \right) + \frac{1}{\rho_f C_f} Q_r, \tag{4}$$

where u and v are the velocity components in the directions x and y, respectively. P is the ratio of pressure to constant density ρ_f, g_x and g_y are body accelerations in the directions x, y, respectively. Also, Tf is the temperature, Cf the heat capacity, λf the conductivity of the flames, and Q_r, the quantity of heat lost by radiation. The energy equation of the cask is:

$$\frac{\partial Tc}{\partial t} = \frac{\lambda c}{\rho_c Cc} \left(\frac{\partial^2 Tc}{\partial x^2} + \frac{\partial^2 Tc}{\partial y^2} + \frac{\xi}{x} \frac{\partial Tc}{\partial x} \right), \tag{5}$$

where Tc is the temperature, λc, the conductivity, ρ_c, density, and Cc the heat capacity of the cask. These equations include a parameter ξ, and $\xi = 0$ corresponds to plane geometry and $\xi = 1$ for cylindrical coordinates. The heat flux on the surface of cask is induced by convection and by radiation. The latter is:

$$qr = \frac{ac \cdot \varepsilon_f}{\pi} \sigma \int_{f_c} \int_{f_f} \left(T_f^4 - T_c^4 \right) \frac{\cos\psi_f \cos\psi_c}{r^2} df_f \, df_c, \tag{6}$$

here, df_c and df_f are surface elements on the cask and flames, respectively. They are connected by a straight line, r, which makes an angle ψ_c with the normal to df_c and an angle ψ_f with the normal to df_f. The constant **ac** is the obsorptivity upon the surface of the cask, and σ is Stefan-Boltzman constant. The parameter ε_f represent the emissivity of luminous flames.

3. Method of solution

The method to solve this problem consists of two parts. The first part is to analyse the flow of the flames by means of a finite difference method called SOLA[3] and estimate the flow and thermal distribution around the cask. The second part is to evaluate the temperature distribution induced in the cask by the heat from flames, with use of the finite element code, MARC[4].

The original SOLA code is designed to solve the Navier-Stokes equations for an incompressible fluid flow. Some modifications were made to SOLA code in order to solve the energy equation and to evaluate the effect of radiation. The SOLA code is connected with MARC as one of the user subroutines.

The outline of computation sequence is in the following. First, SOLA solves eqs.(1) to (4) using the temperature in th cask at the previous time step to evaluate the heat flux into the cask. Then, MARC evaluate the temperature distribution in the cask using given heat flux. The same sequence is repeated.

4. Numerical Results

Numerical simulations of a fire experiment with model cask[2] were made in order to examine whether the proposed method was effective or not. The cask model is of cylinder type and composed of three layers as in Fig. 1. In this experiment, the cask model was exposed to 800°C atmosphere in a furnace for about 500 sec., and then pulled out.

Analytical model of this experiment was shown in Fig. 2. Outer cylinder showed the flow field of fluid and inner small cylinder corresponded to the cask. The fluid which has the physical properties of combustion gas flows into the model through the bottom. Fig. 3 shows the finite element model of the cask which is used in MARC. The surrounding space of the cask was divided into the finite difference mesh for SOLA as shown in Fig. 4.

The velocity of the fluid at the bottom is 0.5m/sec. and the temperature of the fluid at the bottom is kept at 800°C for 500 sec. from the beginning of heating and after the heating period kept at 25°C for 300sec..

The temperature history on the outer and inner surface of the cask obtained by the proposed method and the experiment are shown in Fig. 5, where the dashed curves represent the numerical solution and the solid ones illustrate the experimental data. As can be seen, a good agreement is obtained. The temperature distribution in the model cask at 500 sec. is shown in Fig. 6.

Fig. 7 shows the flow distribution around the cask at 500 sec. In the down stream of the cask, a downward flow is observed and a mixing of the fluid occurs there. The temperature distribution at the same time with Fig. 7 is shown in Fig. 8.

Heat transfer coefficients are difficult to obtain by experiments, but they can be calculated by use of this method. In the Fig. 9, the mean heat transfer coefficient on the boundary is plotted against the flow rate across the bottom. It can be said that the α_m is almost independent of the flow rate.

Fig. 10 shows the profile of heat transfer coefficients on the boundary, where α_c denotes the heat transfer coefficient due to convections and α_r is that of radiation. It shows that the α_r increase with distance from the bottom of the cask in some cases, while the α_c decrease with distance. Heat transfer induced by radiation depends upon the geometrical relation between the cask and flames as denoted in eq.(6), so the local change of heat transfer coefficient due to radiation considered to depend on the problem.

5. Conclusion

A method to evaluate the temperature distribution in the object has been proposed which include the calculation of flames. As a result of the numerical simulation, it is shown that the proposed method produces a reasonable estimate of the temperature history and its distribution in the cask which is surrounded by flames.

References

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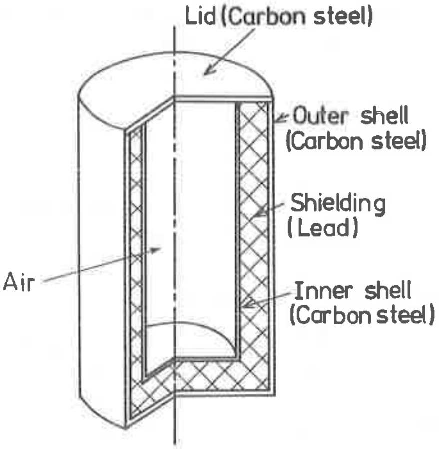

Fig. 1 Model of Shipping Cask for Fire Test

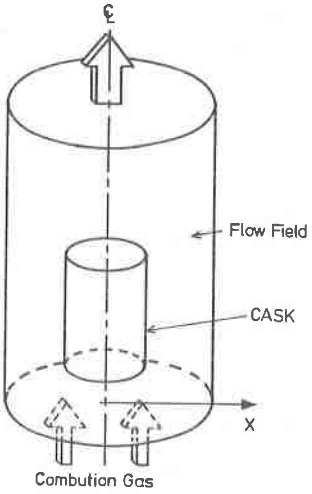

Fig. 2 Analytical Model of Cask Fire Test

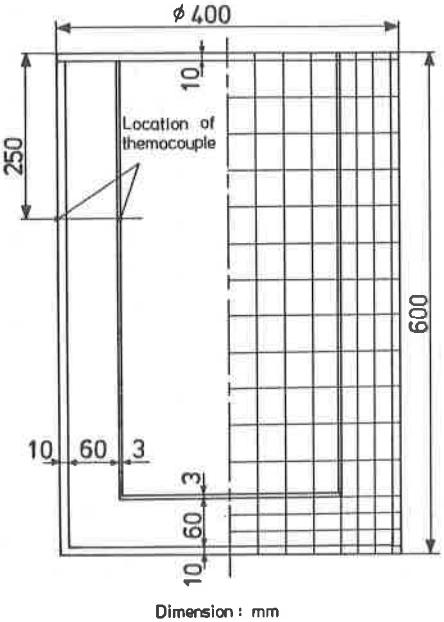

Fig. 3 Finite Element Mesh for Shipping Cask

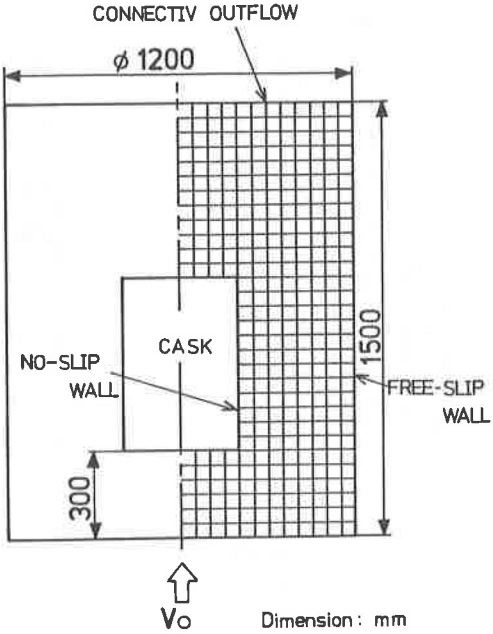

Fig. 4 Finite Difference Mesh for Cask Fire Test

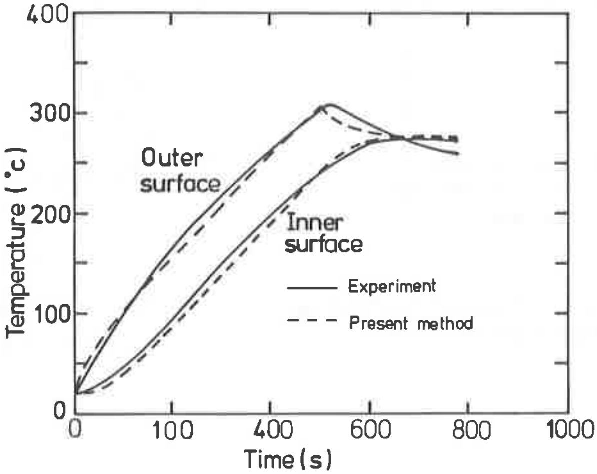

Fig. 5 Compersion of Temperature History

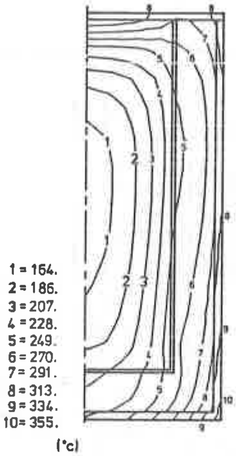

Fig. 6 Isotherms in the Cask at 500 sec.

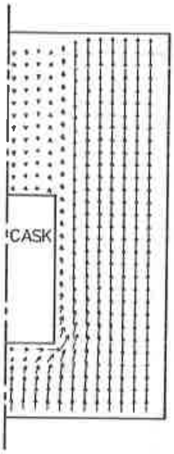

Fig. 7 Flow Distribution around the Cask at 500 sec.

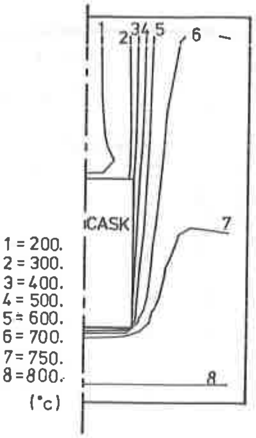

Fig. 8 Isotherms around the Cask at 500 sec.

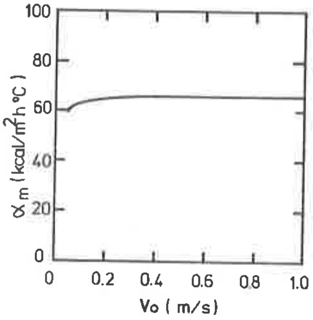

Fig. 9 Mean Heat Transfer Coefficient vs. Flow Rate at Bottom

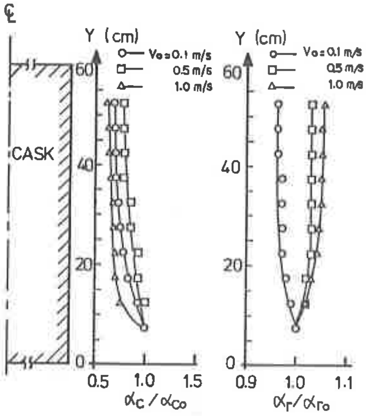

Fig. 10 Profile of Heat Transfer Coefficient on the Boundary