Turkish Journal of Nuclear Sciences, 9 (1982) 3-9

AN ANALYTICAL APPROACH FOR LOCA (LOSS OF COOLANT ACCIDENT)

E.S. SALDIRAY - A. İŞYAR - T. YARMAN

Institute For Nuclear Energy
Technical University of Istanbul, Istanbul

ABSTRACT

It is proposed to display the main characteristics of a LOCA via a simple model. For this purpose we consider a fuel rod surrounded by a cylindrical coolant channel. The heat transfer equations related to the fuel rod and coolant are written down supposing that the heat conduction is on the radial direction only; the source term that represents the fission products decay can be put into an exponential form; there is no radial temperature gradient within the coolant channel; the fluid is incompressible and (for simplicity) the coolant velocity does not change after LOCA takes place. The heat transfer equations are now undertaken via a weighted residual technique through which appropriate space dependencies for the rod and coolant temperatures respectively in the radial and axial directions are adopted. Mathematical manipulations lead us to time dependent equations only, that show very well the anatomy of LOCA in terms of coolant velocity, fission products heat release, and the center line, the rod wall and the coolant temperatures. An analytical solution of the equations in question is given. A parametric study on the solution is carried out and the behaviour of the related temperatures are drawn with respect to time.

ÖZET

Soğutucu Kaybı Kazası (SKK) oldukça karmaşık dinamik bir süreçtir. İncelenmesi çoğunlukla, ele alınması külfetli bilgisayar programlarının ilgili verilerle koşulmasını gerektirir. Bu programlar üzerinde egemen olunması birikim ister. Bu sağlansa bile elde olunan sonuçların yer yer, fiziksel mi, yoksa çeşitli bilgisayar cilvelerinden bir demet mi olduğunu anlamak kolay olmayabilmektedir. O nedenle, özellikle de eğitimsel amaçla, SKK'nın anatomisinin resmedilmesinde çok yarar bulunmak gerekir. Burada sunulan çalışma işte böyle bir yaklaşımla oluşturulmaktadır. Mümkün en basit düzenek ele alınmış olup, SKK analitik bir çerçeve

içinde formüle edilmek istenmektedir. Geliştirilen modelin eğitimsel açıdan yararı, SKK'yi birçok karmaşık çizgisinden kurtarıp, yakıt içi artık ısı üretimi ve kanal girişindeki soğutucu akışkan hızı gibi iki ana parametresi cinsinden adeta karikatürize ediyor olmasıdır. Sonuçta-süreç boyunca seyri merak konusu olan yakıt merkez sıcaklığı, yakıt duvar sıcaklığı ve akışkan sıcaklığı, yakıt yüksekliği üzerinden ortalanmış anlamda-sözü edilen iki ana parametreye bağlı ve analitik olarak ifade olunabilmektedir.

INTRODUCTION

It is aimed do display the main characteristics of LOCA via a simple model. LOCA, in general is a very complex phenomenon. It is usually undertaken with clumsy codes which require an enormous amount of computer time. Moreover, these codes do not always clearly display the physics behind the case under study. Sometimes it may even be very difficult to understand whether the output reflects an exact prediction or it is question of some undesirable numerical jokes. It should thus be useful to sketch the anatomy of LOCA, chiefly for pedagogical purposes. This is the insight of the work presented here.

We thus consider a fuel rod surrounded by a cylindrical coolant channel (Fig.1). (Cladding is neglected.)

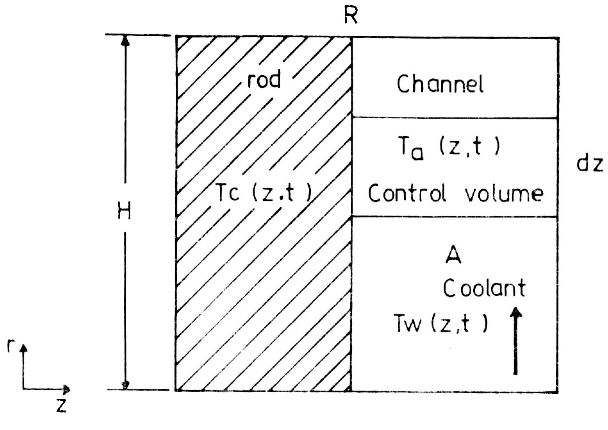


Fig. 1. Fuel rod and its surrounding coolant channel. $T_c(z,t)$: center line temperature, $T_w(z,t)$: wall temperature, $T_a(z,t)$: coolant temperature, A : channel cross section

It is supposed that the configuration represented in Fig.1 is part of a reactor that operates under steady state conditions until time t = 0. At this time a loss of coolant accident takes place. Thereafter the initial velocity v_o of the coolant at the entrance of the channel is supposed to drop to a value v that stays constant throughout the accident. As soon as the accident starts the reactor is supposed to shut down. Thus the initial steady state heat production within the fuel rod is assumed to be suddenly replaced by the fission product decay heat production.

DERIVATION AND RESULTS

The equations that describe the heat transfer phenomena throughout the accident within the fuel rod and coolant channel are, with the usual notation, as follows:

$$\nabla . k(\underline{r},T_f)\nabla T_f(\underline{r},t) + q(\underline{r},t) = \frac{\partial c_f(T_f)\rho_f(T_f)T_f(\underline{r},t)}{\partial t}, \qquad (1)$$

$$-k(\underline{r},T_f)\nabla T_f(\underline{r},t)\big|_{\underline{r}:\text{rod wall}} = h(T_a)\left|T_w(z,t)-T_a(z,t)\right|, \qquad (2)$$

$$\frac{2\,\Pi R h(T_a)}{A\, c_a(T_a)\rho_a(T_a)}\left|T_w(z,t)-T_a(z,t)\right| - v\frac{\partial T_a(z,t)}{\partial z} = \frac{\partial T_a(z,T)}{\partial t} \qquad (3)$$

Here the following definitions are used:

$k(T_f)$: fuel heat conduction coefficient at temperature T_f.
$T_f(\underline{r},t)$: temperature at the location $\underline{r}$ within the fuel and time t.
$q(\underline{r},t)$: residual heat release per cm^3 around the point $\underline{r}$ and per sec. around time t.
$c_f(T_f)$: fuel rod specific heat at temperature T_f.
$\rho_f(T_f)$: fuel rod density at temperature T_f.
$h(T_a)$: heat transfer coefficient from the fuel rod wall to the coolant at temperature T_a.
$T_w(z,t)$: fuel rod wall temperature at elevation z and time t.
$T_a(z,t)$: coolant temperature at the elevation z and time t. (No radial dependency of this quantity is assumed.)
$c_a(T_a)$: coolant specific heat at temperature T_a.
$\rho_a(T_a)$: coolant density at temperature T_a.

The heart of the derivation we present here is to make assumptions about the space dependencies of fuel and coolant temperatures. It is thus assumed that the fuel rod temperature, with a symmetric parabolic radial spatial dependence can be written in terms of the center line temperature $T_c(z,t)$ and the rod wall temperature $T_w(z,t)$, as follows:

$$T_f(\underline{r},t) = T_c(z,t)\left(1-\frac{r^2}{R^2}\right) + T_w(z,t)\frac{r^2}{R^2} \qquad (4)$$

The axial space dependency of the coolant temperature is assumed to be linear and is written in terms of the coolant inlet temperature, T_g and the coolant outlet temperature $T_ç(t)$:

$$T_a(z,t) = T_g + \frac{T_ç(t) - T_g}{H} z \qquad (5)$$

The coolant inlet temperature is further assumed to stay constant throughout the accident.

We now go back to Eqs. 1, 2 and 3 with the approximate expansions of Eqs. 4 and 5 and integrate our original heat balance equations over the fuel rod and coolant channel volumes, respectively.

We thus define :

$$\overline{T}_c(t) = \frac{1}{H}\int_0^H d_z\, T_c(z,t) \qquad , \qquad (6)$$

$$Q(t) = \frac{1}{H}\int_0^H dz \int_0^R dr \quad q(r,z,t) \quad , \qquad (7)$$

$$\overline{T}_w(t) = \int_0^H dz \quad T_w(z,t) \qquad , \qquad (8)$$

$$\overline{T}_a(t) = \int_0^H dz \quad T_a(z,t) \qquad . \qquad (9)$$

With these definitions we, thus, obtain:

$$-2k\left|\overline{T}_c(t) - \overline{T}_w(t)\right| + Q(t) = \frac{R^2 c_f \rho_f}{4}\frac{d}{dt}\left|\overline{T}_c(t) - \overline{T}_w(t)\right| , \qquad (10)$$

$$\frac{2k}{Rh}\left|\overline{T}_c(t) - \overline{T}_w(t)\right| = T_w(t) - \overline{T}_a(t) \qquad , \qquad (11)$$

$$\frac{2\Pi Rh}{\rho_a c_a A} \mid \overline{T}_w(t) - \overline{T}_a(t)\mid - \frac{2v}{H} \mid \overline{T}_a(t) - T_g\mid = \frac{d\,\overline{T}_a(t)}{dt} \qquad (12)$$

To write these equations we supposed that k, c_f, ρ_f, h, c_a and ρ_a are not functions of the related temperatures and stay constant throughout the transient. It is moreover assumed that heat conduction in the axial direction within the fuel rod can be neglected.

The usefulness of the Eqs. 10, 11 and 12 lies in the fact that they display the interrelated behaviour of the center line, rod wall and coolant temperatures, defined in a average way, in terms of the two main characteristics of LOCA, i.e. the residual heat production and the coolant inlet velocity.

To carry out the integration of the above equations, Q(t) should be known. This quantity is, with appropriate constants Q_o and p, written to be

$$Q(t) = Q_o e^{-pt} \quad . \qquad (13)$$

The initial conditions for $\overline{T}_c(t)$, $\overline{T}_w(t)$ and $\overline{T}_a(t)$, on the other hand, are determined by setting the time derivatives in the above equations to zero, with Q(t) taken as the steady state heat production term, and v as v_o. (It should be noted that Q(0) is completely different from Q_o of Eq. 13, for Q_o is the initial condition for the residual heat production that takes place with the reactor already shut-down.)

The integration of Eqs. 10-12 finally gives:

$$\overline{T}_c(t) = B\, e^{d_1 t} + G\, e^{d_2 t} + D\, e^{-p\,t} + E \quad , \qquad (14)$$

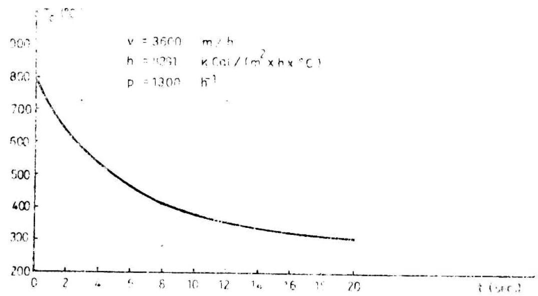
$$\overline{T}_w(t) = F\, e^{d_1 t} + G\, e^{d_2 t} + H\, e^{-p\,t} + I \quad , \qquad (15)$$

$$\overline{T}_a(t) = J\, e^{d_1 t} + K\, e^{d_2 t} + L\, e^{-p\,t} + E \quad . \qquad (16)$$

Various coefficients which occur in these equations have cumbersome expressions in terms of the parameters that enter into our original equations and the dimensions of the fuel rod and the channel /1/.

A computer program is created to make calculations required by the above expressions. Further a parametric study is carried out by taking various values for v and p.

A typical output is shown on Fig. 2.



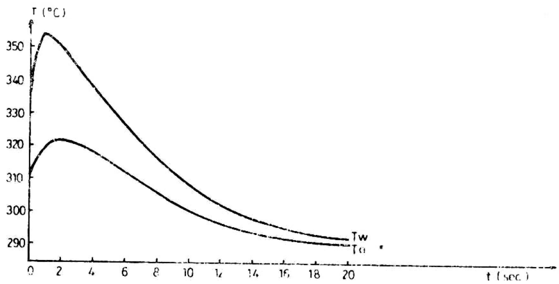


Fig. 2. Behaviour of the average center line, rod wall and coolant temperatures with respect to time.

CONCLUSION

We were able to show via Eqs. 11-13 the interrelated behaviour of the center line, rod wall and coolant temperatures, defined in an average way, in terms of the two main characteristics of LOCA, i.e. the residual heat production and the coolant inlet velocity.

This should be considered, mainly from a pedagogical point of view, as a privilege, since the more difficult form of Eqs. 1-3 is avoided. It should, in effect, be noted that, a similar problem on a relatively fast computer takes about an hour, whereas the predictions that we present here, are made in a few seconds of computation time, only /2/. An attempt is further made to check the health of our "approximate" predictions /3/. The result is just very satisfactory. A detailed analysis that considers various space dependencies with various weight functions on the way from Eqs. 1-3 to Eqs. 11-13 will be soon undertaken. This analysis will hopefully show the best material to be associated, in a thermal-hydraulics problem, with the weighted residual criteria, which was the main mathematical tool of our present work.

It is noteworthy that our approach can constitute the nucleus of a detailed prediction through which, various parameters that are considered to be constant in our analysis, may now vary. Successive time integrations should thus be carried out by taking constant values for the parameters in question through each of the time steps that will be considered.

REFERENCES

/1/ Saldıray, E.S., İşyar, A., Yarman, T., "Soğutucu Kaybı Kazasına Analitik Bir Yaklaşım" (A Bulletin of Institute for Nuclear Energy, Technical University of Istanbul, to be published, in Turkish).

/2/ Aybers, N., Yarman, T., Alp, C., Akalın, O., Loss of Coolant Accident Analysis of a Water Cooled Reactor With the Code. ECCSA-4, 1. National Nuclear Sciences Congress, May 20-24 1980, İzmir.

/3/ Yarman, T., Aybar, H., Menekay, B., A Parametric Study of a LOCA on ESSCA-4 (work still being carried out at the Institute for Nuclear Energy, Technical University of Istanbul).