TRANSIENT THERMAL PERFORMANCE OF A SINGLE COOLING CHANNEL IN A PWR REACTOR CORE

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الأداء الحراري الغير مستقر لقناة تبريد واحدة

في قلب مفاعل ماء مضغوط

خلاصة : يتناول هذا البحث دراسة تحليلية للأداء الحراري لقناة تبريد في مفاعل الماء المضغوط، ولهذا الغرض تم تطوير نموذج تحليلي رياضي يأخذ في الاعتبار انتقال الحرارة في الاتجاهين القطري r والمحوري z، ويعتمد النموذج على تقسيم قناة التبريد وقضيب الوقود الى عناصر حجمية في r,z وبتطبيق المعادلة التفاضلية الأساسية لانتقال الحرارة بالتوصيل والغير مستقر في وجود مصدر طاقة داخلي على كل عنصر تم الحصول على نظام من المعادلات الخطية التي يتم حلها آليا بالطرق العددية مع تطبيق الشروط الحدية المناسبة . ولقد تم حساب معامل انتقال الحرارة بالحمل باستخدام علاقة Sieder-Tate مع أخذ تغير الخواص الثرموديناميكية للمبرد في الاعتبار، ويتم حساب هذه الخواص في برامج فرعية باستخدام علاقات اتحاد المهندسين الألمان VDI.

ABSTRACT

The objective of this paper is to investigate the transient thermal performance of a single cooling channel in a pressurized water reactor (PWR). A new developed two dimensional fuel rod code in which the radial and axial heat transfer are taken into consideration is used for calculation. This code is used to study the steady-state and transient temperature behavior of nuclear fuel rods in light water reactors. In addition, the real thermodynamic conditions - as the variation of the coolant heat transfer coefficient along the channel length and the gap thermal resistance- are taken into consideration. These real thermodynamic properties of the coolant are calculated using VDI correlations.

INTRODUCTION

In nuclear industry, temperature development in both steady and transient operation is important in evaluating reactor core thermal performance. The behavior of the fuel-coolant combination in response to reactivity insertions, loss of coolant or other transient effects is of vital importance such parameters as the time taken by the fuel to reach steady-state temperatures from the cold start if the rate of heat generation q''' (due to fission) is suddenly raised. In case of loss of coolant accident, the time after which the fuel or cladding meltdown temperatures is reached is very important, therefore a *fuel rod code* is used in

conjunction with a nuclear code, core code, and loop code to determine the temperature behavior of cladding surface [1-3].
In light water reactors , the coolant in the core is considered as a boundary condition which supplies the fuel rods with a sink temperature and a heat transfer coefficient. Conduction in the radial direction is usually taken into account [4,5] and some codes consider conduction in the axial conduction also [3]. With nonuniform cooling, conduction in the azimuthal direction must be considered [6]. Thermal radiation from rod-to-rod is negligible when the core is filled with liquid. There are many excellent fuel rod codes to predict the steady and transient temperature behavior of nuclear fuel rods. Additionally, it is required to improve the time and space of computation [2,5]. The present fuel rod code is an enhanced developed code, in which two dimensional transient heat transfer in both radial and axial directions are taken into consideration.

MATHEMATICAL CONSIDERATIONS

The general heat conduction equation is given by

$$\nabla^2 T + \frac{q'''}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial \theta} \tag{1}$$

where α is the thermal diffusivity ($\alpha = \frac{k}{\rho c}$).
To transform the above equation into algebraic equation, the time variable θ and space variable r are broken into discrete intervals $\Delta\theta$, Δr, and ΔZ as shown in Fig.(1). Multiplying Eq.(1) by $r\,dr\,dZ\,d\theta$ and integrating over Δr, ΔZ, and $\Delta\theta$ at the nodal point i,j for two dimensional Laplacian in cylindrical coordinates and rearranging, one gets the following linear equation :

$$T^{\theta+\Delta\theta}_{i,j} = (1-F_1-F_2-F_3-F_4)T^{\theta}_{i,j} + F_1 T^{\theta}_{i-1,j} + F_2 T^{\theta}_{i+1,j} + F_3 T^{\theta}_{i,j-1} + F_4 T^{\theta}_{i,j+1} + Fo_R \cdot \Delta T_g \tag{2}$$

where $F_1 = \frac{2Fo_R\, R_i\,\Delta R}{A}$, $F_2 = \frac{2Fo_R\, R_{i+1}\,\Delta R}{A}$,

$A = R^2_{i+1} - R^2_i$, $Fo_R = \frac{k\,\Delta\theta}{\rho c\,\Delta R^2}$,

$F_3 = F_4 = Fo_Z = \frac{k\,\Delta\theta}{\rho c\,\Delta Z^2}$,

and $\Delta T_g = \frac{q'''\Delta R^2}{k}$

The following boundary conditions are applicable for the considered case :

* For the innermost nodal points i=1, we have

$$(\partial T/\partial r)_{r=0} = 0.0$$

To satisfy this condition , the coefficient F_1 must equal zero.

* For the outermost cladding nodal points i=N, we have

$$(\partial T/\partial r)_{r=R_o} = -(\alpha_j / k_c).(T_{N,j} - TF_j)$$

To satisfy the above condition, the coefficients F_1, F_2 are given by:

$$F_1 = \frac{2(FO)_c R_N \Delta R_c}{(R_o^2 - R_N^2)} \quad , \text{ and } \quad F_2 = \frac{2(FO)_c \ \alpha \ R_o \ \Delta R_c^2}{k_c(R_o^2 - R_N^2)}$$

To account for the effect of the helium gas gap at the interface between the fuel surface and the inner cladding surface, the coefficients F_1 and F_2 for both the last fuel layer NF and the first cladding layer NF+1 are given by :

* For i=NF

$$F_1 = \frac{2.FO_F \ R_{NF} \ \Delta R_F}{(R_{NF+1}^2 - R_{NF}^2)}$$

$$F_2 = \frac{2.FO_F \ R_{NF+1} \ \Delta R_F}{k_F(R_{NF+1}^2 - R_{NF}^2)[(\Delta R_F/2k_F)+(1/\alpha_g)+(\Delta R_c/2k_c)]}$$

* For i=NF+1

$$F_1 = \frac{2(FO)_c \ R_{NF+1} \ \Delta R_c}{k_c(R_{NF+2}^2 - R_{NF+1}^2)[(\Delta R_F/2k_F)+(1/\alpha_g)+(\Delta R_c/2k_c)]}$$

$$F_2 = \frac{2(FO)_c \ R_{NF+2} \ \Delta R_c}{(R_{NF+2}^2 - R_{NF+1}^2)}$$

* For bottom nodal points j = 1, we have

$$(\partial T/\partial z)_{Z=0} = (\alpha/k).(T_{i,1} - TF_1)$$

The coefficients F_3 and F_4 are then given by :

$$F_3 = Fo_Z.\frac{h\Delta Z}{k} \quad , \quad F_4 = Fo_Z = \frac{k\Delta\theta}{\rho c \Delta Z^2}$$

* For top nodal points j = NZ, we have

$$(\partial T/\partial z)_{Z=H} = -(\alpha_j/k).(T_{i,NZ} - TF_2)$$

To satisfy this condition, the coefficients F_3 and F_4 are then given by :

$$F_3 = Fo_z = \frac{k\Delta\theta}{\rho c \Delta Z^2} \quad , \quad F_4 = Fo_z.\frac{h\Delta Z}{k}$$

where Fo_z is based on material properties of fuel or cladding material according to the considered nodal point, and TF_1, TF_2 are the inlet and outlet fluid temperatures respectively.

SOLUTION OF THE FINITE DIFFERENCE EQUATIONS SYSTEM

Each body of the fuel and cladding is divided into a number of concentric cylindrical layers of equal thickness ΔR_F and ΔR_c and each layer is then divided into a number of axial volume elements of equal height ΔZ as shown in Fig.(1). Applying Eq.(2) to each volume element one gets a system of finite difference equations. The method of iteration is used for solution of this equations system [2,7]. Starting from initial temperature values, a nodal temperature is recalculated in successive steps using the five adjoining temperatures as shown in Eq.(1). The sequence is stopped when further iteration does not result in significant changes in values of the whole temperature field. A KWU 1300 MWe pressurized water reactor is chosen as an illustration example [8]. The following data are required :

Heat generation $q'''_{av} = 3.1\times10^8$ W/m^3 with $q'''_c = 4.8\times10^8$ W/m^3

Inlet temperature 564 ^oK,

Mass velocity G = 3.65 Kg/m^{2}s, Fuel rod pitch = 12.7 mm,

Fuel is UO_2, Cladding is Zircaloy-4,

Pellet radius R_F = 4.025 mm, Cladding thickness = 0.64 mm,

Fuel rod outside radius R_o = 4.75 mm,

Fuel rod active height H = 3.9 m

The calculation of the coolant heat transfer coefficient is performed using a separate subroutine in which the thermodynamic properties of water are calculated according to VDI correlations [9].

RESULTS AND DISCUSSION

In order to examine the validity of the proposed code, a comparison with the analytical results is required. For this purpose code, the calculations are performed for the ideal situation which is characterized by the following conditions :

1- material properties are considered temperature independent.

2- the cladding to coolant heat transfer coefficient is considered constant along the axial direction Z. (4.0×10^4 W/m^2), while the heat resistance in the gas gap is neglected.

The volumetric heat generation rate q''' obeys the relation :

$$q''' = q'''_c \; COS(\pi z/H_e)$$

where q''' and q'''_c are the volumetric heat generation rate at any point z (z=Z-0.5H) and the center of the fuel element, and H_e is the extrapolated fuel element height (He ≈ H).

Fig.(2) shows the time behavior of both fuel and cladding temperatures for different volumetric heat generation rates. It is clear that the steady state fuel temperature is reached in more than 25 and 27 seconds for $q'''=4.8\times10^{8}$ and 1.0×10^{9} W/m^3 respectively.

Fig.(3) illustrates a comparison between the results as obtained from the one-dimensional code [10] and the present two-dimensional code. The curves indicate that the one-dimensional results lie over the two-dimensional behavior. This situation is physically expected because the axial heat conduction is ignored in one dimensional code which leads to higher temperature values. Comparing the values of fuel steady state temperatures (1425 for one dimensional and 1412 °K for two dimensional), it is concluded that neglecting the axial heat conduction is a satisfactory assumption. This conclusion can be also drawn by examining figure (4), which illustrates the axial fuel , cladding, and fluid distribution. Again, the two-dimensional numerical fuel temperature distribution lies just under the corresponding analytical one dimensional distribution.

The obtained results show that the one dimensional code gives temperature values which agree with that obtained using the two dimensional code. It is expected that this situation is not longer valid if the time and spatial variations of heat generation rate and heat transfer coefficient are to be taken into consideration. Figures (5-7) illustrate the temperature behavior under more actual operating conditions where temperatures are plotted in °C. The considered realistic conditions are :

1- the heat resistance in the gas gap is taken into consideration, where $\alpha_g=4500\ W/m^2$,

2- the heat transfer coefficient along the cooling channel is variable and calculated using the following Sieder-Tate correlation [2]:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4}\ (\frac{\mu_w}{\mu})^{0.14}$$

According to Fig.(6), it is clear that the fuel centerline temperatures for realistic conditions are higher than that for idealized case due to the thermal resistance in the gas gap. On the other hand, the cladding temperature curve for realistic case lies under that for idealized case due to the variation of the local heat transfer coefficient along the length of the cooling channel as shown in Fig.(8). In addition, it is important to notice that the time taken to reach the steady state temperature for realistic case is higher (32 seconds) than that for idealized conditions (27 seconds).

CONCLUSION

Although neglecting the axial heat transfer is a satisfactory assumption for ideal conditions, it is not valid for more actual situations. Taking the realistic operating conditions into consideration delays the time required to reach the steady state temperature. The proposed code is structurally simple and requires relatively small storage capacity. Consequently, the speed and accuracy of the calculations are greatly enhanced.

NOMENCLATURE

C Specific heat (J/Kg.deg.)
F Coefficients (dimensionless)
Fo Fouriers modulus (dimensionless)
G Mass velocity (Kg/m^2s)
H Fuel element active height (m)
k Thermal conductivity (W/m.deg.)
q''' Volumetric heat generation rate (W/m^3)
NF Number of fuel layers
NC Number of cladding layers
NZ Number of divisions in the axial direction
Nu Nusselt number
R Radius (m)
Re Reynolds number
Pr Prandtl number
T Temperature (°K)
Z Vertical distance above fuel rod bottom
α Cladding to fluid heat transfer coefficient (W/m^2deg)
α_g Gas heat transfer coefficient (W/m^2deg)
ρ Density (Kg/m^3)
θ Time (seconds)
ΔR Thickness of a cylindrical layer (m)
ΔZ Height of a volume element (m)

SUBSCRIPTS

F Fuel/Fluid
c Cladding / center
g Generation
w wall

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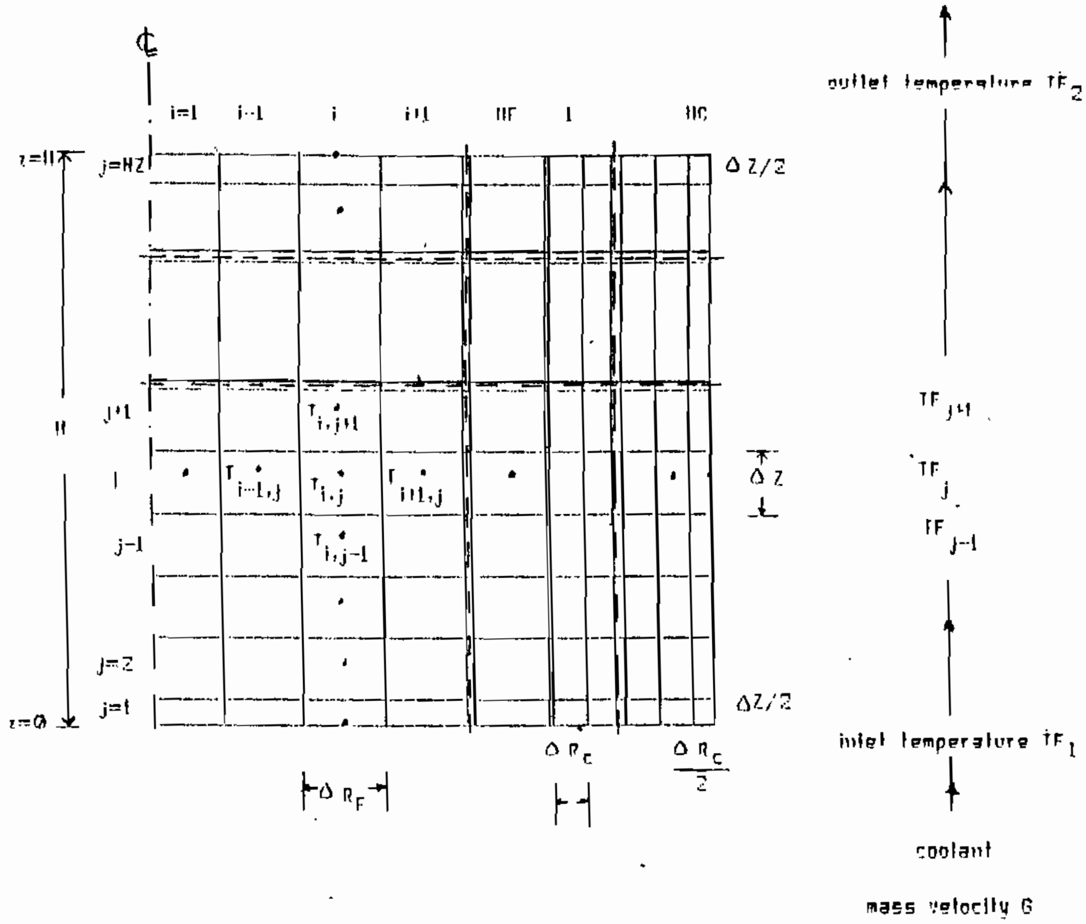

Fig. (1) Nodal points design

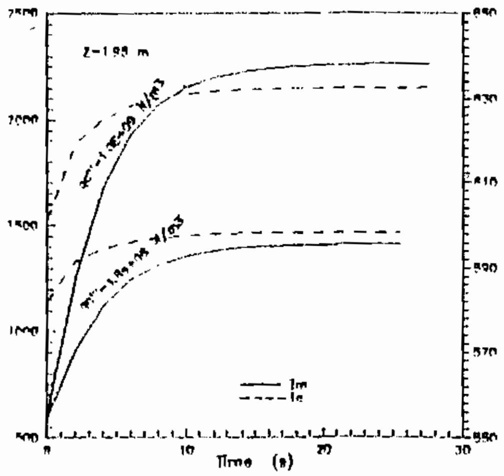

Fig. (2) Time temperature behavior

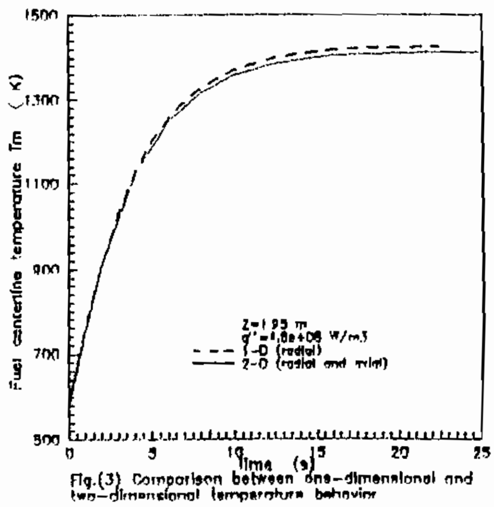

Fig.(3) Comparison between one-dimensional and two-dimensional temperature behavior

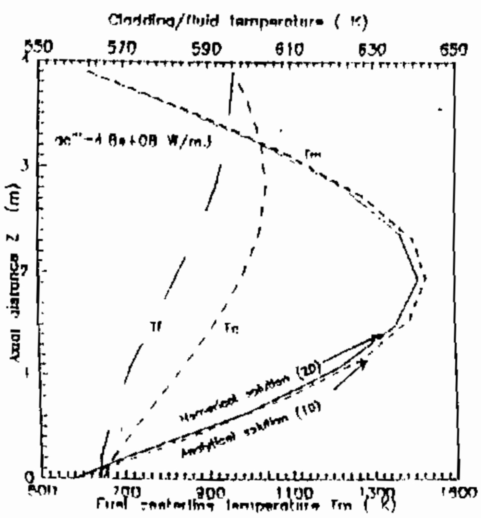

Fig (4) Axial temperature distribution

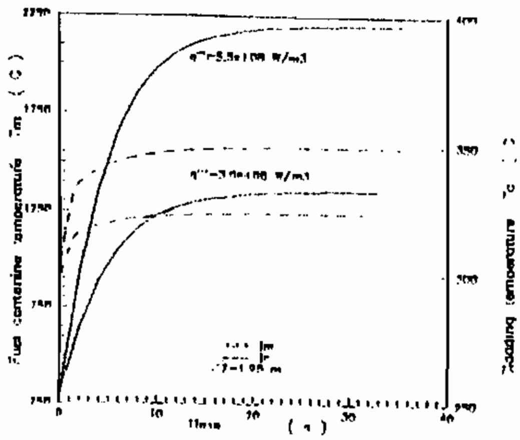

Fig. (5) Realistic temperature behaviour

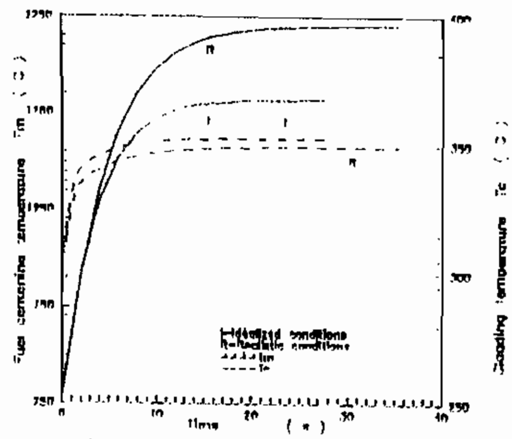

Fig (6) Temperature behavior under realistic and idealized conditions

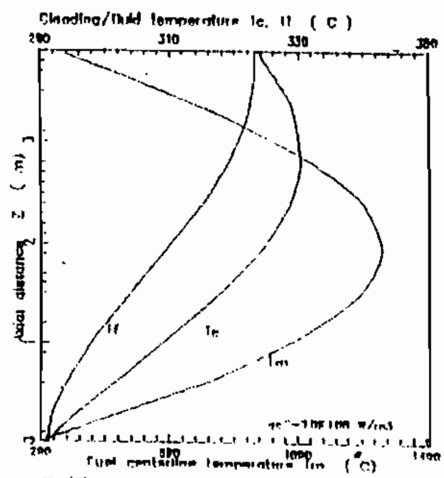

Fig.(7) Axial temperature distribution for realistic conditions

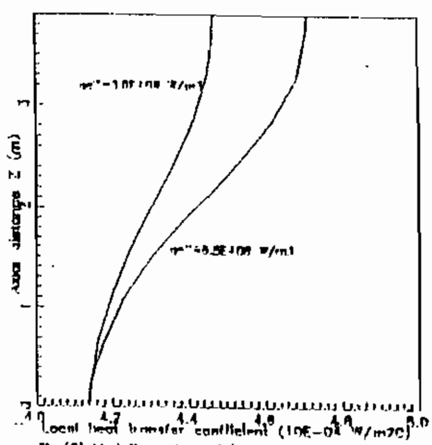

Fig.(8) Variation of local heat transfer coefficient along fuel rod length