ESTIMATION OF THE MAXIMUM TEMPERATURE INTO SHIPPING CASKS USING NEW CORRELATIONS TAKING INTO ACCOUNT THE HOLDING GRILLES OF THE SPENT FUEL ASSEMBLIES

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ABSTRACT

A model for predicting the maximum temperature in a spent fuel assembly located in a shipping cask is given. The model is based on the heat transfer by radiation and convection, and takes specially into account the presence of holding grilles used for fixing the fuel rods. The departure data for making the temperature predictions are: cask temperature, heat generation in the fuel elements, and geometrical/radiative data of the rods and cask. The mean error of the predictions is in the range ±1.4%.

INTRODUCTION

The temperature reached by a spent fuel element confined in containers or shipping casks depends on both the heat generated by the fuel and the rate of heat transfer to the surroundings. The heat transfer can take place by radiation, convection and conduction. It is difficult to evaluate due to the complexity of the system (number of rods, geometry of the assembly, grilles, etc.).

Several studies related with actual fuel assemblies have provided abundant information about topics such as the decay of heat generation, the heat transfer in compact arrays of spent fuel rods 1), the thermal behavior of squared bundles supposing mechanisms of heat transfer by three dimensional convection plus radiation 2), the effects of the fins mounted on the outside of the containers 3), the effects of surfaces-separators 4), and the temperature distributions in storage casks 5). The models for predicting the temperature distribution inside an assembly are scarce. Watson 6) studied the heat transfer in spent fuel assemblies during shipping; his suppositions had been: steady state, non-compact bundles, and radiation as the only heat transfer mechanism. In the model proposed by Nitsche and Rudolf 7), the maximum temperature in the assembly has been evaluated by considering the heat transfer by convection and radiation, but neither the geometry of the assembly nor the presence of internal elements (holding grilles) have been considered.

It is the objective of this work to develop a model for predicting the maximum temperature inside a assembly considering specially the effects produced by the holding grilles. The departure data of the predicting model are: temperature of the cask wall, the heat generation rate in the spent fuel, and geometrical parameters of the assembly, cask, and grilles.

BASIC MODEL

The departure hypothesis of the model is that the thermal behavior of the fuel assembly (a square bundle of rods) can be described by using the concept of single equivalent cylinder, which includes the high complexity of the assembly. This conception allows to simplify the study since the problem is reduced to the calculation of the heat transfer between two concentric cylinders: the assembly-equivalent one (with heat generation) and the enclosing one (the cask), separated by a filling gas (air).

The radiation has an important role in the overall heat transfer of the system above described. Convection can be also important, as has been evidenced previously, with contributions of 74-88% (8) and 30-50% (9) in the overall heat transfer. Consequently, the heat balance used here is:

$$Q_g = (\alpha_c + \alpha_r)\,(T_{Max} - T_O) \qquad (1)$$

where Q_g is the rate of heat generated in the assembly, α_c is the heat transfer coefficient for convection, function of the *Ra* number and several geometrical parameters, and α_r is the transfer coefficient for radiation, given by:

$$\alpha_r = \frac{C_S f}{(T_{Max} - T_O)}\left[\frac{(T_{Max} + 273)}{100}\right]^4 - \left[\frac{(T_O + 273)}{100}\right]^4 \qquad (2)$$

the factor f includes the angle factors between the two cylinders, emissivity of surfaces and geometrical parameters of the assembly.

EXPERIMENTAL

The experiments were carried out in several vertical arrangements of a single tube, and a 6x6 tube bundle with two types of grilles. The tube diameter, D_b, is 0.013 m. The tube and the tube bundle are surrounded by an outer cylinder (different cylinders were tested, with a diameter, D_O, in the range 0.059-0.178 m). The schematics of the grilles, the tube bundle, and the configurations of assemblies with and without grilles are shown in Fig. 1. The diagram of a cross section of the basic layout of grilles is shown in Fig. 1a. The nine tubes marked in Fig. 1b are instrumented with thermocouples and internal electrical resistances (for simulating the heat generation). In the experiments with a single tube the range of electrical power supplied is 16-159 w, and in the tube bundle 1.8-5.5 w/tube. The two types of grilles are similar to the actual ones used in the industrial BWR plants.

The experimental data obtained are abundant, thus we give here only the most representative curves of temperature distribution. The temperature profiles in a single tube (configuration A.1, Fig. 1c) are shown in Fig. 2, and are the typical ones for two concentric cylinders in which the mechanisms of heat transfer are free convection and radiation.

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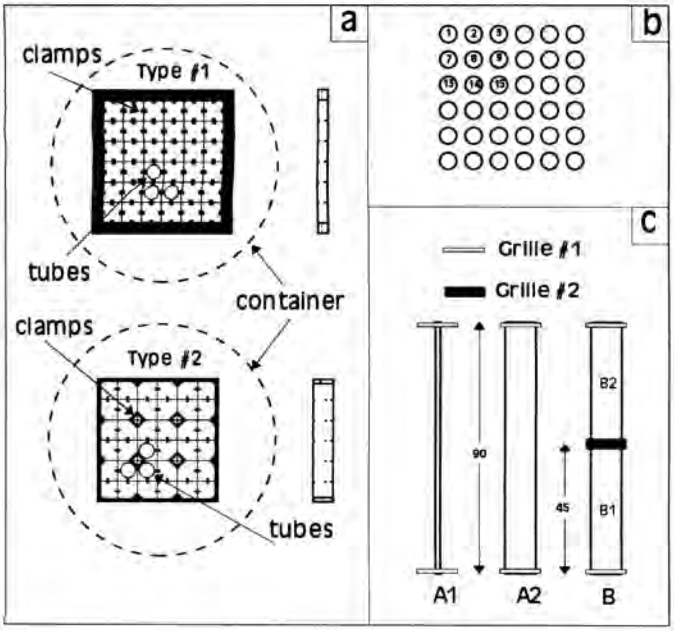

Fig. 1. Schematics of : a) grilles; b) tubes; c) configurations.

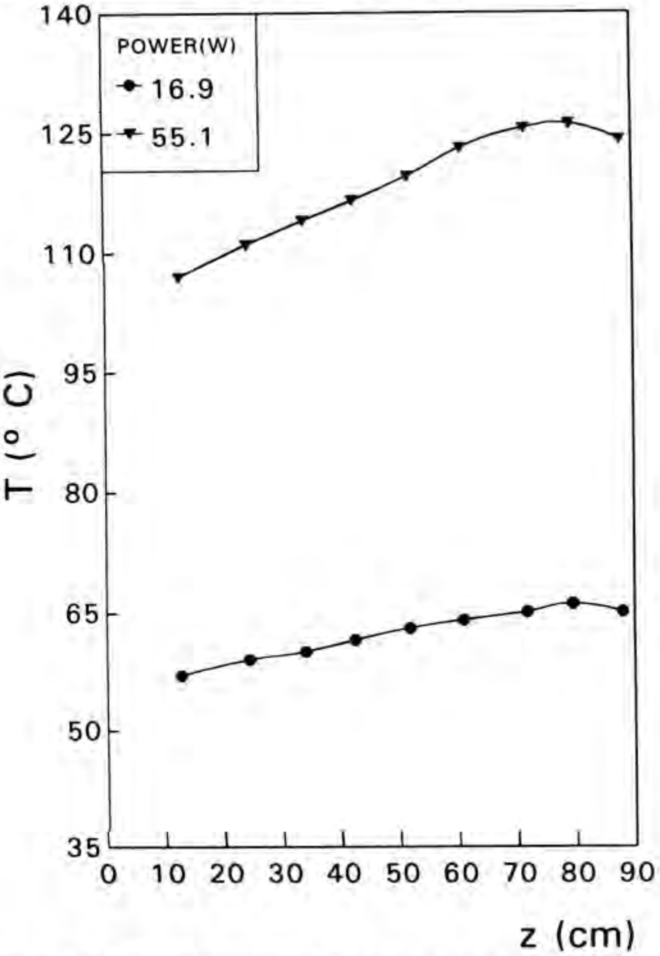

Fig. 2. Profiles of temperature in a tube without central grille.

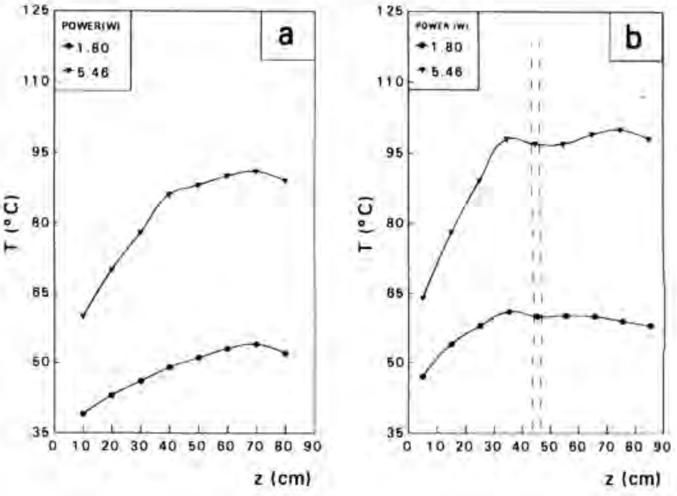

Fig. 3. Profiles of temperature in a 6x6 bundle: a) without central grille; b) with central grille.

The temperature profiles in the tube #9 of the 6x6 tube bundle for two different configurations (configurations A2 and B, see Fig. 1c) are shown in Fig. 3a and 3b (the dotted vertical lines in Fig. 3b represent the location of the central grille). The curves of the configuration A2 (a 6x6 bundle with two grilles) is similar to the profiles of the configuration A1 (a single tube with two grilles). Nevertheless, the profile of the configuration B (which contains three grilles) evidences that the presence of the third, central, grille affects the temperature profile, Fig. 3b.

CORRELATION AND APPLICATION OF THE PREDICTIVE MODEL

The values of α_c and f of Eq. 2 have been evaluated from several experimental temperature distributions in tubes and assemblies. The procedure is described in the following paragraphs.

Calculation of Convection Terms

The heat balance for a rod is:

$$Q_{gi} = Q_{ci} + Q_{ri} \tag{3}$$

The term of heat generation rate, Q_{gi}, is known, and the term of radiation, Q_{ri}, can be easily calculated by a radiation balance between all the elements in the system (rods, grilles, cask wall). In the calculations we take the average temperature in each rod, as well as the mean emissivity of the rods and cask surfaces. Once known Q_{gi} and Q_{ri}, the term Q_{ci} is calculated from Eq. 3. This has been made for a single rod inside the outward cylinder, configuration A1, and for each rod of the 6x6 bundle, configurations A2 and B (the net heat transfer of the bundle was calculated from the contributions of the net heat transferred by every rod). The overall Nu and Ra numbers (both referred to averaged temperatures) have been correlated by:

$$Nu = a\,H^{-0.2377}\,K^{0.4853}\,Ra^{0.2794} \tag{4}$$

where a is a constant depending on the geometry of the grille located at the bottom of the assembly, and H and K are geometrical factors defined by: $H = 2L/(D_o\text{-}D_b)$; $K = D_o/D_b$.

The presence of the central grille have to be taken into account when Eq. 4 is used for predicting Nu. This grille affects the flow-lines of the free convection, and acts as a virtual division of the bundle into two adjacent, almost independent, sections. Thus, for instance in the configuration B, Eq. 4 should be used twice, one for the upper section of the bundle and other for the bottom one, being the values of L and the average temperature of the bundle the corresponding to each one of these sections ($L = 45$ cm) instead of that of the whole bundle.

The size, geometry and type of grille affect on the value of the constant a in Eq. 4. For the grille type #1, $a = 0.1053$, and for the grille type #2, $a = 0.0716$.

The convection coefficient, α_c, can be calculated by:

$$\alpha_c = \frac{Nu\,k}{D_o\,(T_{Max} - T_o)} \tag{5}$$

where the Nu number is previously calculated by Eq. 4.

Calculation of the Radiation Terms

The transfer coefficient for radiation has been calculated by two different ways: a) supposing the bundle as a virtual or equivalent cylinder, and b) taking into account the individual radiation terms of every rod of the bundle, the grilles, and the outer cylinder.

In the first case, the overall radiation term is calculated by Eq. 2, with a value of $f = F_b$, where F_b is given by the expression:

$$\frac{1}{S_b\,F_{bo}} = \frac{1}{S_b}\left[\frac{1}{\varepsilon_b} - 1\right] + \frac{1}{S_o}\left[\frac{1}{\varepsilon_o} - 1\right] + \frac{1}{S_b\,F_{bo}} \tag{6}$$

where F_{bo} is the angle factor between the equivalent cylinder and the outward one, S_b and S_o the surfaces of the equivalent cylinder and the outward one, respectively, and ε_b and ε_o the emissivities of the rods and outward cylinder, respectively.

In the second case, the heat transfer by radiation between all the elements of the actual system (rods, cask inner surface, grilles) are considered. The radiation coefficient is then:

$$\alpha'_r = \frac{Q_{rb}}{T_{Max} - T_o} \tag{7}$$

The overall heat transferred by all the rods of the bundle, Q_{rb}, is calculated by:

$$Q_{ro} = \frac{Q_{ro}\,S_o}{S_b} \tag{8}$$

where Q_{ro} is the net heat transferred by radiation between the cask and all the rods of the assembly (it has been calculated by resolving the system of equations resulting from the radiation balances between all the elements of the system).

Taking present that the radiation coefficient $\alpha_r{}^1$ is the best estimation of the *real one*, we have calculated the correction factor f, which used in Eq. 2 allows to calculate the coefficient α_r proposed in our model, and to use the simplificative concept of equivalent cylinder for representing and calculating the heat transfer coefficients of a tube bundle. The factor f has been calculated from several experimental runs and correlated by:

$$f = 0.259\,F_b\left[\frac{1}{\varepsilon_o}\right]^{0.4895} H^{0.9054} \tag{9}$$

VALIDATION OF THE MODEL

The accuracy of the proposed model has been tested by calculating the maximum temperature in the hottest rod of different assemblies (6x6 tube bundles with two or more grilles) and comparing it with the data of experiments not used in the obtention of the previous correlations, Eqs. 4 and 9. The convection and radiation terms was calculated by supposing that the tube bundle is analog to a system formed by one single equivalent cylinder. The overall Nu and Ra are referred to the average temperature of the hottest tube of the bundle, thus, the temperature difference T_{Max}-T_o is the average temperature of the tube #15 (the nearest one to the centre of the bundle) minus the average temperature of the enclosing cylinder. The convection coefficient, h, is referred to the equivalent outer surface of the bundle, $\pi D_i{}^2 L$. The mean error of the predicted temperature, mean error $= 100[\sum((T_{Maxtheo}$-$T_{Maxexp})/T_{Maxtheo})^2/n(n\text{-}1))]^{1/2}$, was in the range ±1.4%.

CONCLUSIONS

1. The heat transfer in a system constituted by a vertical single tube, or a tube bundle, enclosed by a cylinder involves free convection and radiation, which can be affected by the holding grilles. The presence of grilles affects both the longitudinal and the radial temperature profiles of the tubes.
2. The maximum temperature in a shipping cask can be calculated easily by considering the assembly of fuel rods as a single equivalent cylinder. Appropriate corrections in transfer coefficients and geometric parameters have to be made.
3. The presence and location of the grilles must be taken into account for the calculation of the correction factors above cited.
4. The generalization of the model and method for other types of grilles and configurations can be established looking for additional particularizations. For instance, further relations of the constant a, Eq. 4, with geometrical parameters such as the distance between tubes, and between grilles, thickness of the grille frame, and size of clamps are being investigated, as well as the effects of the emissivity of the surfaces of the rods and the inner surface of the cask.

NOMENCLATURE

C_s	black body radiation constant, 5.78 10^{-4} w cm^{-2} K^{-4}.
D_b	diameter of a single tube, m.
D_i	equivalent diameter of the bundle, $D_i = 6D_b$, m.
D_o	diameter of the external cylinder, m.
f, F_b	correction factors, dimensionless.
F_{bo}	angle factor, dimensionless.
g	gravity acceleration, m s^{-2}.
H	dimensionless parameter.
h	convective heat transfer coefficient referred to the outer surface of a tube (for the tube bundle it is referred to the equivalent outer surface of the bundle), w m^{-2} K^{-1}.
K	dimensionless parameter.
k	thermal conductivity, w m^{-1} K^{-1}.
L	length of tube (length of a section in bundles with central grille), m.
n	number of data.
Nu	overall Nusselt number, hD_o/k, dimensionless.

Q_g	electrical power supplied, w m^{-2}.
Ra	overall Rayleigh number, $(g\beta D_o 3/\alpha\nu)(T_{Max}-T_o)$, dimensionless.
T	temperature, °C.
T_{Max}	average temperature in the hottest tube, °C.
T_o	average temperature in the outer cylinder, °C.
z	distance from the bottom of the bundle to a given point, m.

Greek letters:

α	thermal diffusivity, $m^2 s^{-1}$.
ß	isobaric coefficient of thermal expansion, K^{-1}.
ε	emissivity, dimensionless.
ν	kinematic viscosity, $m^2 s^{-1}$.
ρ	density, kg m^{-3}.

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