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중수로 핵연료채널 고온 열화학반응 실험모사를 위한 View Factor Matrix 생산

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Generation of a View Factor Matrix for a CATHENA Simulation for a High Temperature Thermal-Chemical Experiment

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1. Introduction

During the post-blowdown (or late heat-up) phase of a postulated Loss of Coolant Accident (LOCA) with an impaired Emergency Core Cooling (ECC) in CANDU reactors, most of the coolant of the fuel channels downstream of the break location is discharged and the fuel and the fuel channel are likely to be further heated due to the continued generation of the decay heat. In case of a CANDU reactor all the fuel channels are usually submerged in a huge amount of cold heavy water in the moderator tank, and if the decay heat is properly discharged to this tank via radiation, the integriity of the fuel channel can be maintained. However if this mode of heat transfer is not enough to discharge the decay heat, too high a temperature of the fuel may initiate an auto-catalytic exothermic zirconium-steam metal water reaction and, if progressed to a worse situation, a severe oxidation of the fuel cladding may lead to a failure of the mechanical integrity of the fuel bundle and slumping of the fuels at the bottom of the fuel channel, which may in turn cause a collapse of a fuel channel. Therefore the confirmation of an adequate cooling capability of this heat transfer mechanism has been of great concern for the CANDU-6 safety analysis. In this paper, a CANDU fuel channel model based on a Canadian safety analysis code, CATHENA, that can model this hypothetical extreme radiation cooling condition is described and the view factor matrix necessary to analyze the CANDU fuel channel at this extreme condition is presented. The result of the analysis for a steady state is described and discussed for its physical soundness.

2. Theory

A radiant intensity distribution along each ray of a radiation is calculated by solving a discretization equation for a radiative heat transfer. The fundamental equations for the transfer of a thermal radiation may be expressed as:

$$\frac{dI}{ds} = -(k_a + k_s)I + k_a \frac{E_g}{\pi} + \frac{k_s}{4\pi} \int_{4\pi} P(\underline{\Omega}, \underline{\Omega}')\, I(\underline{\Omega}')\, d\Omega' \tag{1}$$

where I is the radiant intensity in the direction of $\underline{\Omega}$, s is the distance in the $\underline{\Omega}$ direction, $E_g \equiv \sigma T_g^4$ is the black body emissivity power of the gas at temperature T_g, k_a and k_s are the gas absorption and scattering coefficients, and

$P(\underline{\Omega},\underline{\Omega}')$ is the probability that an incident radiation in the direction Ω' will be scattered into the increment of a solid angle $d\Omega$ about Ω. This is a method to inversely integrate the radiation heat transfer equations while considering an emission and absorption in a medium, into emission points from a wall element where the ray of a radiation reaches.

The CATHENA [1] code is a multipurpose thermal-hydraulic code developed primarily to analyze the postulated LOCA scenarios for CANDU reactors and is the code used as the major tool for this study. To calculate the radiation heat transfer for a system of solid surfaces with coolants in-between then, the following assumptions are made:

(1) All the solid surfaces in the system are diffusive and gray,
(2) The surfaces form a closed system (enclosed surfaces),
(3) The inter-solid surface regions such as vapor or cooling gas region are transparent to a radiation(non-participating medium), and
(4) The instantaneous temperature of each segmented solid surface is uniform.

The radiation view factor is calculated, prior to the radiation calculation, by the CATHENA utility program, MATRIX [2]. The MATRIX program uses the Hottlel's crossed-string method [3] to find view factors between infinitely long cylinders in the equilateral triangular and square arrays. It was shown that the MATRIX program provides accurate radiation view factors for the CANDU bundle geometries. [4]

A Network Method for an Analysis of a Radiation Heat Transfer

The analysis of a radiation heat transfer among the surfaces of an enclosure is complicated because of the fact that when the surfaces are not black, radiation leaving a surface may be reflected back and forth several times among the surfaces, with a partial absorption occurring at each reflection. An assumption commonly used in these enclosure calculations is that the surfaces are diffuse-gray, which means that they absorb a fixed fraction of an incident radiation from any direction and at any wavelength. Several methods of this kind of analysis can be found in the literatures. Some of the most popular methods are the view factor method introduced by Hottel and the network method introduced by Oppenheim [5]. Both methods are basically the same for simple problems which do not involve many surfaces.

The radiation heat transfer between two gray surfaces, of areas A_1 and A_2, emissivities ε_1 and ε_2, maintained at absolute temperatures T_1 and T_2, is generally estimated by the following equation:

$$\dot{Q}_{12} = \sigma A_1 (T_1^4 - T_2^4) \cdot C_{1,2} \quad (2)$$

$C_{1,2}$ is a dimensionless effective view factor for the gray surfaces, which depends on the emissivity of each surface and the geometrical configuration of the surfaces specified by the view factor for black surfaces, $F_{1,2}$.

$$C_{1,2} = \frac{1}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{1,2}} + \frac{A_1}{A_2}\left(\frac{1-\varepsilon_2}{\varepsilon_2}\right)} \quad (3)$$

However, the network method by Oppenheim is relatively convenient for problems which involve many surfaces, as the matrix formulation of a radiation exchange for enclosures is introduced.

For an enclosure consisting of several surfaces or "zones"with prescribed temperatures T_i for each surface (i = 1, 2, ... N), of areas A_i and emissivities ε_i, the radiation heat transfer from any one of the surfaces can be calculated by solving an algebraic matrix equation for the unknown radiosities, J_i which can be formulated by the following expression:

$$\frac{1}{\varepsilon_i} J_i - \frac{1-\varepsilon_i}{\varepsilon_i} \sum_{j=1}^{N} J_j F_{i,j} = \sigma T_i^4 \quad (4)$$

The radiosity is the sum of the energy emitted and reflected when no energy is transmitted. The application of this matrix formulation to the network method is called the Radiosity Matrix Method (RMM) [6]. Equation (4) can be written for each of the N surfaces of the enclosure giving N equations for N unknowns. This can be, for a convenience, expressed in a matrix form as:

$$[M_{ij}] \cdot [J_i] = [\sigma T_i^4] \quad (5)$$

where $[J_i]$ is the radiosity vector, $[\sigma T_i^4]$ is the surface input vector and $[M_{ij}]$ is the N×N coefficient matrix:

$$M_{ij} = \frac{\delta_{ij} - (1-\varepsilon_i) F_{i,j}}{\varepsilon_i} \quad (6)$$

and δ_{ij} is the kronecker delta, defined as

$$\delta_{ij} = \begin{cases} 1 & \text{for i} = \text{j} \\ 0 & \text{for i} \neq \text{j} \end{cases} \quad (7)$$

Once the radiosities J_i are known from the solution of Eq. (5), the net radiation heat flux q_i, for the surface zone i can be calculated by the following equation:

$$q_i = J_i - \sum_{j=1}^{N} J_j F_{i,j} \quad (8)$$

For an enclosure where the temperatures T_i are prescribed for some of the surfaces (i = 1, 2, ..., k), and the net heat fluxes q_i for the remaining surfaces (i = k+1, k+2,...., N), the N equations for a determination of the N unknown radiosities J_i (i = 1, 2, ..., N) are obtained as follows:

For surfaces i = 1, 2, ..., k with the prescribed surface temperatures, we use Eq. (5).

For surfaces i = k+1, k+2, ..., N with the prescribed net heat fluxes, the following matrix formation is used:

$$[\delta_{ij} - F_{i,j}]\cdot[J_i] = [q_i] \quad (9)$$

For a practical use of the RMM, the matrix algebraic equations in Eq. (5) and (9) are solved by a variety of numerical computing methods. In this study the Gauss-Jordan elimination method is used for solving sets of linear equations.

3. Analysis Results and Discussions

During the post-blowdown phase of a LBLOCA in a CANDU reactor, a conjugated heat transfer of a steam cooling convection and radiation as well as a heat conduction occurs in a fuel channel. Proper modeling involves a very complicate modeling of the associated heat structures in a very careful manner using various modeling features of the CATHENA code. Fortunately owing to the utility program, MATRIX of CATHENA developed to calculate the view factor matrix (VFM) of these complicated geometries of the associated heat structures, one can model a delicate and complex heat transfer among these structures, namely a 28-element fuel bundle, and the surrounding pressure tube, and the outer calandria tube which is submerged in a huge cold moderator. The following section describes the way this view factor matrix is calculated for the test CS28-1, 2 [7] which ranges the fuel channels in an as-designed pressure tube and aged crept pressure tube geometry. The schematic diagram of the test CS28-1 test bundle is shown in Fig. 1.

3.1 Definition of the View Factor and its Relation with the GENHTP model

The view factor is a dimensionless solid angle that one segment of a surface can have to other segment of surface of any adjacent structure. The view factor defines which solid surfaces in a GENHTP, a solid structure heat transfer package, model or models may radiate heat between each other. All the surfaces defined in the GENHTP model must be accounted for in the view factor matrix. CATHENA uses the information in the view factor matrix and in the RADIATION MODEL input to calculate a radiation matrix. The radiation matrix is used to determine the heat transfer between the surfaces under construction. The view factor matrix stores a view factor value (dimensionless solid angle) for each pair of "temperature stations"in the current axial segment of the solid component model under consideration. A temperature station is any surface of a solid structure which is collectively defined as a representative heat transfer surface group in the GENHTP model as they are thought to have similar heat transfer characteristics, geometrically and phenomenally.

As an example, the surface segments numbered 3 and 7 in Fig.2 can be expected to have the same temperatures if the gravitational effect is negligible, thus these two surfaces can be grouped as one temperature station. Similarly many surfaces, if their symmetric characteristics are accounted for, can be grouped as a "temperature station". This feature permits the user to contract an existing view factor matrix file into a reduced view factor matrix file. This reduced file requires less memory and computation than the original at a slight lose of the accuracy. Also as CATHENA does no support an axial heat conduction, no view factor calculations are done for temperature stations in adjacent axial segments.

3.2 Generation of the VFM for the CS28-1 Bundle

The view factor matrix is generated separately by using the utility program MATRIX. A detailed view factor matrix between the pressure tube and each of the 28 FES is generated first, and then converted to the contracted view factor matrix file which is consistent with the solid component models.

According to the recommendation of the User's Manual of MATRIX 1.05, the fuel bundle geometry in a pressure tube is described by specifying the radius of the fuel ring with the starting angle of the arbitrarily chosen 'first' fuel rod's center as measured in a counter-clock-wise with respect to the horizontal line drawn from the ring center to the right direction. In this case, the first rod of the first fuel ring is chosen as the one denoted by the segment number (1,2), the first rod of the second fuel ring is the one denoted by the segment number (9,10), and the first rod of the third fuel ring is the one denoted by the segment number (27,28). Thus the starting angles for these three 'first rods; are 45.0^{o}, 67.5^{o} and 78.75^{o} respectively. The radius of the three fuel rings are 0.01175m, 0.02685m, and 0.04229m respectively. The geometry of the pressure tube surrounding these fuel bundle is specified by its center position in a polar coordinate with respect to the fuel bundle center, and the radius of the pressure tube with the starting angle of the first circumferential sector to be numbered in a clock-wise fashion.

One good way of checking the appropriateness of the VFM is checking that the symmetry of the numerical values is consistent to the geometric symmetry of the fuel bundle. Another way of checking the goodness of the result is to confirm whether the view factor for a completely blocked object is really zero in the matrix. In modeling the conjugated heat transfer phenomena among the conduction, convection and radiation, one of the most difficult parts is preparing the CATHENA input for a set of heat transfer models (fuel element, pressure tube, calandaria tube, subchannel models, and the associated thermalhydraulic and radiative boundary conditions) consistent with each other among these three different heat transfer models and View Factor Matrices (VFM).

4. Conclusion

Based on the fact that the asymmetric solid temperature distribution of the test bundle at various heights is consistent with the experimentally measured ones as shown in Fig.3. it can be concluded that the radiation heat transfer model of the test section is correct and physically reasonable.

5. References

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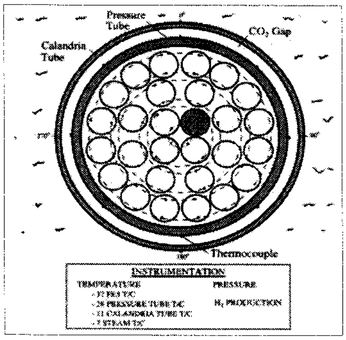


Fig. 1. Cross Section of the CS28-1 Test Bundle and the Thermocouple Locations.[7]

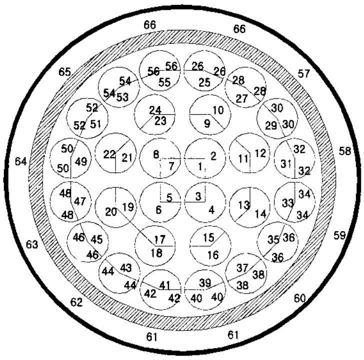
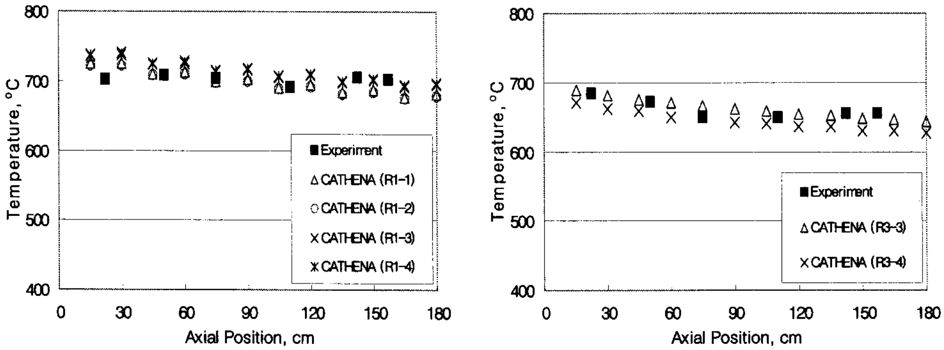


Fig. 2. Contracted Solid Structure Model for the CS28-1 Experiment



Inner Ring Fuel   Middle Ring Fuel

Fig.3. Comparison of the CATHENA Prediction with the Measured One for the CS28-1 Expt [7]