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Enthalpy and Void Distributions in Subchannels of PHWR Fuel Bundles

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Abstract

Two different types of the CANDU fuel bundles have been modeled for the ASSERT-IV code subchannel analysis. From calculated values of mixture enthalpy and void fraction distributions in the fuel bundles, it is found that net buoyancy effect is pronounced in the central region of the DUPIC fuel bundle when compared with the standard CANDU fuel bundle. It is also found that the central region of the DUPIC fuel bundle can be cooled more efficiently than that of the standard fuel bundle. From the calculated mixture enthalpy distribution at the exit of the fuel channel, it is found that the mixture enthalpy and void fraction can be highest in the peripheral region of the DUPIC fuel bundle. On the other hand, the enthalpy and the void fraction were found to be highest in the central region of the standard CANDU fuel bundle at the exit of the fuel channel. This study shows that the subchannel analysis is very useful in assessing thermal behavior of the fuel bundle that could be used in CANDU reactors.

I. Introduction

Subchannel technique is known to be very useful for investigating the thermal behavior of a fuel in nuclear reactors. The subchannel analysis of a fuel bundle normally yields detailed thermal-hydraulic information of the local flow field which can be utilized in assessing thermal margin of the fuel. Moreover, the results of subchannel analysis can be a valuable feedback to the neutronics design of reactor core loaded with new fuel.

In this study, the ASSERT-IV computer code[1] is used for subchannel analysis of the standard and the DUPIC (Direct Use of spent PWR fuel In CANDU) fuel bundle strings. Using the reference DUPIC fuel design parameters[2], mixture enthalpy, void fraction, equilibrium quality distributions in the subchannels of the DUPIC fuel have been calculated by the ASSERT code. The radial distributions of these parameters in the DUPIC fuel bundle are compared with those of the standard CANDU fuel bundle (i.e., the 37-element fuel bundle).

The ASSERT subchannel code was developed to address the computation of flow and phase distribution within subchannels of CANDU fuel bundles. Unlike conventional subchannel codes such as COBRA, which are designed primarily to model in vertical fuel bundles and use a homogeneous mixture model of two-phase flow, ASSERT uses a drift-flux model[3,4] that permits the phase to have unequal velocities. ASSERT includes gravity terms that may make it possible to analyze separation tendencies which could occur in horizontal flow. During its developmental stage, computational results of the ASSERT code were validated against the real scale 37-element bundle experimental data[5].

The thermal-hydraulic modeling equations used in ASSERT were derived from the two-fluid formulation[6]. Like COBRA-IV computer code[7], the ASSERT code is based upon subchannels which are divided axially into a number of control volumes. The closure relationships for the governing equations used in ASSERT include the equation of state, relative velocity relationship, fluid friction, wall heat transfer and the thermal mixing to primary variables, phasic flow velocities, densities, enthalpies and pressure.

The transverse interchange models of the ASSERT code are based upon three physical models, that is, the flow diversion, turbulent mixing and the void drift. The so-called void diffusion includes the second and the third effects. The second effect can be modeled by the classical Reynolds stress term. Nevertheless, it is known that the turbulent mixing alone fail to produce the required results since infinite turbulent mixing implies that subchannel void fractions must be the same for a finite value of crossflow while the observed void distribution is a nonuniform equilibrium distribution. Therefore, it was hypothesized that net two-phase turbulent mixing is proportional to the nonequilibrium void fraction gradient. This hypothesis implies that there is a strong trend toward the equilibrium distribution and that when this state is achieved, the net exchange due to mixing ceases. In the ASSERT code, the phasic relative velocity can be induced by two effects which are the mixing and the net buoyancy. It should be noted that the equilibrium void distribution in a horizontal channel may be different from that in a vertical channel. The net buoyancy effect was claimed[1] to be taken into account by using the drift flux model in the ASSERT code.

The crossflow is directed flow caused by pressure gradients between the subchannels. In the horizontal fuel channel in PHWR, the gravity influences the crossflow since the direction of gravity is perpendicular to the channel flow. Since the exit flow quality in CANDU fuel channels could be greater than zero, the void drift can be promoted and the net buoyancy may make preferential direction in the transverse exchange. Since in two-phase flow, not only the energy and the momentum exchange but also the mass exchange occur between subchannels, the equal volume exchange concept is applied in the ASSERT code. It should be noted that the effect of the transverse exchange can be diminished when the mass flow is large. The transverse exchange model could affect the location of CHF in the fuel bundle significantly in the fuel channel of CANDU reactors[8]

The numerical solution of ASSERT-IV can be subdivided into two parts: The first part solves the energy and the state equations using block iterative method to calculate the mixture and phasic enthalpies for all subchannels using the current estimates of flow. Once the inner iteration for energy equation solution converges, the second part calculates the flows and pressure gradients at that axial position by direct matrix solution of the crossflow equations. With this information, axial flows and pressures can be calculated. Both parts are repeated once to ensure a higher level of convergence of both energy and flow solutions prior to moving to the next axial position. The channel is successively swept from the inlet to the exit. This outer iteration continues until convergence is achieved, or until the iteration limit is reached. Successful completion could yield a steady-state solution, or one time-step of a transient solution. The solution scheme works with either a flow boundary condition or a pressure boundary condition.

II. Subchannel Models

Half bundle subchannel models for the DUPIC and the standard CANDU fuel bundles have been modeled. Since gravity is perpendicular to the direction of channel flow in CANDU reactors, at least half of the bundle should be modeled for the subchannel analysis. The model for the DUPIC fuel bundle includes 23 powered elements and 35 subchannels. It should be noted that a slight difference is expected between different rotations of fuel bundles in the fuel channel since the half symmetry can not be maintained for the other rotational angles of the fuel bundle. It is known that in general, for the 37-element fuel bundle string, the minimum CHFR occurs at three fourths of the fuel channel length from the inlet and at upper subchannels in radial direction. On the other hand, this is not necessarily true for the 43-element fuel

The ring power distribution of the DUPIC fuel bundle has been obtained from the DUPIC reference fuel design which is based upon the neutronics properties of a CANDU core loaded with the DUPIC fuel. The lattice parameters and the resulting ring power ratio, as shown in Table I, used for neutronics and thermal-hydraulics calculations were produced by the WIMS-AECL code.

Table I. Ring Power Ratios Used for Subchannel Analysis

	Ring 1	Ring 2	Ring 3	Ring 4
Standard Fuel	.761	.805	.921	1.131
DUPIC Fuel	.4985	.8567	.8193	1.192

III. Results and Discussion

The operating conditions and thermal-hydraulic parameters of the fuel bundles used in the subchannel analysis are shown in Table II. For the purpose of valid comparison between two fuel types, the channel average mass flux and the average heat flux of the DUPIC fuel have been adjusted to yield the same mass and energy input/output for the fuel channel. By doing this, for specified values of channel average mass and heat fluxes, the difference in the flow area between two fuel types may yield the equivalent channel energy balance for the coolant. It will be shown later that the bundle average quality profile between the two fuel types can also be matched along the fuel bundle strings.

Table II. Fuel Parameters and Operating Conditions Used for Subchannel Analysis

	Standard Fuel	DUPIC Fuel
Flow Area [m^2]	.00176	.00180
Heated Perimeter [m]	.7603	.8018
Wetted Perimeter [m]	.9236	.9641
Avg. Mass Velocity [Mg/m^2-s]	5.00	4.89
Avg. Heat Flux [MW/m^2]	1.100	1.043
System Pressure [MPa]	10.0	
Inlet Temperature [Degree C]	260.0	
Inlet Enthalpy [KJ/KG]	1095	

The calculated mixture enthalpy at the exit of the standard fuel channel is shown in Figure 1. If we consider the subchannels neighboring the central fuel element, the mixture enthalpies in the upper subchannels are consistently higher than those in the lower subchannels. Since the fuel element powers in the Ring 2 are identical, we know from this result that the ASSERT-IV code may take into account the gravity effect properly. This fact was confirmed from the subchannel-wise density distribution which is not shown here. It is clear that this type of non-uniform enthalpy distribution is impossible for the flow through a fuel assembly used in LWRs where the fuel assemblies are vertically loaded. As can be seen, the mixture enthalpy in the upper peripheral region of the bundle is higher than that in the lower region due to gravity. In this simulation, the bundle average quality and the void fraction at the exit of the fuel channel were found to be 0.23 and 0.77, respectively. The subchannel where the mixture enthalpy is highest has been found to be in the central region of the fuel bundle as shown in Figure 1. However, this may not be necessarily true near the location where the CHF occurs. In contrast, for the DUPIC fuel bundle, as shown in Figure 2, the subchannel where the mixture enthalpy is highest has been found to be the upper part of the fuel bundle at the channel exit. It is not clear at this moment why this different tendency in the radial enthalpy distribution between two fuel bundles occurs at the high void fraction regime (i.e., at the exit of the fuel channel). It is interesting to note, however, that the mixture enthalpy of subchannels around the center fuel element of DUPIC fuel bundle is much less uniform than the standard fuel case as shown in Figures 1 and 2. Based upon this result, it is a concern that the radial flow distribution can be aggravated due to the pronounced net buoyancy effect in the DUPIC fuel bundle.

The radial void distributions at the exit of the fuel channel are shown in Figures 3 and 4. From these figures, the tendency of void migration in the upper region of the fuel bundle is clear and the void fraction in the central region is highest for the standard fuel bundle, while the void fraction is highest in the upper region of the DUPIC fuel bundle.

IV. Summary and Conclusion

The enthalpy and void distributions of PHWR fuel bundles have been presented. The mixture enthalpy and the density distributions around the central region of the fuel bundle show clear net buoyancy effect, which is pronounced in the DUPIC fuel bundle. Further investigation on this effect should be followed. The CHF location is known to be very sensitive to the crossflow and the void diffusion models used in the subchannel model. It should be noted that validity of this analysis strongly depends on the transverse interchange model and the related parameters so that further effort should be devoted for validating transverse interchange in the horizontal fuel channel. Finally, it is hoped that this study would be useful for developing more realistic subchannel analysis code for assessing thermal behaviors of fuel bundles in CANDU reactors.

References

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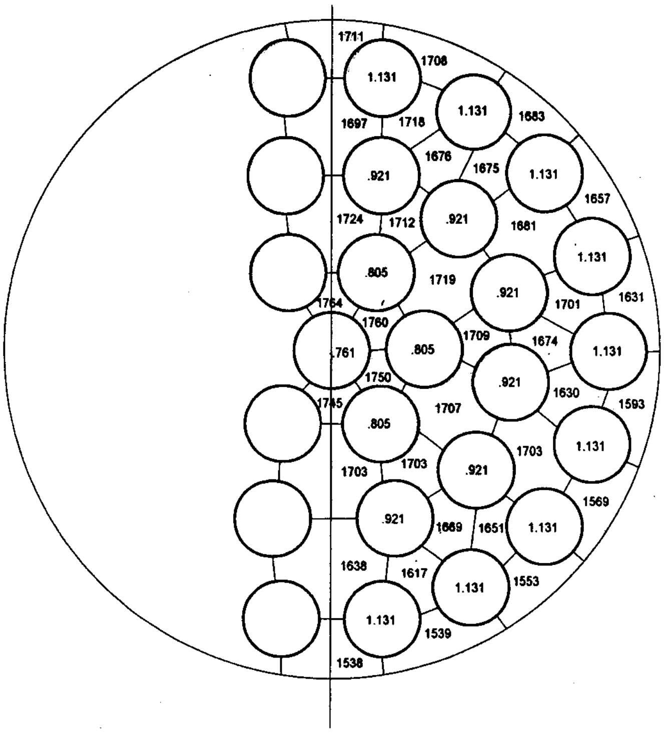

Figure 1. Channel Exit Enthalpy Distribution of Standard Fuel Bundle

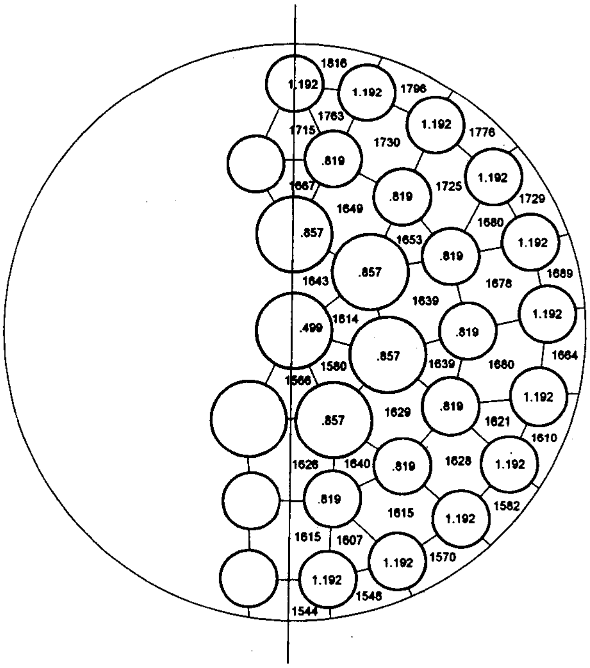

Figure 2. Channel Exit Enthalpy Distribution of DUPIC Fuel Bundle

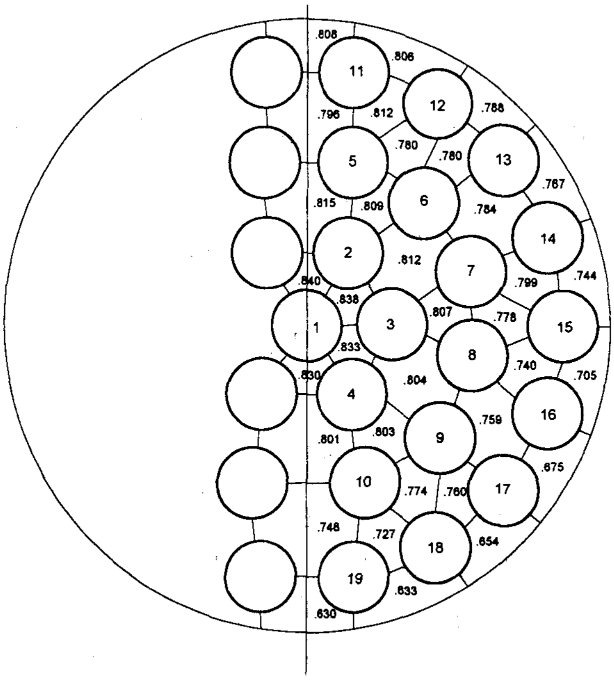

Figure 3. Channel Exit Void Distribution of Standard Fuel Bundles

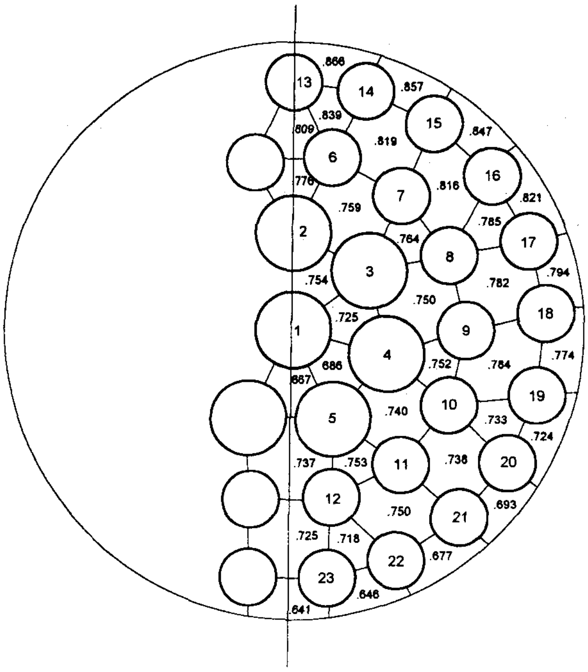

Figure 4. Channel Exit Void Distribution of DUPIC Fuel Bundles