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Thermal Hydraulic Calculations in the SAS-DIF3DK Coupled Reactor Physics and
Thermal Hydraulics Code*

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ABSTRACT

The SAS-DIF3DK code couples a detailed 3-D neutron kinetics treatment with a detailed thermal hydraulics treatment. One goal of the work on SAS-DIF3DK is to produce a detailed code that will run a wide range of transients in real time. Achieving this goal will require efficient numerical methods and efficient coding, and it will probably require the use of multiple processors for larger problems. It has previously been reported that the thermal hydraulics treatment in the code achieves the required speed for typical PWR and BWR cases. This paper presents results from thermal hydraulic analysis of severe LOCA cases in a Soviet design RBMK reactor, and shows that the computing speed goals are also met in these cases.

I. INTRODUCTION

The SAS-DIF3DK code is being developed to do detailed safety calculations in real time, using a 3-D neutron kinetics treatment coupled with a detailed thermal hydraulics treatment. The thermal hydraulics treatment supplies detailed material densities and temperatures to the neutron kinetics treatment, and the neutron kinetics treatment supplies detailed power densities to the thermal hydraulics treatment. The 3-D neutron kinetics treatment is described in Ref. 1. This paper describes the thermal hydraulics treatment and some applications of the thermal hydraulics analysis.

The thermal hydraulics treatment of the reactor core uses a multiple channel treatment in which each channel represents one or more fuel assemblies. In order to do the calculations for larger cases in real time, it is intended to run the thermal hydraulics calculations for one or more channels on a single computer processor, with multiple processors used to run cases involving a large number of channels. This means that the thermal hydraulics calculations must run fast enough to run a wide range of single channel transients in real time.

II. MULTIPLE CHANNEL MODEL

In order to provide a detailed thermal hydraulic representation of the reactor core, SAS-DIF3DK uses a multiple channel treatment in which each channel represents one or more assemblies. Detailed three dimensional, distributions are provided to the kinetics treatment even though the channel calculations are one dimensional. As illustrated in Fig. 1, a channel contains coolant; and it can also contain one or more fuel pins, duct walls, water pins, control rods, axial shields, or a pressure tube surrounded by graphite. A channel usually runs the full length of a fuel assembly, including the regions above and below the fuel pins. In the RBMK case, a channel also includes inlet and outlet piping. Channels are largely independent of each other, and currently cross flow between channels is not accounted for. All core channels see common inlet and outlet pressures that drive the coolant flow rates. Thus, transient flow redistribution between channels is automatically accounted for.

In the axial direction a channel is divided into zones. In each zone the coolant flow area and hydraulic diameter are constant. Also, within a zone the solids in contact with the coolant do not change.

III. COOLANT TREATMENT

A five equation homogeneous non-equilibrium model is used for the coolant. The liquid and vapor velocities at a given location are assumed to be the same, but the liquid and vapor temperatures can be different. The coolant calculations include single phase liquid, subcooled boiling, nucleate boiling, post departure from nucleate boiling (post-DNB) heat transfer, and pure vapor. Starting from single phase liquid, when the cladding surface temperature exceeds saturation, the Chen correlation is used, with a nucleate boiling term added to a forced convection term in the heat transfer coefficient. For the onset of net void generation, the correlation of Saha and Zuber is used. The Biasa correlation is used for the critical
heat flux. For the post-DNB region the Dougall-Rohsenow heat transfer correlation is used.

IV. NUMERICAL METHODS

The thermal hydraulics treatment includes both steady-state and transient calculations. For the steady-state calculations, a direct solution is used; and it is necessary to iterate to obtain a consistent solution. For the transient solution fully implicit time differencing can be used so there is no Courant limit on the size of the time steps. The time step size is limited mainly by accuracy considerations, and relatively large time steps can be used unless the quantities being calculated are changing very rapidly. There are no iterations in the transient thermal hydraulics solutions in SAS-DIF3DK. For a transient time step, the equations are linearized about the values at the beginning of the step, and the changes in all temperatures, coolant flow rates, vapor flow qualities, and pressures are solved for simultaneously and directly. This provides an efficient numerical solution.

V. EXAMPLES

A number of one channel test cases have been run in the thermal hydraulics part of the SAS-DIF3D code to demonstrate capabilities and to determine running times. For these test cases the neutron kinetics was not used; the power was specified as a function of time. Results from the first two cases have previously been reported. These two cases are based on NEACRP benchmarks. The first case is a pressurized water reactor (PWR) rod ejection case, starting from low power. The second case is a boiling water reactor (BWR) cold water injection case. In both of these cases the solution was numerically stable with time step sizes of 0.1 seconds or more, and the time step size was limited mainly by accuracy considerations. Stable and accurate solutions were obtained with time steps large enough that the cases ran significantly faster than real time.

Both large break and small break loss of coolant accident (LOCA) cases have been run for Soviet RBMK reactors. Both cases involved leaks or ruptures of a group distribution header that feeds water into a group of core channels. In the large break case a large rupture is assumed in the group distribution header, whereas in the small break case a moderate sized leak is assumed. These cases were run only to demonstrate the capability of the code to handle severe transients. No scram was considered. In both cases the reactor power was held at its nominal value for the duration of the transient.

Figure 1 shows the SAS-DIF3DK model used for the RBMK cases. An RBMK reactor consists of a large graphite stack penetrated by a large number of fuel channels and control rod channels. A fuel channel contains a pressure tube, water coolant, a fuel assembly, an extension rod, and a shield or flow mixer. The fuel assembly contains a central rod and two concentric rows of fuel pins. In the axial direction there are upper and lower fuel pins, separated by a small gap. The total length of the fuel in the axial direction is 7 meters. Because the outer row of fuel pins partially shields the inner row from the thermal neutrons coming in from the graphite moderator, the power level in the outer row of pins is somewhat higher than that in the inner row. For these calculations a single fuel channel was modeled. The model includes piping from the group distribution header to the fuel channel, the whole length of the fuel channel, and the piping from the top of the fuel channel to a steam separator drum. Four fuel pins (inner and outer, upper and lower) are modeled. The pressure tube wall and the graphite beyond it are included in the model.

For the large break case a large rupture is assumed in a group distribution header. The pressure in the header is assumed to drop from its nominal operating pressure to atmospheric pressure in 0.1 second. This leads to a rapid flow reduction in the core, followed by flow reversal. Figure 2 shows the calculated coolant flow rates at the top, middle, and bottom of the core. Figure 3 shows the flow quality in the core. Near the time when the flow goes through zero, the vapor fraction rises to almost pure vapor in the core. Figure 4 shows the mid-core cladding and coolant temperatures. The cladding temperature rises rapidly by about 30 K during the period of low coolant flow rates. After the flow reversal and the establishment of significant negative flow, the core is cooled by downstream flow from the outlet steam drum. Figure 5 shows the mid-core fuel centerline temperature. The fuel centerline temperature does not respond to the rapid flow reduction and flow reversal, but it does eventually respond to the long term drop in the cladding temperature.

In an RBMK reactor the small break LOCA is potentially much more severe than a large break LOCA. A moderate sized leak of just the right size in a pressure distribution header can lead to sustained flow stagnation in some core channels. For the small break LOCA calculations the pressure in a group distribution header is assumed to drop from its initial steady-state value of 74.946 bars to a value of 70.151 bars as a result of a leak. The pressure drop occurs in 0.1 second, and the group distribution header pressure is held constant after the drop. As shown in Fig. 6, this leads to low coolant flow rates in the core. There are some flow oscillations, since the computed boiling behavior is not completely steady. During the transient much of the core is filled with pure steam or
almost pure steam: there is little water in the core. Figure 7 shows the mid-core cladding and vapor temperatures. These temperatures rise rapidly after the start of the transient. DNB is predicted early in the transient. The steam-zirconium chemical reaction that would start at a temperature of about 1000 K was not accounted for in this calculation. This reaction would cause the cladding temperature to increase more rapidly. Figure 8 shows the mid-core fuel center line temperature for this transient. The fuel would start melting soon after 40 seconds into the transient. Figure 9 shows the mid-core graphite temperatures. There is some heat deposited in the graphite by neutrons and gamma rays. The graphite surface temperature rises rapidly in response to the rise in the coolant temperature. The graphite is thick enough that the temperature in the middle of the graphite hardly responds at all for the first 40 seconds of the transient.

Table 1 shows the computer timing information for the two RBMK LOCA cases run on a workstation with a speed typical of that of currently available machines. The steady-state calculation is very fast. The large break LOCA runs faster than real time. The small break LOCA runs essentially in real time.

<table>
<thead>
<tr>
<th></th>
<th>small break</th>
<th>large break</th>
</tr>
</thead>
<tbody>
<tr>
<td>transient time (s)</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>steady-state computer time (s)</td>
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<td>.1</td>
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<tr>
<td>transient computer time (s)</td>
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<td>13.8</td>
</tr>
<tr>
<td>average coolant time step size (s)</td>
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<td>.0129</td>
</tr>
</tbody>
</table>

Note: timings are for a Sun Ultra-Sparc 30 work station with a single 300 MHz processor.

VI. FUTURE WORK

A significant amount of work remains to be done on the thermal hydraulics part of the SAS-DIF3DK code. One task is adding a detailed thermal hydraulic treatment beyond the core channels. Currently only the core channels are treated in any detail, with a very simple treatment for the remainder of the primary loop. A second task is adding a separated flow model for the coolant as an alternative to the homogeneous non-equilibrium model currently in the code. A third task is comparing SAS-DIF3DK predictions with other codes. Some work has been done in this area but more work is necessary. A fourth task is comparing code predictions with actual experimental data. A fifth task is setting the code up for parallel operation on a number of processors.

VII. CONCLUSIONS

The SAS-DIF3DK code is capable of running a wide range of PWR and BWR transients. Because of the use of efficient numerical methods, the thermal hydraulic treatment in the code can run a wide range of single channel transients faster than real time or essentially in real time. Thus, by the use of multiple processors with one or more channels running on each processor, it should be possible to run large multi-channel cases in real time.

For a leak in a pressure distribution header of an RBMK reactor, a small break LOCA can be much more severe than a large break LOCA.

ACKNOWLEDGMENTS

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REFERENCES


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Fig. 1. SAS-DIF3DK Representation of an RBMK Fuel Channel and Associated Piping
Fig. 2. RBMK Large-Break LOCA Core Coolant Flow Rates

Fig. 3. RBMK Large-Break LOCA Flow Quality

Fig. 4. RBMK Large-Break LOCA Mid-Core Cladding and Coolant Temperature

Fig. 5. RBMK Large-Break LOCA Peak Fuel Center Line Temperature
Fig. 6. RBMK Small-Break LOCA Core Coolant Flow Rates

Fig. 7. RBMK Small-Break LOCA Mid-Core Cladding and Coolant Temperatures

Fig. 8. RBMK Small-Break LOCA Peak Fuel Center Line Temperature

Fig. 9. RBMK Small-Break LOCA Mid-Core Graphite Temperatures