Integrating Sudo-Kaminaga Correlation to the Safety Analysis Code PARET-ANL

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INTRODUCTION

The accuracy and reliability of the reactor safety analysis code are critical because the specifications of the safety systems will depend on the analytical results for initiating events that could occur to the reactor. In safety analyses for power reactors, there exist many proficient and applicable computer codes such as RELAP5, CATHARE, RETRAN, or CATHENA. For non-power research reactors, an issue arises, however, due to lacking of such specialized codes. As a result, computer codes developed for the transient analysis of power reactors need to be applied carefully after proving their applicability to a specified research reactor [1].

The safety analysis discussed in this paper concerns the prevention of fuel damage in hypothetical accidental scenarios for the new research reactor design at National Institute of Standards and Technology (NIST) [2, 3]. One fuel integrity criterion is analyzed by investigating the Minimum Critical Heat Flux Ratio (MCHFR) in the core during the accidental transients. Some previous studies develop a relationship that correlates the nominal value of the minimum CHFR with the probability of CHF occurring and causing fuel damage [4]. Using a statistical approach, the nominal value of the MCHFR for the low-enriched uranium (LEU) reactor needs to remain above the recommended limiting value to better ensure the safety of the research reactor. Table I summaries the statistical analysis results of the MCHFR for a LEU fuel at multiple probability levels.

Table I. Statistical Analysis Results for LEU Fuel

Probability Level	MCHFR
90.0%	1.301
95.0%	1.391
99.9%	1.778

As seen in Table 1, the probability of no fuel failure increases as the MCHFR increases. More importantly, as long as the MCHFR remains above the recommended limiting value of 1.301, the reactor will have a 90% probability that CHF is not reached [4].

The safety analysis program PARET [5], developed by Argonne National Laboratory (ANL), is employed to obtain the CHFR information in this study. PARET/ANL is a digital computer programming code intended primarily for the analysis of test and research reactors that use plate-type (flat) fuel elements. This program has its own set of correlations that are used to calculate the CHFR. One of them is the Mirshak correlation [6], which was believed to provide the best estimation of the critical heat flux under the operating conditions of the new reactor at the time [7].

Following the critical heat flux (CHF) experiments for vertical rectangular channels in the JRR-3 (Japan Research Reactor unit 3), the CHF calculations now use the Sudo-Kaminaga correlation [8]. This correlation is of our interest because this method has an enhanced geometric similarity and an increased range of applicability that are more representative of the actual operating conditions of our current design, and has a more mechanistic approach [9]. Since the source code of PARET/ANL is inaccessible, a MATLAB-based utility has been written to integrate the Sudo-Kaminaga correlation as a substitute for the Mirshak correlation in the code. As a result, both the Mirshak and the Sudo-Kaminaga correlations are used to analyze the standard output from the PARET program to calculate the CHFR.

INTEGRATION OF THE CORRELATION

The PARET output file provided the raw data necessary to perform the CHFR calculations using the Sudo-Kaminaga correlation. A sequence of coding modules was made within MATLAB in order to perform data extraction and manipulation, CHFR calculations, and analysis, to yield the desired results. These modules can be summarized into the following three steps.

The first step is to import the data from the PARET/ANL output file, which was essential in the implementation of the safety analysis. The modules of data extraction and manipulation are standardized for a general application. The differences, however, that need to be taken into account are the type of file, the format within the file, and differentiating between the important and irrelevant data for the purposes of the analysis.

After the necessary data from the output file has been obtained, the second step is to calculate the CHFR for every node and time step, which requires a loop procedure and modules to generate a matrix after calculating all of the

CHFR values. The coding efforts in this step is comparable to that in first step regarding its overall functionality. They both follow a loop and generate an array to organize the necessary information. The uniqueness in this part is that instead of searching for keywords, it defines and redefines the node and time step throughout the loop while applying the calculations for the CHFR with the appropriate correlations. It is worthy to mention that there are multiple existing correlations that can be used to find the CHFR values. The ones involved in this analysis are the Mirshak correlation and the Sudo-Kaminaga correlation.

The Mirshak correlation is an equation designed calculate the CHFR in research reactors with plate-type fuels. For this correlation, the CHF is a function of the coolant temperature, equivalent diameter, coolant velocity, and pressure [7]. It was the original method used in the CHFR calculations for the reactor at NIST. It was also incorporated in the PARET/ANL program. The Sudo-Kaminaga correlation is another method used to determine the CHFR for vertical rectangular channels in a research reactor. The CHF experiments used to derive this correlation included the effects of pressure, inlet sub-cooling, outlet sub-cooling, mass flux, flow direction, and channel configuration [9]. The correlations proposed by Sudo and Kaminaga are dependent on mass flux and flow direction and have three separate regions based on the dimensionless mass flux, G*, as shown in Fig. 1.

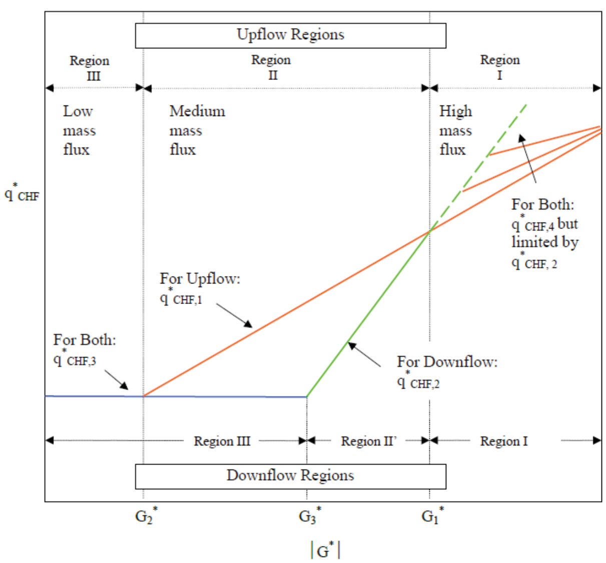

Fig. 1. Sudo-Kaminaga correlation scheme [9].

The module that calculates the CHFR with the Sudo-Kaminaga correlation was designated as a function called *CHF_SK(Nodenum,iteration)*. This user-defined function can be called upon as a single line in another module as long as the input values, *Nodenum* and *iteration*, were given. Within this module, the function *ExtractData* is called upon in order to use the variable information that was extracted from the PARET output file. A calculation loop is necessarily generated in order to systematically differentiate the nodes between the three to calculate the corresponding CHFR values.

In the last step, the axial dependent CHFR was calculated via the Sudo-Kaminaga correlation and placed into a matrix, and compared with the CHFR value of the Mirshak correlation. The minimum values of the CHFR at each time step for both the Sudo-Kaminaga correlation and the Mirshak correlation were found. Moreover, the time steps in seconds needed to be homogenized so that each set of CHFR values could be consistently compared in a single plot figure. Afterward, the absolute minimum value and its occurring time were determined and recorded for future reference.

RESULTS

Safety analyses of two categories of hypothetical design basis accidents at the end of an equilibrium cycle were performed using PARET/ANL code, and the minimum CHFR during the abnormal operation transients based on Sudo-Kaminaga correlation were evaluated using the standard outputs of PARET and the utilities we developed. The results were compared to the values calculated by PARET based on Mirshak correlation. For the safety point view, the minimum CHFR is required to remain above the determined minimum CHFR for an LEU reactor shown in Table I according to its corresponding probability confidence level.

The first category of design basis accident is the reactivity insertion accident (RIA). Two cases are considered under this category. The first case (Case 1) is the small reactivity insertion case, in which the reactor is assumed to be initially critical and operating at a very low power (~ 0), while a positive reactivity is inserted to the core with a slow ramp rate $0.1/s. The second case (Case 2) is the large reactivity insertion case, in which the reactor is assumed to critical and operating at a full power, while a large reactivity $1.5 is inserted to the core within 0.5 s. In both cases, the reactor scram occurs when power exceeds 120% of normal operating power. For simplicity and conservatism, all reactivity feedbacks are neglected in the transient analyses.

The comparisons of the minimum CHFR calculated from Mirshak and Sudo-Kaminaga correlations for case 1 and case 2 are shown in Fig. 2 and Fig. 3, respectively. In Fig. 2, both correlations seem to have a nearly identical trend during the runtime in the small RIA. The only difference is that the estimation from Mirshak correlation (denoted by the color blue) is slightly smaller than the estimation from Sudo-Kaminaga correlation (denoted by the color red). The minimum CHFR value occurs about 11 seconds into the accident.

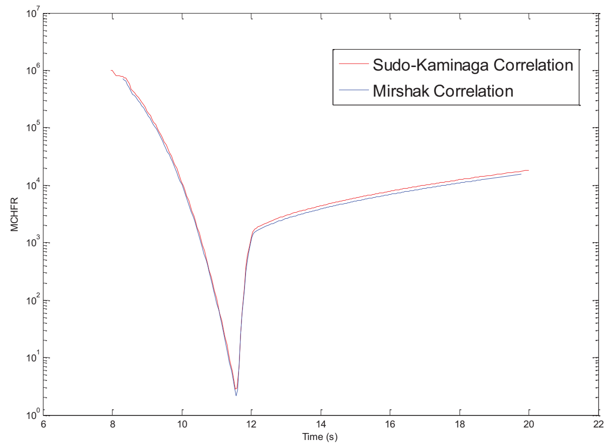

Fig. 2. Variation of the minimum CHFR in the hot channel during a small RIA.

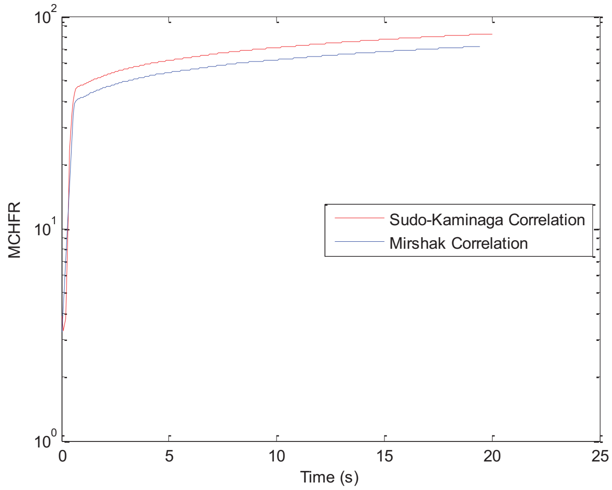

Fig. 3. Variation of the minimum CHFR during in the hot channel during a large RIA.

In Fig. 3, the curve for the minimum CHFR of the Sudo-Kaminaga correlation lies below the other curve in the beginning, but slowly rises above the curve of the Mirshak correlation during the rest of the event. Fig. 3 also indicates that the minimum CHFR occurs at the beginning of the transient in this case.

The second category of design basis accident being studied is the loss of flow accident (LOFA), in which the reactor assumed to be initially operated at full power. At the onset of the accident, the flow decay occurs due to the pump coast down and modeled as an exponential decrease with a time period *T*. There are also two cases are considered in this category: the slow LOFA (Case 3) and the fast LOFA (Case 4) with the *T* respectively assumed to be 25 s and 1 s. In both cases, the reactor scram occurs when the flow decay is reduced by 15%. The comparisons of the minimum CHFR calculated from Mirshak and Sudo-Kaminaga correlations for Case 3 and Case 4 are shown in Fig. 4 and Fig. 5, respectively.

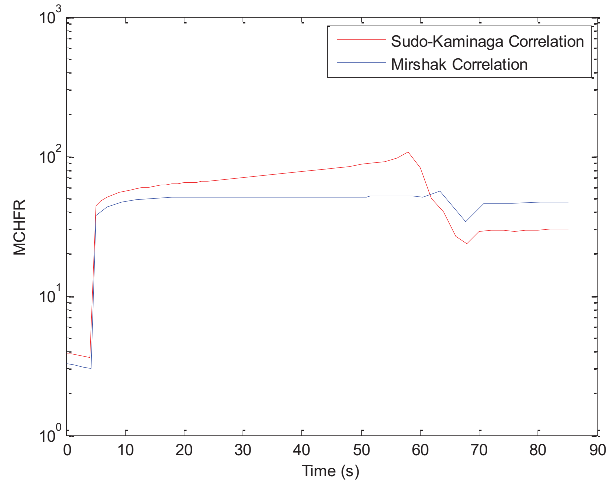

Fig. 4. Variation of the minimum CHFR for SLOFA.

In Fig. 4, the curve for the Sudo-Kaminaga correlation remains above the curve of the Mirshak correlation until about 60 seconds. At this point, the minimum CHFR for the Sudo-Kaminaga drops below the Mirshak curve through to the conclusion of the runtime. There is a greater chance for CHF to occur at about 4 seconds into case 3 because that is where the minimum CHFR is at its lowest.

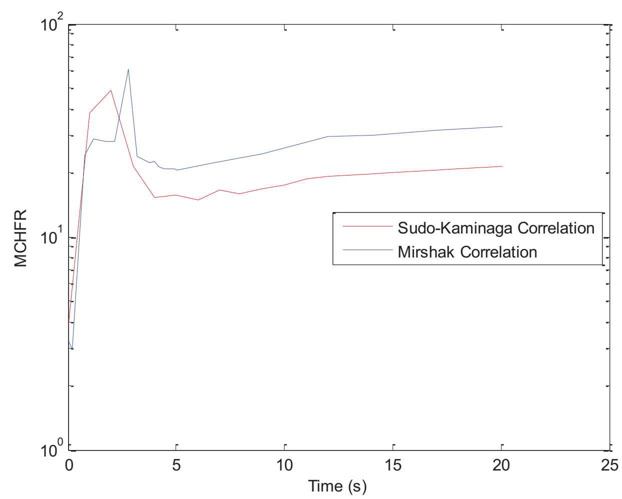

Fig. 5. Variation of the minimum CHFR for FLOFA.

In Fig. 5, the curve of the Sudo-Kaminaga correlation drops below the other curve at an earlier time compared to the other cases. The trend of the red curve (Sudo-Kaminaga correlation) differs from the shape of the blue curve (Mirshak correlation) unlike in the other cases. CHF is more likely to occur at the beginning of case 4 than anywhere else because that is where the minimum CHFR value is at its lowest.

The assessment of the probability of the critical heat flux will be reached is determined by observing the lowest CHFR values throughout each case. Table II summarizes the specific values of the minimum CHFR for both correlations and the time for which they occur during the simulation for the tested accident cases.

Table II. Minimum CHFR for Each Tested Correlation

	Sudo-Kaminaga		Mirshak	
Case #	MCHFR	Time(s)	MCHFR	Time(s)
1	2.81	11.55	2.17	11.57
2	3.29	0.10	2.50	0.14
3	3.63	4.00	2.99	4.28
4	3.85	0.01	2.80	0.38

As seen in Table II, the minimum CHFR of both correlations are comparable in regard to these analyzed accident cases. The results show that the minimum CHFR values for the Sudo-Kaminaga correlation were marginally higher than for the Mirshak correlation in all four cases. However, for all cases, the times when the minimum CHFR value occurred for both correlations were within 0.5 seconds of each other. All CHFR values are above 1.778, so there is at least a 99.9% chance that there will be no fuel failure (see Table I) during these four accident cases.

CONCLUSION

The results predicted by the Sudo-Kaminaga correlation has slightly larger margins than those by the Mirshak correlation for all the tested cases most of the time. For the RIA cases, the curve for the Sudo-Kaminaga correlation is slightly above the curve for the Mirshak correlation. For the LOFA cases, the Sudo-Kaminaga correlation starts off being above the other curve until it drops downward and remains below the Mirshak curve until the end of the runtime. The minimum CHFR, as calculated from the Sudo-Kaminaga correlation, is clearly above the recommended minimum CHFR for a low-enriched uranium (1.301) at all times, therefore, indicating that the fuel in the reactor will be virtually guaranteed (at least 99.9%) to not reach CHF. In short, the Sudo-Kaminaga correlation supports that the fuel in the reactor is thermal-hydraulically within safety limits and provides enough margin of safety while having a more compatible geometry compared to the Mirshak correlation.

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