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Capability of the Best Estimate Code RELAP5/Mod 3.2 to Analyze the Steady State and Stability of Boiling Two-Phase Natural Circulation Systems

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Abstract – *System codes have been used in the past four decades in the areas of design, operation, licensing and safety evaluation of Nuclear Power Plants (NPP) due to the prohibitive cost of experimentations. New generation reactors are designed by incorporation of several passive systems in the design so as to enhance the safety as compared to the current generation reactors. The thermal hydraulic characteristic of passive systems (e.g. natural circulation) can be different from that of a pumped circulation system. Hence, the system codes need to be benchmarked against experimental data of such passive systems before applying them to the new generation reactors. In this paper an attempt has been made to evaluate the uncertainties of one such system codes (RELAP5) by comparing the code prediction with the natural circulation data generated in several facilities in BARC. To find out the uncertainty in the code prediction for steady state and stability, a new methodology for has been proposed. While it is easier to evaluate the uncertainty in steady state natural circulation prediction, however, there are no established techniques to quantify the uncertainties for flow instability since the later phenomenon has several parameters such as amplitude, frequency, threshold of instability etc.. Due to the non-linearity nature of flow instabilities the characteristics of oscillation is very complex. The uncertainty for steady state and flow instability in natural circulation was evaluated from the error distribution of the code prediction and measurement.*

I. INTRODUCTION

Many advanced reactor designs incorporate passive systems mainly to enhance the operational safety and possible elimination of severe accident condition. Some passive systems are even designed to remove the nominal fission heat without using mechanical pumps e.g. ESBWR[1](Cheung et al., 1998), AHWR[2] (Sinha and Kakodkar, 2006), CHTR[3] (Maheshwari et al., 2004), CAREM (Delmastro, 2002), etc., while in most other new reactor concepts, passive systems remove the decay heat following the pump trip conditions. In addition, such systems also are designed to remove the containment heat using passive condensers, to inject subcooled water into the core in a postulated LOCA situation, to cool the moderator (Sinha and Kakodkar, 2002, 2003), etc. The major benefits arising from the use of passive systems are:

- simple in design, easy to build, operate and maintain;
- enhancement in safety and reliability as compared to the active systems, leading to reduction in off-site emergency planning;
- reduction in human interventions resulting in fewer potentially unsafe actions;
- increased operability and capacity factors.

Passive systems, by definition, rely upon natural laws such as gravity, buoyancy, etc. to accomplish their functions. Since their operation does not depend on active components such as motor driven pumps or electro-driven valves, etc., their availability is considered to be more reliable vis-à-vis the active systems. In spite of that, there has been a lot of discussions recently on the reliability of such systems. When we say reliability of passive systems, it refers to the probability of their ability to carry out the mission for the required condition when desired. That means there are certain conditions or situations, when the passive system fails to function to meet the desired objectives.

Then the question arises how a passive system can fail.

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[1] Economic Simplified Boiling Water Reactor
[2] Advanced Heavy Water Reactor
[3] Compact High Temperature Reactor

While an active system can fail due to failure of active components like pumps, etc.; sometimes, it seems absurd when someone talks about failure of a passive system. For example; can natural convection fail when the fluid is heated? Can gravity fail to bring water from an overhead tank? Hence, the mechanisms for the operation of passive system can never fail because they operate by natural laws. However, even though the mechanisms do not fail, sometimes, such systems may not be able to carryout their missions or deliver the requirements if there are small changes or disturbances in their nominal operating conditions even though their system geometry remains the same. For example, a passive system designed to generate necessary natural circulation flow rate at nominal power condition, may not be able to generate required flow rate if there is a deviation from nominal condition due to perturbation of power or pressure or water level in downcomer or the core inlet subcooling. This happens mostly due to the smaller driving force of natural circulation system, which can be easily influenced due to any disturbance of the parameters listed above. If the disturbance leads to reduction in flow rate below a threshold value, it may fail to remove the required heat without exceeding certain temperature in the flow system (which is its mission). In simple words, while the mechanism of natural convection has not failed, the system is declared to fail since it is unable to carryout its mission.

II. ASSESSMENT OF THE FAILURE OF PASSIVE SYSTEM

As said earlier, a functional failure to meet the mission of the system can arise due to deviations from the specified operational condition for a given geometry. Similar phenomena may occur if there is a change in the system geometry even though the operating condition remains the same. To assess the functional failure of a passive system, the designer must have a clear understanding on the operational mechanism of the passive system not only for the nominal conditions but also in transients including accidents. At the current perspective, there is lack of experience in the operation of passive systems since they are mostly in conceptual design stages. Even there are not enough experimental databases in integral test facilities or simple experimental loops in order to assess the failure mechanisms of passive systems under all operational transients. In the absence of the experiments or plant data, the designers have to depend on the so called ‘best estimate codes’ such as RELAP5, TRAC, CATHARE (Barre and Bernard, 1990), etc. to evaluate the performance of such systems including their failure conditions. It may be noted that these codes are developed for active systems wherein the driving mechanism is completely different and it is not well understood how good the models built in these codes can simulate the passive system phenomena. Some of the key phenomena which are difficult to model but are significantly important to assess the passive systems performances are

- low flow natural circulation; mainly because the flow is not fully developed and can be multi-dimensional in nature
- flow instabilities which include flashing, geysering, density-wave, flow pattern transition instabilities, etc.
- critical heat flux under oscillatory condition
- flow stratification with kettle type of boiling particularly in large diameter vessel
- thermal stratification in large pools such as in GDWP
- effect of non-condensable gases on condensation, etc.

At present, existing best estimate codes either do not consider modeling some of the above phenomena or use empirical or mechanistic models to predict such phenomena. As a result there could be large uncertainties in the code predictions particularly when analyzing the performance of passive system. This would certainly impose significant bearing on the prediction of failure conditions of passive systems. From these considerations, it is essential to evaluate the uncertainties of the best estimate codes by comparing the model prediction with test data of experimental facilities, and also by carrying out sensitivity analysis by varying the models or input nodalization in the code.

II.A. Sources of Uncertainties

Uncertainties in the best estimate codes can arise due to

- inappropriate models incorporated in the codes to represent a specific phenomena;
- absence of models to represent a particular phenomena;
- deviations of the input parameters due to the uncertainties of the instruments and control systems and that of the geometry of the loop;
- uncertainties in the material properties such as fuel thermal conductivity; fuel-to-clad gap conductance, etc.

In reality, there could be several sources of uncertainties which can affect the code prediction of passive system performance. These parameters can have different degrees of effect on passive system performance. In fact, it is not possible to consider all the uncertainties either together or even independently in the computer programme since it would involve enormous number of computations. Hence, it is essential to utilize expert judgment to find out which parameters have moderate to high severity effect on the passive system performance through a Failure Mode and Effect Analysis (FMEA).

II.B. A brief history of uncertainty analysis

The term "uncertainty" is used to refer to "a possible value that an error may have." Kline and McClintock (1953) attribute this definition to Airy (1879) and still seems an appropriate and valuable concept. The concept of uncertainties in the experimental results has been described by Moffat (1988). The use of uncertainty analysis for thermal hydraulic calculation is a recent phenomenon owing to the extensive use of best estimate codes for safety analysis. D'auria and Galassi (1998) have presented the state of art in the area of thermal hydraulic system codes assessment and uncertainty evaluation. More recently Apostolakis et al. (2005) and Burgazzi (2002, 2004 and 2007) have addressed the uncertainties related to evaluation of passive system reliability. In this paper we have evaluated the uncertainty of the code RELAP5 from the comparison of experimental results with code prediction. The uncertainty approach has been applied to both steady state as well as instability behavior of boiling two-phase natural circulation system.

III. MATHEMATICAL TREATMENT OF UNCERTAINTIES

The uncertainty attributed to a variable is an estimate of the possible residual error in that variable after all proposed corrections have been made. Experiments can be Single-sample or Multiple-sample. Single-sample experiments are those where each test point is run only once or at most very few times. Multiple-sample tests are those in which enough data are taken at each test point to support a sound statistical interpretation.

For example, consider a variable X_i, which has a known uncertainty δX_i. The form for representing this variable and its uncertainty is

$$X_i = X_i\,(\text{calculated}) \pm \delta X_i$$

The uncertainty in the model of a best estimate code (ignoring the uncertainty in the input) can be calculated in the following way:

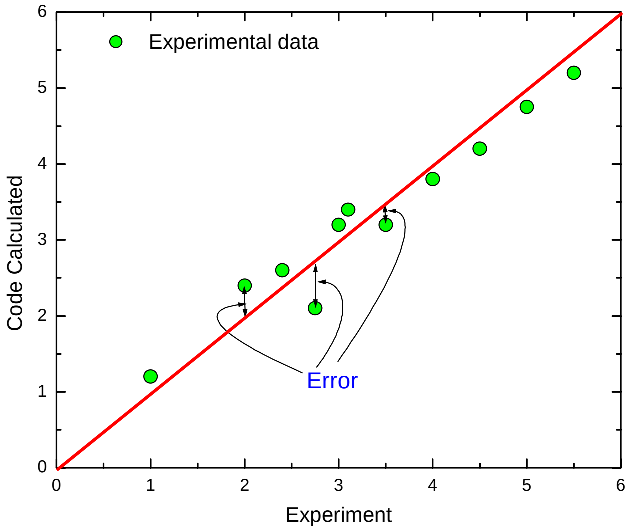


Fig.1 Example of error estimation between code prediction and experiment

First the error between the calculated and measured value is made as shown in Fig. 1. Next, the error distribution is plotted according to their frequency of occurrence as shown in Fig. 2.

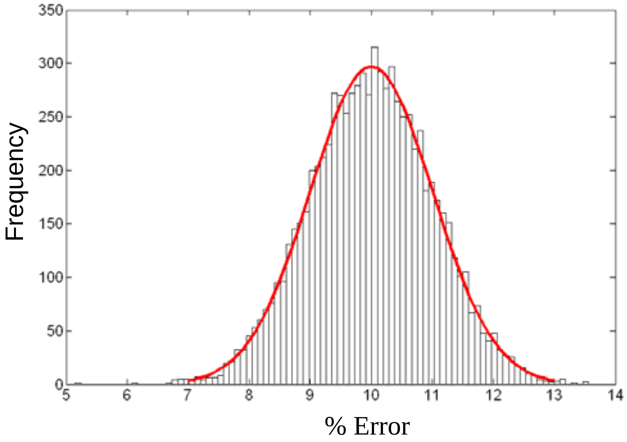


Fig.2 An example of error distribution for calculation of uncertainties

In the above figure (Fig. 2), the area under a particular bar is numerically equal to the probability that a particular reading will fall in that associated interval. The area of the entire histogram integrated between the limits –infinity to + infinity is 1.0 (100%). The probability of a value falling between any two values x_1 and x_2 is the area bounded by this interval, i.e.

$$P(x_1 < x < x_2) = \int_{x_1}^{x_2} f(x)\ dx \ \text{ and } \int_{-\infty}^{\infty} f(x)\ dx = 1 \tag{1}$$

The random error follows a statistical distribution and generally it is a normal or Gaussian distribution. In fact, if the error distribution follows a normal distribution as shown above, this can be expressed by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{2}$$

where μ is the mean value given by,

$$\mu = \frac{\sum_i f_i x_i}{n} \tag{3}$$

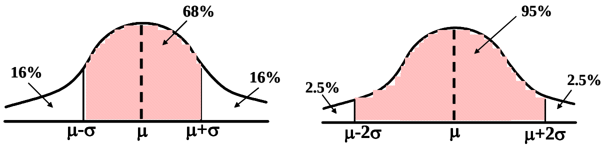


Fig. 3 An example of Normal distribution and its application

For the above expression, a physical quantity is measured n times. The measurements (in present case it is errors) are $x_1, x_2, ...x_n$, which occur with frequencies $f_1, f_2, ... f_n$ such that

$$f_1 + f_2 + ... + f_n = n \tag{4}$$

The variance is given by

$$\sigma^2 = \frac{\sum_i f_i (x_i - \mu)^2}{n} \tag{5}$$

Square root of variance is standard deviation (*S*). However, if the number of observations are not very large

$$S = \sqrt{\frac{\sum_i f_i (x_i - \mu)^2}{n-1}} \tag{6}$$

The small value of *S* means that there is a high probability that the reading will be near the mean value and the high value of *S* means a larger scatter.

III.A. Calculation procedure

Step-1: Calculate the error in the prediction of Best Estimate code. Now, errors are our samples, say x_i. Then estimate the distribution parameters.

Compute mean of errors, $\mu = \frac{\sum_i f_i x_i}{n}$ and obtain the variance of the sample as

$s^2 = \frac{\sum_i f_i (x_i - \mu)^2}{n-1}$. Here n is the total number of data points or observations available.

Step-2: Choose a confidence interval Γ (95%, 99% or like)

For example, if we choose Γ = 95%, then we can expect that about 95% of the samples that we may obtain will yield confidence intervals that do include the parameter θ. Mathematically,

$P(\Theta_1 \le \theta \le \Theta_2) = \Gamma$ i.e. in other words, the probability that Θ_1 and Θ_2 include the exact unknown value of the parameter θ is equal to Γ.

Step-3: Determine solution 'c_1' and 'c_2' of the equations.

$$F(c_1) = \frac{1}{2}(1-\Gamma)\ ;\ F(c_2) = \frac{1}{2}(1+\Gamma)$$

From the Chi-square distribution table, corresponding to $(n-1)$ degrees of freedom and $F(c_1), F(c_2)$ values, find the value of c_1 and c_2.

Step-4: Compute $k_1 = \frac{(n-1)\, s^2}{c_1}, \quad k_2 = \frac{(n-1)\, s^2}{c_2}$

Confidence interval is $CONF\{k_2 \le \sigma^2 \le k_1\}$

Step-5: $(\sigma^2)_{\max} = k_1 - k_2$ Uncertainty is $\delta X_{i,1} = \pm 2\sigma_{\max}$

Without loss of generality, the above procedure is shown for the normal distribution. The authors would like to point out that, other probability distribution, like for example, truncated normal, log normal, Weibull, Inverse Gauss, log-logistic, Gamma or inverse Gamma, might be suitable for specific cases. Here, we have used a Chi-square distribution for estimating the confidence limits as in statistical theory it is generally used for statistical testing, goodness-of-fit tests and evaluating statistical confidence.

IV. EVALUATION OF UNCERTAINTY IN BEST ESTIMATE CODES FOR NATURAL CIRCULATION SYSTEMS

While there are several best estimate codes such as RELAP, CATHARE, TRACE, RAMONA, etc. being used by utilities around the world, in this paper we have attempted to evaluate the uncertainty associated with the prediction of computer code REALP5/MOD 3.2 to boiling two-phase natural circulation systems. The code RELAP5 provides a two-fluid treatment for the liquid and vapor phases separately, and uses inter-phase relationships for mass, momentum and energy transfer depending on flow regimes. The flow regimes are evaluated depending on the flow conditions and geometry of the component using validated flow regime models. There has been a lot of concern about the use of RELPA5 for situations wherein there is a large pressure fluctuation such as a large break LOCA, etc. due to the ill-posedness of the basic equations describing the flow. Otherwise, the code has been successfully applied for the transient and safety analysis of several water cooled nuclear power plants (D'Auria et al., 1994, 1999). Besides, the code has been found to simulate several transients in integral facilities successfully. In spite of that, the code applicability to passive systems has not been tested adequately. In this paper, we will verify the code capability to simulate steady state natural circulation data of three natural circulation loops operating in BARC. Also, the code has been applied to simulate the instability data of HPNCL at different pressure and SD level conditions. The uncertainties arising due to the error between the measured value and code predictions have been estimated.

IV.A. Experimental loops considered

(a) High pressure natural circulation loop (HPNCL)[4]

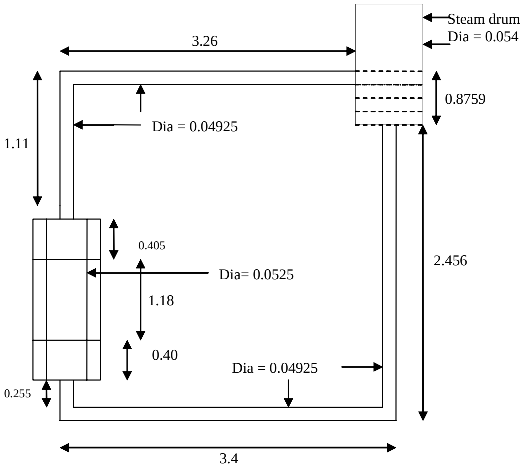
A schematic of the loop is shown in Figure 4. The HPNCL (Kumar et al., 2000) can be operated to a maximum pressure of 70 bar. In this loop, the riser and downcomer are of uniform diameter and equal to 0.04925 m and their lengths are 1.11 m and 2.456 m respectively. Test section diameter and length are equal to 0.0525 m and 1.18 m respectively. The steam drum diameter is 0.054 m. A detailed description of the facility can be seen in the above reference. Several natural circulation steady state data were generated in this loop earlier at different pressure conditions. The computer code RELAP5/MOD3.2 has been used to simulate those natural circulation conditions in this loop for the uncertainty evaluation.

(b) Apsara loop (Dubey et al., 2004)

A schematic of this loop is shown in Figure 5. This loop is having uniform diameter of 0.01 m; however, there were provisions to change the loop diameter in order to study the effect of diameter on natural circulation behavior. The length of the test section, riser and downcomer are 0.29 m, 1.797 and 2.227 m respectively. The diameter of the steam drum is 0.054 m. This l loop is designed for 125 bar and 315^0 C. The loop is heated up to a maximum power of 10 kW. Several natural circulation data, under stable and unstable conditions were generated in this loop earlier at different pressure and power conditions. Besides, limited CHF data under unstable conditions were also obtained in this loop. The computer code RELAP5/MOD3.2 has been used to simulate those natural circulation conditions in this loop for the evaluation of uncertainty.

(c)The Integral Test Loop (ITL) (Rao et al., 2002)

The ITL, the Integral Test Facility, simulates various systems of the AHWR such as the Main Heat Transport System, ECCS using advanced accumulators and GDWP, Decay Heat Removal System using ICs, etc. It is designed based on a 3-level approach such as Global Scaling based on power-to-volume scaling philosophy for the entire system, Local Scaling to simulate the important local phenomena and Boundary Scaling to simulate the operating boundary conditions of respective systems. It uses one average full power channel of the AHWR along with one full size feeder and tail pipe of the reactor. That way, the power-to-volume scaling of the loop is roughly 452 since the reactor has 452 channels. Since the loop uses one full size feeder and tail pipe (same diameter, length and elevation) besides that of the channel, it simulates exactly the distributed and local losses of the corresponding system of the reactor. Further, both the AHWR and ITL have the same elevation, operating at the same pressure and temperature and channel power condition; the data generated in the ITL can be directly extrapolated to the prototype. A detailed description of the geometries and other parameters of different systems of the loop are given in above reference.



All dimensions are in meter

Fig. 4 A Schematic of the HPNCL

IV.B. Evaluation of uncertainty for steady state natural circulation

Steady state natural circulation means the natural circulation flow rate is stable over the entire time period as observed in the above experimental facilities at different powers, pressures and subcooling conditions. To evaluate the uncertainty for steady state natural circulation, code calculations were performed for nearly 127 experimental conditions in the above three loops and the predictions were compared with the measured data for evaluations of the errors. Fig. 6 shows the error between the measurements and predictions at different powers in these loops. Leaving the APSARA loop, in the other two loops the predicted flow rates were found to be mostly higher than the measurements. Fig. 7 shows the corresponding statistical distribution of the errors for calculation of the

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[4] High Pressure Natural Circulation Loop

uncertainty in the code prediction. The uncertainties in the steady state prediction were given in Table 1, which is about 17%.

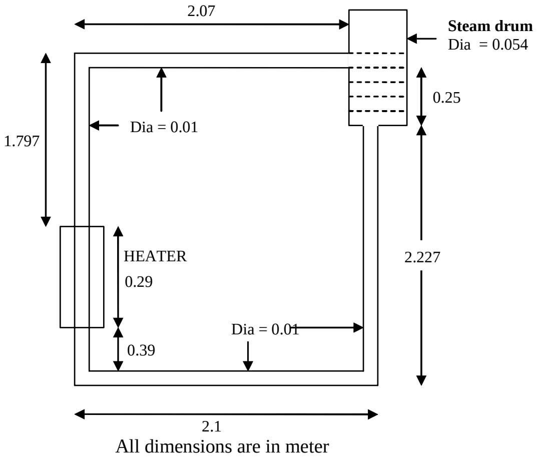

Fig. 5 A Schematic of Apsara loop

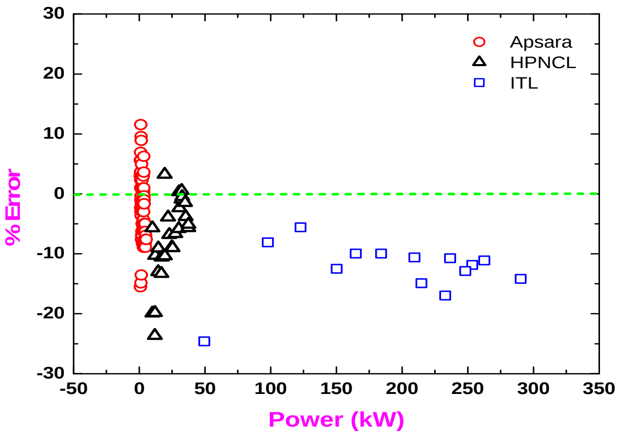

Fig. 6 Error estimation between the RELPA5/MOD3.2 code prediction and measured natural circulation flow

Table 1: Uncertainties in prediction of steady state natural circulation flow

Experimental Loop	Number of steady state data points	% Overall uncertainty
Apsara ½”	87	17.0
HPNCL	26	
ITL	14	

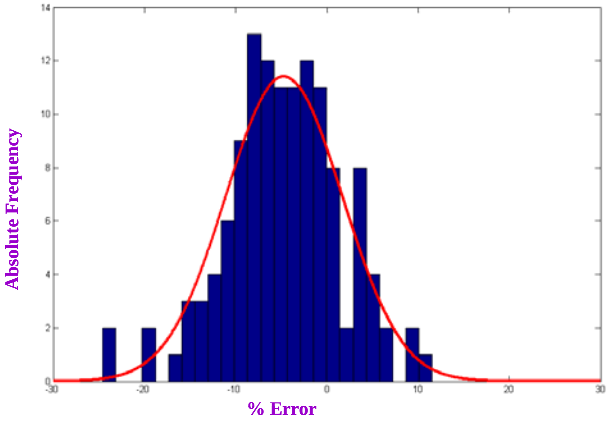

Fig. 7 Statistical error distribution for steady state natural circulation data

IV.C. Evaluation of uncertainties for natural circulation instabilities

Simulation of natural circulation instabilities is a major challenge of any best estimate code including that of RELAP5/MOD3.2. Unlike steady state natural circulation flow where it is much easier to quantify the uncertainty by comparing the code prediction with the measured data, however, in case of oscillatory flow or unstable flow, it is much more difficult to quantify the uncertainties due to occurrence of multiple phenomena such as

- Simulation of condition of stability, i.e. whether the code predicts the condition of natural circulation to be stable or unstable including that of threshold of instability as observed in experiments,
- Even though the code simulates accurately the condition of flow instability, next question is whether it can predict the amplitude and frequency of oscillations (i.e. characteristics of instabilities). This is particularly important to simulate the clad surface temperature or occurrence of CHF which is known to degrade significantly due to flow instabilities.

IV.C.1 Sensitivity of nodalization

In order to study the sensitivity of nodalization in the input to flow instability, a numerical experiment was conducted by varying the number of nodes in the riser part of the natural circulation system of AHWR. The height of riser in the system is about 26 m. The number of volume in this region was varied form 4 to 52 keeping all other nodalization fixed. The result shows that (Fig. 8) the nodalization adopted play a significant role in revealing the natural circulation behavior. With finer nodalization, the characteristics can change from stable flow to highly oscillatory flow even for the same operating condition. That really puts another challenge in evaluating the uncertainty for flow instabilities. In the present analysis since the test data were known, the nodalization adopted was the best one to capture the natural circulation behavior in the respective test facilities through trial and error run.

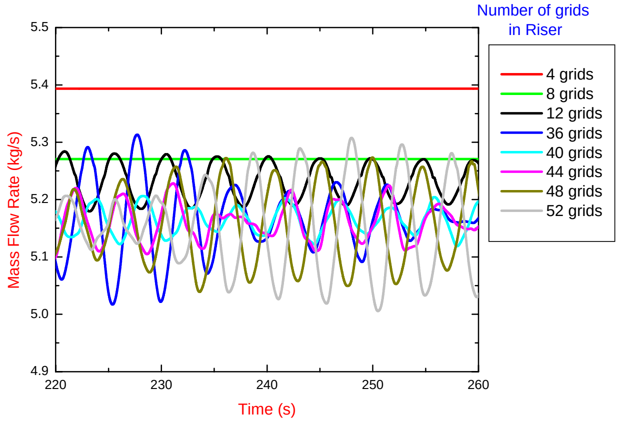

Fig. 8 Sensitivity of code to nodalization

IV.C.2 Simulation of instability behavior in HPNCL

To determine the uncertainty in RELAP5 prediction, a large number of experiments were conducted in HPNCL at various pressures (1-35 bar) and SD levels (5%-85%). Here, comparisons at low SD levels are only presented in Table 2. The largest amplitude of oscillation during the power range has been taken for comparison keeping in mind that failure generally occurs at the largest amplitude. A typical comparison between mass flow rates at 1 bar and 10 bar pressure are shown in Fig. 9 and Fig. 10 respectively. The error distribution for amplitude and frequency of oscillations are shown in Fig. 11 and Fig. 12 and overall uncertainty is as indicated in Table 2.

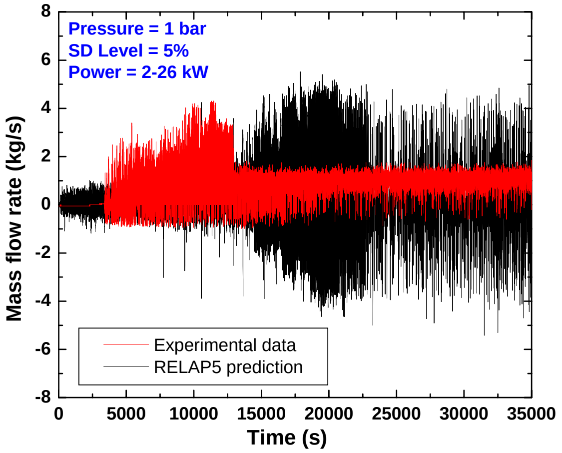

Fig. 9 Comparison of unstable behavior between the measurements and the RELAP5 code prediction at low pressure (1 bar) and low SD level (5%)

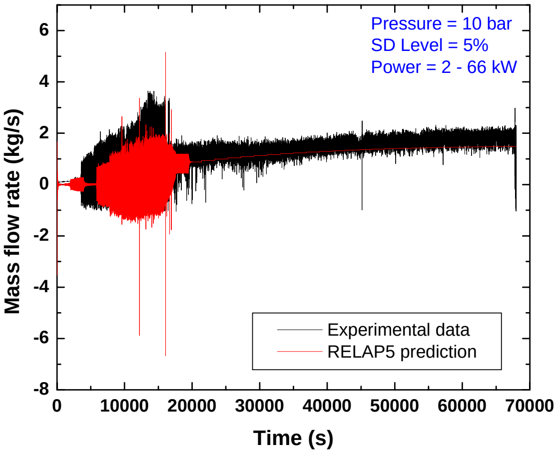

Fig. 10 Comparison of unstable behavior between the measurements and the RELAP5 code prediction at high pressure (10 bar) and low steam drum level (5%)

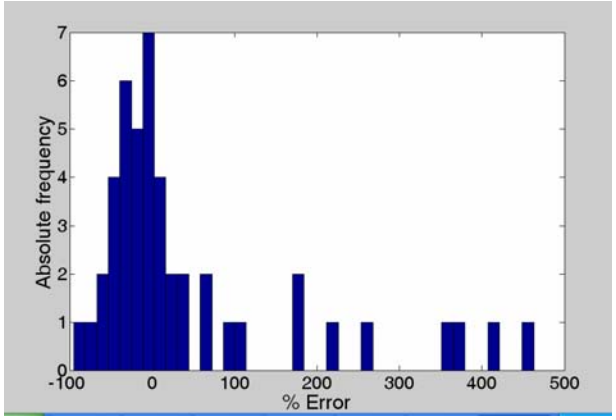

Fig. 11 Statistical error distribution for amplitude of oscillations in HPNCL

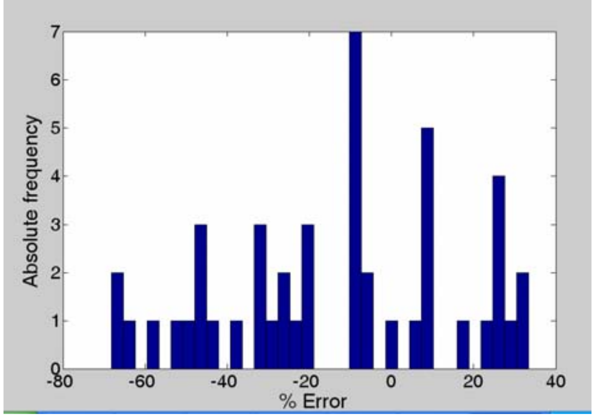

Fig. 12 Statistical error distribution for frequency of oscillations in HPNCL

Table 2: Uncertainty in prediction during natural circulation instabilities

Pressure (bar)	**Power (kW)**	**% Error in amplitude**	**% Error in frequency**	**% Overall uncertainty in amplitude**	**% Overall uncertainty in frequency**
1.0	2.0	35.3	59.3	252.22	54.42
	4.0	63.3	65.0		
	6.0	46.2	68.2		
	8.0	32.1	65.4		
	10.0	27.5	45.8		
	12.0	7.6	20.0		
	14.0	0.2	10.0		
	16.0	172.6	45.5		
	18.0	256.0	10.0		
	20.0	462.8	10.0		
	22.0	413.0	8.3		
	24.0	362.5	48.7		
	26.0	375.2	7.1		
2.0	4.0	28.9	33.3		
	6.0	0.4	27.3		
	8.0	45.3	21.4		
	10.0	16.7	28.6		
	12.0	67.1	7.7		
	14.0	91.3	42.1		
	16.0	29.0	46.7		
	18.0	40.8	25.0		
	20.0	61.5	10.0		
	22.0	173.1	25.0		
5.0	6.0	6.1	28.6		
	8.0	6.5	33.3		
	10.0	31.8	36.4		
	12.0	36.7	33.3		
	14.0	46.6	25.0		
	16.0	59.9	10.0		
	18.0	12.1	10.0		
	20.0	13.5	20.0		
	22.0	30.9	16.7		
	24.0	22.8	25.0		
	26.0	13.4	22.2		
	28.0	8.6	5.0		
	30.0	4.5	9.5		
10.0	4.0	68.6	7.7		
	6.0	95.0	0.0		
	8.0	46.5	30.8		
	10.0	13.4	30.8		
	12.0	6.5	53.3		
	14.0	4.8	6.3		
	16.0	19.2	23.1		
	18.0	105.7	7.7		
	20.0	215.5	9.1		
	22.0	21.4	27.3		
	24.0-66.0	No oscillation in RELAP5	No oscillation in RELAP5		

V. CONCLUSIONS

In this paper, the uncertainties in the best estimate code for simulation of natural circulation flow behavior in boiling two-phase flow systems have been evaluated due to its importance for assessment of passive system reliability. For this, the computer code used was the RELAP5/MOD3.2. The experimental data used for code assessment were from three experimental facilities located in BARC. The uncertainties were evaluated considering about 127 natural circulation steady state data and 68 test data for flow instabilities. Since assessment of uncertainty requires large number of test data, more experimental data are being generated in these loops for flow instabilities. Nevertheless, a new approach for evaluating the uncertainties in steady state and instability test data for natural circulation loop has been presented.

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