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A practical sensitivity analysis method for ranking sources of uncertainty in thermal–hydraulics applications

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HIGHLIGHTS

- Existing uncertainty ranking methods prove inconsistent for TH applications.
- Introduction of a new method for ranking sources of uncertainty in TH codes.
- Modified PIRT qualitatively identifies and ranks uncertainty sources more precisely.
- The importance of parameters is calculated by a limited number of TH code executions.
- Methodology is applied successfully on LOFT-LB1 test facility.

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ABSTRACT

In application to thermal–hydraulic calculations by system codes, sensitivity analysis plays an important role for managing the uncertainties of code output and risk analysis. Sensitivity analysis is also used to confirm the results of qualitative Phenomena Identification and Ranking Table (PIRT). Several methodologies have been developed to address uncertainty importance assessment. Generally, uncertainty importance measures, mainly devised for the Probabilistic Risk Assessment (PRA) applications, are not affordable for computationally demanding calculations of the complex thermal–hydraulics (TH) system codes. In other words, for effective quantification of the degree of the contribution of each phenomenon to the total uncertainty of the output, a practical approach is needed by considering high computational burden of TH calculations. This study aims primarily to show the inefficiency of the existing approaches and then introduces a solution to cope with the challenges in this area by modification of variance-based uncertainty importance method. Important parameters are identified by the modified PIRT approach qualitatively then their uncertainty importance is quantified by a local derivative index. The proposed index is attractive from its practicality point of view on TH applications. It is capable of calculating the importance of parameters by a limited number of TH code executions. Application of the proposed methodology is demonstrated on LOFT-LB1 test facility.

1. Introduction

Thermal–hydraulics codes are among the tools for calculation of nuclear power plants response to abnormal and accident conditions. The approach of the deterministic safety assessment is to compare the figure of merit (as the code output) to the regulator's acceptance criteria. However, these predictions are not precise due to significant sources of uncertainty in fully understanding of the physical phenomena occurring during the accident, in the models due to simplification, and in computational numerical methods approximations (Hoseyni and Pourgol-Mohammad, 2016). The state of the art in the TH applications is best estimate plus uncertainty (BEPU) approach which quantifies the uncertainty of calculations. The first step in conducting uncertainty analysis is to identify the uncertainty sources. To analyze the degree of importance of the identified sources, sensitivity analysis provides

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Nomenclature

AHP	analytical hierarchical process
BDC	break discharge coefficient
BEPU	best estimate plus uncertainty
CSAU	code scaling, applicability and uncertainty
COV	coefficient of variation
DSA	deterministic safety assessment
FOM	figure of merit
GSA	global sensitivity analysis
IM	importance measure
IMTHUA	integrated methodology on th uncertainty analysis
LWR	light water reactor
LOCA	loss of coolant accident
LOFT	loss of flow test
MPIRT	modified phenomena identification and ranking table
MC	Monte Carlo
NPP	nuclear power plant
PCT	peak clad temperature
PEC	primary evaluation criteria
PIRT	Phenomena Identification and Ranking Table
PPF	power peaking factor
PRA	Probabilistic Risk Assessment
PWR	pressurized water reactor
RSM	response surface methodology
SIT	Safety Injection Temperature
TH	thermal–hydraulics
USNRC	United States Nuclear Regulatory Commission

Symbols

Y	model output
X	model input vector
X_i	ith input parameter
$Y\|X_i$	conditional output given fixed parameter
Var (y)	variance of parameter Y
δ	delta Importance measure
$S(X_i)$	change in the distribution underneath area by fixing X_i
σ	standard deviation
μ	mean value
k	number of input parameters
n	sample size for Monte Carlo calculations

information about the input variables, mostly affecting the simulation results of the system of interest. Most sensitivity analysis methods turn to be themselves computationally unaffordable. A most limiting feature of TH codes in this area is the large computational burden of the calculations. As a result, the variance based approaches (as the most popular methodology for sensitivity analysis) are not practical for this purpose unless a surrogate/meta model [e.g. response surface model (RSM)] is utilized to replace original complex model with a simpler one. The challenge arises with the validation of the RSM model. In addition, RSM is criticized for:

- Difficulty of developing an appropriate experimental design.
- Use of a limited number of values for each input variable.
- Possible need for a large number of design points; Ineffective as the number of uncertain parameters increases, requiring larger number of code executions.
- Difficulties in detecting thresholds, discontinuities, and nonlinearities.
- Challenges in including correlations and restrictions between input variables.

The previous article by the authors (Hoseyni et al., 2014) demonstrated a hybrid qualitative/quantitative framework for the uncertainty analysis plus importance in severe accident calculations. The qualitative phase identifies, ranks, and screens the important phenomena in the course of severe accident progression. Moreover, the quantitative phase covers the contribution of the parameters obtained through the first phase to the total uncertainty of the output variable of interest. To overcome high computational cost of variance based importance measures in this phase, the code was replaced with a RSM-model of the code. The obtained meta-model of the complex code (RSM Model here) could then be easily utilized for calculation of uncertainty importance measures.

The authors concluded (Hoseyni et al., 2014) that the extension of this area could be devising a new effective uncertainty importance measure (UIM) that is more suitable for thermal–hydraulics as well as severe accident uncertainty analysis. Considering the large computational cost of the calculations, it would be very useful to devise a methodology that identifies the uncertainty ranking of the parameters at lower cost, the driving motivation for the research reported in this paper. The main challenge in this area is impracticality of the existing methodologies for uncertainty importance of complex system codes calculations (e.g., RELAP5 code), mainly due to limitations in available resources. This study aims primarily to evaluate the inefficiency of the existing approaches. It then introduces a solution to cope with the challenges in this area by modification of existing variance-based UIM. As a hybrid approach, important parameters are identified by the modified PIRT (Phenomena Identification & Ranking Table) method qualitatively while their uncertainty importance is quantified by a local derivative index (quantitative part). The proposed index is attractive from the view point of its practicality on TH applications. It calculates the importance of parameters by a limited number of TH code executions.

In the following subsections, first a review of existing UIMs is provided, and available approaches are discussed for their quantification. Next, the application of 4 UIMs is demonstrated on a case of TH Modeling by RELAP5 computer code. The paper then devises a practical approach in Section 2 for TH uncertainty analysis considering the high cost of the calculations. The application of the methodology is demonstrated on a selected TH calculation in Section 3. Section 4 provides discussions on the obtained results, and finally Section 5 summarizes the concluding remarks.

1.1. Review of existing uncertainty ranking methods

This research is motivated by understanding that the current uncertainty importance methods are ineffective to work with the complex system codes. This is of significant importance especially for advanced multi-physics and multi-scale codes employed for reactor design and safety analyses mainly due to growing tendency towards systematic integration of uncertainty and sensitivity analysis for the performed simulations (Avramova et al., 2015). The OECD Light Water Reactor Uncertainty Analysis in Modeling benchmark activities is an ample proof of the need for developing our understanding of reactor safety (Maria et al., 2010).

Available methods for TH uncertainty quantification (Pourgol-Mohammad, 2009) do not provide the whole distribution of the model response; nevertheless they do not evaluate the uncertainty importance of the input parameters. With respect to this issue, Sensitivity Analysis (SA) quantifies the contribution of each parameter to the uncertainty of the model output. SA therefore identifies