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INVESTIGATION OF THE UNCERTAINTY OF GOVERNING EQUATION SYSTEMS IN THERMAL-HYDRAULIC CALCULATION

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Abstract

Investigation of the effect of uncertainty of the governing equation system on the results of the code ATHLET has been performed on the basis of an uncertainty and sensitivity analysis of the ROSA/LSTF SB-PV-09 experiment. The analysis has been conducted for the 5 and 6 equation systems in ATHLET. The results confirmed that for the selected test case the uncertainties resulting from both momentum equation approximations are very similar. The analysis also showed that some output variables are influenced by approximation of momentum equation, e.g. water level in the core whereas other output variables like maximum clad temperature are not. In some cases the uncertainty of closure relations contributes considerably more to uncertainty of the results than the uncertainty of momentum equation approximation.

1. Introduction

In the uncertainty analysis of thermal-hydraulic transients the model uncertainties are related usually to the closure relations, in particular constitutive models. The set of governing equations is assumed “a priori” as “certain” and its uncertainty is not taken into account. However, it can be expected that this is not always the truth. It is of interest to compare uncertainties of different equation systems applied for thermal-hydraulics simulation. Such an investigation has been performed for the code ATHLET [1] on the basis of an uncertainty and sensitivity analysis of the ROSA/LSTF SB-PV-09 experiment [2]. Making use of the code ATHLET capability where the 5 and 6 equation models are available optionally the selection of the equation system has been defined as an uncertain discrete input parameter. The main difference between the 5 and 6 equation systems in ATHLET is the approximation of the momentum equation: one momentum equation for gas-liquid mixture for the 5 equation system and separate momentum equations for gas and liquid phases in the case of the 6 equation system. Since, the SB-PV-09 test is a 1.9% SB LOCA at pressure vessel upper head, both approximations of the momentum equation are expected to be applicable.

2. Short description of the experiment

The Japanese ROSA-V/LSTF test facility [3] is the volumetrically scaled (1/48) model of a Westinghouse type pressurised water reactor with four loops and a thermal power of 3423 MW. The facility is designed for a full system pressure of 16 MPa. The four reactor loops of the reference plant are combined into 2 double loops. The horizontal legs of the loops are scaled by means of the Froude number in order that two phase flow regime transitions can be reproduced in a reactor-typical manner. The heights are scaled on a 1/1 scale to allow a realistic simulation of natural circulation. The power of the electrically heated core of the LSTF is 10 MW. This allows simulation of the reactor heating with the scaled-down decay heat of the real plant.

Test SB-PV-09 was conducted in November 2005 within the OECD/NEA project "Rig of Safety Assessment“(ROSA) [2]. The main goals of this test were the analysis of the thermal-hydraulic phenomena in the reactor coolant system in case of a postulated break of a control rod drive mechanism penetration nozzle, the evaluation of the impacts of symptom-oriented accident management measures on the coolability of the reactor core as well as the provision of experimental data for the validation of advanced numerical codes. For this purpose, a small break at the pressure vessel upper head was simulated, under the assumption of a total failure of the high pressure injection system. A secondary side depressurization was foreseen as an accident management (AM) action. The leak size selected for the test setup corresponds to a 1.9 % break in the cold leg of the reference reactor.

This test was initiated by opening the break valve. The break flow rates depended strongly on the water level in the upper head. The coolant in the upper plenum flowed via the control rod guide tubes into the upper head until the water level in the upper plenum sank below the penetration holes in the lower part of the control rod guide tubes. The relatively large break area led to a quick pressure drop in the reactor coolant system. Primary pressure dropped below secondary pressure at approx. 800 s, simultaneously with the beginning of core uncovery.

With the temperatures increasing in the upper core region, the limit (623 K) for the activation of the planned accident management measure was reached at approx. 1090 s after opening of the break. The secondary side depressurization was initiated by manually opening the relief valves. However, this measure was not effective since the primary pressure was lower than the secondary pressure in this phase. The cladding tube temperatures kept increasing until the limit value for the response of the LSTF core protection system was reached, which caused an automatic reduction of the core power by approx. 75 % at t = 1200 s. After approx. 1300 s, the actuation pressure of the accumulator was reached.

3. Reference calculation

The post-test calculation of the experiment has been performed with the code ATHLET 2.1A. The nodalisation of the primary and secondary circuit used in the analyses is shown in Figure 1. For the 1-D spatial nodalisation 227 control volumes and 274 junctions were used. Altogether, ATHLET could simulate satisfactorily the main phenomena observed experimentally. The influence of the water level in the upper head on the break mass flow was reproduced correctly by the code. Both the calculated time point of initiating the accident management measure and the beginning of the accumulator injection are in good agreement with the experimental values.

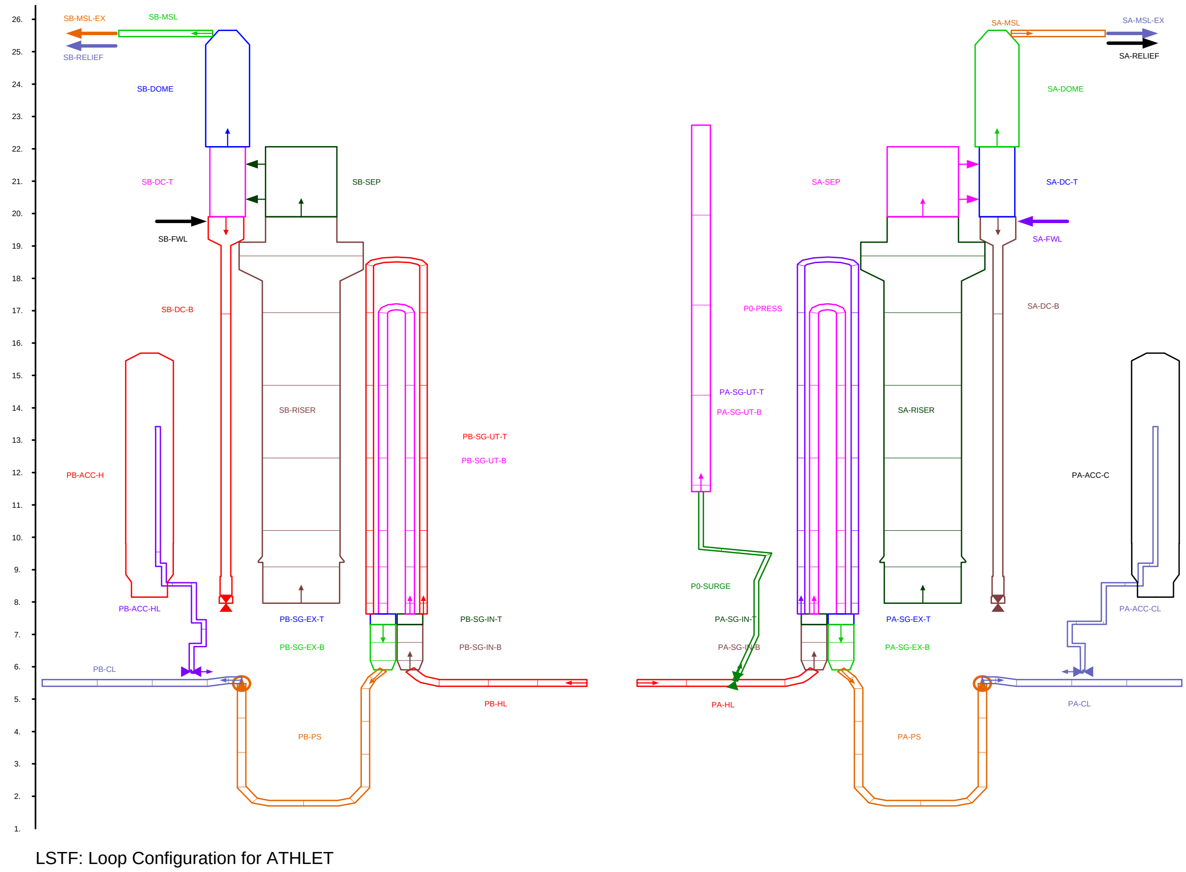

Figure 1 LSTF Primary and secondary circuit nodalisation.

4. Quantification of input uncertainties

The identification of the input uncertain parameters and the probabilistic quantification of their uncertainty are essential for the uncertainty and sensitivity analyses. Different classes of uncertain parameters are quantified in differetnway using appropriate source of information. The basis for state of knowledge quantification of facility description and operation are construction plans, information from facility operators and engineering judgement. For the initial and boundary conditions uncertainties quantification the accuracy of measurements is of importance. The basis for physical model uncertainties quantification is evaluation of separate effect experiments. Other information sources for quantification of model uncertainties are experience from code validation, survey of expert state of knowledge, published data about model uncertainties and if necessary application of theoretical limitations. Detailed description of the applied methodology of the input uncertainties quantification can be found in [4].

For the present study, a total of 50 potentially important uncertain parameters were identified and their uncertainty was quantified probabilistically. Among them, there are 40 parameters which describe the uncertainties of the physical modelling and the numerical simulation and another 10 parameters which refer to the uncertainties of the test facility and the experiment conducted.

The model uncertainties include:

- 4 parameters for the determination of the critical discharge flow
- 20 parameters to describe the uncertainties in the momentum equations
- 9 parameters for the heat transfer from fluid to structures
- 4 parameters for the two-phase heat and mass exchange through evaporation and condensation.
- 1 parameter for the axial nodalization in the bundle area
- 2 parameters to describe the form pressure losses in the facility

Table 1 Model related uncertain input parameter

No	Parameter	Range		Reference
		Min.	Max.	
Critical discharge				
1	Pressure loss in the nozzle	0.02	0.08	0.02
2	Turbulence factor for evaporation	1.0	50.0	15.0
3	Contraction factor at break	0.6	1.0	0.8
4	Contraction factor for relief valves	0.7	0.9	0.8
Momentum equation approximation				
5	Selection of equation system	1(5Eq.) (50%)	2(6Eq.) (50%)	2
Drift model uncertainties (5 Eq.) – multiplication factors				
6	Relative velocity in vertical pipe	0.5	1.5	1.0
7	Relative velocity in horizontal pipe	0.75	2.25	1.0
8	Relative velocity in rod bundle	0.3	1.5	1.0
9	Relative velocity in vertical annulus	0.5	1.5	1.0
10	Relative velocity in cross-connections	0.5	2.0	1.0
Interfacial friction in 6 equation model				
Horizontal flow – multiplication factor				
11	Stratified flow	0.2	2.0	1.0
12	Bubble and intermittent flow	0.35	3.5	1.0
13	Droplet flow	0.7	1.4	1.0
14	Stratified-intermittent transition velocity	1.0	3.0	1.0
15	Intermittent-droplet transition velocity	1.0	2.0	1.0
Vertical flow –multiplication factors				
16	Annulus	0.33	3.0	1.0
17	Bundle	0.2	2.5	1.0
18	Pipe	0.33	2.5	1.0
19	Droplet flow in all geometry	0.7	1.4	1.0
20	Transition velocity to droplet flow	1.0	2.0	1.0
Water entrainment in 5- and 6-Eq. system – multiplication factor				
21	Bundle – onset velocity	1.0	3.0	1.0

Heat transfer coefficients – multiplication factors				
22	Forced convection to water	0.85	1.15	1.0
23	Nucleate boiling	0.8	1.2	1.0
24	Film boiling – correlation selection	1(50%)	2(50%)	1
25	Dougall-Rohsenow cor. -1	0.65	1.3	1.0
	Condie-Bengson cor. – 2	0.75	1.25	1.0
26	Minimum film boiling temperature	0.9	1.3	1.0
27	Convection to vapour – cor. Selection	1(50%)	2(50%)	2
28	Dittus-Boelter cor. – 1	0.8	1.2	1.0
	McEligot – 2	0.85	1.25	1.0
29	Critical heat flux	0.7	1.3	1.0
30	Heat losses to environment	0.5	2.5	1.0
Evaporation and condensation				
31	Number of bubbles per unit volume	10^8	10^{10}	$5*10^9$ 1/m³
32	Number of droplets per unit volume	10^8	10^{10}	$5*10^9$ 1/m³
33	Direct condensation – multiplication factor	0.5	2.0	1.0
34	Local condensation by ECC injection – factor	10^{-6}	1.0	1.0
Pressure losses				
35	Form losses at cross-connections – factor	0.4	2.5	1.0
36	Form losses at ACCU lines – multiplication factor	0.67	1.5	1.0
37	Wall friction factor – model selection: 1 – constant, 2 – correlations for laminar and turbulent flow	1(50%)	2(50%)	1
38	Two-phase multiplier – vertical lines	~0.2	~2.0	1.0
39	Two-phase multiplier – horizontal lines	~0.1	~2.0	1.0
Nodalisation				
40	Number of nodes in core	9	18	9

Among parameters describing model uncertainties there are 4 discrete parameters (parameters 5, 24, 27, 37 in the Table 1) related to the model selection. In all fourth cases the equivalent application probability of 50% for each model has been choosen.

The remaining 10 test-specific uncertain parameters represent the uncertainties regarding the core bypasses, the bundle power, and leakage through the venting pipe at the reactor pressure vessel upper head as well as the accuracy of the temperature measurements which are used for initiating the accident management measure and triggering the core protection system. The experiment related uncertainties are listed in Table 2.

Table 2 Experiment related uncertain input parameter

No	Parameter	Range		Reference
		Min.	Max.	
Bypasses				
41	Downcomer-upper plenum cross-section factor	0.06	0.6	0.5
42	Downcomer-upper head – form losses	$5*10^3$	$5*10^7$	10^7
43	Rod bundle – upper plenum: form losses	$6*10^3$	$6*10^5$	$6*10^4$
44	Rod bundle – upper plenum: cross-section factor	0.33	3.0	1.0
Measurement accuracy				
45	Core power – multiplication factor	0.99	1.01	1.0
46	Vent flow – multiplication factor	0.8	1.2	1.0
47	Clad temperature – additive factor	-3K	3K	0
48	Fluid temp. at core outlet – additive factor	-3K	3K	0
Initial and boundary conditions				
49	Initial temperature in break line	314°C	320°C	314°C
50	Environment temperature	20°C	35°C	30°C

In the uncertainty analysis the uncertainty of the momentum balance equation has been performed in a particular way. It has been done comparing two approximations of the momentum equation. Making use of the ATHLET capability where 5- and 6-Equation systems are optionally available [1], an uncertain parameter for model selection (parameter 5 in Table 1) between 5-Eqn. system with one momentum equation for gas-liquid mixture and 6-Eqn. system with two separate momentum equations for gas and liquid phase has been introduced. The uncertainty of the momentum equation approximation has been expressed as uncertainty due to model selection and uncertainty of adequate closure relations. The input uncertainties of the constitutive models related to the two approximations have been quantified. Uncertain parameters 6 – 10 describe uncertainty of drift models in mixture momentum equations. Parameters 11-20 describe uncertainty of interfacial friction modelling for separate momentum equations. Parameter 21 describes modelling uncertainty of entrained liquid fraction in the bundle geometry, which applies the same correlation in both equation systems. Parameters 37 – 39 describe the uncertainty of wall friction modelling which is very similar in both approximations.

5. Uncertainty and sensitivity analysis

Using Simple Random Sampling 208 vectors of uncertain input parameters were generated randomly and inserted into the ATHLET input data sets. All ATHLET runs have been finished successfully. The performed calculations can be divided in two groups according to applied equation system. Due to the sampled values of parameter 5 (equation system selection) 98 calculations were performed with 5 equation system and 110 calculations with 6 equation system. The results of calculations with one and two momentum equations are quite similar. It can be seen on the example of pressure in the primary circuit and collapsed water level in the core in the Figures 2 and 3 expressing the family of the calculated pressure and water level curves (reference calculation in red) calculated with 1 and 2 momentum equations.

The influence of the momentum equation approximation and closing equations can be evaluated comparing uncertainty bands and sensitivities of uncertain parameters and parameters groups. In the standard sensitivity analysis the rank correlation coefficient as implemented in GRS software SUSA [5, 6] has been used as sensitivity index. The rank correlation coefficient (called also Spearman's correlation coefficient) is correlation coefficient calculated on rank transformed data. In addition to the standard sensitivity analysis a parameter group sensitivity analysis has been performed to quantify the joint sensitivity of the model output to all the parameters of the group simultaneously [7]. In this group sensitivity analysis the following groups of parameters have been introduced:

- Group 1: parameters related to uncertainty of relative velocity determination: parameters 6 -10 and 21
- Group 2: parameters related to uncertainty of interfacial shear determination: parameters 11 – 21
- Group 3: selection of equation system: parameter 5

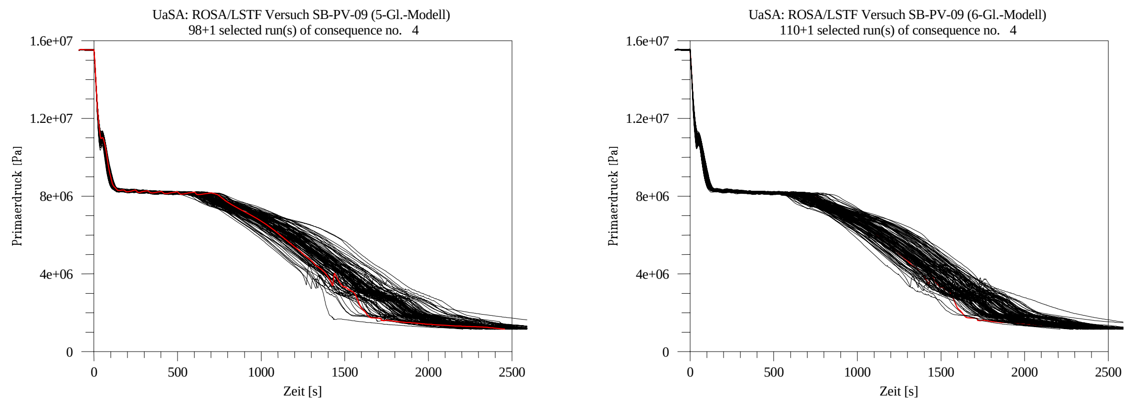

Figure 2 Pressure curves in primary circuit calculated with 5 and 6 equation systems.

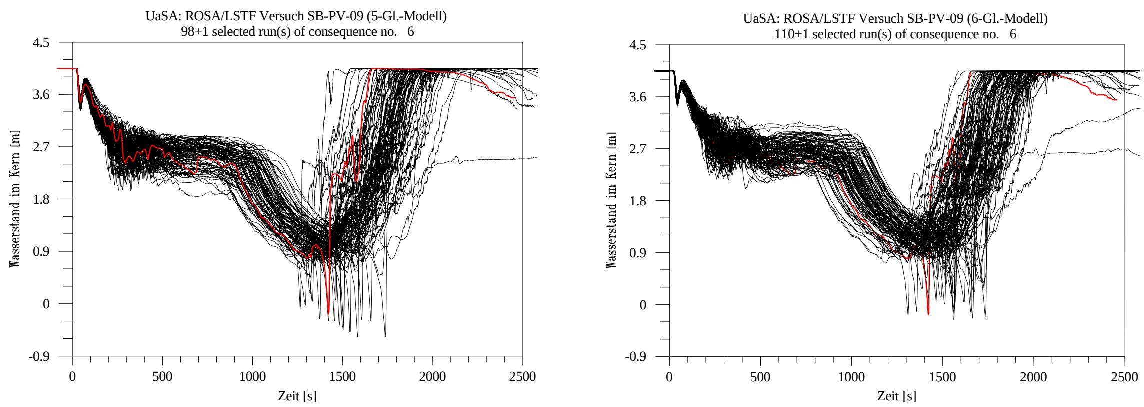

Figure 3 Water level curves in the core calculated with 5 and 6 equation systems.

The selection of the 5 equation systems leads to application of relative velocity model (Group 1) and selection of 6 equation system leads to application of interfacial shear model (Group 2). The uncertain input parameters of the group 1 correspond with parameters of the group 2, which describes the same geometry or flow pattern (see Table 3).

Table 3 Corresponding uncertain input parameters for closure relations in the 5 Eqn. and 6 Eqn. models

Geometry or flow pattern	Parameters in 5 Eqn. model - Group 1	Parameters in 6 Eqn. model - Group 2
Vertical pipe	6	18 + 19 + 20
Horizontal pipe	7	11 + 12 + 13 + 14 + 15
Vertical bundle	8 + 21	17 + 19 + 21
Annulus (vertical)	9	16 + 19 + 20
Cross-connections in bundle geometry	10	11 + 12 + 13 + 14 + 15

In the sensitivity analysis the variability of the output variables, which is related to the uncertainty of the selected momentum equation, is understood as sum of variability related to the uncertainty of mathematical formulation of the momentum equation and variability related to corresponding closure relations. It means that the sensitivity coefficient due to selection of the momentum equation approximation (parameter 5) express only variability due to the mathematical formulation of the selected approximation and it does not involve variability related to the uncertainty of the closure relations used in this equation.

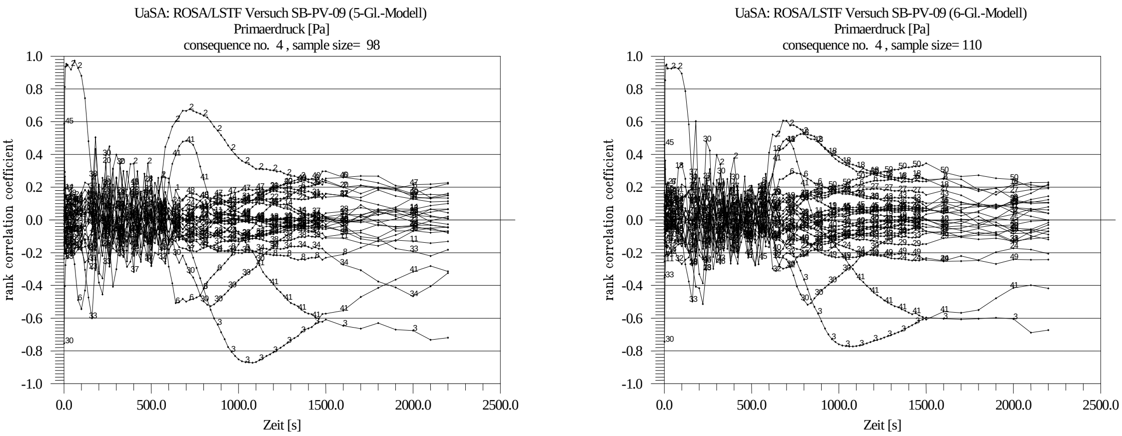

Figure 4 Sensitivities obtained with 5 and 6 equation systems for primary pressure.

The results of the sensitivity analysis showed that some output parameters are influenced by selection of momentum equation whereas others are not. It can be expected that in the case of closing relations the corresponding uncertain input parameters will be found as important for both momentum equation approximations. For instance, for primary pressure in the case of mixture momentum equation parameter 6 and in the case of separate momentum equations parameter 18 have been found of importance (see Figure 4). However, for the whole sample size of 208 calculations neither parameter 6 nor parameter 18 has been found as important (cf Fig. 5). The reason is probably that each parameter is used in the half of the calculated cases only and in the relation to the whole sample its influence is less pronounces comparing with others parameters considered in all calculations.

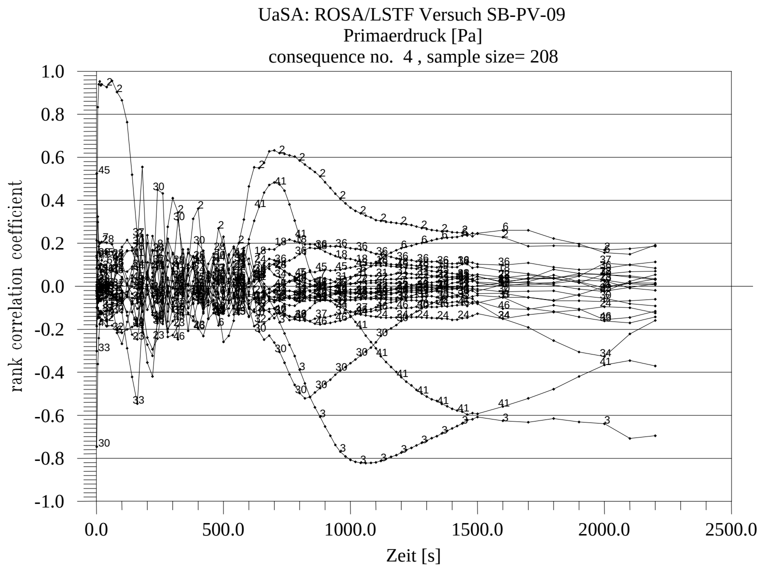

Figure 5 Sensitivity obtained with whole sample size for primary pressure.

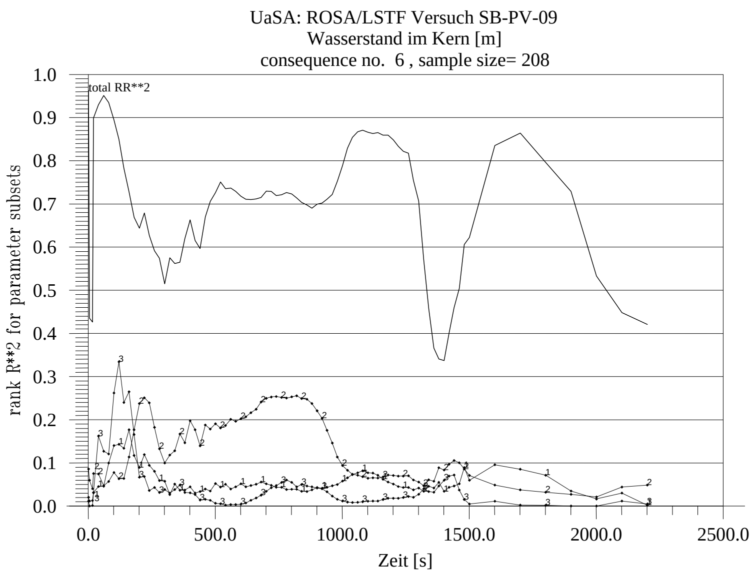

Figure 6 Group sensitivities obtained for water level in the core.

In Figures 6 and 7 the influence of the three groups of parameters on the water level in the core and differential pressure in the upper plenum is shown. The selection of the equation system (group 3 = parameter 5) is important in the first phase of the experiment. After the break opening strong acceleration of the phases takes place. In such condition approximation of the momentum terms in the both equation systems is of importance. In the later phase of the experiment during a less rapid transient development the uncertainty of constitutive relations appears to be more important. Comparison of influence of parameter groups 1 and 2 shows that in the time between 200 s and 1000 s the influence of the group 2 is much larger than the influence of the group 1. It means that impact of the uncertainty of the interfacial shear model is much larger than of the uncertainty of the phase relative velocity model. In this time period the most important are parameter 8 for 5-Equation system and parameter 17 for 6-Equation system (see Figure 8).

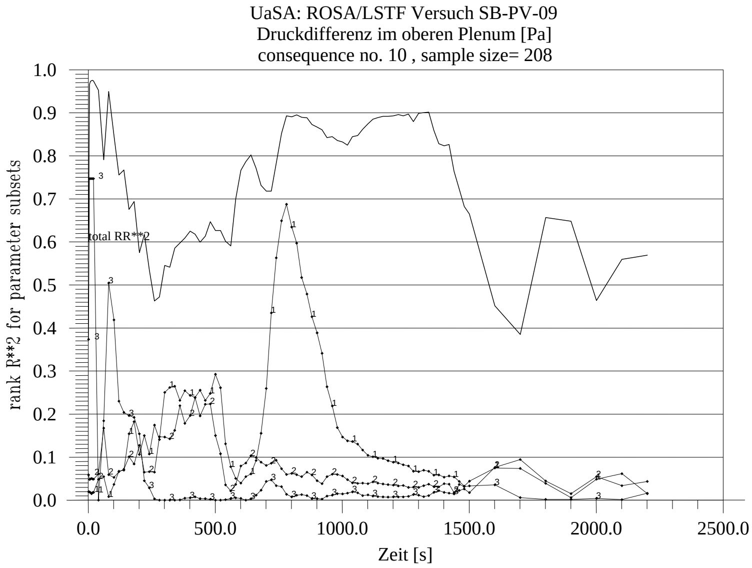

Figure 7 Group sensitivities obtained for differential pressure in upper plenum.

These parameters express the uncertainty of the relative velocity and interfacial friction determination in the bundle geometry. It means that the larger uncertainty of the group 2 results from prediction of interfacial friction for bundle geometry, which is less accurate than the prediction of the relative velocity in the bundle geometry. The sensitivity results indicate that for interfacial friction determination for the bundle geometry further validation is necessary for better quantification of the model uncertainty; or the modelling of the interfacial frictions needs further development.

For the differential pressure in upper plenum in the time period between 300 s and 500 s the influence of the two groups is equivalent. However, between 700 s and 900 s the influence of the group 1 is very large while the group 2 has practically no influence. In this time period the last phase of upper plenum drainage through the break takes place. The stratification at the break is modelled in ATHLET using one momentum equation only and therefore the group 1 (due to relative velocity in the vertical pipe – parameter 6) is so dominant (see Figure 9).

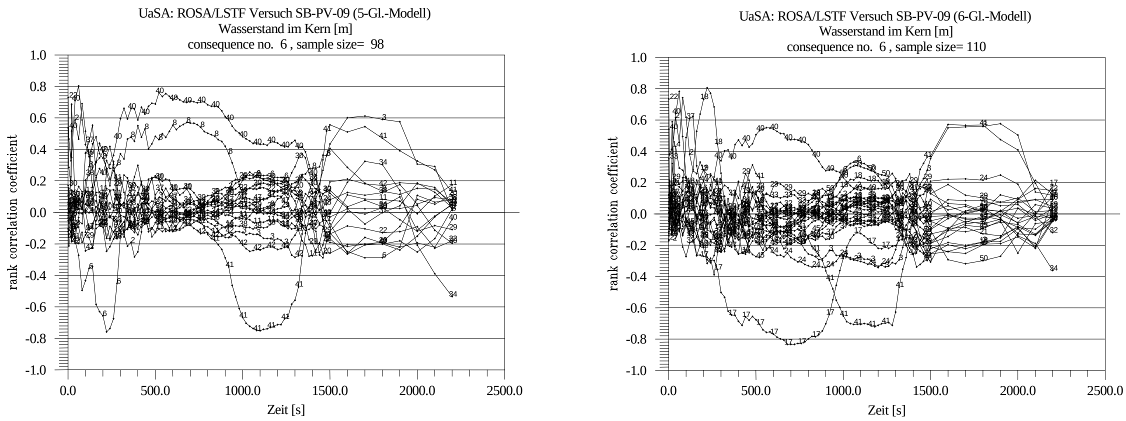

Figure 8 Sensitivities obtained with 5 and 6 equation systems for water level in the core.

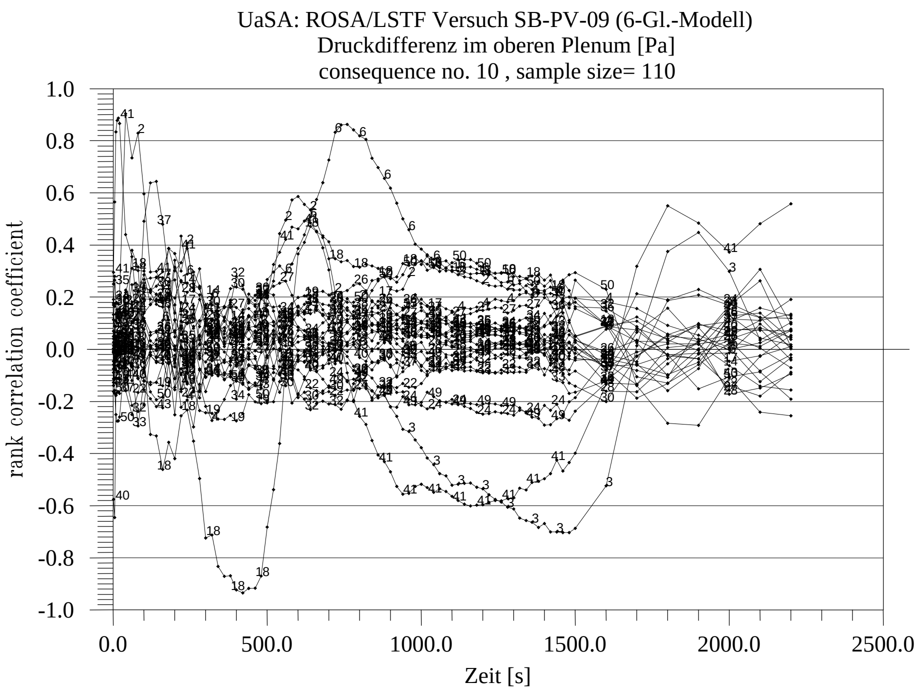

Figure 9 Sensitivities obtained for differential pressure in the upper plenum.

According to the sensitivity analysis and calculeted uncertainty limits the influence of the momentum equation approximation on the cladding temperature is negligible in the analyzed experiment. The cladding temperatures calculated with both equation systems are very similar.

6. Conclusion

The results of the performed uncertainty and sensitivity analysis confirmed that for the selected test case the effect of uncertainty of the both momentum equation approximations are very similar. The analysis shows that some output variables are influenced by approximation of momentum equation, e.g. water level in the core whereas other output variables like maximum clad temperature are not.

The result uncertainty due to the uncertainty of the closing relations, i.e. drift velocity and interfacial shear stress models depend on their state of knowledge quantification and numerical sensitivity of the momentum equation due to corresponding closure relations. In some cases the closure relations uncertainty contributes considerably more to uncertainty of the results than the uncertainty of momentum equation formulation. The analysis showed that the selection of momentum equation approximation is important only at the relative short time after break opening. In the later phase of experiment the uncertainty of closing relations is important for the simulation of some phenomena as it has been shown.

The results of the study confirmed the correct modelling of the both momentum equation approximations as well as their correct implementation in the code. They also confirmed the expectation that both momentum approximations are applicable for small break LOCA. The performed investigation is to our knowledge the first attempt to analyse the uncertainty of balance equation approximation within a consistent uncertainty study ever performed.

7. References

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