Uncertainty and Sensitivity Analysis of Hewitt-Govan model for dryout prediction using DARIA system code

Michał Spirzewski

Division of Nuclear Energy and Environmental Studies

Michal.spirzewski@ncbj.gov.pl

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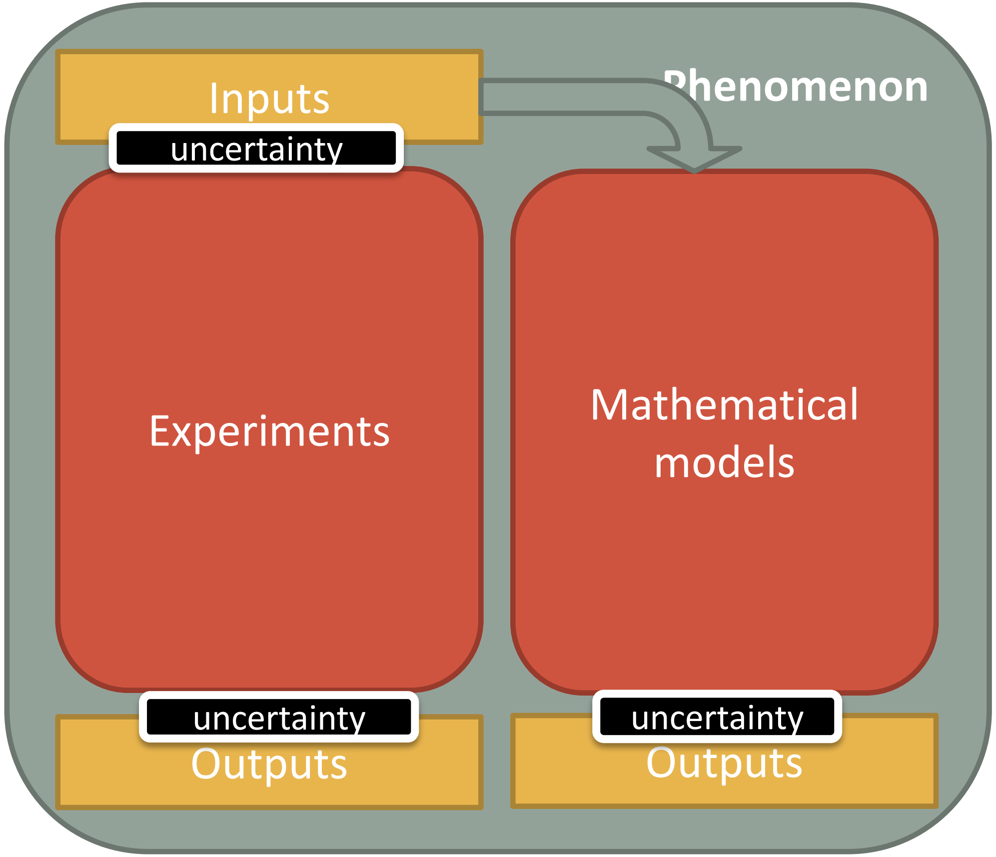
Agenda

1. Big picture
2. What are uncertainty and sensitivity analyses.
   - Definitions
   - Methods
3. How are sensitivity analyses performed?
4. What is dryout in BWRs?
   - Definitions and calculation approaches.
5. Used tools.
6. Results and discussion of uncertainty and sensitivity analyses of dryout prediction.

Big picture



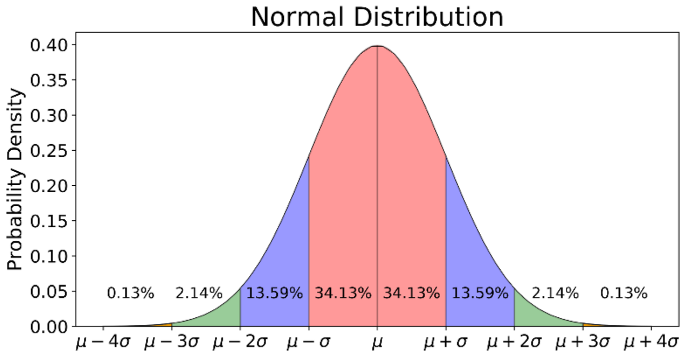
- Evaluation of the model comes down to the comparison between the outputs
  - Y_{exp} vs Y_{calc}
- The complete evaluation of the mathematical model consists of:
  - Accurracy evaluation.
  - Uncertainties evaluation.
    - Y_{exp} ($\pm$ σ_{exp}) vs Y_{calc}($\pm$ σ_{exp})
  - Sources of uncertainties identification

Basic statistics

- Discussion of uncertainties comes down to description of distributions.
- E.g. normal distribution is described as:
  - Mean value - μ
  - Standard deviation - σ
- 6 atm +/- 0.1 atm
- Both are in the same unit.
  - Normalised standard deviation:

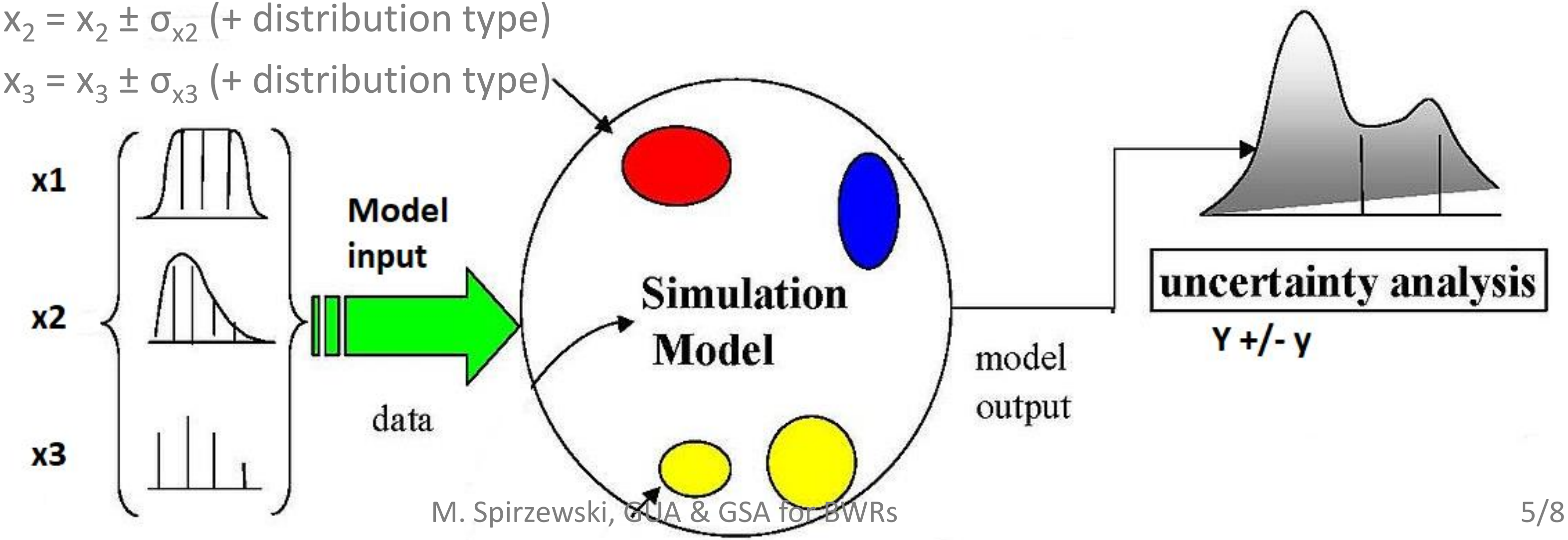
$$\hat{\sigma} = \frac{\sigma}{\mu}$$

- 6 atm +/- 1.6%



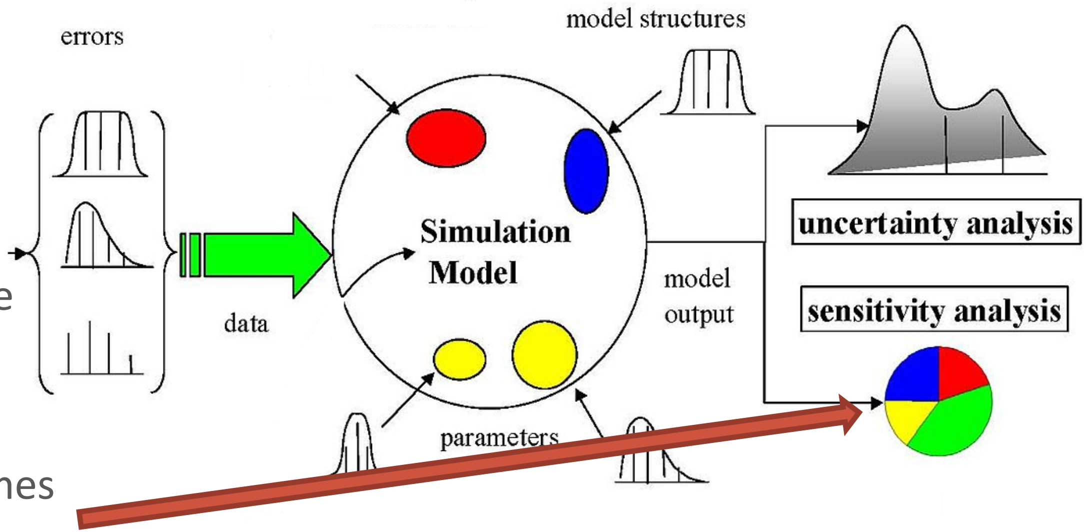
Uncertainty Analysis in calculations

- We want to know how uncertain the result is.
  - $Y \pm \sigma_y$
- The uncertainties in the output come from uncertainties in the input.
- In order to acquire this, we need to simulate the input uncertainty.
  - $X = [x_1, x_2, x_3]$
    - $x_1 = x_1 \pm \sigma_{x1}$ (+ distribution type)
    - $x_2 = x_2 \pm \sigma_{x2}$ (+ distribution type)
    - $x_3 = x_3 \pm \sigma_{x3}$ (+ distribution type)



Sensitivity Analysis

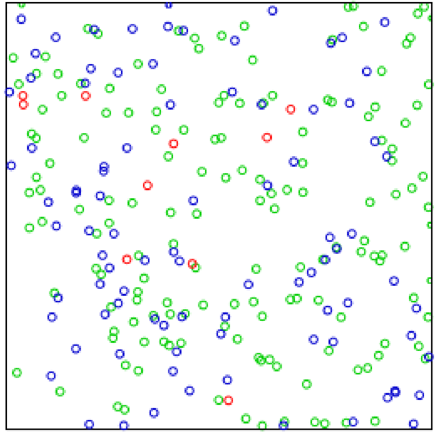
- What are the sources of the uncertainty?
  - How uncertainty in the input contributes the uncertainty of the output?
- The result e.g.:
  - 90% of the result uncertainty comes from the uncertainty of mass flux



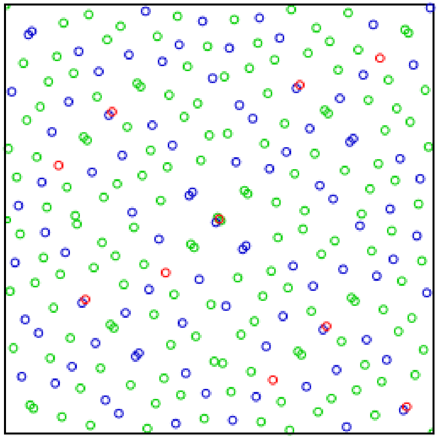
Methods

- Saltelli et al. Method.
- Preparation of the input space using **Sobol sequence**.
- Sobol sequences are generated using Experimental input values

Monte Carlo



Sobol sequence



- Input-Output Analysis

$$Y = f_0 + \sum_{i=1}^{n} f_i(X_i) + \sum_{i<j}^{n} f_{i,j}(X_i, X_j) + \ldots + f_{1,2,\ldots,n}(X_1, X_2, \ldots, X_n),$$

$$f_0 = \mathbb{E}(Y),$$
$$f_i = \mathbb{E}(Y|X_i) - f_0,$$
$$f_{i,j} = \mathbb{E}(Y|X_i, X_j) - f_0 - f_i - f_j,$$

$$\mathrm{V}(Y) = \sum_{i=1}^{n} V_i + \sum_{i<j}^{n} V_{i,j} + \ldots + V_{1,2,\ldots,n},$$

$$V_i = \mathrm{Var}_i(\mathbb{E}_{\sim i}(Y|X_i)),$$
$$V_{i,j} = \mathrm{Var}_{i,j}(\mathbb{E}_{\sim i,j}(Y|X_i, X_j)) - V_i - V_j,$$

- Output uncertainties can be acquired at the same step.

Sobol Sequence - characteristics

$\mu_P = P_{exp}$ $\mu_G = G_{exp}$ $\mu_T = T_{exp}$

1 input

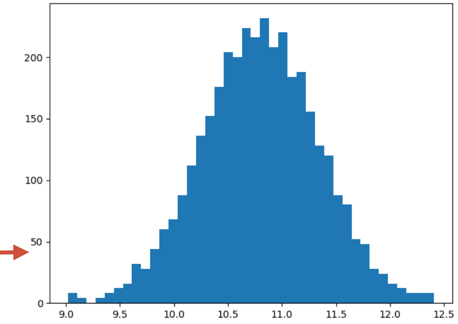
- P, G, Tsub

```
[[9.58460116e+06 2.88735811e+03 1.08251243e+01]
 [1.01986378e+07 2.88735811e+03 1.08251243e+01]
 [9.58460116e+06 2.99832884e+03 1.08251243e+01]
 [9.58460116e+06 2.88735811e+03 1.15148887e+01]
 [9.58460116e+06 2.99832884e+03 1.15148887e+01]
 [1.01986378e+07 2.88735811e+03 1.15148887e+01]
 [1.01986378e+07 2.99832884e+03 1.08251243e+01]
 [1.01986378e+07 2.99832884e+03 1.15148887e+01]
 [1.02601417e+07 3.12599372e+03 9.67433829e+00]
```

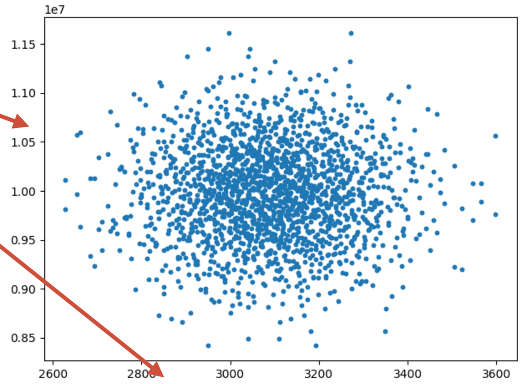
- ΔP ΔG ΔTsub

```
[[ 6.14036661e+05  0.00000000e+00  0.00000000e+00]
 [-6.14036661e+05  1.10970733e+02  0.00000000e+00]
 [ 0.00000000e+00 -1.10970733e+02  6.89764438e-01]
 [ 0.00000000e+00  1.10970733e+02  0.00000000e+00]
 [ 6.14036661e+05 -1.10970733e+02  0.00000000e+00]
 [ 0.00000000e+00  1.10970733e+02 -6.89764438e-01]
 [ 0.00000000e+00  0.00000000e+00  6.89764438e-01]
 [ 6.15038349e+04  1.27664879e+02 -1.84055045e+00]
 [-7.52645826e+05  0.00000000e+00  0.00000000e+00]
```

- Histogram of T_sub values



- Pressure versus mass flux



Sensitivity measures

- First-order Sobol index:
  - Measures the contribution that the input variable Xi has on the variance of the output variable

$$S_i := \frac{V_i}{\mathrm{Var}(Y)}$$

- Second-order Sobol index:
  - Measures the contribution that the interactions between input variables on the variance of the output

$$S_{i_1,\dots,i_d} := \frac{V_{i_1,\dots,i_d}}{\mathrm{Var}(Y)}$$

- Total-order Sobol index:
  - It accounts for all the variance in the output that is caused by the input Xi including its interactions with all the remaining input variables

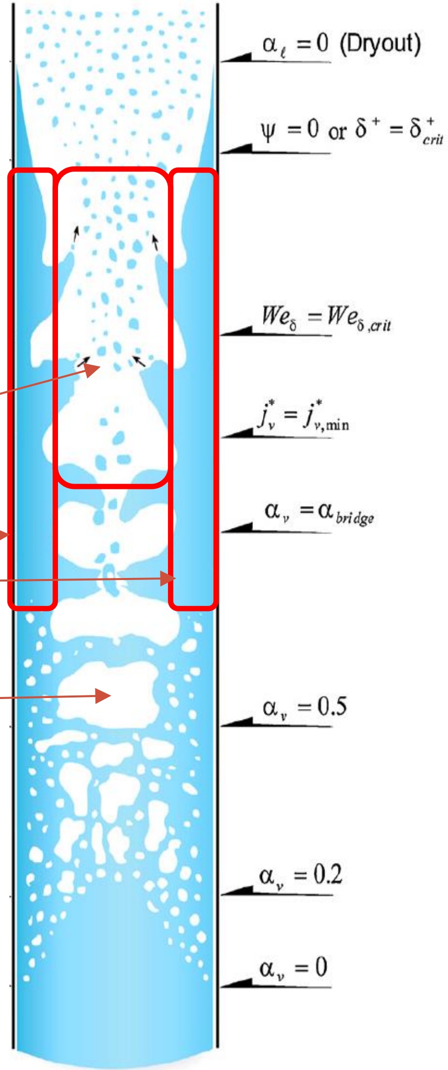
$$S_{Ti} = \frac{\mathbb{E}_{\sim i}\left(\mathrm{Var}_i\left(Y|X_{\sim i}\right)\right)}{\mathrm{Var}(Y)} = 1 - \frac{\mathrm{Var}_{\sim i}\left(\mathbb{E}_i\left(Y|X_{\sim i}\right)\right)}{\mathrm{Var}(Y)}.$$

Sensitivity analysis

- Pros
  - Allows to identify the sources of the uncertainty
  - Identifies interactions between parameters
  - Models can be improved
- Cons
  - Really high computational demand
    - N*(2P+2)
    - 3 parameters yield 8 inputs
    - N – nr of changes of a value
  - Difficulties in selection of the proper input distribution.
  - Not exciting

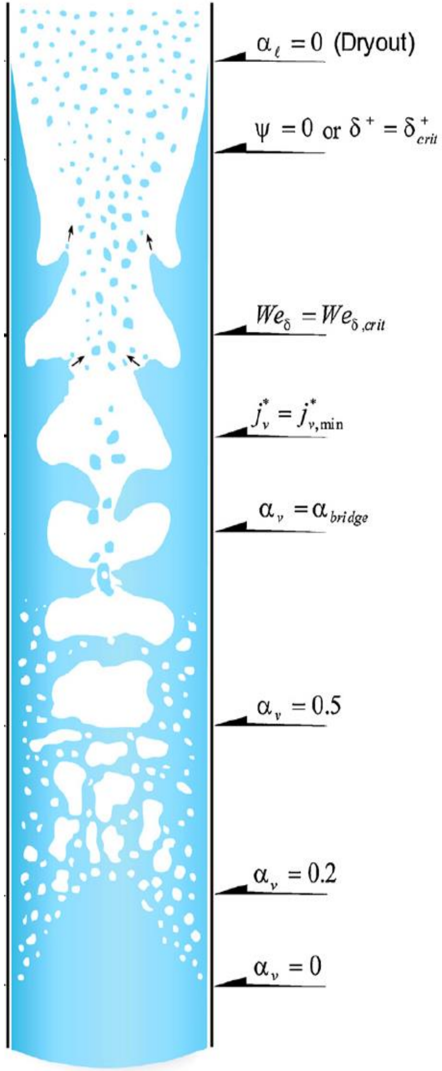
Boiling Water Reactor flow characteristics

- 2 phases
  - Water
  - Vapour
- High void fraction
- High quality
- 3 fields
  - Liquid film
  - Liquid droplets
  - Vapour
- All flow regimes
  - Bubbly, slug, churn-turbulet and annular.



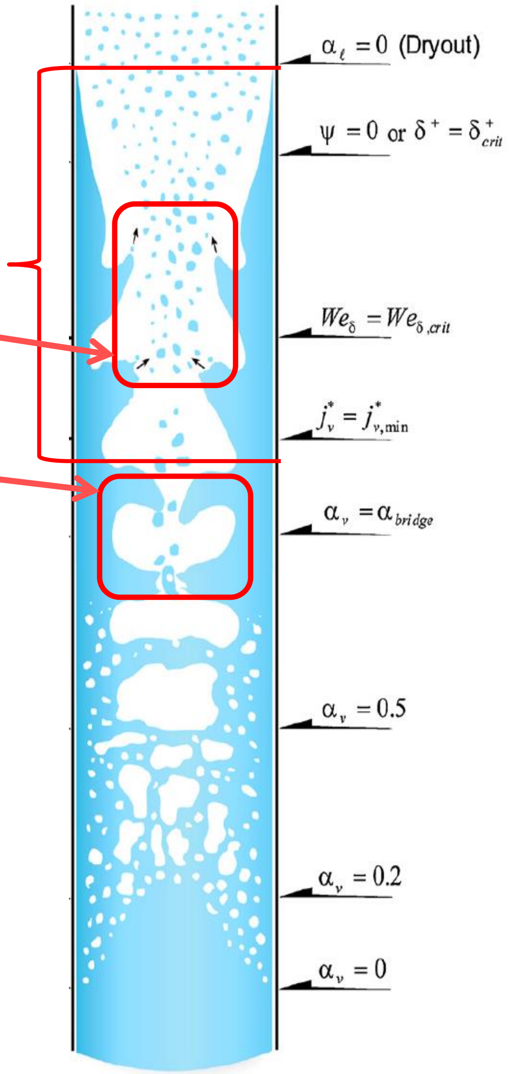
What is dryout?

- Dryout is the phenomenon occurring in Boiling Water Reactor when the Critical Heat Flux is reached.
- It results in a sudden increase of the heater's temperature.
- It can lead to melting of the cladding.
- Thus, it usually is the limiting factor of BWR power production, due to complexity of the phenomenon.



What influences Dryout prediction

- Heat flux
- Entrainment and deposition mass fluxes
- Initial mass distribution at the onset of annular flow
- Length of the annular flow



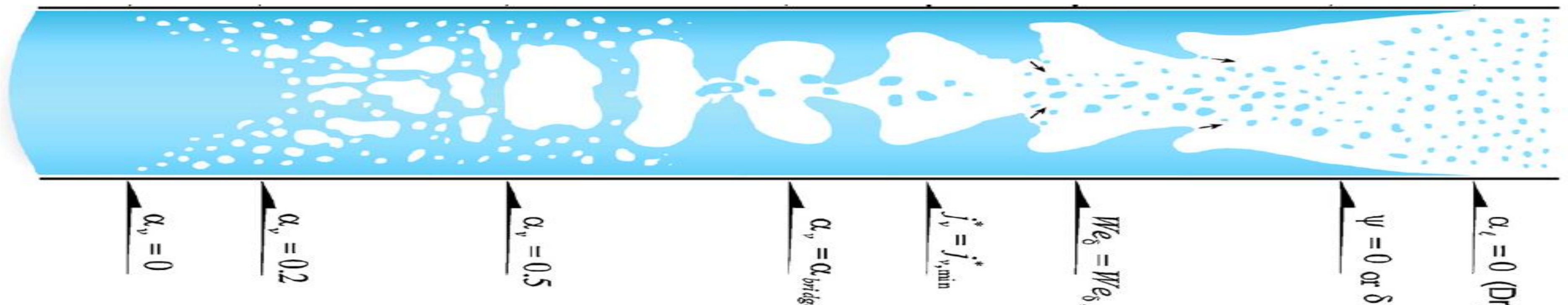
Modelling approach and physics of the phenomena

- Film Flow model – a film mass balance approach
  - Entrainment – source of droplet flow
  - Depostion – sink of droplet flow
  - Evaporation – sink of film flow
  - Initial Entrained Fraction
    - $\frac{m_d}{m_d+m_f} = 0.7$

$$\frac{dG_f}{dz} = \frac{4}{D_h}(m_D - m_E - m_g),$$

$$m_E = G_g \cdot 5.75 \cdot 10^{-5} \left[(G_f - G_{\mathrm{lfc}})^2 \frac{D_h \rho_l}{\sigma_l \rho_g^2} \right]$$

$$m_D = C \cdot 0.083 \cdot max \left(0.3, \frac{C}{\rho_g} \right)^{-0.65} \sqrt{\frac{\sigma_l}{\rho_g D_h}}$$



Previous work

- Accuracy of the entrainment and deposition models in CATHARE-3 code
  - So called Y_{calc} vs Y_{exp}
- Influence of the IEF parameter
- Model for the IEF

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An improved phenomenological model of annular two-phase flow with high-accuracy dryout prediction capability

Michał Spirzewski[a,c,*], Henryk Anglart[b,c]

[a] National Centre for Nuclear Research (NCBJ), A. Soltana 7, 05-400 Otwock-Swierk, Poland
[b] Nuclear Reactor Technology, KTH Royal Institute of Technology, Roslagstullsbacken 11, SE-106 91 Stockholm, Sweden
[c] Warsaw University of Technology, Institute of Heat Engineering, Nowowiejska 21/25, 00-665 Warsaw, Poland

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ABSTRACT

This paper presents a new phenomenological model of annular two-phase flow with dryout prediction capability, implemented in the CATHARE-3 system code. The model comprises existing correlations for entrainment and deposition rates and a new equation to determine the initial entrained fraction (IEF) of the liquid phase at the onset of annular two-phase flow. The proposed new model allows for a significant reduction of mean error variations with pressure and mass flux, when compared with measured dryout in pipes with internal diameter from 8 to 14.9 mm, system pressure from 3 to 10 MPa, mass flux from 500 to 6000 kg/m^{2}s, test section length from 1 to 7 m, inlet subcooling form 10 to 100 K, and critical heat flux from 0.15 to 3.90 MW/m^2. It has been also shown that, at certain conditions, the phenomenological model is unable to provide an accurate prediction, irrespective of the chosen value for the IEF parameter. Such behavior is thoroughly investigated in this paper and seldom addressed in the literature, even though it sets limits on the applicability of the model to dryout predictions.

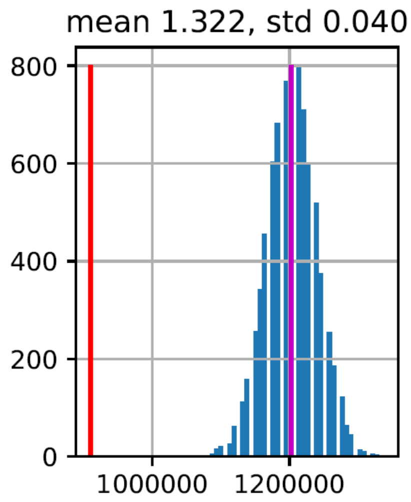
Initial Setup

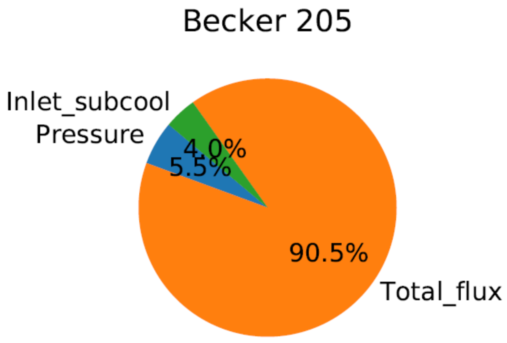
- Experimental data of:
  - Becker et al.(1983)
  - Soderquist et al. (1994)
  - Roughly 330 experimental runs were used
- Operating conditions:
  - Pressure: 30 – 100 [bars]
  - Mass Flux: 500– 3000[kg/m^{2}s]
  - Diameter 8 – 14.9 [mm]
  - Length 1 – 7 [m]
  - T_{sub} 10 [K]

- GSA - Input parameters
  - Variation of:
    - Pressure
    - Mass flux
    - Inlet subcooling
  - Normal distribution's standard deviation of 5%.
  - 3000 samples per exp. run.
    - 24 000 calculation per experiment
    - High accuracy of Sobol Indices estimation.
    - 7 920 000 calculations in total
  - IEF = 0.7

Used tools

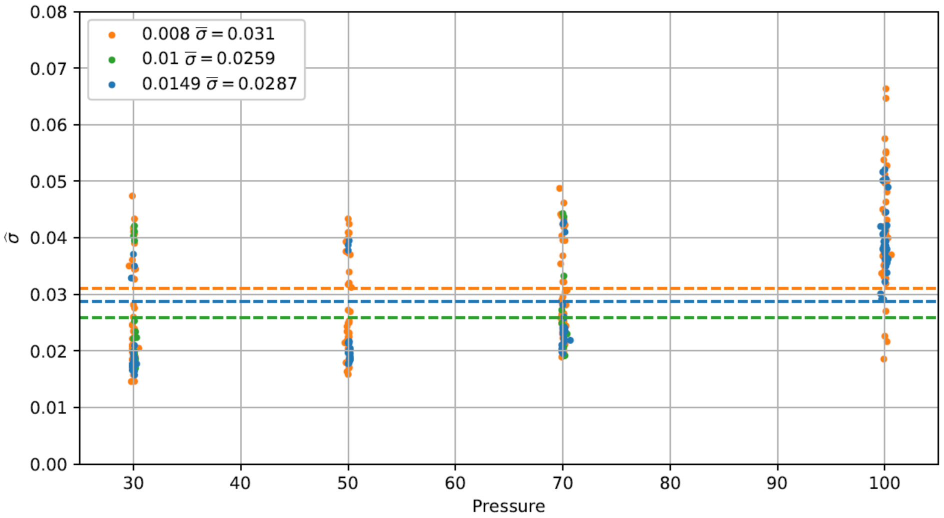
- CIŚ HPC
- DARIA – Deterministic Analysis code for maRIA reactor.
  - 1-D system code developed in Python
- SALib – Sensitivity Analysis Library in Python
- Sample result for 1 case:



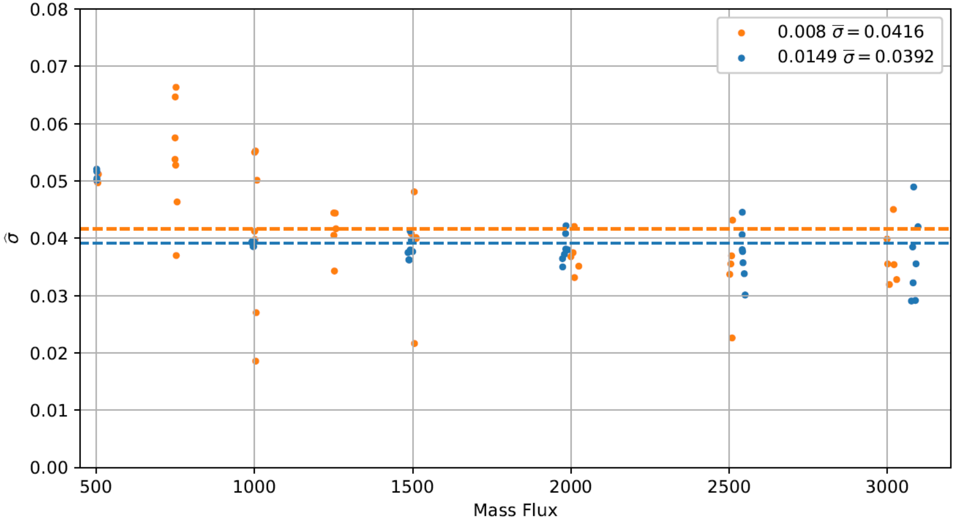


Results and Discussion – Uncertai

- Uncertainty of the CHF w.r.t. pressure
- Pressure ranges:
  - 30-70 bars – σ < 0.05 (input value)
  - 100 bars – significant increase in σ

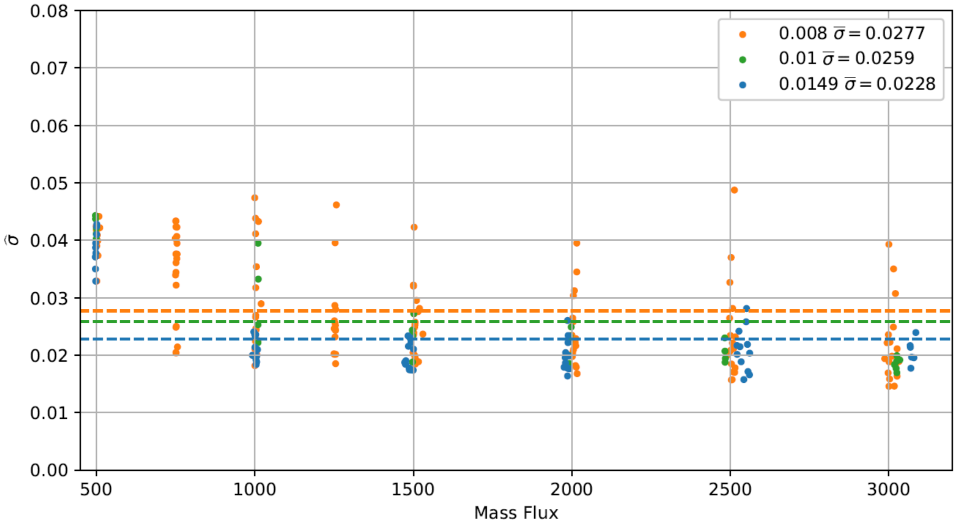


- Uncertainty of the CHF w.r.t. mass flux at pressure = 100 bars
- Mass flux ranges:
  - 500 – 1000 [kg/m²s] σ > 0.05
  - 1500 – 3000 [kg/m²s] σ < 0.05



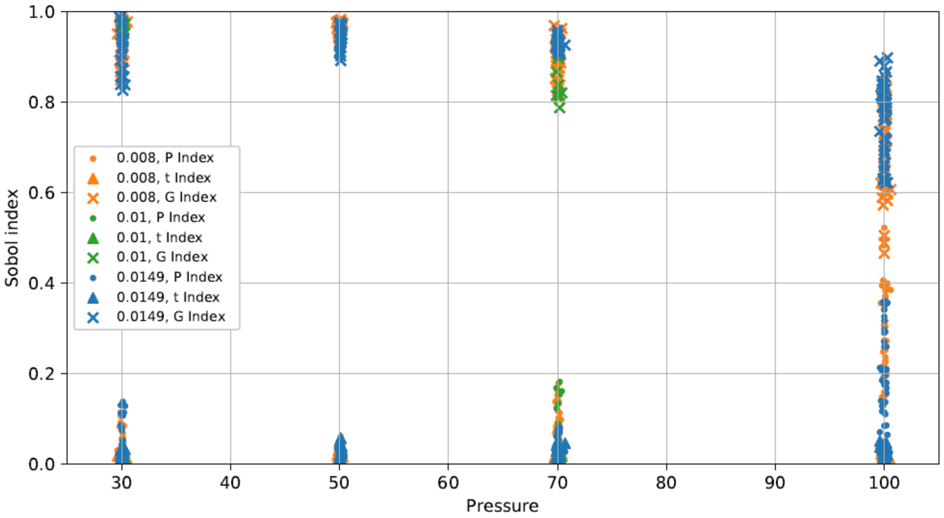
Results and Discussion – Uncertainty

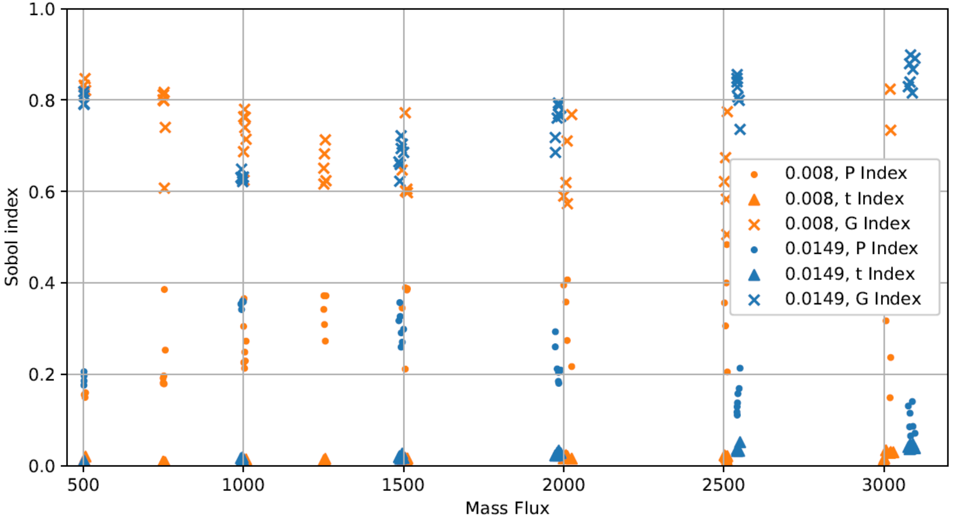
- Uncertainty of the CHF w.r.t. mass flux at pressure = 30-70 bars
  - Similar trend of increased uncertainties at mass fluxes 500 – 1000 [kg/m^2s]
  - Other mass flux ranges uncertainties are roughly 0.025



Results and Discussion – Sensitivi

- Total Order Sobol Index w.r.t. pressure
- Pressure range 30-70:
  - Mass Flux contribution:
    - 80-100%
  - Pressure contribution:
    - 1-10%
  - Inlet subcooling contribution:
    - 0-3%
- Pressure 100 bars:
  - Mass Flux: 50-90%
  - Pressure: 20-50%
  - Inlet Sub: 0-3%





Summary

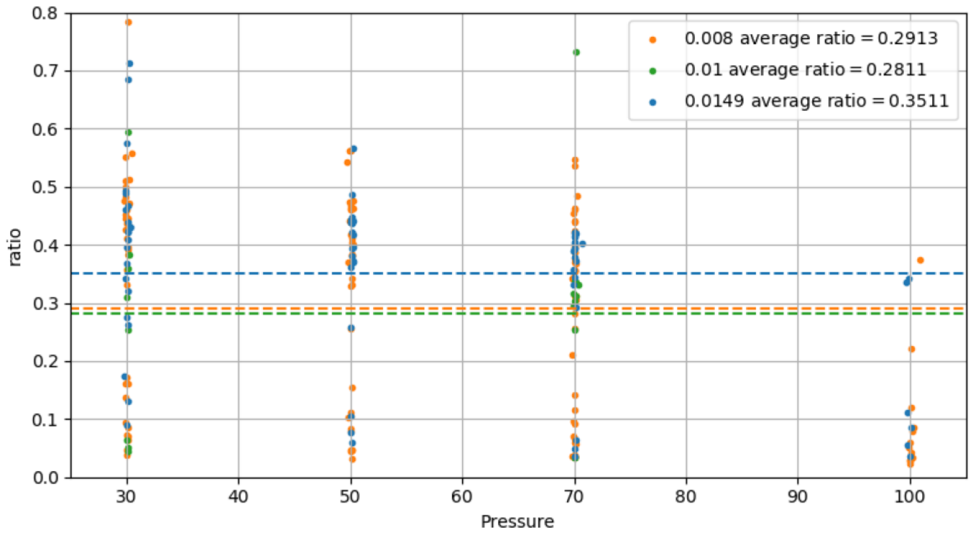
- Mass flux as a main source of uncertainty
- Interactions between parameters do not contribute to uncertainty
- High pressure with long test section exhibit interaction between pressure and mass flux as a source of uncertainty

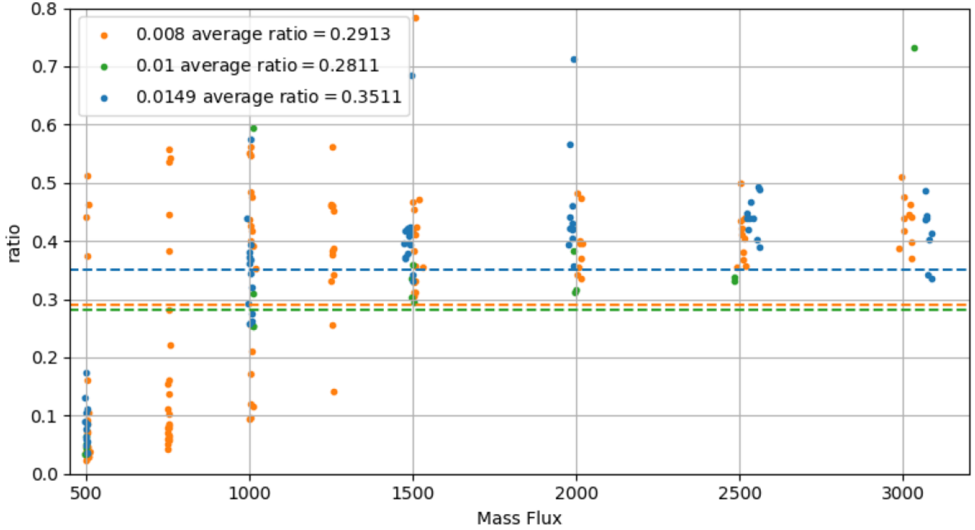
P	Mass Flux	$\frac{L_{boil}}{d_h}$	$\overline{\sigma}$ [0.008, 0.01, 0.0149]	S_1^p, S_2^p, (S_T^p)	S_1^G, S_2^G, (S_T^G)	S_1^t, S_2^t, (S_T^t)
30	0-750	400-	2.46, —, 3.39	0.72, 0.51, (1.23)	97.8, 0.69, (97.8)	0.4, 0.55, (0.94)
		400+	3.92, 4.12, 3.71	1.48, 0.5, (1.95)	98.1, 0.53, (97.1)	0.29, 0.57, (0.86)
	1000-1500	400-	2.14, —, 1.82	4.66, 0.96, (5.62)	92.6, 1.03, (92.7)	0.81, 0.8, (1.6)
		400+	2.72, 2.58, 2.1	1.72, 0.77, (2.48)	96.7, 0.88, (96.3)	0.29, 0.83, (1.16)
	2000-2500	400-	2.69, —, 1.74	8.23, 0.94, (9.14)	87.5, 1.13, (88.1)	1.8, 0.88, (2.68)
		400+	1.87, 1.98, 1.57	1.15, 0.91, (2.11)	95.6, 1.54, (96.2)	0.43, 1.22, (1.64)
	3000	400-	2.86, —, —	6.52, 0.99, (7.27)	90.9, 1.52, (90.0)	2.1, 0.66, (2.7)
		400+	1.62, 1.84, —	1.56, 1.15, (2.77)	94.6, 1.62, (94.8)	0.72, 1.62, (2.34)
50	0-750	400-	3.17, —, 3.87	2.16, 0.57, (2.71)	96.6, 0.6, (96.4)	0.25, 0.52, (0.8)
		400+	4.02, —, —	3.27, 0.28, (3.54)	95.7, 0.37, (95.9)	0.25, 0.29, (0.54)
	1000-1500	400-	2.18, —, 1.92	0.31, 0.7, (1.06)	96.9, 1.24, (96.9)	0.75, 1.27, (2.01)
		400+	2.65, —, 2.14	1.85, 0.86, (2.69)	96.5, 0.63, (96.1)	0.38, 0.74, (1.17)
	2000-2500	400-	2.49, —, 2.0	1.11, 1.22, (2.32)	94.9, 0.88, (94.3)	2.26, 1.15, (3.37)
		400+	1.84, —, —	0.87, 0.64, (1.55)	95.5, 1.47, (96.1)	1.1, 1.23, (2.31)
	3000	400-	2.75, —, 2.01	1.76, 1.8, (3.51)	93.2, 1.47, (92.0)	3.08, 1.44, (4.43)
		400+	1.73, —, —	1.27, 0.81, (2.08)	94.2, 1.31, (95.0)	1.59, 1.31, (2.9)
70	0-750	400-	3.31, —, 4.17	8.5, 0.54, (8.97)	90.5, 0.44, (90.2)	0.28, 0.56, (0.83)
		400+	4.14, 4.4, 4.28	7.08, 0.46, (7.45)	92.2, 0.52, (91.6)	0.3, 0.56, (0.85)
	1000-1500	400-	2.66, 2.34, 2.29	6.67, 0.58, (7.19)	90.9, 0.68, (91.0)	1.03, 0.73, (1.75)
		400+	3.48, 2.83, —	8.63, 0.63, (9.15)	90.1, 0.69, (89.8)	0.43, 0.61, (1.04)
	2000-2500	400-	3.12, —, 2.35	2.6, 0.78, (3.35)	93.9, 0.85, (93.5)	2.31, 0.8, (3.07)
		400+	2.38, 2.3, —	11.8, 0.92, (12.6)	85.7, 0.73, (85.4)	1.08, 0.82, (1.89)
	3000	400-	2.4, —, 2.17	1.06, 0.93, (1.99)	93.7, 1.12, (94.7)	2.71, 0.55, (3.26)
		400+	2.1, 1.92, —	11.7, 0.79, (12.3)	84.8, 0.81, (85.3)	1.47, 0.79, (2.27)
100	0-750	400-	4.65, —, 5.11	21.6, 0.42, (21.9)	77.6, 0.31, (77.3)	0.36, 0.38, (0.74)
		400+	5.72, —, —	16.9, 0.57, (17.3)	82.2, 0.47, (81.7)	0.36, 0.53, (0.88)
	1000-1500	400-	4.29, —, 3.84	32.1, 0.54, (32.3)	66.4, 0.56, (66.2)	0.93, 0.56, (1.47)
		400+	2.74, —, —	16.9, $\boxed{13.4}$, (29.9)	53.0, $\boxed{15.6}$, (65.1)	0.29, 4.09, (4.86)
	2000-2500	400-	3.3, —, 3.77	20.7, 0.85, (21.2)	71.8, 0.79, (71.5)	-2.0, 0.48, (7.14)
		400+	2.37, —, —	30.1, $\boxed{14.6}$, (42.9)	42.6, $\boxed{15.3}$, (55.1)	0.81, 1.13, (1.92)
	3000	400-	3.74, —, 3.65	13.4, 0.64, (13.9)	82.7, 0.61, (82.2)	3.24, 0.59, (3.79)
		400+	3.61, —, —	45.4, 0.85, (45.6)	52.5, 0.7, (52.4)	1.26, 0.62, (1.86)

IEF influence on Uncertainty

- $\Delta\sigma = 1 - \frac{\sigma_{07}}{\sigma_{00}}$
- Highest uncertainty reductions:
  - Pressure: from 30 to 70 bars
  - Mass flux: from 1500 to 3000 [kg/m^{2}s]
- Lowest uncertainty reductions
  - Pressure: 100 bars
  - Mass flux: 500-1000 [kg/m^{2}s]

- IEF has negligible influence on the sources of the uncertainties.





Future work

- GSA
  - Other entrainment-deposition correlations analysed
  - Analysis of different IEF models
  - Analysis of correlation’s coefficients
- Dryout
  - More development of DARIA code
    - Two-fluid model
    - Rod bundle geometry
    - Application to HTR (different coolants)

Thank you for attention

Michal Spirzewski

Division of Nuclear Energy and Environmental Studies

Michal.spirzewski@ncbj.gov.pl

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