Verification of Simulation Results of Mixture Level Transients and Evaporation Processes in Pressure Vessels using Needle-shaped Probes

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1 Experiments with depressurisation

For a continuous monitoring, control, and diagnosis of high transient technical processes in safety-related systems in Nuclear Technology it is necessary to provide the knowledge about the actual state of process in form of measurable and non-measurable state variables. Especially the monitoring of water level within pressure vessels with water-steam mixture (pressuriser, steam generator, reactor pressure vessel) during accidental depressurisations is very important. A lot of hydrostatic measuring systems are installed at the technical facility for this task. Our subject of investigation is the monitoring of the mixture level within the pressure vessel, which comes into existence in case of evaporation processes (Fig. 1). The paper deals with the simulation (ATHLET-Code [4]) of mixture level transients and evaporation processes in pressure vessels during the depressurisation. For the verification of the simulation results needle-shaped probes were applied.

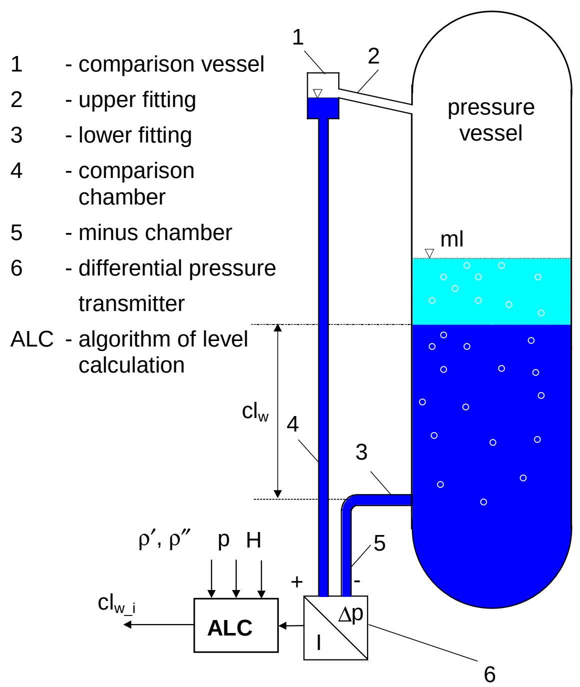

Fig. 1: Pressure vessel with water steam mixture and hydrostatic measuring system,
cl_w – measurable collapsed level between the fittings of wide range system,
ml – non-measurable mixture level within pressure vessel

The additional information about the mixture level is important for e. g. :

⇒ prevention of turbine damage by water entrainment and

⇒ prevention of uncovering of heating systems.

The problem is the fact that the mixture level is a high transient non-measurable value concerning usual hydrostatic water level measuring systems.

Our methodology for the verification of the mixture level transient is the following conception [6]:

⇒ Blow Down experiments with application of measuring systems for transient two-phase mixtures (needle-shaped probes - NSP),

⇒ simulation of thermal hydraulic processes in pressure vessels with water steam mixture using thermal hydraulic ATHLET-Code,

⇒ comparison between experiment and simulation.

For simulation, test and verification of mixture level by needle-shaped probes a lot of Blow Down experiments at the test facility DHVA at the IPM with different boundary conditions were carried out.

The procedure of the experiments will be exemplified:

⇒ achieving a steady state ($p = 7.0$ MPa)

⇒ opening of leak (starting point of Blow Down)

⇒ feed in of water from the preheater ($p \approx 1.5$ MPa ; $\vartheta \approx 200°C$)

⇒ closing of leak (end of Blow Down)

⇒ new steady state ($p \approx 0.2 ... 0.3$ MPa).

In Table 1 characteristic values of experiment parameters are listed for an example of one Blow Down experiment (BD15SG0). This corresponds to real procedures of disturbances in boiling water reactors (BWR).

Parameter	**Value**
Initial collapsed level	2.09 m
Initial pressure	6.8 MPa
Final collapsed level	1.29 m
Final pressure	0.19 MPa
Maximum rising up of mixture level	2.91 m

Action	**Time**
Opening of leak (starting point Blow Down)	100 s
Begin of feed in	157 s
End of feed in	245 s
Closing of leak	426 s
Time of investigation	500 s

Table 1: Characteristic values of boundary conditions of Blow Down experiment BD15SG0

Fig. 2 shows the associated time response of pressure within vessel and preheater during the depressurisation as well as the post-calculated by ATHLET-Code in comparison.

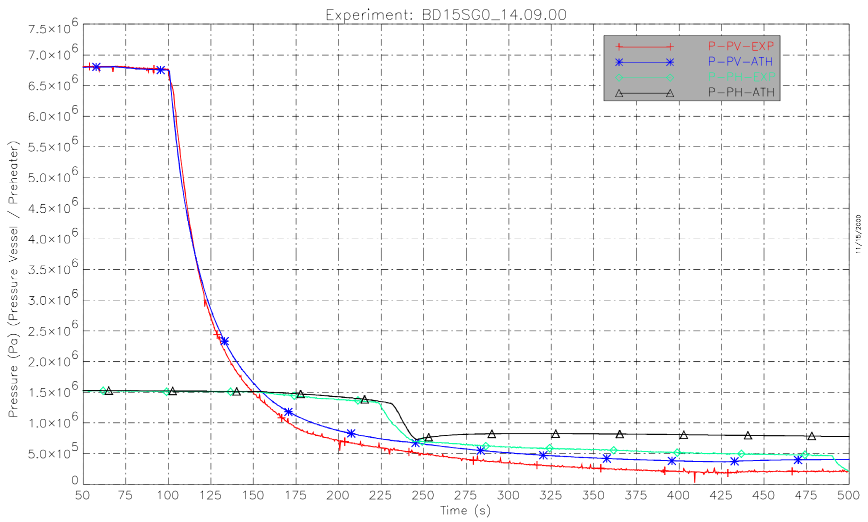

Fig. 2: Time response of pressure within vessel (PV) and preheater (PH) during experiment (EXP) and post-calculated by ATHLET-code (ATH)

The post-calculation reaches a good agreement to the experimental data in high pressure values and a sufficient in the low pressure values.

The mixture level transient is identified by following effects in the vessel:

⇒ rapid increase of mixture level as a result of the initiated evaporation (opening of leak)

⇒ gradual decrease of all water levels as a result of the boiling in connection with mass loss beyond the leak

⇒ gradual increase of all water levels as a result of feed in

⇒ rapid decrease of mixture level as a result of the collapse of water steam mixture (closing of leak)

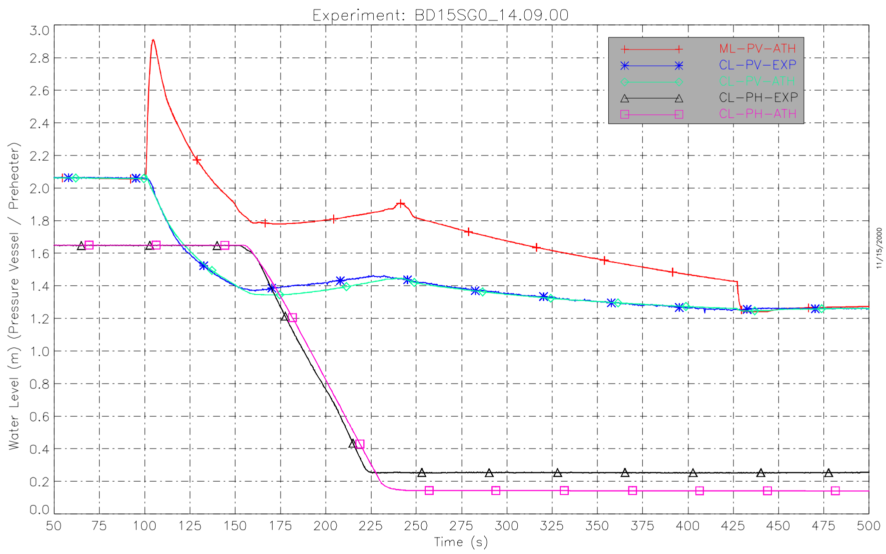

Fig. 3: Time Response of collapsed (CL) and mixture level (ML) within pressure vessel (PV) as well as collapsed level of preheater (PH) during Blow Down experiment (EXP) and post-calculated by ATHLET-code (ATH)

In Fig. 3 the comparison of water level response is illustrated. The mixture level response is the calculated by ATHLET-Code, which is based on the calculated collapsed level. Between the experimental and calculated data of collapsed level is a very exact correspondence. That means the ATHLET-Code reflects the process behaviour very well [6]. The deviation in the preheater water level after t ≈ 225 s results in fact of the limitation by the measuring system range.

The interesting parameter mixture level, which is non-measurable by usual hydrostatic measuring system, has to be verified by needle-shaped probes for two-phase flow.

2 Detection of mixture level transfer by using needle-shaped probes (special instrumentation)

Needle-shaped probes (NSP) are a special instrumentation for two-phase flow to detect the mixture level interface area as well as a local steam content [1, 2, 3, 6]. In Fig. 4 a construction scheme of NSP in principle is demonstrated. The basic point of the signal processing is established by the different conductivity of steam and water phase. A short overview about the measuring principle gives Fig. 4, too. It deals with a water-steam mixture moving within a time interval. The threshold value phi_65 is fixed, which represents an optimal threshold for detecting steam (U = 3700 mV after ADC in a range between 2800 ... 4100 mV). Depending on this threshold value an impulse-shaped measuring signal with binary character will be generated. It corresponds to respective phases which will be detected at the top of the NSP‘s.

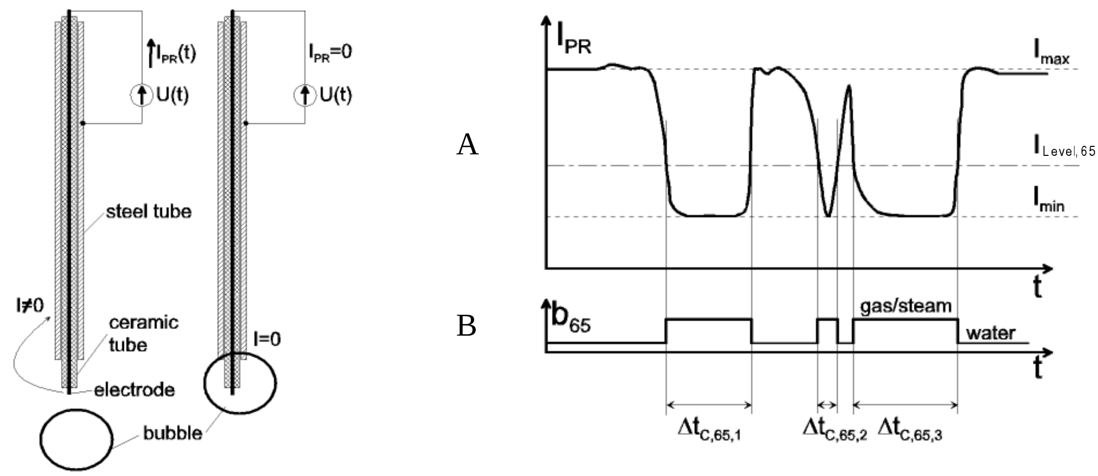

Fig. 4: Construction scheme and signal processing of needle-shaped probes [2]

A The analogous signal (signal of contact with steam bubble and probe top) will be formed in consequence of steam bubble deformation at the needle-shaped probe top. This signal is the basis for the digital signal.

B The binary signal is built on the basis of the threshold value phi_65. Above this threshold value steam will be assumed.

The application is possibly in transient (in this example) and stationary flows with a resolution of ca. 10^{-4} s. As the result a measuring signal by the post operating software module will be generated, which represents the local steam content. The influence of flow parameters may be lead to failures. That must be attend. The exact functionality of NSP is described in [1, 2, 3].

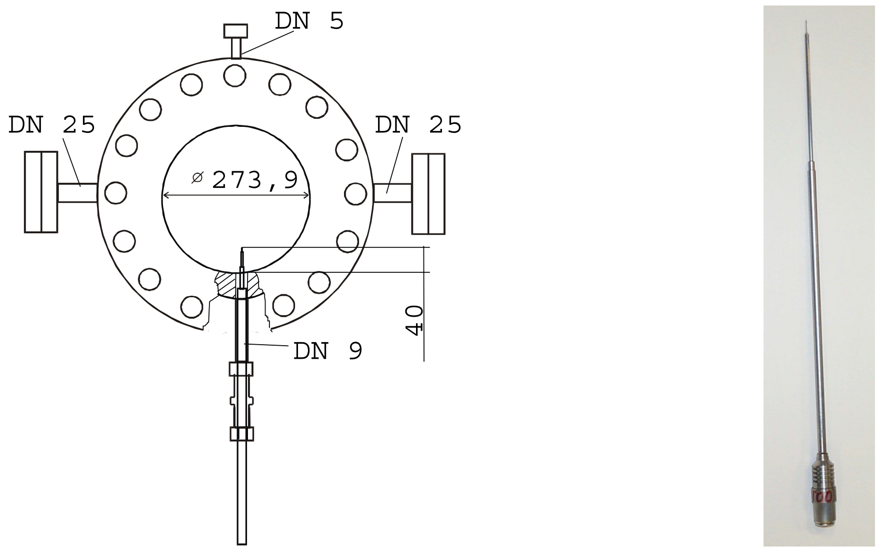

Fig. 5: Scheme of installation position of needle-shaped probes in the pressure vessel and a photo of it

Fig. 5 illustrates the installation position of the NSP‘s in the pressure vessel. The installation length amounts 40 mm within the vessel with an inner diameter of 273.9 mm. The diameter of probe top is 0.12 mm, and the length of contact is 0.3 mm.

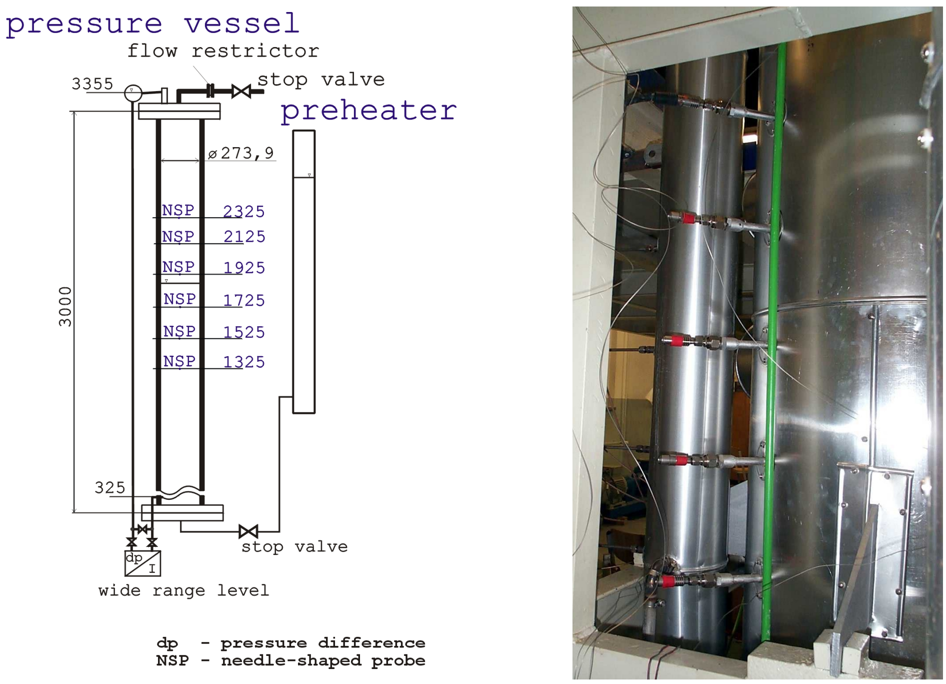

Fig. 6.: Principle scheme of test facility (pressure vessel and preheater) with axial distribution of NSP’s and its photo

The NSP‘s are configured in the pressure vessel orthogonal to the flow path every 200 mm within a height of most likely range of mixture level (Fig. 6).

3 ATHLET-Code calculation of mixture level

This part of contribution deals with the calculation of mixture level by ATHLET-Code. At first, it is necessary to predefine the nodes in the pressure vessel, considering the configuration of measuring instrumentation. The code subdivides every predefined node in two homogeneous volumes:

⇒ one volume for water phase (below the mixture level)

⇒ one volume for steam phase (above the mixture level)

In Fig. 7 the nodalization scheme of pressure vessel is illustrated. The number of nodes over the whole vessel height of 3000 mm is 23. It is necessary to predefine small nodes at the NSP-positions to reproduce local parameters, like steam content at every measuring point. So the ATHLET-Code generates a local steam content at the NSP-position, which is comparable with the measured one by NSP. Thus, an adaptation to real circumstances is considered.

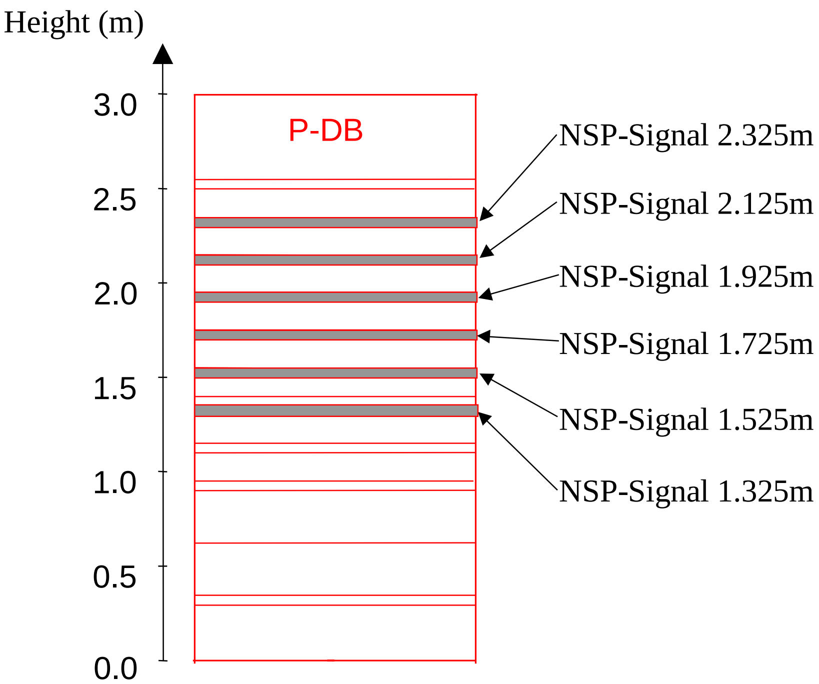

Fig. 7: Nodalization scheme of pressure vessel for ATHLET-Code

The next step is the calculation of mixture level height, which results from the volume-height-polygon formula corresponding to the volume below mixture level. That means, the water phase is the basis for the calculation of mixture level. The basic models for this are the lumped parameter models for different control volumes and flow track as well as drift flow models [5]. The specific characteristic of the ATHLET calculation is, that ATHLET assumes a plain surface of the mixture level without a foam zone in contrast to the experiment. The reality shows, that the surface of mixture level is moved and wavy with a foam zone in case of high transient evaporation process.

4 Evaluation of measured and calculated results

The following time responses of measured and calculated values will be compared for defined NSP-Position:

⇒ mixture level calculated by ATHLET (*ML-ATH*)

⇒ collapsed level calculated by ATHLET (*CL-ATH*) and measured by hydrostatic measuring system (*CL-EXP*)

⇒ local steam content measured by NSP (*PHI-65, PHI-65-MAV*)

⇒ local steam content calculated by ATHLET (*PHI-ATH*)

The PHI-65-MAV was built as moving average signal to reduce the stochastics of the needle-shaped probe signal.

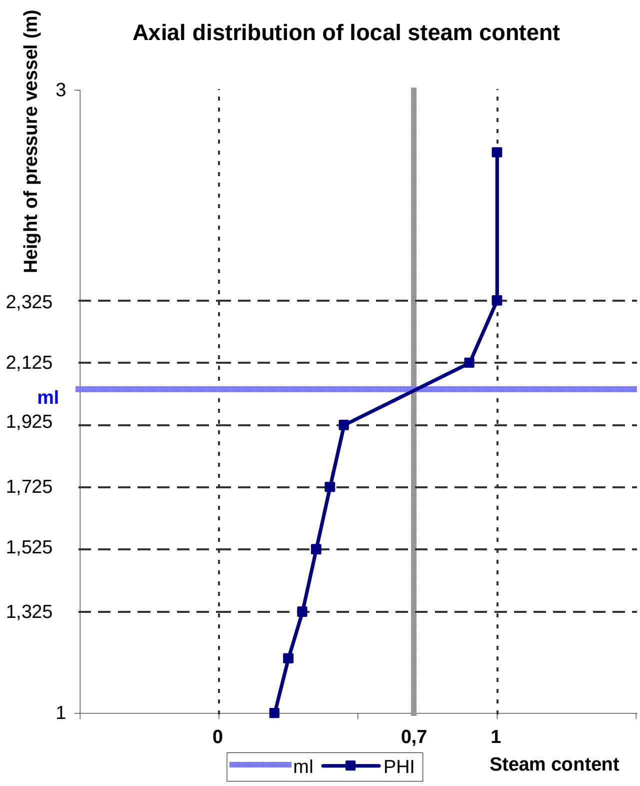

Fig. 8: Definition of mixture level depending on the axial distribution of local steam content

Fig . 8 illustrates the definition of mixture level depending on the axial distribution of local steam content. At the point, where the steam content crosses the value of PHI = 0.7 (70%), the mixture level was determined. The 70% value of steam content is the fixed threshold value, at which the experimental mixture level transfer is completed. So the 70% value signs a dominant phase changing. A continuous fluid phase does not longer there exists. It corresponds to the theoretical, by ATHLET-Code calculated steam content.

Fig. 9 shows the mixture level transfer calculated by ATHLET-Code and measured in experiment for the NSP-position 1.525 m. In the above part the water and mixture level response is illustrated. The part below includes steam content calculated by ATHLET-Code and measured by NSP. By the 70% value the intersection point with measured (by NSP) and calculated (by ATHLET-Code) local steam content is given.

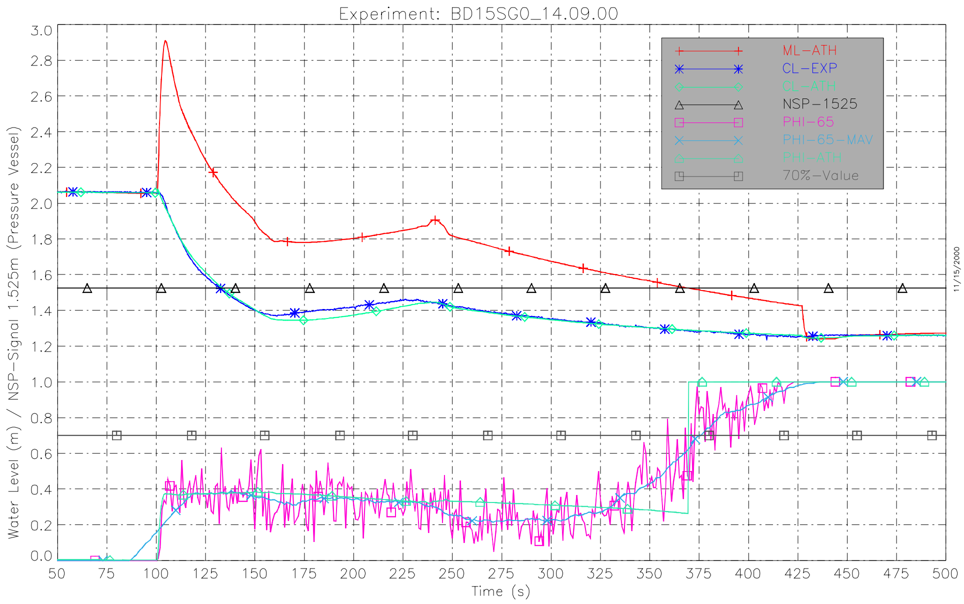

Fig. 9: Mixture level transfer given by time response of calculated mixture level (ATHLET-Code) and measured local steam content (experiment) NSP 1.525

The point of attention is the transfer region of mixture level, the differences between calculated and measured values. The theoretical, by ATHLET-Code calculated steam content, corresponds to the mixture level transfer. The difference between prompt jump of local steam content, calculated by ATHLET-Code and the gradual increasing of NSP-signal should be checked. The result of the investigation regarding the transfer region is, that the time difference between ATHLET-Code and NSP-signal is 5 s in maximum. This fact is very good to be seen in Fig. 10 with a zoom of the scale. There is drawn in a window of Δt_max = 5 s over the transfer region. It shows the time difference of calculated mixture level transfer (above) and measured steam content (PHI-65), which passes the 70% value (below). The blue curve (NSP-BIN) represents the impulse rate, which is a measured result of the NSP, too (middle). Within the window, the end of the continuous fluid phase is indicated. This is reflected also by the PHI-65 signal in the parameter range of 70% steam content value. That denotes a process of the mixture level transfer with a foam zone.

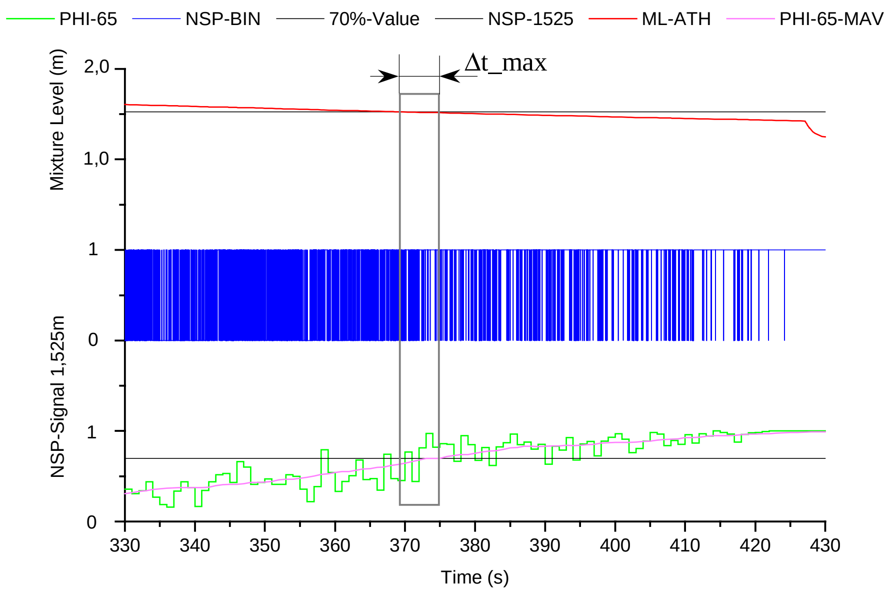

Fig. 10: Mixture level transfer and impulse rate (ATHLET-Code and experiment, NSP 1.525)

The equivalent results for NSP-Position 1.925 m are given in Fig. 11 and 12. There is reached a very good agreement between measured and calculated steam content at the local NSP-position, too.

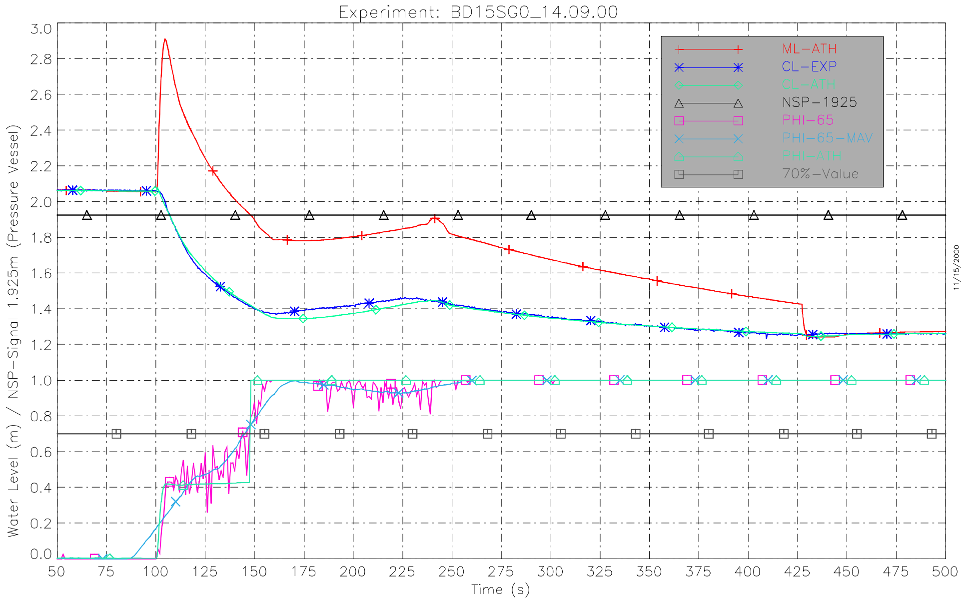

Fig. 11: Mixture level transfer given by time response of calculated mixture level (ATHLET-Code) and measured local steam content (experiment) NSP 1.925

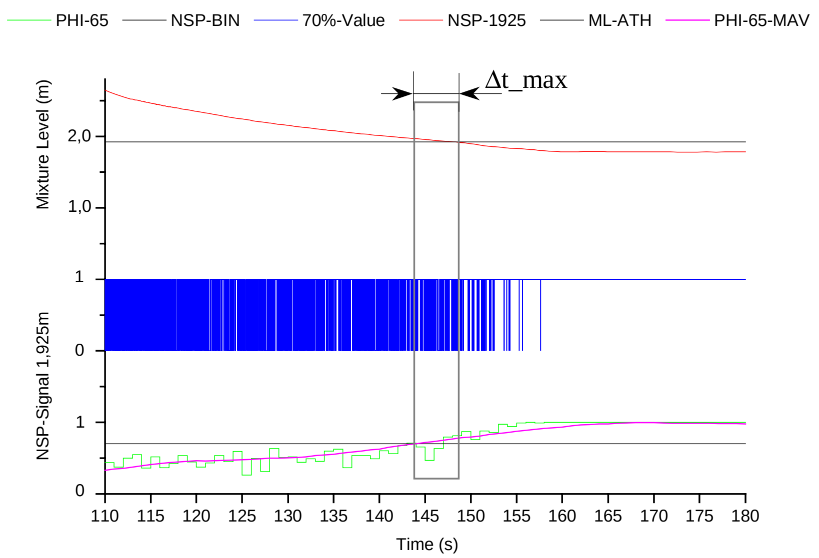

Fig. 12: Mixture level transfer and impulse rate (ATHLET-Code and experiment, NSP 1.925)

In Table 2 quantitative results of experiment and post-calculation are collected. For every NSP-position the time point of mixture level transfer will be confirmed. The formula for evaluating Δt_max is the following:

$$\Delta t\_max = PHI\_65\_MAV - PHI\_ATH \quad (1)$$

Equ. (1) determined the failure of mixture level between calculated and measured signals. The very good result, converted in deviation of mixture level height, is about 1 ... 8 cm. That is an absolute failure of 5% based on the difference of maximal increasing and final value of mixture level.

	PHI_ ATH (pass)	PHI_65 (pass)	PHI_65_ MAV (pass)	**Δt_max**	dml/dt (cm/s)
P1325	428 s	429 s	433 s	**5 s**	-7.7
Δml		8 cm			
P1525	370 s	373 s	375 s	**5 s**	-0.19
Δml		0.6 cm			
P1725	281 s	283 s	283 s	**2 s**	-0.33
Δml		0.7 cm			
P1925	148 s	148 s	145 s	**3 s**	-1.2
Δml		0 cm			
P2125	132 s	133 s	130 s	**2 s**	-1.5
Δml		1.5 cm			
P2325	122 s	124 s	120 s	**2 s**	-2.3
Δml		7 cm			

Table 2: Comparison of mixture level transfer for needle-shaped probe positions between experiment (PHI_65, PHI_65_MAV) and ATHLET-Code (PHI_ATH)

In Fig. 13 the mixture level transfer for all NSP-position (marked) in the pressure vessel is integrated. The NSP-signals are plotted for the parameter range 0 ... 1 at the NSP-position. The figure shows, that the good results corresponding to the mixture level transfer are valid for all needle-shaped probes at the 70% value.

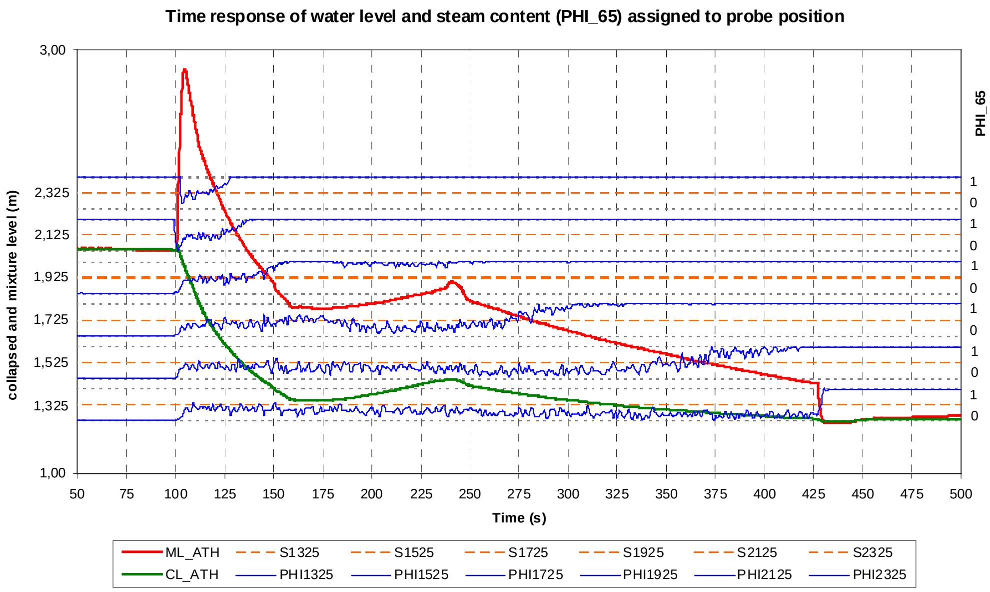

Fig.13: Mixture level transfer (ATHLET-Code and experiment) for all (6) needle-shaped probe positions in the pressure vessel

This fact will be pointed by the presentation in Fig. 14. Here is shown the axial distribution of local steam content in comparison to mixture level transfer at the needle-shaped probe positions scaled for defined points of investigation time. The slight curve of steam content is the measured value PHI-65, the thick one, PHI-ATH is the by ATHLET-Code calculated.

Especially the good correspondence between measured and calculated steam content and the change at the phase border (between 0 and 1) is demonstrated. For example at the time point t = 105 s, short after opening of leak, all NSP‘s are in the mixture (maximal increased value of mixture level). That means, during mixture level rapid increasing the measured and calculated result is an axial distribution of steam content with gradual increasing in the range of ca. 35-45%. The other axial distributions characterise the lay open of the NSP’s corresponding to the mixture level transfer.

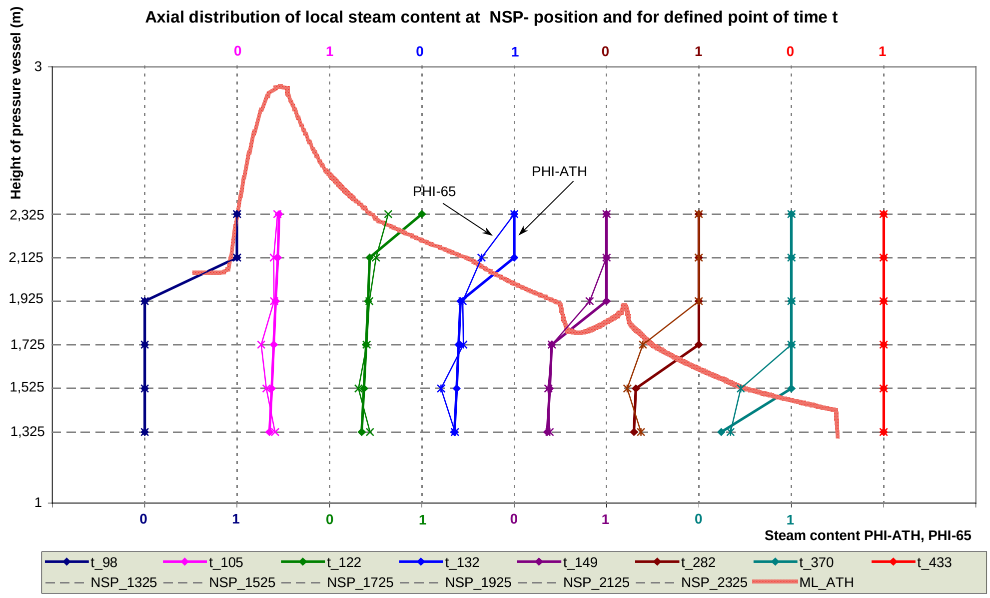

Fig. 14: Axial distribution of local steam content in comparison to mixture level transfer

In Fig. 15 the space curve of mixture level and the assignment of different phases of process state are described. The values absolute mixture level and its gradient are presented. It is to read off, with which gradient and which absolute height the mixture level passes the NSP-positions.

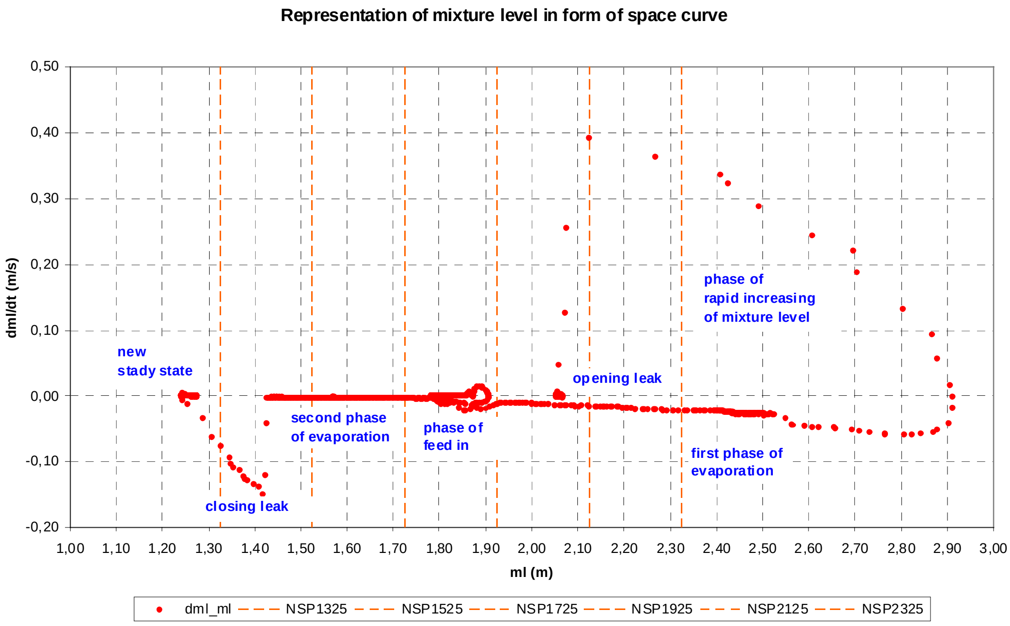

Fig. 15: Space curve of mixture level and assignment of different phases of process state

5 Conclusions

⇒ Needle-shaped probes are well qualified for

* detection of mixture level transfer,
* determination of local steam content.

⇒ A very good correspondence between local steam content calculated by ATHLET and determined by needle-shape probes was achieved.

⇒ Global parameter mixture level was verified by local values of steam content at NSP-positions.

⇒ The simulation program for thermal hydraulic processes in pressure vessels with water steam mixture (ATHLET-Code) was verified.

* That means a proof of iterative link of experiment and simulation.

⇒ Consequently it is possible to verify hydrostatic measuring systems.

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