The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-354

Measurement of two-phase flow parameters with multi-channel gamma densitometry and local void probes at the INKA test facility

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Abstract

At AREVA's integral test facility INKA, different passive safety systems of the generation III+ boiling water reactor KERENA™ are being tested. For the detailed analysis of condensation phenomena, an improved understanding and quantitative assessment of the occurring two-phase flow phenomena is essential. In this paper, we describe the special instrumentation of the INKA test facility with high-temperature high-pressure thermo needle probes and a special multi-channel gamma densitometer. The paper gives a short overview of the passive safety concept of the KERENA™ system, the fundamentals of the special instrumentation and discusses some experimental results from the INKA test facility in Karlstein.

1. Introduction

The KERENA™ boiling water reactor concept of AREVA NP combines a number of passive safety systems with common active safety systems of service-proven design. The goal is to control all anticipated accident scenarios by passive systems only. Therefore, the passive safety systems utilize basic physical laws such as gravity, pressure differences and natural convection to run automatically without any electrical power or action by instrumentation and control equipment [1]. Passive safety systems are of very high priority for nuclear safety research. Elements of the KERENA™ passive safety systems are: the emergency condenser (EC), the containment cooling condenser (CCC), the passive core flooding system and passive pressure pulse transmitter. An overview of the KERENA™ concept and the passive safety systems is given in Figure 1. At the integral test facility INKA at Karlstein in Germany all passive safety systems are tested and characterized separately as well as in integral operation for different scenarios under authentic operating conditions [2]. Since heat removal is essentially based on condensation heat transfer, various two-phase flow phenomena in the cooling circuits must be accounted for. Therefore, standard instrumentation, like thermocouples, pressure and filling level sensors, has to be complemented by special instrumentation for void fraction and phase-related temperature measurement as well as flow regime characterization. The Helmholtz-Zentrum Dresden-Rossendorf has developed special needle pin probes and a special multi-channel gamma-ray densitometer to measure the void fraction inside a single representative emergency condenser (EC) tube, in the condensate line of the EC as well as in the hot leg of the containment cooling condenser. For the exact balance and description of the thermal hydraulics in the emergency condenser and the containment cooling condenser, a detailed knowledge of the two-phase flow conditions in the pipes is essential. The data obtained by the special instrumentation help to describe the two-phase flow within the pressurized pipes and components under authentic operation.

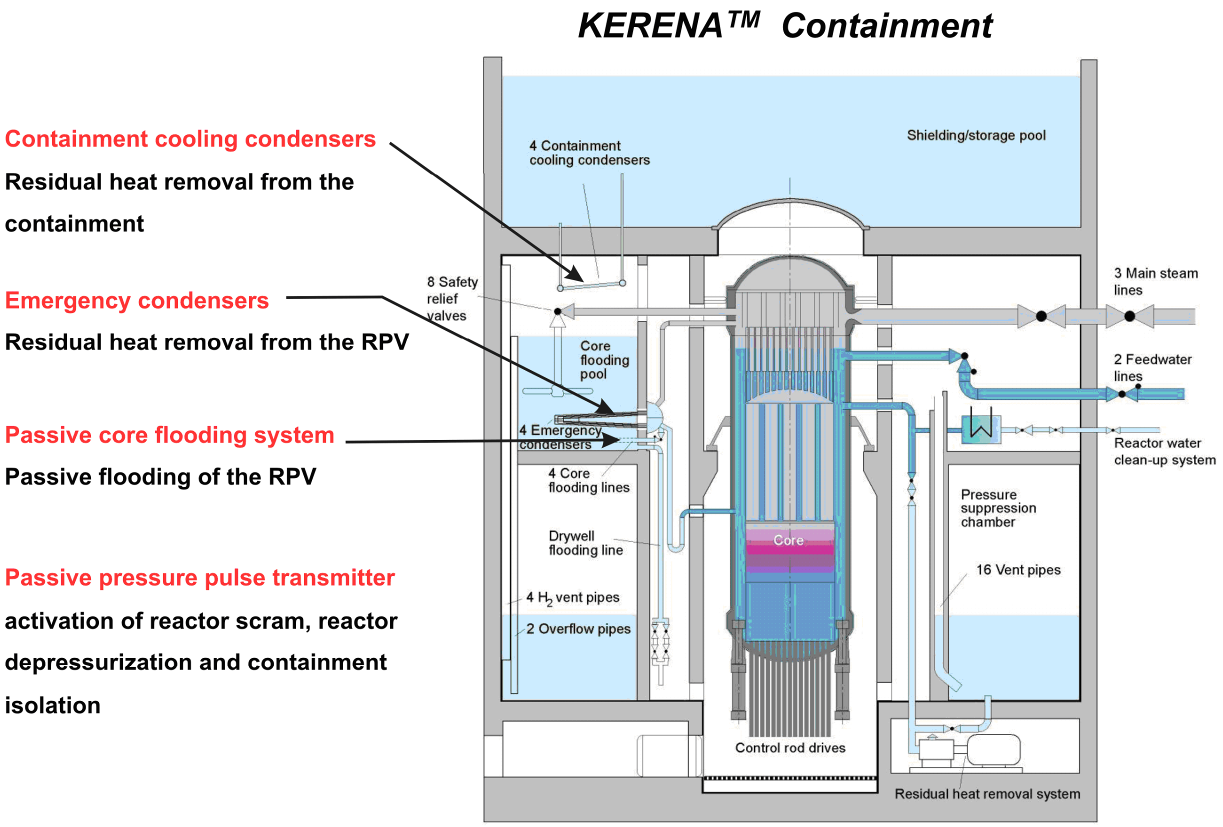


Figure 1 Schematic view of the passive safety system of KERENA™ . [1]

2. Multi-channel gamma-ray densitometer

2.1 Design and functional principle

The objective for the design of the multi-channel gamma-ray densitometer was the measurement of the void fraction in the DN200 condensate line of the emergency condenser and in the outlet pipe of the containment cooling condenser with a temporal resolution of 10 Hz and a void fraction accuracy of about 3%. Since the structure of the two-phase flow (bubbly, slug, annular, stratified) was not evident before the experiments, a single gamma-ray densitometer measurement along the vertical axis of the cross-section of the pipes was considered as being not sufficient for accurate measurements. On the other hand, a gamma-ray computed tomography setup like the ones proposed in [3] - [4] would have been over-engineered since only the mean cross-sectional void fraction is of interest. The design of the gamma-ray densitometer is shown in Figure 2. The radiation comes from an isotopic source (Cs^{137}, E_γ = 662 keV, 285 GBq) which is contained in a special isotopic source transport container with a handle for opening and closing by a Bowden cable. The source container is placed into a radiation collimator, which collimates the radiation to a fan beam towards the whole detector arc. The radition fan has a height of 10 mm. The detector arc comprises 34 single scintillation detectors operated in single photon counting mode. The detectors are distributed along a 50° arc with 700 mm radius. Each detector consists of a BGO scintillation crystal with an active area of $17 \times 17\ mm^2$ coupled to a photomultiplier tube (PMT). The charge signals generated by interacting gamma photons are amplified by transimpedance amplifier stages and are then subjected to proper pulse shaping and energy discrimination and counting. The energy discrimination stage allows to exclude scattered photon events from counting, which guarantees linearity of the attenuation measurement. A temperature control of the detector arc was implemented to guarantee a drift-free operation for varying ambient temperatures. This is necessary to achieve superior measuring accuracy in an outside environment with varying climatic conditions and varying heat emissions from the facility itself. The detector data are transferred to the data acquisition computer by use of an Ethernet connection with special data acquisition software.

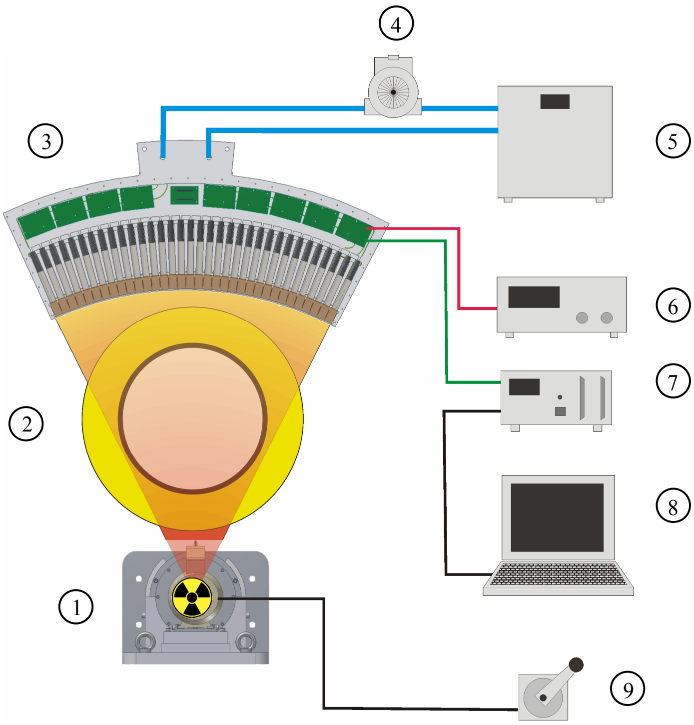


Figure 2 Schematic design of the multi-channel gamma-ray densitometer: 1) collimator with isotopic source, 2) object (pipe), 3) detector arc, 4) pump, 5) water cooling unit, 6) high voltage supply, 7) digital electronics, 8) data acquisition computer, 9) handle for opening and closing the isotopic source.

2.2 Data processing for the multi-channel gamma-ray densitometer

To calculate the cross-sectional void fraction from the measured count rates, two different methods based on different flow structure assumptions were implemented. For a single radiation beam between the source and one detector, the radiation attenuation E is defined as the negative natural logarithm of the ratio of the radiation intensity after (I) and before (I_0) the object (Figure 3, left). Here intensity I is equal to the count rate $\dot{N}$, that is

$$E = -\log \frac{\dot{N}}{\dot{N}_0} . \tag{1}$$

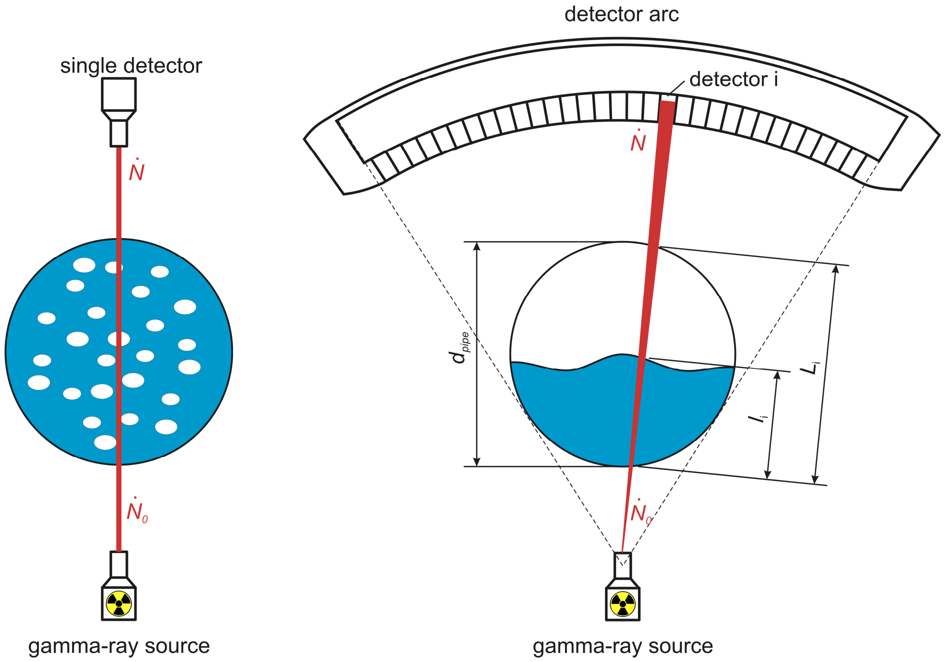


Figure 3 Measurement of the radiation attenuation for a single gamma-ray densitometer for bubbly flow (left) and stratified flow conditions with a detector arc (middle) and detail of geometric dependencies for the multi-channel gamma-ray densitometer (right).

If steam and water are equally distributed in the cross-section, e.g. in disperse bubbly flow, the actual void fraction α for a single beam can be derived easily from the measured extinction E and two calibration measurements $E^{(w)}$ at 100% water and $E^{(s)}$ 100% steam (empty pipe), as

$$\alpha = 1 - \frac{E - E^{(s)}}{E^{(w)} - E^{(s)}} . \tag{2}$$

For a homogeneous gas distribution in the liquid, this value is representative for the complete pipe cross-section if the radiation beam is nearly parallel. In case of stratified flows, things become more complicated since the real ray geometry as well as the gas-liquid distribution have to be taken into account (Figure 3, right). Thus, for a stratified flow, equation 2 would result in an error since the real covered area by water in the pipe is a segment of a circle and therefore the ratio of the path lengths of the beam trough water and the chord length of the beam in the pipe is not the same as the ratio of the areas covered by steam and water. To calculate the real void fraction, these areas filled by water and steam have to be calculated.

Denoting $\dot{N}_i^{(s)}$ as the count rate of the ray to detector i for the steam filled pipe, $\dot{N}_i^{(w)}$, as the count rate for the completely water filled pipe and $\dot{N}_i$ as the count rate for a partially filled pipe it follows that

$$\frac{\dot{N}_i}{\dot{N}_i^{(w)}} = exp\left(\mu_{H_2O} l_i\right) \tag{3}$$

and

$$\frac{\dot{N}_i^{(s)}}{\dot{N}_i^{(w)}} = exp\left(\mu_{H_2O} L_i\right). \tag{4}$$

Hereby, μ_{H_2O} is the linear attenuation coefficient of water, l_i the path length of the ray i in water for the partially filled pipe and L_i the geometrical path length of the ray i in the pipe (the chord length). With (3) and (4) the filling level l_i can be calculated by

$$l_i = \frac{1}{\mu_{H_2O}} \log\left(\frac{\dot{N}_i}{\dot{N}_i^{(w)}}\right) = L_i \frac{\log\left(\dot{N}_i / \dot{N}_i^{(w)}\right)}{\log\left(\dot{N}_i^{(s)} / \dot{N}_i^{(w)}\right)} \tag{5}$$

If μ_{H2O} was known a priori, only one calibration measurement with water filled pipe is required. However, a dual calibration measurement serves to determine this value or to eliminate it respectively, as can be seen from (5). Moreover it is necessary to account for the temperature dependence $\mu_{H2O} \sim \rho(T)$ by appropriate corrections. Having obtained the path lengths l_i for all detectors the interfacial area for the stratified flow can be calculated and the overall average void fraction computed from the integral area $A^{(w)}$ under the interface and then the void fraction from

$$\alpha = 1 - \frac{A^{(w)}}{0.25 \cdot \pi \cdot d_{pipe}}. \tag{6}$$

In practice, a selection must be made whether to use the disperse or the stratified flow model for void fraction calculation. By visualization of the filling level within the data processing software, one can clearly see if the stratified flow model produces unrealistic water distributions. Then selection of the dispersed bubbly flow model is necessary.

2.3 Experimental validation and measurement accuracy

Before using the gamma-ray densitometer at the INKA test facility, several experiments have been performed to validate the measurement accuracy. At first, the long term stability was assessed by measuring attenuation profiles over a four hours period with integration time of 140 s per sample. The count number was approximately 350,000 per interval in all detectors. No significant drift of the count rates has been detected. The root mean square deviation over the whole measurement time was less than 0.3% for all detectors. To determine the over all accuracy of the void fraction measurement, a special experiment with a model for a partially filled pipe has been performed. The pipe mock-up has an inner diameter of 300 mm and had two compartments separated by a buckled wall (see Figure 4). After two calibration measurements with completely empty and filled mock-up, the larger compartment was filled with water. Figure 4, right, shows the reconstructed interface. A void fraction value of α = 21% was calculated compared to a theoretical value of 21.4%, which is 0.5% accurate.

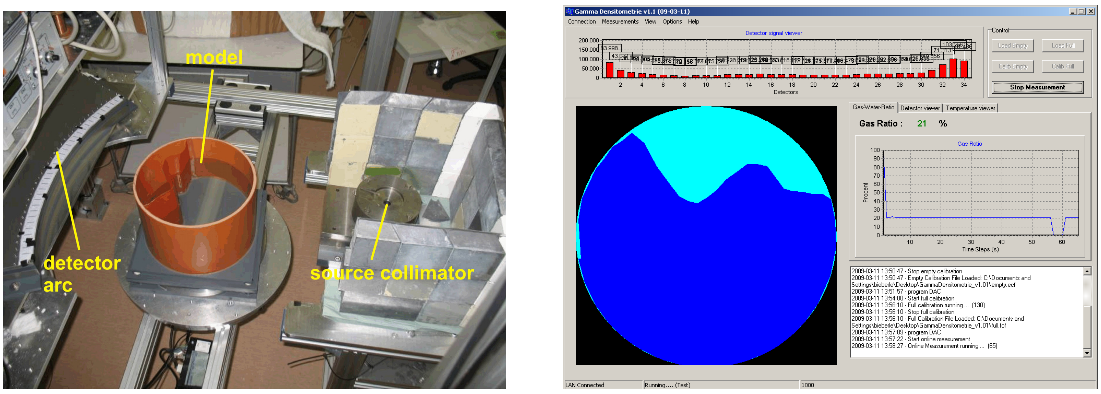


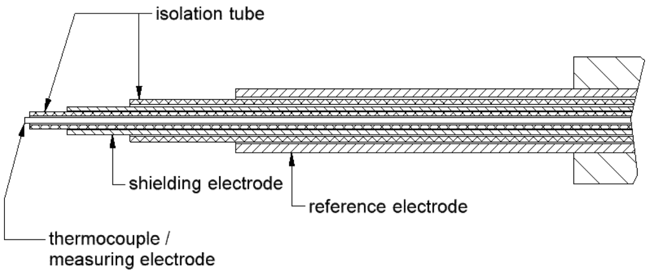
Figure 4 Experimental setup for partially filled pipe (left) and visualization in the user software (right). The setup was horizontal for radiation safety reasons.

3. Needle probes for local void fraction measurement

For the measurement of local void fractions in two-phase flow scenarios, pin or needle probes are commonly used. Such probes typically distinguish phases via some characteristic physical parameter, such as electrical conductivity or impedance or light refractive index [6] - [8]. Often such probes can only discriminate between two different phases. In the past, advanced needle probes with integrated micro-thermocouples have been introduced by Prasser et al. [9], [10]. Such probes can measure local temperatures along with void fractions at the tip. In these probes micro sheath thermocouples are used whose sheaths serves as the measuring electrode for electrical conductivity measurement. The small thermocouples allow a fast temperature measurement such that temperature can be associated with the present phase. With direct sheathed thermocouples of 150 µm outer diameter, time constants of about 4 ms have been achieved. This enables to differentiate steam from non-condensable gases in highly transient steam-water flow [11]. Applying such probes in the emergency condenser tubes thus helps to detect phase change, bubbles and the presence of non-condensable gases, which can diminish or even suppress condensation because of their higher density compared to steam.

3.1 Design and functional principle

The needle probe system used for these investigations consists of 9 needle probes distributed along one pipe of the emergency condenser inside the core flooding pool vessel and two probes outside the pool, one in the standpipe and one in the return line of the EC. The needle probes have been designed for fast local measurement of void fraction and temperature for primary side process conditions of up to 310 °C and 90 bar.



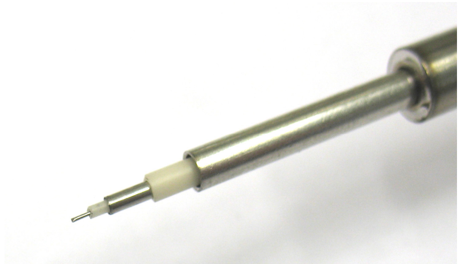
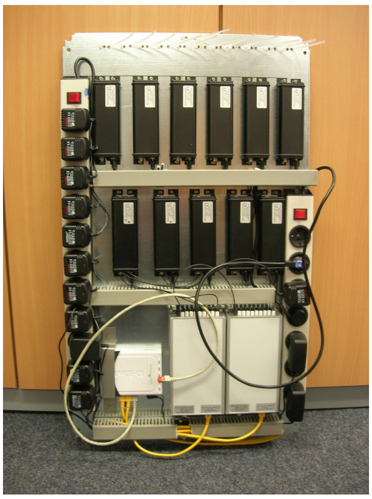


Figure 5 Basic design the tri-axial needle probe structure (left) and photograph of the probe tip (right).

For the EC tube probes which are inside the pool flooding vessel, a challenging special design was required, which accounts for the fact that the probe tails (secondary side) are submerged in a 150 °C water pool at up to 4 bar pressure. Additionally, the probes are subjected to heavy vibrations of up to ±4 g and frequencies in the range of some kHz occurring in the EC during condensation. Features of the probes are a rigid body design using high-performance polymer insulators in a tri-axial electrode structure and water-tight cable connections with 12 m cables to the electronics outside the pool flooding vessel. Still some problems were experienced with the long term stability of the small thermocouples under these extreme conditions. Therefore, some of the probes have been only realized as conductivity probes without thermocouples so far.

Conductivity signals are sampled with 10 kHz and the temperature signals with 1 kHz respectively by a special data acquisition electronics. The data are transferred by this data acquisition system to a PC via an Ethernet connection. The electronic system and a single probe are shown in Figure 6.



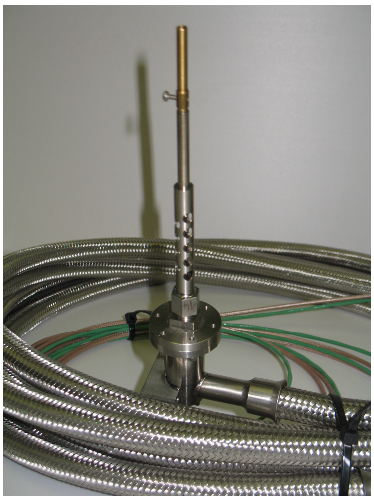


Figure 6 Thermo needle probe electronics (left) and single probe for the emergency condenser (right).

3.2 Needle probe data processing

After measurements are completed, the recorded probe data can be loaded to the data evaluation software package “Void Wizard”. The software first allows the visualization of the conductivity raw data. Advanced zoom and scroll functions as well as additional information (gas and liquid level, averaged values etc.) facilitate the raw data assessment. The data processing routines first search for global and local signal maxima and minima of the conductivity signal C in user specified time steps. Thereby the signal levels for water C_{water} and gas phase C_{gas} are obtained. Fixed global levels are not useful since liquid conductivity changes over the temperature range. Liquid and gas levels can be manually adjusted to prevent wrong calculations due to measurement artefacts. From these two levels, a threshold level L_{35} (35% void) is derived to obtain binary information of the two phase flow. If the signal level is below this threshold level of 65% of the total signal amplitude, it is assumed that probe tip is covered by gas phase.

$$L_{35} = C_{water} - 0.35 \cdot \left(C_{water} - C_{gas} \right) \tag{7}$$

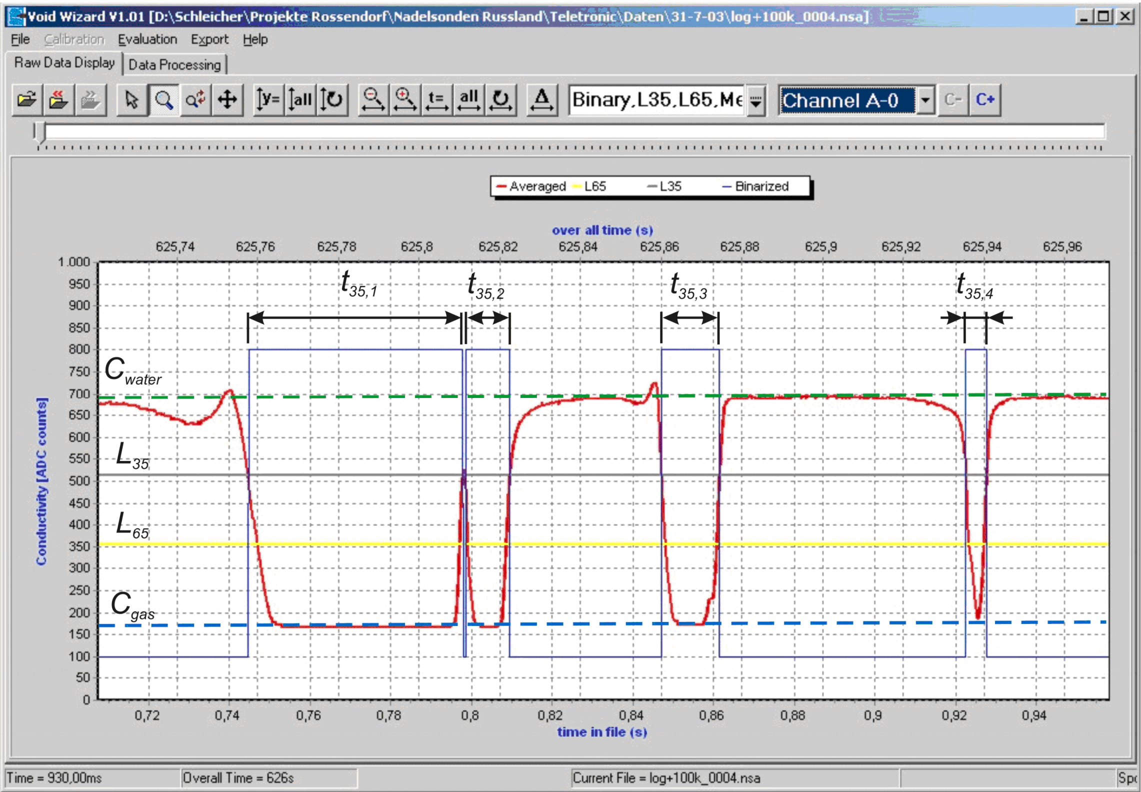


Figure 7 View of the user interface of the needle probe data processing software “Void Wizard” with an exemplary data set. The view illustrates the data binarization procedure.

The local void fraction can be derived as the ratio of summarized time intervals while the probe tip is in gas phase t_{35} and the total evaluation period t_{meas}. This period is set as default to one second, that means, 10,000 single measurement points.

$$\alpha_{35} = \frac{\sum_i t_{35,i}}{t_{meas}} = \frac{t_{35}}{t_{meas}} . \tag{8}$$

This single level method is used if the transimpedance amplifier is in logarithmic mode. In linear operation, a second threshold level L_{65} can be derived for 35% of the liquid signal level.

$$L_{65} = C_{water} - 0.65 \cdot \left(C_{water} - C_{gas} \right) . \tag{9}$$

This additional level can be used for bubble detection. In this operation, a bubble is only detected if the conductivity level becomes less than L_{65} and rises above L_{35} afterwards. Therefore, the bubble detection algorithm works like a Schmitt trigger by adding a hysteresis to the phase discrimination algorithm. Additional to the determination of time-averaged local void fractions, information about each individual phase change is stored. So also bubble number and bubble lengths can be calculated. The results of the data evaluation are stored into text files with data header for further utilization with standard software tools like Matlab® or EXCEL.

4. Experimental results

The complete instrumentation with needle probes and gamma-ray densitometer has already been used in a number of experiments for the characterization of capability of the emergency condenser to remove decay heat from the reactor. Exemplarily, one transient experiment with an initial pressure of 85 bar is presented in Figure 8. Before start of the experiment, the filling level of the stand pipe was reduced. The experiment was initiated by opening the valve in the condensate line of the EC. The water flowed towards the stand line and steam flowed into the EC. Immediately, the void probes showed gas in the EC pipe one after another. During the experiment, the pressure reduced from 85 bar to about 20 bar and the filling level in the standpipe increased due to the condensate reflow. After a period of about 7 minutes, the amount of condensate inside the EC pipes reached the probe positions and one probe after another showed the water level increase. The temperature in the steam line decreased from nearly 300 °C to about 220 °C.

These experiments were performed with completely degassed water and without thermocouples in the probe tips due to the above mentioned problems. Earlier experiments with complete thermo needle probe instrumentation under the presence of non-condensable gases have shown the capability of the thermo needle probes to detect non-condensable gases. Fig. 9 shows the results for probe "α_EC_1" in the emergency condenser. The experiment was started at 30 bar pressure. From the raw signals for temperature and conductivity, the void fraction and the phase temperatures for gas and fluid phase have been derived. The plot clearly reveals the occurrence of non-condensable gases at probes where the gas temperature (at 100% void) does not follow the saturation line. Moreover, the diagram also shows the strong dependency of the conductivity signal on the temperature of the fluid.

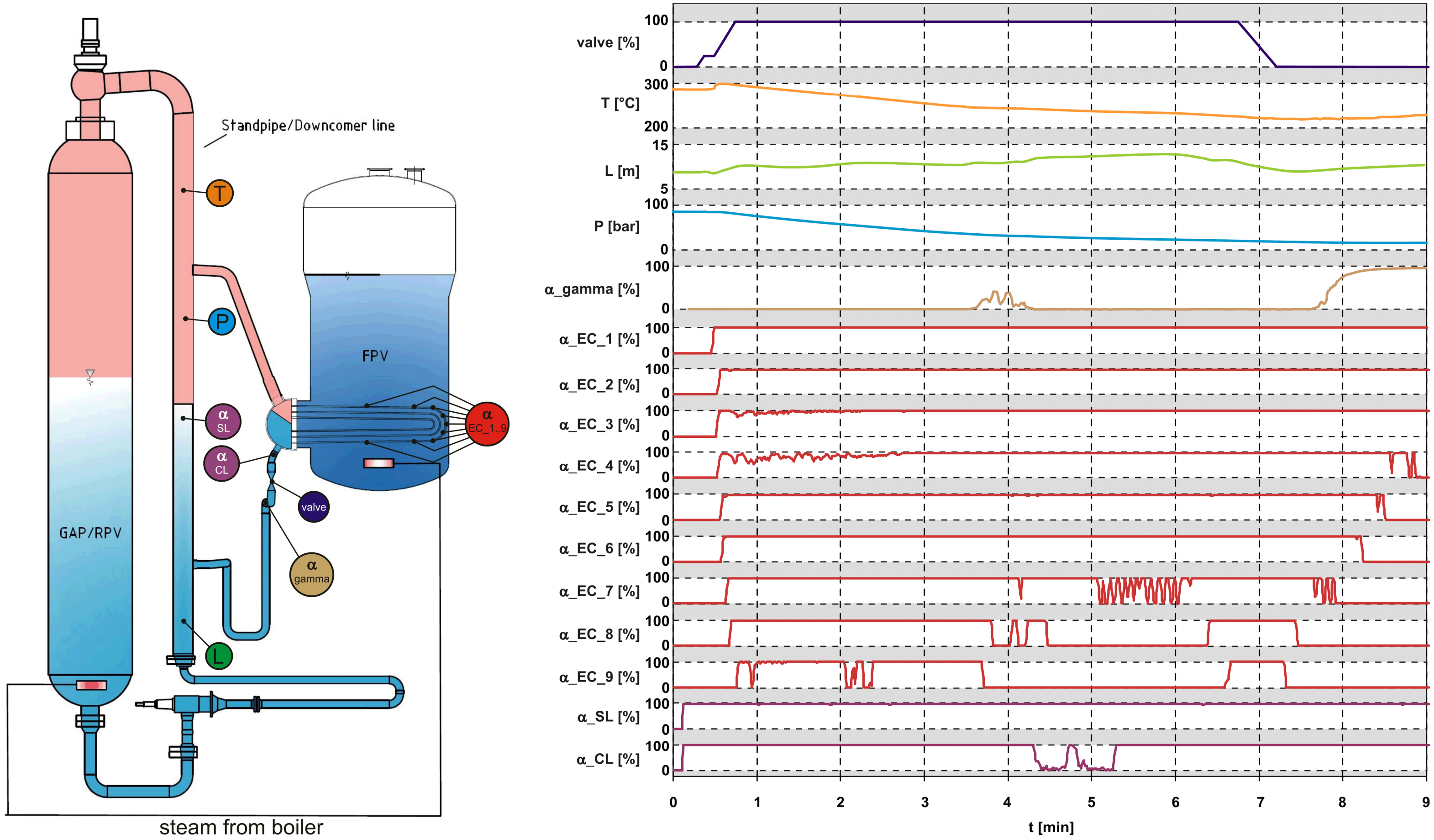


Figure 8 Measurement results for a transient experiment starting at 85 bar pressure. The graphs show the signals of the needle probes inside and outside the EC, the gamma-ray densitometer void data as well as temperature, filling level and pressure in the standpipe. The experiment was performed by lowering the filling level in the stand pipe and opening the valve in the condensate line of the emergency condenser.

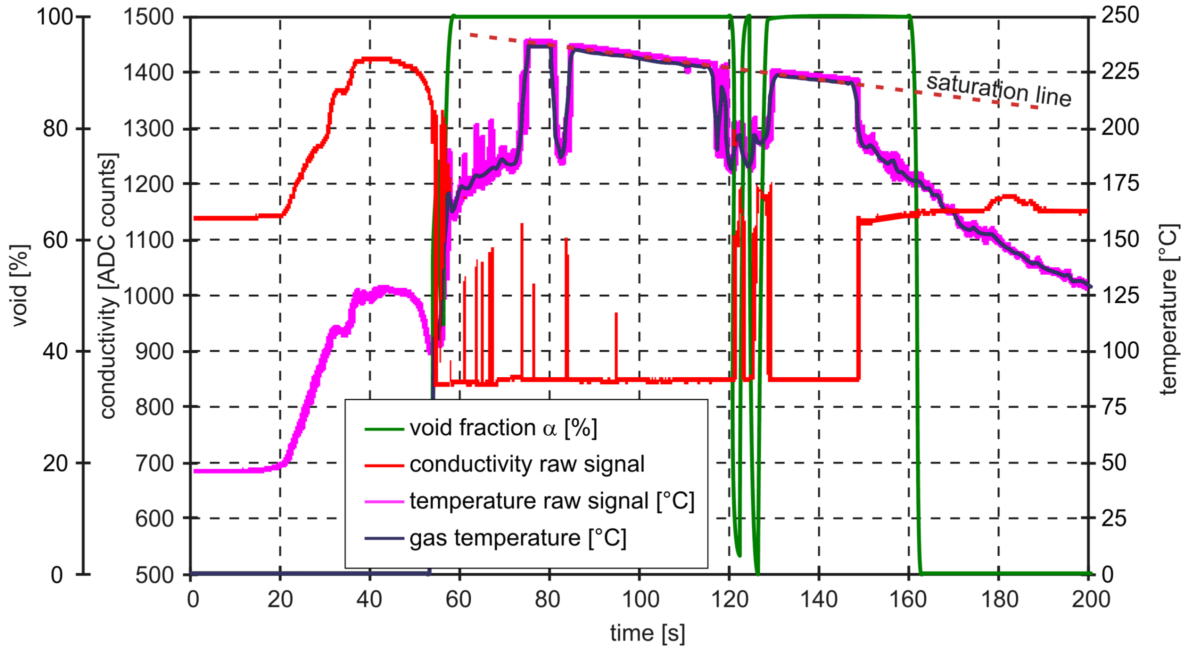


Figure 9 EC experiment with 30 bar initial conditions. While the magenta coloured line shows the mean temperature without respect to the phase, the dark blue line shows the gas temperature only. Gas temperatures below the saturation line represent non-condensable gases, since steam would condense below that temperature.

5. Conclusion

We introduced and discussed the design and application of special two-phase flow instrumentation for the integral test facility INKA at AREVA NP GmbH in Karlstein, Germany. A needle probe system and a multi-channel gamma-ray densitometer was used to obtain additional information on void fraction distributions during the validation experiments for the passive safety systems of the boiling water reactor concept KERENA™. The needle probes have been proven to work under severe conditions, that is, at up to 310 °C and 90 bar on the primary side of the EC and 150 °C and 4 bar on the secondary side. The use of the filigree 250 microns micro-sheath thermocouples as the measuring electrode has turned out to be a challenging problem with respect to long-term stability of the temperature measuring function. The multi-channel gamma-ray densitometer was installed for average void-fraction measurement in larger connecting pipes of the facility. Special algorithms allow to distinguish between disperse bubbly flow and stratified flow conditions, which is important to have reliable void fraction values. In the near future, the thermo needle probe design will be changed for 0.5 mm micro-thermocouples to improve long-term stability.

6. References

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