# INVESTIGATION OF MULTIDIMENSIONAL FLOW MIXING PHENOMENA IN THE REACTOR PRESSURE VESSEL WITH THE SYSTEM CODE ATHLET

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**ABSTRACT**

Loss-of-coolant accidents in light water reactors can induce under certain conditions, depending on the location and the size of the leak, complex phenomena such as the pressurized thermal shock or the boron dilution processes. The realistic numerical prediction of these transients including the highly complex, three-dimensional flow mixing phenomena occurring in the reactor pressure vessel is an important topic in reactor safety. The German thermal-hydraulic system code ATHLET (Analysis of Thermal-hydraulics of Leaks and Transients) is being continuously developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) for the analysis of operational transients and accidents anticipated for nuclear energy facilities. The code's one-dimensional six-equation two-fluid model is being extended towards a fully multidimensional set of thermal-hydraulic conservation equations. The capability of ATHLET to model multidimensional coolant mixing behavior in the reactor pressure vessel has been analyzed and validated against the experimental data from the Rossendorf Coolant Mixing (ROCOM) test facility, which replicates the reactor pressure vessel of a German KONVOI-type pressurized water reactor with a scale of 1:5. The chosen experiment was dedicated to the fast cool-down transient induced by a main steam line break. Two different ATHLET models for the representation of the lower plenum of the test facility were employed, adopting different grid discretization and balance equation systems, namely one-dimensional or multidimensional respectively. In general the results of the computer simulations show a good agreement compared to the experimental data. Furthermore the presented analyses highlight the advantages of ATHLET's newly developed multidimensional model for the computer simulation of flow mixing processes especially in the reactor pressure vessel.

**KEYWORDS**
Thermal-mixing, multidimensional system code simulation, fast cool-down transient, ATHLET

## 1. INTRODUCTION

The realistic computer simulation of complex, three-dimensional transient flow processes in the cooling circuit of a Light Water Reactors (LWR) during operational transients and accidents is an important topic in reactor safety assessments. The assumption of a full degree of fluid mixing due to emergency coolant injection, with different temperatures and mass flows, within the components of the cooling circuit of a LWR can lead to non-conservative results in several safety assessment cases. For instance the accurate knowledge of the three-dimensional distribution and the degree of mixing of the colder liquid injected from one of the Pressurized Water Reactor (PWR) primary loops during a loss-of-coolant accident, are crucial to the investigations of Pressurized Thermal Shock (PTS) or boron dilution processes in the Reactor Pressure Vessel (RPV). Both Computational Fluid Dynamics (CFD) tools as well as system analysis codes, such as ATHLET, are used to model these transients.

CFD codes are capable of accurately representing the mixing processes with the cost of a large required computing power to simulate long-term transients. Detailed CFD investigations of mixing processes within the RPV of a PWR are described in Schaffrath et al. [4] and Herb [2]. On the other hand system codes are still extensively used for thermal-hydraulic computer simulations of complex system set-ups by employing relatively coarse numerical grids. As a result these codes require less computing resources compared to the CFD tools, while offering a wide range of dedicated single- and multiphase models. These modelling approaches are capable to solve the main mixing flow and provide acceptable results compared to CFD codes. Some of the system codes provide also the possibility to use simplified multidimensional approaches. Such approaches broaden the application spectrum of system codes to calculate three-dimensional mixing processes. Some examples of mixing flow calculations with multidimensional system codes are described in Glantz and Freitas [3].

The German thermal-hydraulic system code ATHLET is being developed by the GRS for the analysis of the whole spectrum of operational transients, design-basis accidents and beyond design-basis accidents, without core degradation, anticipated in nuclear energy facilities. The code provides a wide range of specific models for the computer simulation of LWR of both western and Russian (VVER, RBMK) designs, of advanced Generation III, III+ and IV nuclear power plants as well as of Small Modular Reactor concepts. For the calculation of the multiphysical phenomena involved in the operation of nuclear reactors, the code is composed of several basic modules: (1) a thermo-fluiddynamic module, (2) a heat conduction and heat transfer module, (3) a neutron kinetics module, (4) a general control and balance-of-plant simulation module, and (5) the general-purpose sparse-matrix solver FEBE [5]. The thermal-hydraulics module is based on a two-fluid model with fully separated balance equations for liquid and vapour. Alternatively, a five equation model with a mixture momentum equation and a full range of drift-flux formulation for the calculation of the relative velocity between phases is also available. Additionally, various non-condensable gases and a boron tracking model are available in the system analysis code together with specific models for pumps, valves, steam separators, turbines or compressors. To extend the existing simplified multidimensional so-called parallel channel approach of ATHLET, the one-dimensional six-equation two-fluid model is being enhanced with a fully three-dimensional set of thermal-hydraulic conservation equations. The capability of the new model is assessed against measurement data of the Test 2.1 performed at the ROssendorf Coolant Mixing (ROCOM) integral test facility. Test 2.1 investigates fluid mixing processes in the Downcomer (DC) and Lower Plenum (LP) following a main steam line break.

## 2. DESCPRITION OF THE ROCOM EXPERIMENT

The four-loop integral test facility ROCOM replicates with a scale of 1:5 the cold legs, the DC and the LP of the primary circuit of a German KONVOI-type PWR. Each of the loops includes a pump to adjust the coolant mass flow. The test facility was constructed to provide a validation basis focusing on mixing processes for multidimensional computer codes, such as CFD and system codes [1].
The experiments are carried out with water at atmospheric pressure and room temperature. The temperature difference between the primary coolant and the emergency core coolant is represented through a density difference reached by means of added sugar solution. The mixing behavior is measured exploiting the local electrical conductivity of the fluid. Additives such as salt or brine tracer are used to label the water and subsequently study its distribution within the system. This is monitored by the specially designed electrical conductivity Wire Mesh Sensors (WMS) which provide high-resolution measurements of the tracer concentration both in space and time [6], [7]. WMS are installed at the RPV inlets, at two concentrical layers close to the inner and outer DC wall, stretched along nearly the entire length of the DC, and at the Core Inlet (CI). Figure 1 shows the RPV model of the ROCOM facility and the locations of the installed WMS. The geometry of the core and the upper plenum is simplified within the ROCOM facility and considered only by means of its hydraulic resistance. The core contains 193 rod

correspondents simulating the 193 fuel assembly of the KONVOI reactor. Each of the core channels is equipped with one WMS at the CI, integrated into the lower core support plate. The DC wire mesh sensors are subdivided into 64 azimuthal and 29 (outer sensor) or 15 (inner sensor) axial measuring planes.

The linear scaling factor of 1:5 corresponds to a volume ratio of 1:125 between the ROCOM facility and the primary coolant circuit of the original PWR. Additional to the geometrical similarity also the dynamical similarity must be fulfilled in order to replicate the buoyant and turbulent flow processes. Therefore dimensionless similarity based on the Reynolds, Strouhal and Froude numbers must be complied with. The three dimensionless numbers are defined in Equation 1.

$$Re = \frac{L\,w}{\nu}\ ; \qquad Sr = \frac{L}{w\,\tau}\ ; \qquad Fr = \sqrt{\frac{\rho\,w^2}{\Delta\rho\,g\,L}} \tag{1}$$

In equation (1) $L$ represents the characteristic length, $w$ the velocity, $\nu$ the kinematic viscosity, $\tau$ the characteristic time, $\rho$ the density and $g$ the gravitational acceleration. In the particular experimental scenario, however, since the density difference is the driving force for the natural circulation phenomena, the similarity based on the Froude number had to be fulfilled. This imposed a velocity scaling factor of $\sqrt{5}$ for the ROCOM experiment 2.1.

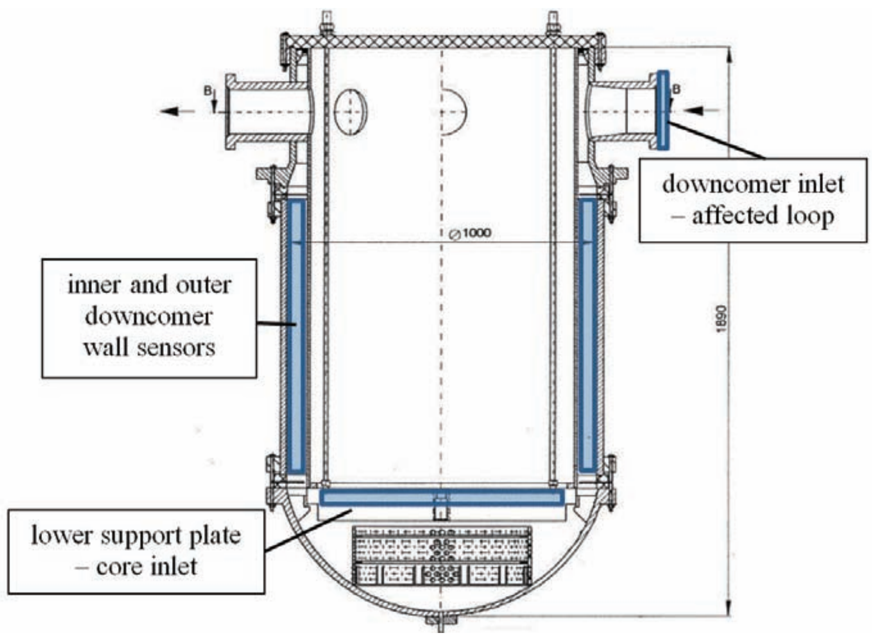


**Figure 1. RPV of the ROCOM facility with the installed WMS [1].**

The ROCOM experiment 2.1 was carried out as a counterpart test in the frame of the OECD PKL-2 project, dedicated to the fast cool-down transient induced by a main steam line break. The experiment scenario can be divided in two main phases. The first phase starts immediately after the main steam line break on the secondary side, resulting in an increase of the heat transfer due to the enhanced evaporation in one Steam Generator (SG) following the pressure decrease. As a result the corresponding primary loop is strongly affected. This first phase lasts until the entire fluid inventory of the affected SG evaporates. The first phase is also called the cool-down phase of the primary coolant. The second phase on the other hand is characterized by the activation of the Emergency Core Cooling (ECC) system, which injects cold and highly borated water into the cold legs. The over-cooling phase can for example trigger a recriticality processes due to boron dilution while the ECC injection in the second phase can lead to a PTS phenomenon.

**Table I. Initial and boundary conditions of the ROCOM experiment 2.1**

| **Cooling Circuit Loop** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Normalized volume flow rate, [-] (nominal value: 185 $m^3$/h) | 10.2 | 4.8 | 4.8 | 4.8 |
| Volumetric flow rate, [l/s] | 5.24 | 2.47 | 2.47 | 2.47 |
| Relative density, [-] | 1.067 | 1.00 | 1.00 | 1.00 |
| Temperature, [˚C] | 199.3 | 241 | 241 | 241 |
| **Experimental procedure** | | | | |
| **Time** | **Experiment log** | | | |
| Experiment preparation | Preparation of the water/sugar solution with the desired density value; Labelling of the water with salt | | | |
| t = - 30 s | Stationary flow conditions in loops 2, 3, 4 established | | | |
| t = 0 s | Start of injection of the water with the higher density into the loop 1 | | | |
| t = 150 s | End of injection | | | |

The ROCOM experiment 2.1 was dedicated to the over-cooling phase. Constant Boundary Conditions (BC) of the quasi-stationary experiment were fixed based on the results of the G3.1 PKL-2 experiment. A summary of the initial and BC are summarized in Table I.

The leak was postulated during the Test 2.1 in the steam line of the steam generator of loop 1. The over-cooled fluid with the increased density was therefore modelled in this loop. A necessary amount of sugar was diluted into the RPV injected water to achieve the density difference measured during the PKL experiment since the ROCOM experiments were conducted with water at room temperature. Loop 1 was plugged behind the main coolant pump. The fluid mass flow rate with the appropriate density ("over-cooled fluid") was directly pushed into the cold leg of the Affected Loop (AL), between the main pump and the DC inlet (see Figure 2). The injected water mass was consistently discharged from the corresponding hot leg during the experiment. In the other three loops the fluid was circulated with the main coolant pumps.

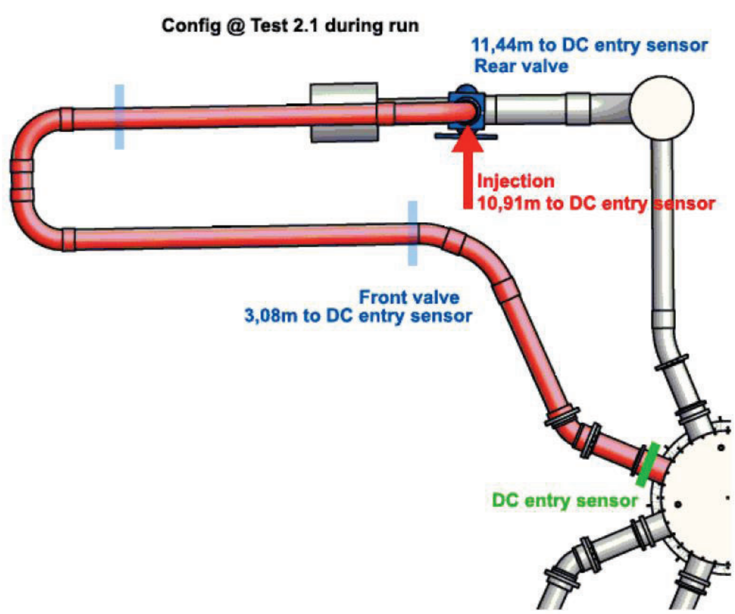


**Figure 2. Configuration of loop 1 (affected loop) during the ROCOM experiment 2.1 [1].**

## 3. MODELLING APPROACH

Over-cooling transients with an asymmetrical flow behavior in the RPV, such as the hereby considered ROCOM 2.1 experiment, are triggered by abnormal flow conditions deviating from normal operation within just one of the coolant loops. A best-estimate representation of the flow mixing phenomena in the RPV during asymmetrical fast cool-down transients requires a multidimensional description of the flow. Chapter 3 presents a detailed description of ATHLET's multidimensional flow model together with the employed nodalization of the RPV model.

### 3.1. ATHLET's multidimensional flow model

For the calculation of the ROCOM Test 2.1 with the thermal-hydraulic computer code ATHLET the two-fluid-model with separate equations for the liquid and the vapor phase was applied. ATHLET provides a one-dimensional formulation of this model based on six conservation equations for mass, momentum and energy respectively. In addition, for a better representation of the multidimensional flow phenomena a 2D/3D model is currently under development [5]. This approach is based on the three-dimensional momentum equations implemented as an enhancement of the one-dimensional two-fluid six-equation model of ATHLET. A simplified description of the improvements can be given in terms of the convective part of the phase separated momentum balance equations:

$$\rho \frac{\partial}{\partial t}(\mathbf{w}) + \rho(\mathbf{w} \cdot \nabla)\mathbf{w} + grad(p) = \mathbf{RHS} \tag{2}$$

The term labeled *RHS* comprises contributions e.g. due to external forces, fluid internal forces and phase change. The convective term, i.e. the second term on the left hand side of equation (2), can be handled by ATHLET in three different ways as presented in Table II. For the sake of simplicity the three-dimensional form is skipped here. The one-dimensional approach represents the well-known classical system code approach. ATHLET provided so far a pseudo multidimensional method, where the one-dimensional model equations are applied separately to each coordinate direction of a multidimensional numerical grid. Herein, the multidimensional grid is provided by cross-connected parallel flow paths. These two model alternatives are now supplemented with the fully multidimensional fluid-dynamics balance equations, which are implemented in both Cartesian as well as cylindrical coordinates. The presented work aims to compare two approaches: the traditional one-dimensional flow model and a multidimensional model.

**Table II. Available approaches for the consideration of the convective term of Equation 1**

| | |
|---|---|
| **One-dimensional flow model** | $(w \cdot \nabla)w = w_x \frac{\partial w_x}{\partial x}$ |
| **Pseudo-multidimensional parallel channel model** | $(w \cdot \nabla)w = \begin{bmatrix} w_x \frac{\partial w_x}{\partial x} \\ w_y \frac{\partial w_y}{\partial y} \end{bmatrix}$ |
| **Multidimensional flow model** | $(w \cdot \nabla)w = \begin{bmatrix} w_x \frac{\partial w_x}{\partial x} + w_y \frac{\partial w_x}{\partial y} \\ w_x \frac{\partial w_y}{\partial x} + w_y \frac{\partial w_y}{\partial y} \end{bmatrix}$ |

### 3.2. The ROCOM model

The system analysis code ATHLET uses a finite volume approach for the spatial decomposition of the fluid simulation domain. For the system analysis code simulation of the ROCOM experiment 2.1 the DC region of the RPV consisted of sixteen azimuthal distributed control volumes (CV) and an axial nodalization of twelve CV. The complex set-up of the lower core plate was considered in the ATHLET model of the ROCOM facility. The core was divided into 33 parallel hydraulic channels arranged in two rings around the central channel. Each channel has an axial resolution of five computational cells. A schematic drawing of the sixteen azimuthal DC CV and the 33 core channels together with the indication of the broken loop is presented in Figure 4.
Two different modelling approaches have been used for the computer simulation of the LP of the ROCOM test facility. Within the first approach so called branch-objects have been used for the modelling of the LP region of the RPV. This method corresponds to the typical lumped parameter system code nodalization. In the second approach pipe components have been employed instead. The two methods were named BRLP and 3DLP respectively to differentiate more easily between them. From a topology point of view the LP consisted in both cases of two axial layers. The upper layer contains two rings and one central region while the lower layer contains one single element. Figure 3 shows a schematic representation of the multidimensional nodalization of the LP. A sieve drum mounted in the LP of the ROCOM facility is modelled in ATHLET by an increase of the local form loss coefficient between the outer and the inner LP ring.
The BRLP model employed the classical (one-dimensional) description of the flow in the LP of the RPV, while the 3DLP model employed the three-dimensional model equations in cylindrical coordinates in the same region. Nevertheless both approaches used the two-dimensional flow model in the DC.

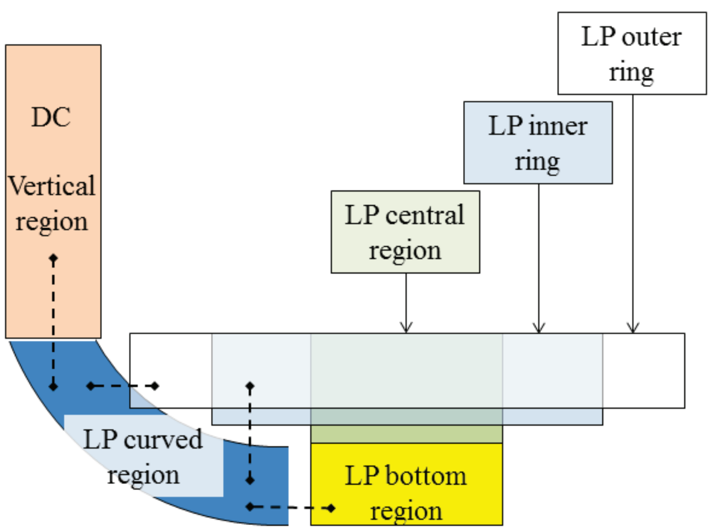


**Figure 3. Schematic representation of nodalization employed in the LP**

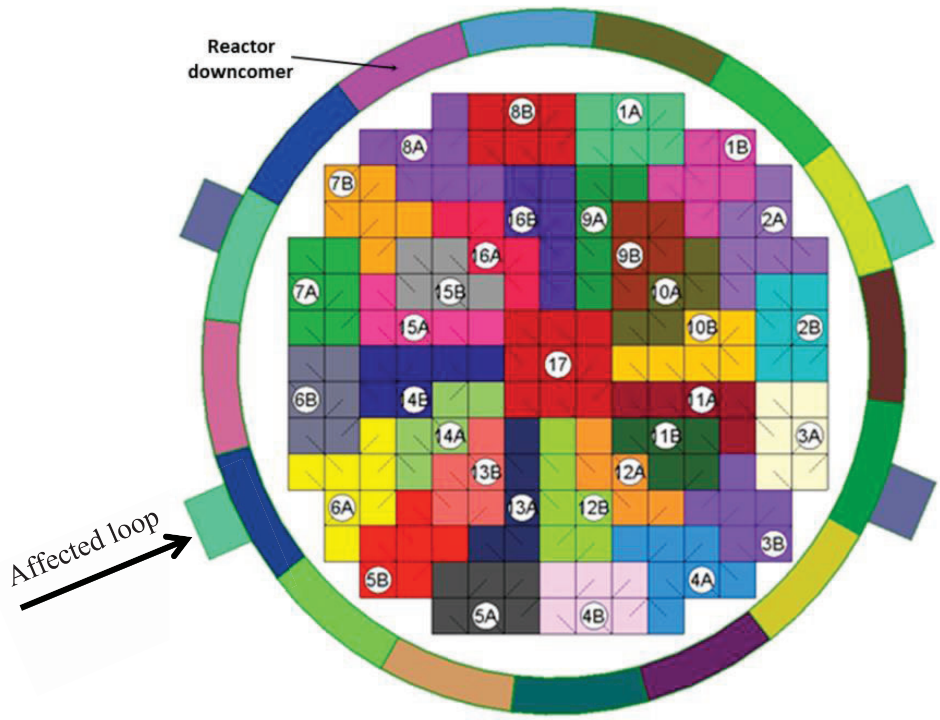


**Figure 4. Schematic drawing of the ATHLET sixteen azimuthal CV representation of the DC and the thirty-three core channels.**

## 4. COMPUTER SIMULATION RESULTS

The discussion of the computer simulation results will begin with the general presentation of key time points in the experiment progress. These include:

a) The denser liquid injected into the AL reaches the DC at approx. Problem Time (PT) 12.4s.
b) The helicoidal flow of the denser liquid downwards the DC creates two strands of denser liquid, approx. PT 15.1s to 18.4s.
c) The denser liquid reaches the LP. At the same time the two denser liquid strands merge to form a continuous plume of dense liquid below the AL RPV inlet nozzle, approx. PT 24.7s.
d) The denser liquid reaches the CI, approx. PT 24.7s.
e) The lighter liquid is replaced by denser one in the core, starting approx. with PT 26.5s and lasting until the end of the experiment. The replacement occurs from the core periphery towards its center, approx. starting at PT 55.0s.

The assessment of the system analysis code simulation results will start with the qualitative comparison against the measurement data in the DC and the LP regions of the RPV, according to the locations indicated in Figure 1. A direct comparison between the results of the two computer simulations and the WMS captured data is presented in Figure 7 and Figure 8. The color scheme used to represent the temperature field in the DC and at the core inlet is set up as follows: the color “blue” always corresponds to the value of 241°C, while the color “red” corresponds to the value 198.3°C and 214.8°C in the DC region and at the CI respectively. In the second part of this assessment the temperature trends reconstructed from the WMS electrical conductivity data at key locations in the RPV will be compared against the measured data.
As depicted in Figure 7, the time point at which the denser liquid reaches the DC is well predicted by both ATHLET simulations, key point a). The interpretation of the measurement data reveals a non-uniformly

mixture of the coolant at the RPV inlet nozzle in the first few seconds of the experiment. This detail influences the degree of coolant mixing in the DC of the RPV. Owing to ATHLET's one-dimensional description of the coolant flow in the cold legs, this effect could not be observed in any of the numerical simulations, but it will have an impact on the temperature distribution in the DC region.

The denser liquid creates a plume of approx. 90° azimuthal width below the RPV inlet nozzle of the AL. This flow behavior can be observed in the experiment between PT 12.4s and 15.1s. Subsequently, the denser liquid flows downwards to the LP in form of two diverging strands, a behavior characteristic for the time-interval PT 15.1s to 24.7s. The ATHLET simulation, employing the genuine multidimensional flow description, captures well the effect of the liquid strand separation over an azimuthal sector of approx. 90° at PT 15.1s. Still the two resulting strands flow in a more compact pattern towards the LP in the 3DLP simulation than in the experiment. On the other hand the BRLP model failed to capture this effect, as the denser liquid flows in form of a plume through the DC of the RPV, as it can be noticed in Figure 7 and Figure 8.

At the key point c) denser liquid reaches the LP over almost the entire periphery and it starts to enter the core, key point d) in Figure 8. At this point both ATHLET simulations show a similar behavior for the denser liquid plume as it reaches the LP in a compact pattern. In the case of the 3DLP simulation, the two denser liquid strands merged around PT 18.4s, approx. 6s sooner than in the experiment. Still the time point when the first over-cooled liquid reaches the core tie plate is well predicted by this model. The BRLP simulation, however, shows a slightly different flow behavior, as the denser fluid reaches the LP earlier entering the core around PT 24.7s. In the case of the BRLP simulation the denser liquid is redirected into the core channels neighboring the DC region linked with the AL. In comparison, both, the time delay by which the denser liquid reaches the core inlet as well as the temperature distribution pattern at the CI at PT 26.5s highlight ATHLET's new multidimensional capability to transport the fluid momentum more realistically along and within the curved shape of the LP. In the experiment the denser liquid momentum transport along the curved shapes of the LP results in a temperature distribution as the denser liquid reaches the CI, with colder liquid at the periphery than at the core center. The core channels diagonally opposite to the AL are reached sooner than the ones neighboring the AL. A sequence qualitatively captured by the 3DLP model, PT 26.5s presented in Figure 8. Thus, it is evident that the genuine multidimensional flow model implemented in ATHLET improves the local flow description in comparison to the BRLP approach and reproduces the transient flow behavior more realistically.

Starting with the time point when the core is reached by the denser liquid, a continuous replacement until the end of the experiment, of the lighter liquid by denser one is observed, key point e). The lighter liquid is displaced at this stage from the periphery of the core towards its center, resulting in a cold liquid bulk in the core center at PT 149.5s, as seen in Figure 8. The time point at which the denser liquid bulk is starting to form in the core center is well captured by the 3DLP simulation, around PT 55.0s. Nevertheless, the pattern of the denser liquid bulk is not as sharp as it appears in the measurement data. The overestimation of the degree of mixing is a consequence of the relatively coarse LP mesh and the first order upwind scheme employed to the spatial derivatives in the model equation (2), thus resulting in a relatively high numerical diffusion. The complex phenomenon of the coolant mixing in the region of the LP would benefit from a higher grid resolution, but at this point a grid independence study was only performed in axial direction of the flow channels. A further refinement of the computational grid in the axial direction brought only a minimal improvement to the simulation results. Rather the goal of this work was to analyze the influence of the multidimensional flow description on the phenomenon of coolant mixing in the LP.

The comparison of the two ATHLET simulations over the time period starting with PT 55.0s until the end of the experiment, presented in Figure 8, highlights the improved capabilities of the genuine multidimensional model to adequately reproduce the flow field in large vessels such as the RPV. In the case of the BRLP model a clear preferred flow path can be observed towards the core channels adjacent to the DC region below the affected loop, PT 55.0s and 149.5s.

The interpretation of the measured temperature field in the DC between PT 26.5s and 55.0s reveals a transient behavior of temperature stratification in this region. It can be noticed that a temperature front builds up and then quickly decreases as the denser fluid stored in the DC is continuously pushed towards the core. This effect can be better observed when analyzing the temperature trend of the average temperature calculated at the upper and the lower DC region, represented in Figure 5. The curve labeled as *aveTempDCU* corresponds to the average temperature in the upper DC region while *aveTempDCL* represents the average temperature in the lower DC region. The average temperatures were calculated on the basis of all azimuthal measuring points at the two mentioned levels provided by the installed WMS. Both temperature trends show a sudden decrease, first noticed in the upper region around PT 20.0s and some seconds later also in the lower DC region close to the LP. This sudden temperature decrease is reversed by the recirculation in the LP, thus resulting in a temperature increase to a quasi-steady value. A similar behavior was predicted by the ATHLET simulations in the upper DC region. The system analysis code simulation employing the genuine multidimensional flow model predicts very well the flow behavior in this region compared to that employing the BRLP model. The small difference between the simulated and measured temperature profiles in the case of the 3DLP model is also influenced by the predicted degree of mixing at the RPV nozzle. The one-dimensional description of the cold leg, assumes a homogenous coolant temperature for the entire cross section which is in partial contradiction to the experimentally observed temperature layering in the first seconds after the injection of the overcooled liquid in the affected loop. On the other hand the relatively large discrepancy between the numerical analyses and the measured data in the lower DC region, depicted in Figure 5, is caused by the simulated temperature stratification in the DC. This effect is not confirmed by the ROCOM experiment; still in both ATHLET simulations this effect is observed.

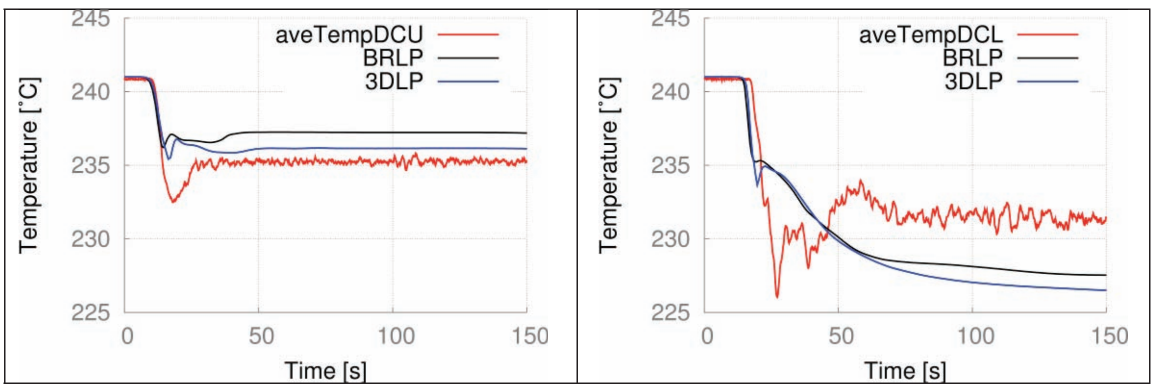


**Figure 5. Average temperature trends in the DC upper and lower region.**

The temperature trends at the CI of seven representative ATHLET core channels together with the average CI temperature derived over all core channels are presented in Figure 6. The representative core channels are located in the core center as well as in the periphery of the core, i.e. the outer core ring of the ATHLET geometry model. Three channels are respectively located diagonally opposite to the AL (channel 1B, 2A and 2B), while three are next to the AL (5B, 6A, 6B). The exact location of each of the considered core channels can be identified using the core mapping presented in Figure 4. Concerning ATHLET's prediction capabilities for the temperature trends in the channels diagonally across the core it can be noticed that both models, 3DLP and BRLP, capture well the overall flow behavior, with a slight advantage in favor of the 3DLP model. The 3DLP model predicts better the overall behavior since even the time point when the denser fluid reaches the CI is accurately predicted. This capability is additionally underlined by the comparison of the temperature trends in the core channels neighboring the AL, i.e. channel 5B, 6A and 6B. In these particular channels the unrealistic LP flow prediction of the BRLP method affects the coolant distribution at the CI plate. The momentum transport is highly underestimated as the over-cooled water preferentially reaches the core channels neighboring the AL and failing to reach other channels at the opposite core periphery. This effect can lead to an overestimation of the over-cooling effect in these channels.

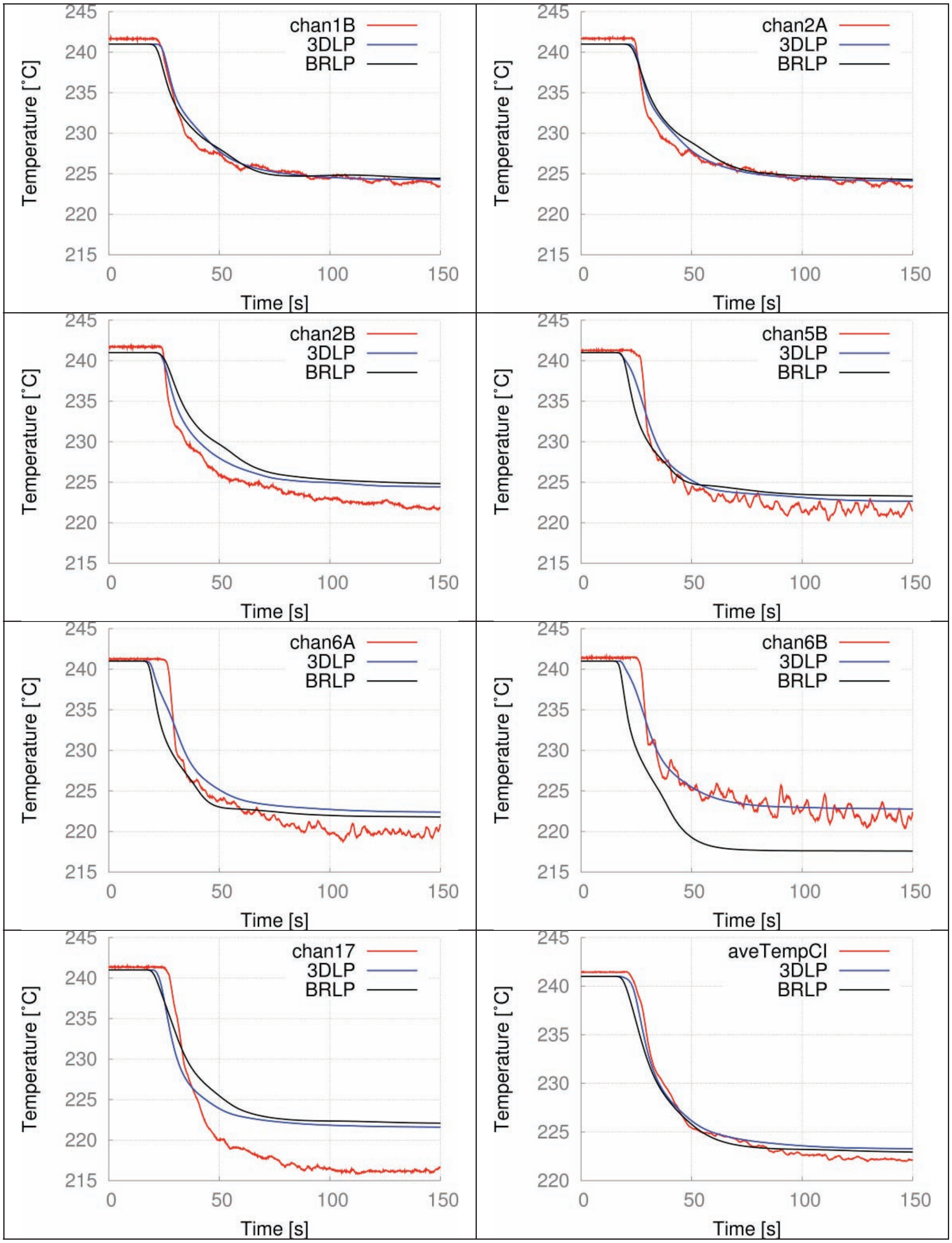


**Figure 6. Temperature trends at the CI for representative core channels and average CI temperature.**

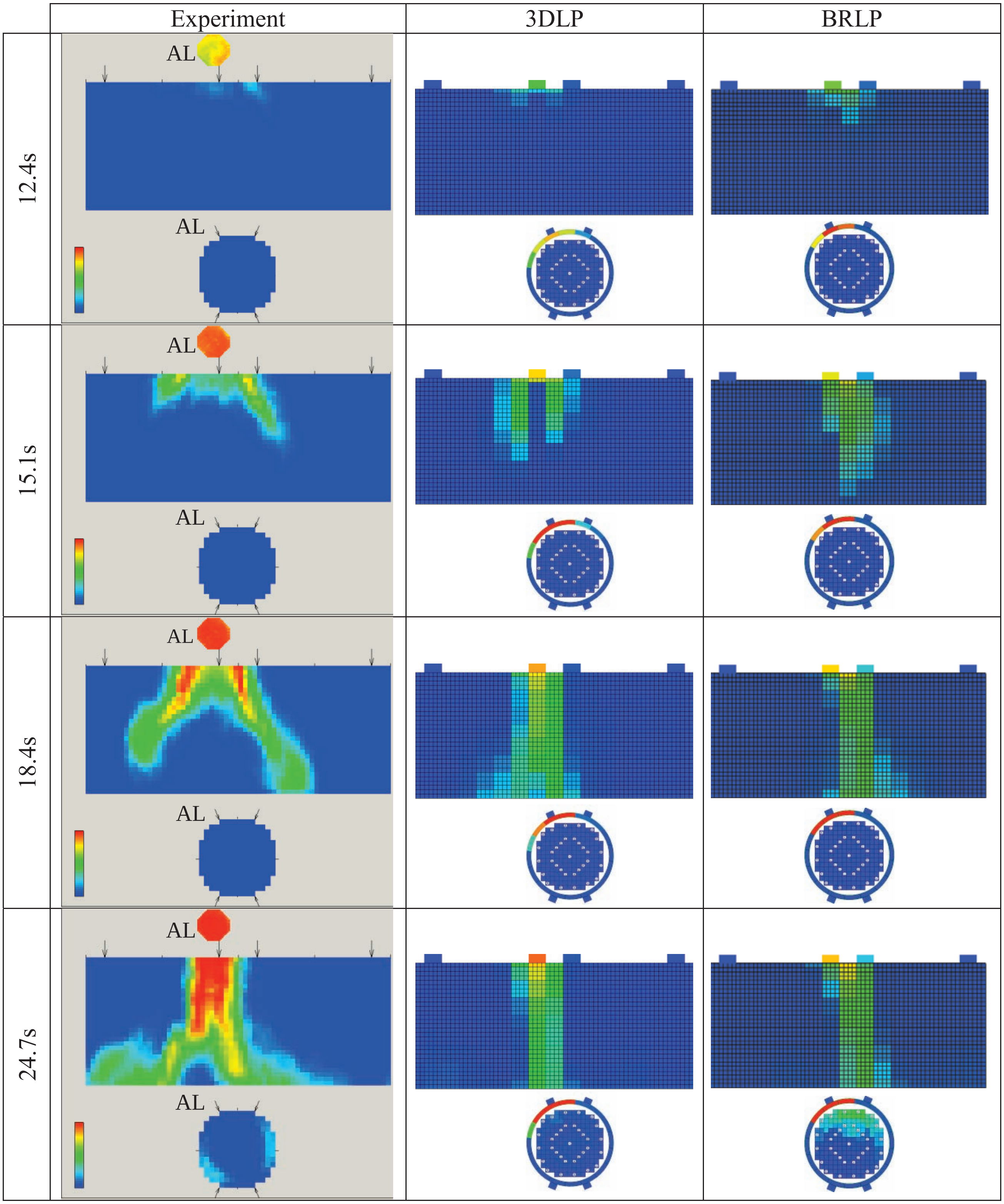


**Figure 7. Comparison of the temperature fields derived from measured data and simulated by means of the 3DLP and BRLP models, in the DC and at the CI at temporal key points of the experiment (PT 12.4s to 24.7s).**

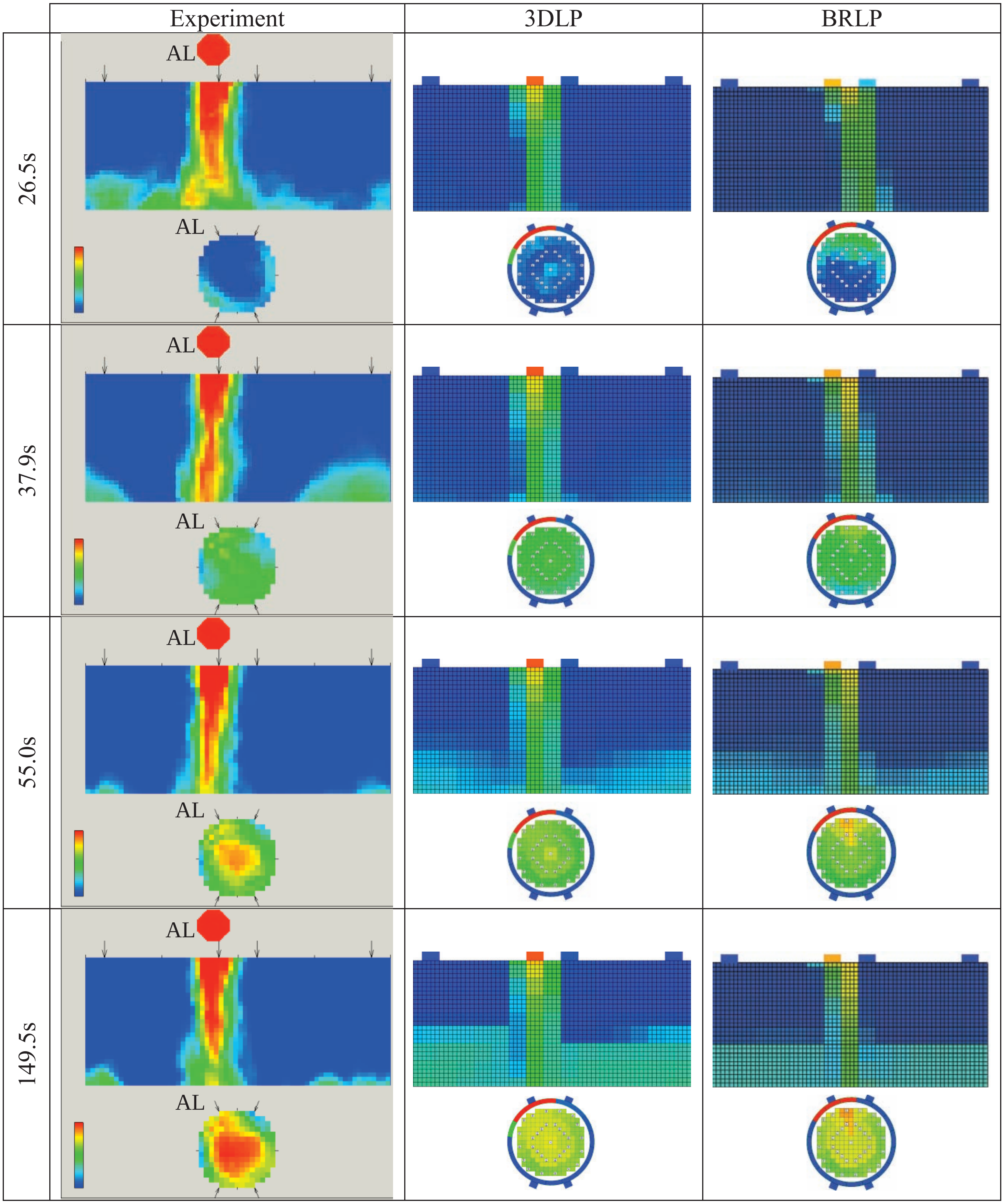


**Figure 8. Comparison of the temperature fields derived from measured data and simulated by means of the 3DLP and BRLP models, in the DC and at the CI at temporal key points of the experiment (PT26.5s to 149.5s).**

The comparison of the temperature trends for the core central channel highlights again the advantage of the genuine multidimensional flow description model. However, both computer simulations overestimate the degree of mixing before reaching this channel, labeled *chan17* in Figure 6, and, hence, the resulting temperature shows higher values than in the experiment. Judging only based on the average CI temperature it can be noticed that both models predict a similar flow behavior. Still the time point at which the average temperature decreases at the central core channel is again more accurately predicted by the 3DLP model. Additionally the shape of the temperature decrease is very well matched in the simulation employing the genuine multidimensional model. The lower value of the temperature towards the end of the experiment in the case of the BRLP model is caused by the direct transport of the over-cooled liquid from the DC through only a narrow region of the LP into the core channels, thus resulting in only a minimal degree of mixing in the LP.

## 5. CONCLUSIONS

The current work presents simulation results of the ROCOM coolant mixing experiment 2.1 obtained with the German system analysis code ATHLET Mod. 3.0 Cycle B, employing two different modelling approaches for the LP region of the RPV replicated by the integral test facility, i.e. one- and three-dimensional respectively. Within this benchmark ATHLET's newly developed multidimensional model is validated against WMS data acquired in the DC region and at the CI showing the typical behavior of a coolant mixing process. ATHLET yields good results for the temperature distribution during over-cooling transients in complex geometries such as the RPV, provided that the multidimensional flow model is employed together with an advanced nodalization scheme of the LP. Both enable a clearly improved and realistic flow modeling in annular and hemispherical geometries, thereby increasing ATHLET's prediction capabilities.
The comparison of the simulation results against the experimental data was performed in a two-step approach. First a qualitative comparison was performed. During this step, the multidimensional flow model applied to the improved nodalization in the LP region proved good overall prediction capabilities of the flow distribution both in the DC region, after the activation of the emergency core cooling system, and at the CI. The formation and shape of the denser coolant plume in the DC could satisfactorily be simulated, although the overall calculation results were slightly impaired by a temperature stratification in the lower part of the DC region towards the end of the investigated transient, that was not observed in the experiment. In particular, only the three-dimensional LP model was able to reproduce a coolant temperature distribution across the CI with a low temperature bulk in the central core region, thus highlighting the improvement compared to the classical one-dimensional description of the LP. In the second step of the validation process a comparison against temperature trends at key locations in the RPV was performed. These included the upper and the lower part of the DC, three core channels neighboring the AL, three core channels diagonally across the AL and the central core channel. Additionally a comparison against the average core inlet temperature was performed. Again the three-dimensional LP model outperformed the classical one-dimensional approach.
Nevertheless the development of the multidimensional flow model will be continued at the GRS in parallel to an extensive validation process.

## ACKNOWLEDGMENTS

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