Scaling of Thermal-Hydraulic Phenomena and System Code Assessment

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Abstract. In the last five decades large efforts have been undertaken to provide reliable thermal-hydraulic system codes for the analyses of transients and accidents in nuclear power plants. Many separate effects tests and integral system tests were carried out to establish a data base for code development and code validation. In this context the question has to be answered, to what extent the results of down-scaled test facilities represent the thermal-hydraulic behaviour expected in a full-scale nuclear reactor under accidental conditions. Scaling principles, developed by many scientists and engineers, present a scientific–technical basis and give a valuable orientation for the design of test facilities. However, it is impossible for a down-scaled facility to reproduce all physical phenomena in the correct temporal sequence and in the kind and strength of their occurrence. The designer needs to optimize a down-scaled facility for the processes of primary interest. This leads compulsorily to scaling distortions of other processes with less importance. Taking into account these weak points, a goal oriented code validation strategy is required, based on the analyses of separate effects tests and integral system tests as well as transients occurred in full-scale nuclear reactors. The CSNI validation matrices are an excellent basis for the fulfilling of this task. Separate effects tests in full scale play here an important role.

1. INTRODUCTION

For the design and evaluation of safety systems, for the elaboration and evaluation of accident management procedures as well as for operator training, reliable and thoroughly assessed thermal-hydraulic system codes are required, which describe the reactor system response under normal, off-normal and accidental conditions. In the early stage of this development the codes were primarily applied for the design of the engineered safety systems. In 1978 the “Appendix K Requirements” [1] were issued, defining conservative model assumptions as well as conservative initial and boundary conditions with the aim to warrant conservative code results for critical safety parameters. On the other hand, the development and elaboration of accident management procedures, the application of probabilistic safety analyses and the operator training asked for so called “best estimate analysis”, that means an accident simulation as realistic as possible. Today, a distinctive trend to best estimate analyses with quantification of code uncertainties can be noticed in the licensing practice. During the last five decades several system codes have been developed oriented on these goals.

2. MODELLING OF TWO-PHASE FLOW PHENOMENA

Contrary to single-phase flow, in two-phase flow large density differences between the water and vapour phase exist, where the local phase distribution is influenced by the surface tension at the phase-interfaces [2]. Two-phase flow is characterized by various flow patterns, which are a result of the interactions between surface tension, pressure drop, shear stresses, and gravity force. The turbulence in a two-phase mixture is usually much higher than in a single-phase flow, and both phases do not flow with the same velocity. These features make the understanding and the description of two-phase flow, particularly in multi-dimensional systems, much more difficult.

Whereas the first system-codes, developed at the beginning of the 1970ies, utilized the homogenous equilibrium model with three balance equations to describe the two-phase flow, the more advanced system-codes are based on the so called “Two Fluid Model” with separation of the water and vapour phases, resulting in systems with at least six balance equations. In Fig. 1 the code development activities in more than four decades are shown.

Depending on the number of balance equations, different sets of constitutive equations are required to close the equation system. In comparison with the homogeneous equilibrium model (HEM), which requires only two constitutive equations, namely the friction loss and the heat transfer relations at the wall, at least seven constitutive equations are required for the two fluid models with six balance equations describing the mass, energy and momentum transfer at the interface and the energy and momentum transfer of the water- and steam-phase at the wall.
Thermal-hydraulic Codes

<table>
<thead>
<tr>
<th>SYSTEM CODES</th>
<th>CFD CODES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Meshes</strong></td>
<td><strong>Representation of Components</strong></td>
</tr>
<tr>
<td>1965</td>
<td>1965</td>
</tr>
<tr>
<td>10</td>
<td>10^3</td>
</tr>
<tr>
<td>10^3</td>
<td>10^6</td>
</tr>
<tr>
<td>Simulation of Entire NSSS with Detailed Representation of Components</td>
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**Figure 1:** Code Development Activities in more than Four Decades.

The constitutive equations have to describe the physical phenomena in a wide span of scale, ranging from down-scaled integral system experiments up to full size reactor geometry. This is one of the most challenging goals in code development and code validation. To develop and validate the scaling laws for individual phenomena, separate effects tests in different scale are necessary.

3. VALIDATION OF THERMAL-HYDRAULIC SYSTEM-CODES

To verify the computational implementation of the numerical model and assess its accuracy, the thermal-hydraulic system codes have to be extensively tested and validated. The test- and validation-process occurs in several steps.

- Comparison of model results with analytical solutions
  Limitation: restricted to particular phenomena
- Comparison of model results with basic test results
  Limitation: basic tests mainly performed in down-scaled test facilities
- Comparison of model results with separate effects test results
  Limitations: separate effects tests mainly performed in down-scaled test facilities
- Comparison of code results with integral system test results
  Limitations: all integral system tests performed in down-scaled test facilities
- Comparison of code results with plant data of transients and accidents
  Limitations: data only available for a very limited region of transients and accidents
- Comparison of results calculated with different models or codes (benchmark calculations)
  Limitations: agreement of the results does not signify necessarily agreement with the real physical process which has been simulated

Taking into account all the limitations listed above, a clearly structured and goal-oriented test- and validation strategy has to be developed for the different types of codes. The CSNI validation matrices [3,4,5,6] are key elements for such a strategy.

Because a full-scale integral test is usually impossible, the scaling of the test facilities becomes a fundamental issue. The question of scaling has to be considered not only in the design of the test facilities; it has also to be taken into account in the code development process.

The codes must describe the results from separate effects tests and from integral system tests of different scaling (for example, the volume scaling of integral system tests ranging from 1:1 to 1:1600). A code model, describing for
example the counter-current flow in the downcomer of a PWR, whose development is based mainly on the results of the 1:1 scaled UPTF experiments, must also have the ability to describe this phenomenon in down-scaled integral system tests (scale-down capability). For the full range of transients and accidents, the interactions of the code models can be checked only on the results of down-scaled integral system test facilities. On the other hand, code models, whose development is based mainly on the results of down-scaled experiments, must have the ability to describe the thermal-hydraulic processes expected in the full scale reactor plant (scale-up capability).

The transfer of experimental results - obtained in a scaled-down test facility - to the reality in an industrial plant is an old problem of engineering [11]. There must be a sufficient similarity of the parameters controlling the processes in the test rig and in the real plant. This similarity can be of geometrical, mechanical, thermal-hydraulic, static or dynamic nature.

There are several methods to develop scaling laws. One of the most known methods is based on the non-dimensional form of the governing differential equations describing the thermal-hydraulic processes. In this method the differential equations are made non-dimensional by choosing proper reference values for various physical quantities involved in the equations. From these equations non-dimensional numbers respectively similarity groups can be obtained. For example, the derivation of the non-dimensional Reynolds and Grashof number will be illustrated for the simplest case, namely for the steady state single-phase flow.

Starting from the momentum equation for the x-coordinate

\[
\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z} = \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 w_x}{\partial x^2} + \frac{\partial^2 w_y}{\partial y^2} + \frac{\partial^2 w_z}{\partial z^2} \right) + g \beta \vartheta
\]

the equation is transformed into dimensionless variables by introducing the reference values \( w_0, \Theta \) and \( l \).

With the introduction of

\[
\xi = \frac{x}{l}, \quad \eta = \frac{y}{l}, \quad \zeta = \frac{z}{l}, \quad \omega_x = \frac{w_x}{w_0}, \quad \pi = \frac{p}{\rho w_0^2}, \quad \vartheta = \frac{\vartheta}{\Theta}
\]

we obtain the momentum equation in dimensionless form with Re and Gr/Re

\[
\frac{\partial^2 \omega_x}{\partial \xi^2} + \frac{\partial^2 \omega_x}{\partial \eta^2} + \frac{\partial^2 \omega_x}{\partial \zeta^2} = \frac{w_0 l}{\nu} \left[ \omega_x \frac{\partial \omega_x}{\partial \xi} + \omega_y \frac{\partial \omega_x}{\partial \eta} + \omega_z \frac{\partial \omega_x}{\partial \zeta} + \pi \right] - \frac{l^2 g \beta \Theta}{w_0^2 \nu} \vartheta
\]

Compared with this simple example for a single-phase flow the development of scaling laws for two-phase processes are much more complicated. Not only the high number of differential equations but also the high number of constitutive equations describing the interfacial interactions and the interactions of the two phases with the channel wall hamper enormously the derivation of scaling laws. In the following some examples of scaling laws used for the design of integral system tests facilities and separate effects tests facilities are listed for demonstration.

### 3.1 Integral System Tests

To obtain an overview on the overall system behaviour and on the interaction of the different system components of a NSSS, integral system tests are being performed for more than four decades. However, because a full-scale integral test facility is usually impossible, the facility scaling becomes a fundamental issue.

There have been many studies on thermal-hydraulic scaling laws. The scaling criteria applied for the design of the test reactor LOFT have been examined by Rose already 1965 [7]. Studies for modelling nuclear reactor blow-down scenarios were performed by Carbiener and Cudnik [8]. A set of dimensionless parameters for two-phase flow has been derived by Ishii and Jones [9]. Alternative scaling laws for the modelling of nuclear reactor systems have been developed by Nahavandi et al. [10]. Mayinger assessed the scaling and modelling laws in two-phase flow and boiling heat transfer [11]. Ishii and Kataoka [12] presented scaling criteria specifically for the cooling loops of pressurized water reactors under single- and two-phase natural circulation conditions. Y.Y. Hsu et al. [13] have presented a system scaling modelling analysis for Small Break LOCA, based upon the mass and energy balances.
and the flow-pressure drop relationship. A critical review of scaling criteria has been performed by Kiang [14]. A complete scheme of scaling methods has been developed by Liu and Lee for the design of integral system test facilities with reduced height and reduced pressure [15].

In the following characteristic results of the studies of Nahawandi as well as Ishii and Kataoka are presented for illustration. In Table 1 the scaling laws proposed by Nahawandi are listed. Based on the volumetric scaling, wherein both the power and volume are scaled by the same scaling factor, the time scale is preserved. The hydrostatic head, the driving force for natural circulation, is preserved by the full length respectively the full height. Furthermore, if the configuration of the fuel rods and of steam generator tubes is preserved, except that their number is reduced by the scaling factor $\lambda$, then the heat transfer characteristic length is preserved. Scaling distortions result in particular from the reduction of the cross sections, influencing the flow characteristics as well as the establishment and perpetuation of flow regimes due to the untypical ratio between length and cross sections. Additional scaling distortions, such as untypical flow resistances, heat losses or structural heat releases have to be taken into account when interpreting and assessing the experimental results. The Nahawandi Scaling principle is most popular with LOCA test facilities. Karwat gave an excellent summary of the facilities based on this scaling principle [16].

Ishii and Kataoka have presented similarity groups for two-phase flow, which can be obtained from the set of balance equations directly or from the perturbation analyses. Similarity between test facility and prototype is assumed, if these dimensionless numbers are identical for facility and prototype. Below typical similarity groups are shown for illustration.

Phase change number (flux due to phase change/inlet flux)

$$N_{pch} = \frac{4q^* l_g}{d u_{in} \Delta H_{fg} \rho \rho_g}$$

Subcooling number (sucooling/latent heat)

$$N_{sub} = \frac{\Delta H_{sub}}{\Delta H_{fg} \rho \rho_g}$$

Froude number (inertia/gravity force)

$$N_{Fr} = \frac{u_0^2}{g l_g \langle \alpha \rangle \rho \rho_g}$$

Friction number

$$N_f = \frac{f l}{d \left( \frac{1 + \Delta \rho x / \rho_g}{(1 + \Delta \mu x / \mu_g)^{1/3}} \right) \left( \frac{a_x}{a_z} \right)^2}$$

Orifice number

$$N_o = K \left( 1 + \Delta \rho x^{1/3} / \rho_g \right) \left( a_o / a_z \right)^2$$

<table>
<thead>
<tr>
<th>Table 1: Scaling Laws proposed by Nahawandi.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Area</td>
</tr>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>Velocity</td>
</tr>
<tr>
<td>Acceleration</td>
</tr>
<tr>
<td>Property</td>
</tr>
<tr>
<td>Heat generation rate / volume</td>
</tr>
<tr>
<td>Power</td>
</tr>
</tbody>
</table>

$\sigma = \text{Area-Model} / \text{Area-Prototype}$
Similarity criteria, such as given above, cannot be fulfilled in total. Nevertheless, they present a scientific-technical basis and give a valuable orientation for the design of test facilities.

It is impossible for a down-scaled facility to reproduce all the physical phenomena during a transient process in a real scale plant. The designer needs to optimize a down-scaled facility for the processes of greatest interest. However, this leads compulsorily to distortions of other processes with less importance.

For illustration, the volume scaling with retention of the original plant elevations have resulted in a reduction of the reactor core diameter of about 4 m in the original down to 10 cm in the integral system test facility SEMISCALE. Tests performed in this facility to investigate the effectiveness of hot leg ECC-injection have demonstrated very clearly the limitations of these scaling principles. Contrary to the break through of the injected ECC-water via the upper tie plate in the core, which can be expected in the original plant, and which has been verified in the UPTF-tests, the ECC-water accumulated in the upper plenum and did not contribute to the core cooling. Even worse, the unrealistic accumulation of the ECC-water in the upper plenum blocked the up-flow of the steam-water mixture, which is generated in the core. These two effects, that are definitely a result of the facility scaling, have lead to a completely unrealistic core heat up.

The influence of component scaling has also been demonstrated very impressively by the LOBI Program [17]. These tests were performed with two different gap width of the annular shaped downcomer. In the first test series a downcomer gap width of 50 mm was used which resulted in 6.3 times too large a downcomer volume and therefore in a strong distortion of the mass distribution in the scaled system. The intention was to preserve as far as possible counter-current flow as well as hot wall related phenomena during the refill period. In the second test series a downcomer of 12 mm gap width was installed. The 12 mm was chosen as a compromise between the volume scaled downcomer (7 mm gap width) and a downcomer which would yield the same pressure drop due to wall friction as in the reference reactor (25 mm gap width for the scaled facility). The influence of downcomer gap width and downcomer volume has been shown by a comparative results analysis of two tests. Both tests simulated a double-ended cold leg break with cold leg accumulator injection. Overall initial and boundary conditions were generally equal or directly comparable for the two tests.

No significant influence of downcomer gap width on the system thermal-hydraulic behaviour occurred during the very first blowdown period when subcooled fluid conditions persisted in the downcomer region. However, the course of the transient was strongly affected during the subsequent saturated blowdown and refill periods. When fluid evaporation had also started in the cold regions of the system the reduction of depressurization rate, the relatively higher density fluid persisting near core entrance and the re-establishment of positive mass flow through the core were much more pronounced in the case of the large downcomer where the initial liquid inventory in the downcomer is about 3.6 times larger than in the case of the small downcomer. This in turn ensured enhanced cooling of the heater rod bundle during the late blowdown. As a consequence, completely different conditions existed in the primary system at the time when ECC-injection from the accumulator started. Conversely, a smaller downcomer width tended to inhibit ECC water penetration and lower plenum refill which led to nearly stagnation conditions in the core and relatively poor core cooling.

These examples show very clearly that the thermal-hydraulic behaviour of a down-scaled integral test facility cannot be extrapolated directly to obtain nuclear plant behaviour. Although the facilities have been designed in different volume scaling, ranging from 1:1600 to 1:48 (Table 2), the experimental results of these facilities are not solving the scaling problem. A combination of integral system tests with separate effects tests in full reactor scale is indispensable.

<table>
<thead>
<tr>
<th>Test facility</th>
<th>Country</th>
<th>Volume Scaling</th>
<th>Max. Power (MWth)</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSA IV</td>
<td>Japan</td>
<td>1:48 *</td>
<td>10.0</td>
<td>16.0</td>
</tr>
<tr>
<td>LOFT</td>
<td>USA</td>
<td>1:50</td>
<td>50.0</td>
<td>15.5</td>
</tr>
<tr>
<td>BETHSY</td>
<td>France</td>
<td>1:100 *</td>
<td>3.0</td>
<td>17.2</td>
</tr>
<tr>
<td>PKL</td>
<td>Germany</td>
<td>1:134 *</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>SPES</td>
<td>Italy</td>
<td>1:430</td>
<td>9.0</td>
<td>20.0</td>
</tr>
<tr>
<td>LOBI</td>
<td>EU/Italy</td>
<td>1:712</td>
<td>5.4</td>
<td>15.5</td>
</tr>
<tr>
<td>SEMISCALE</td>
<td>USA</td>
<td>1:1600</td>
<td>2.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

*) Full-Power Scaling not possible
3.2 Separate Effects Tests

In addition to the integral system tests, separate effects tests are being performed for the study of particular phenomena. There are several reasons for the importance and high value of this test type [18].

Firstly, it has been recognised that the development of individual code models often requires some iteration, and that a model, despite well conceived, may need refinement as the range of applications is widened. To establish a firm need for the modification or further development of a model it is usually necessary to compare predictions with separate effects tests data rather than to rely on interferences from integral test comparisons.

Secondly, a key issue concerning the application of best estimate codes to LOCA and transients calculations is the quantification of the uncertainties in predicting safety relevant parameters. Most methods for determining these uncertainties rely on assigning uncertainties to the modelling of individual phenomena. This concept has placed a new emphasis on separate effects tests above that originally envisaged for model development.

The advantages of separate effects tests are:
- clear boundary conditions
- measurement instrumentation can be focused on a particular phenomenon
- reduced possibility of compensating modelling errors during validation
- more systematic evaluation of the accuracy of a code model across a wide range of conditions up to full reactor plant scale
- steady state and transient observations possible.

A further incentive to conduct separate effects tests in addition to experiments carried out in integral system test facilities is the difficulty encountered in the up-scaling of predictions of phenomena from down-scaled integral tests to real plant applications. Where a phenomenon is known to be highly scale dependent and difficult to model mechanistically, there is a strong need for conducting separate effects tests at full scale.

In the following selected results of the 1:1 scaled Upper Plenum Test Facility (UPTF) are shown. The chapter will be rounded off by pointing at the new scaling laws developed for the design of separate effects test facilities for investigating the Direct ECC Bypass phenomenon in the downcomer of power reactors with direct ECC injection into the pressure vessel.

3.2.1 The UPTF tests

UPTF [19] was a full scale (1:1) representation of the primary system of a 1300 MWe pressurized water reactor with a four-loop system (Fig. 2). It was a fluid-dynamic facility especially designed for studying multi-dimensional two phase flow effects in components of large volume like downcomer, upper plenum, entrance region of the steam generator and main coolant pipes. The steam generation in the core and the entrained water flow during emergency cooling were simulated by adding steam and water via a so-called core simulator. The behaviour of the steam generators was simulated by a controlled subtracting or adding of steam from or to the facility from the outside. The required steam was provided by a fossil fired power station. The design of the core simulator and all pressure-vessel internals are shown in Figure 3.

The data of UPTF have remarkably extended the data base required to develop and validate analytical models used in the large thermal-hydraulics codes for the simulation of two-phase flow phenomena in full scale reactor geometry. The large scale test facility has shown in particular multidimensional phenomena which cannot be simulated in test facilities at smaller scales.

In the following results of multidimensional flow in the downcomer, in the upper plenum, and at the upper core tie plate, as well as results related to flow phenomena in the hot and cold leg of the main coolant pipes will be presented.

3.2.2 Thermal-hydraulic Phenomena in the Downcomer

The previous view of downcomer phenomena for cold leg ECC-injection had been developed particularly through the USNRC ECC By-pass Program. In this program, steam-water tests were performed at 1/30, 1/15, 2/15 and 1/5 scale at Battelle Columbus Laboratories and at CREARE. Steady state counter current flow limitation (CCFL) tests with steam up-flow and ECC-water down-flow as well as transient tests involving lower plenum flashing and two-phase up-flow were carried out.

Based on these experimental data of the down-scaled test facilities empirical flooding correlations have been developed, using two dimensional groups: a modified Wallis parameter:
Figure 2: Upper Plenum Test Facility (UPTF), the German Contribution to the Trilateral 2D/3D Program

Figure 3: Test Vessel of the Upper Plenum Test Facility UPTF.
with $W$ as average downcomer annulus circumference, and the Kutateladze number

$$K_w = \frac{\dot{M}_s}{\rho_s A_{ic}} \frac{\rho_s^{1/2}}{[g\rho_s(W - \rho_s)]^{1/2}}$$

Though the tests have been carried out with a variation of the test facility scale between 1/30 and 1/5, the question, to what extent these findings can be extrapolated to full scale downcomer geometry, remained unanswered.

To provide CCFL and by-pass data for full reactor geometry, tests at UPTF were carried out. In Fig. 4 the result of a UPTF experiment, simulating the downcomer behaviour during the end-of-blowdown and refill phases for a large cold leg break is shown.

The test was carried out with a reactor typical steam up-flow of 320 kg/s and ECC-injection (subcooling 115 K) into the three intact loops. The contour plot shows isotherms of fluid temperatures (subcooling) in the unwrapped downcomer. The two-dimensional presentation shows strongly heterogeneous flow conditions which were not obvious from small-scale experiments. The ECC-water delivered from the cold legs 2 and 3, which are located opposite the broken loop, penetrates the downcomer without being strongly affected by the up-flowing steam flow. Most of the EEC-water delivered from cold leg 1, which is located near the broken loop, however flows directly to the break, bypassing the core.

To demonstrate the effect of the facility scaling on downcomer CCFL, the data obtained from UPTF and CREARE with a 1/5 scaling are compared in Fig. 5, using the Wallis parameter as defined in equation 1. In order to compare data of slightly subcooled conditions from UPTF with CCFL results of CREARE obtained with saturated ECC-injection, an effective steam flow (injected minus condensed steam) had been introduced.

![Figure 4: Counter–Current Flow Conditions in Full-Scale Downcomer for Strongly Subcooled ECC, Distribution of Subcooling](image)
Due to the strongly heterogeneous flow conditions in the full-scale downcomer of UPTF the water delivery curves of UPTF and CREARE are significantly different. For dimensionless effective steam flow, \((J^*_{s,\text{eff}})^{1/2}\), greater than 0.2, the dimensionless water down-flows of UPTF are much higher than the results of CREARE. Note that the UPTF data at dimensionless effective steam flows smaller than 0.2 should not be directly compared with the CREARE CCFL curve considering the lower scaled ECC-injection rate of UPTF compared to that in the CREARE experiments. Higher water delivery rates can be expected below the CCFL curve if more ECC-water is injected into cold legs 2 and 3.

The main findings with respect to downcomer behaviour during the end-of-blowdown and refill phases of a large cold leg break with cold leg or downcomer ECC-injection can be summarized as follows:

- there is a significant scale effect on downcomer behaviour,
- the flow conditions in the downcomer are highly heterogeneous at full scale,
- the heterogeneous or multi-dimensional behaviour increases the water delivery rates at full-scale relative to previous tests at down-scaled facilities,
- the CCFL correlations developed from the down-scaled tests are not applicable to full-scale downcomers,
- the downcomer CCFL correlations for cold leg ECC injection based on down-scaled test results underpredict the water penetration to the lower plenum at full scale,
- due to strong heterogeneity in a real downcomer a CCFL correlation has to account for the location of the ECC injection relative to the break.

In order to describe the asymmetric heterogeneous gas/liquid counter-current flow in the full scale downcomer the Kutateladze type flooding equation has been extended by Glaeser [20], correlating the local steam velocities of the multi-dimensional flow field with the superficial steam velocity. A dimensional geometrical lateral distance between the legs with ECC injection and the broken loop is introduced in the gas upflow momentum term. This term relates the local upward gas velocity at the water down-flow locations to the superficial gas velocities. The superficial gas velocity can be calculated from the steam mass flow rate.
If there is more than one ECC injection location, the arithmetic mean value of all distances $L$ between the ECC injection legs and the broken leg has to be used in the correlation. However, only those injection locations can be considered where water can flow downwards. This means that the modified dimensional gas velocity obtained by using the value of $L$ for the individual injection location has to be below the onset of penetration point. Otherwise, the respective ECC injection leg cannot be included in the arithmetic mean value $L$. More details of the derivation and application of the Glaeser-Correlation can be found in [21].

The resulting lowest gas velocity for zero water penetration (onset of penetration) is shown in Fig. 6 compared with the downcomer circumference scale.

Water downflow is impossible for gas velocities above the curve. There are three different scaling regions on which one of the flooding correlations is applicable. These are the classical Wallis- and Kutateladze-type as well as the Glaeser-correlation. The range of applicability is dependent on the dimensionless annulus circumference, which governs the different flooding correlations. It can be seen that it is impossible to extrapolate countercurrent flow correlations from small scale data below one-ninth downcomer circumference scale (equivalent to 1/81 flow cross section scale) to reactor scale. The full scale UPTF data were needed to clarify the influence of scaling on the ECC flooding phenomenon.

### 3.2.3 Thermal-hydraulic phenomena at the Tie Plate and in the Upper Plenum

Dependent on the type of ECC-injection systems, different flow phenomena occur at the tie plate and in the upper plenum of a PWR. For PWRs with cold leg or downcomer ECC injection, countercurrent flow of steam/water up-flow and saturated water down-flow occurs. The water, which is entrained by the up-flowing core steam flow, is either de-entrained at the tie plate, de-entrained in the upper plenum or carried over to the hot legs. The saturated water, which is de-entrained in the upper plenum, either form a pool in the upper plenum or flows counter-currently to the steam/water up-flow back through the tie plate into the core. For PWRs with ECC injection into the hot leg or the upper plenum, counter current flow phenomena at the tie plate involve steam/water upflow and local down-flow of subcooled water.

![Figure 6: Downcomer Flooding Correlation for Zero Penetration of Liquid (Total Bypass)](image-url)
In previous times the knowledge about the thermal-hydraulic phenomena at the tie plate and in the upper plenum was based on results gained from down-scaled test facilities. The tie plate was usually simulated by small perforated plates not exceeding the size of one fuel assembly. The Wallis parameter or the Kutateladze number was applied to correlate the experimental data. To study the tie plate and upper plenum behaviour in full reactor geometry, tests at UPTF were performed. The tests were carried out with three different types of thermal-hydraulic boundary conditions (Fig. 7):

- counter-current flow of saturated steam and water at the tie plate, typical of PWRs with cold leg ECC injection,
- counter-current flow of steam and saturated water injected into the hot legs,
- counter-current flow of saturated steam and water from the core and subcooled water injected into the hot legs, typical of PWRs with combined ECC injection.

### 3.2.3.1 Counter-Current flow of saturated steam and water

To study the counter-current flow at the tie plate and the liquid hold up above the tie plate in case of saturated steam/water up-flow a series of UPTF tests were carried out. Reactor typical steam/water up-flow was adjusted by the core simulator with controlled injection of steam and water.

In Fig. 8 data of these UPTF tests are plotted using the Kutateladze number for up-flowing steam and down-flowing water. In addition, corresponding data are presented from single fuel assembly tests performed at the Karlstein Calibration Test Facility to determine potential scale effects. The figure clearly shows that counter-current flow limitation at the tie plate is occurring at the same Kutateladze number in the single fuel assembly test facility as in the full scale size facility UPTF with a cross section of about 20 m².

The test results indicate that:
- The steam/water up-flow, the two-phase pool above the tie plate, and the water fall back through the tie plate is uniform across the core area,
- The flooding curves for both full-scale and sub-scale test facilities are similar,
- The water down-flow to each fuel assembly is scale-invariant,
- For homogeneous flow conditions at the tie plate the flooding curve can be defined by applying the Kutateladze number as scaling parameter.

![Figure 7: Counter-Current Flow Conditions at the Tie Plate addressed in UPTF.](image)
3.2.3.2 Countercurrent flow of steam and saturated water injected into hot legs

The situation differs strongly from the one described above in that saturated ECC water is delivered to the upper plenum via the hot legs, while steam is injected through the core simulator flowing upward through the tie plate only. This boundary condition is not reactor typical, however tests with saturated water injection allow the investigation of heterogeneous flow distribution in the upper plenum and the tie plate region without the influence of condensation effects.

A series of UPTF tests were carried out investigating different configurations of ECC injection. In Fig. 9 the results of tests with two loop injections (injection rates 2x100 kg/s) and single loop injection (injection rate 1x400 kg/s) are shown.
The main findings of the tests performed to investigate countercurrent flow of steam and saturated water injected into hot loops can be summarized:

− water breakthrough from the upper plenum to the core occurred in front of the injecting hot leg nozzles leading to heterogeneous flow conditions at the tie plate,
− water downflow and steam upflow paths at the tie plate are separated,
− there is no substantial time delay between start of ECC-injection and tie plate water breakthrough,
− water breakthrough rate increases with decreasing core steam flow rate,
− non-uniform distribution of vertical differential pressure in the upper plenum measured across the tie plate had been detected,
− the water downflow is significantly higher than that of the flooding curve determined for homogeneous flow conditions at the tie plate,
− the UPTF tests indicate clearly that classical Kutateladze-scaling cannot be applied for heterogeneous flow conditions without modifications.

3.2.3.3 Counter-current flow of saturated steam/water upflow and subcooled water injected into hot legs

Compared to saturated hot leg injection the conditions for the water breakthrough at the tie plate become more favourable if highly subcooled ECC water is injected.

In Fig.10 the results of an UPTF test with a very high water/steam ratio of the upflow rate of w/s=4 are shown (a typical value for the reflood period of a PWR is w/s=2). Additional results of tests, investigating the effect of the water/steam ratio of the two-phase upflow as well as the effect of transitory flow changes with increasing and decreasing upflow rates are presented.

The UPTF tests have shown that:

− the ECC penetration to the core region always follows the ECC delivery to the upper plenum without substantial delay, and occurs in front of the hot legs with ECC injection,
− the time-averaged water breakthrough at the tie plate is not significantly affected by intermittent water delivery to the upper plenum compared to continuous delivery,
− the water breakthrough at the tie plate increases with decreasing steam flow rate,
− for a given steam upflow rate the water breakthrough at the tie plate increases with decreasing water/steam ratio of the two-phase upflow,
− a two-phase pool of saturated steam and water in the upper plenum at initiation of hot leg ECC injection has only a minor effect on the water breakthrough at the tie plate,
− during the period of increasing core upflow rates the water downflow is higher than for decreasing upflow rates at the same steam upflow rates,
− due to heterogeneous flow conditions at the tie plate, strongly dependent on scale, the classical Kutateladze scaling cannot be applied without modifications.

Figure 10: Counter-Current Flow of Two-Phase Upflow and Subcooled Water Downflow during Hot Leg ECC Injection
3.2.3.4 General Conclusions related to Tie Plate and Upper Plenum Behaviour
In general the UPTF tests reveal that the tie plate CCF behaviour with hot leg ECC injection is quite different from that without hot leg ECC injection, even if saturated ECC-water is delivered to the upper plenum.

The classical Kutateladze type CCFL correlations can only be used to predict the tie plate water downflow rate if no ECC-water is injected into hot legs or upper plenum. Only in this case the tie plate results elaborated in small scale test facilities can be applied to a large tie plate.

In case of hot leg ECC-injection the water downflow through the tie plate is much higher than predicted by the previous tie plate correlations which are based on small scale test data. The reason for this deviating CCF behaviour is the inhomogeneous distribution of the water mass across a full size tie plate due to local ECC-water delivery to the upper plenum. Over the full range of typical reactor core outlet flow rates the injected ECC-water penetrates through the tie plate into the core without delay.

3.2.4 Thermal-hydraulic Phenomena in the Main Coolant Pipes
To investigate the thermal-hydraulic phenomena in the main coolant pipes during ECC-injection and to provide full scale data for the reflux condenser mode phenomena in the hot legs, series of UPTF tests were performed.

3.2.4.1 Flow behaviour in the main coolant pipes during ECC-injection
Pressure and fluid oscillations as well as flow regime transition can occur in the main coolant pipes of a PWR during the end-of-blowdown, refill and reflood phases due to ECC-injection. These oscillations are mainly induced by direct condensation of steam at the injected subcooled ECC-water.

To investigate the flow behaviour in horizontal pipes with cold leg ECC-injection via a side tube, small-scale tests ranging from 1/20 to 1/3 scale were performed previously. The experiments indicated that water plug formation and oscillations may occur.

To investigate the flow behaviour in horizontal pipes with hot leg ECC-injection via an axial injection nozzle, small scale tests with a scaling range of 1/5 and 1/10 were carried out in the past. The tests have shown that complete ECC-water reversal can occur at high steam flow rates from the upper plenum to the hot leg.

To investigate loop flow patterns in the main coolant pipes during cold leg or hot leg ECC-injection, several UPTF tests were carried out. The thermal-hydraulic boundary conditions leading to pressure and flow oscillations have been quantified.

Three different flow patterns have been identified:
- Stable water plug
  refers to the formation of a quasi-steady state water plug in the pipe adjacent to the ECC injection port
- Unstable plug
  implies occurrence of an unstable water plug with large oscillation amplitudes in the pipe accompanied with water hammer events
- Stratified flow
  stands for establishing of water flow at the bottom and steam flow at the top of the pipe, where temperature stratification can occur in the water flow.

The UPTF test data gained at different values of pressure and ECC subcooling are plotted in diagrams (Fig. 11 and Fig. 12) using the actual steam flow rate and the steam condensation potential of the ECC water. Consequently, the maximum steam condensation potential of the ECC water (thermo-dynamic ratio $R_T = M_{S,cond,pot} / M_{S} = 1$.) is represented in these diagrams by a straight line indicating the interface between stratified flow and plug flow ranges.

For steam flows higher than the steam condensation potential of the ECC water ($R_T < 1$) stable stratified flow occurs because there has to be a flow path for the nearly saturated water at the bottom and the surplus steam at the top of the pipe. Stable stratified flow in the cold leg also occurs at steam flow rates slightly below the curve $R_T = 1$ (Fig. 11). The temperature stratification of the water flowing at the bottom of the pipe allows stable stratified flow to occur for $R_T \geq 1$. The extent of this region depends on the turbulence of the injected water.

Fig. 11 and 12 reveal that stable water plug occurs only when the steam mass flow exceeds a certain threshold value. This threshold value is a function of the absolute pressure and also a function of the steam condensation potential of the ECC water in case of countercurrent flow in the hot leg. In this case the water plug formation in the hot leg pipe is linked to complete flow reversal of the injected water.
When the actual steam flow is lower than the threshold value, i.e. the condensation potential of the ECC water is sufficiently higher than the actual steam flow, unstable plug flow with large oscillation amplitudes occurs in the cold leg or in the hot leg pipe. The steam flow condensing on the subcooled ECC water oscillates strongly, while the water plug is expelled to the downcomer or upper plenum, respectively. The intermittent formation of a new water plug can give rise to water hammer loads on the pipe walls.

At low steam flow and ECC injection rates, stable stratified flow can occur up to the vertical dot-dash line (drawn in Fig. 11 and 12) which marks the minimum condensation potential of the ECC water where the steam momentum flux is sufficiently high to form a water plug.

The UPTF tests reveal that:
- plug flow occurs when the condensation potential of the ECC water exceeds the steam flow, typical for accumulator injection,
- the flow is stratified when the condensation potential of the ECC water is less than the steam flow
- plug flow results in intermittent ECC delivery into the downcomer or upper plenum, respectively, while stratified flow causes continuous ECC delivery.
3.2.4.2 Flow conditions in hot leg during reflux condenser mode

In the reflux condenser mode heat is transferred from the core to the secondary side of the steam generators by evaporation of water in the core and subsequent condensation of the steam in the U-tubes of the steam generators. A portion of the condensate flows counter-currently to the steam through the hot leg via the upper plenum back into the core. Due to momentum exchange between the up-flowing steam and the down-flowing water in the hot legs flooding may occur, which could prevent or at least deteriorate the water flow back to the core.

Countercurrent flow in PWR hot legs has been investigated at sub-scale facilities with pipe diameters up to 200 mm (see Fig. 13).

To provide CCFL data for full-size geometry, UPTF tests were performed. The results are plotted in Fig. 14 using the Wallis parameter $J'$. The data show that water runback to the test vessel decreases as the steam flow increases. At high steam flows ($J' > 0.5$), there was complete turn-around of the water-flow. The close agreement of the data at the two-phase pressure indicates that the Wallis parameter adequately accounts for pressure effects.
In Fig. 14 the UPTF tests are compared to CCFL correlations derived from sub-scale experiments. The Krolewski correlation under-predicts UPTF water runback, on the other hand the Ohunki correlation over-predicts runback. The Richter correlation however, passes through the UPTF data, which is obviously due to the similar configuration of the flow channel.

The UPTF test No.11 has demonstrated that a substantial margin exists between the flooding limit and the typical conditions expected in a PWR during reflux condenser mode of a small leak LOCA.

3.2.5 Test Facilities investigating the “Direct ECC Bypass”

Recently, a new scaling law for the EC bypass phenomena during the LBLOCA reflood phase for reactors with “Direct Vessel ECC-injection ” has been developed [22],[23]. The Direct Vessel Injection (DVI) Mode, where the emergency core cooling water is injected via a separate nozzle directly into the reactor vessel downcomer, is one of the characteristic design features of the advanced Pressurized Water Reactor APR1400.

In Fig.15 the two ECC Bypass phenomena, the “Direct ECC Bypass” and the “Water Sweep-out” are indicated. For the situation, that the mixture level in the downcomer is shortly below the elevation of the main primary coolant pipes, the steam flow in the downcomer from the intact cold legs to the broken cold leg sweeps water from the steam-water mixture level in the direction of the broken leg (Water Sweep-out). The supply of ECC coolant, injected via separate nozzles, leads to the refill of the downcomer and in consequence to the reflood of the core. However, a part of the injected ECC water is flowing directly to the broken cold leg (Direct ECC Bypass) and is lost for the downcomer refilling. It is known, that the Direct ECC Bypass is the main bypass mechanism.

As the Direct ECC Bypass is depending from both, the fluid-dynamic boundary and the downcomer geometry, the scaling of a down-scaled test facility is of great importance. Based on a thorough investigation of the main parameters influencing these phenomena a new scaling approach, called “modified linear scaling ” has been developed.

Based on the description of the thermal-hydraulic processes in the downcomer by the two-dimensional continuity and momentum equations of a two-fluid model [24], a set of non-dimensional equations has been derived leading finally to the proposed modified linear scaling law.

This scaling law has the same geometrical similarity as the linear scaling law, however, the Wallis type dimensionless parameter is chosen for velocity scaling of the steam and ECC water. And thus it gives the characteristics where the velocity and time scales are reduced according to the square root of the length scale. In Table 3 the scaling ratios of the “modified linear scaling” are listed.

Validation of codes by using experimental data obtained from different scaled test facilities demonstrated that the “modified linear scaling methodology” is appropriate for the design of a down-scaled facility investigating the Direct ECC Bypass in the reflood phase of a LBLOCA. Nevertheless, there is still work required to complete the scaling method, such as mechanistic scaling analysis of the interfacial heat transfer using an energy conservation equation.

Figure 15: Direct ECC Bypass and Water Sweep-out.
Table 3: Scaling Ratio of the “Modified Linear Scaling”.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scale Ratio</th>
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<tbody>
<tr>
<td>Length Ratio</td>
<td>$l_R$</td>
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<tr>
<td>Area Ratio</td>
<td>$(l_R)^2$</td>
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<tr>
<td>Time Ratio</td>
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4. FUTURE TRENDS IN THE DEVELOPMENT OF THERMAL-HYDRAULIC CODES

The refinement of the thermal-hydraulic system-codes, the completion of the validation and the quantification of the uncertainties in the simulation of full size plant accidents is one of the tasks for the next 5 to 10 years.

However, the main effort in the analytical work will be focused in the future on the development of Two-phase Flow CFD-codes. Due to the high solution in space and the possibility for the three-dimensional description of the single- and two-phase flow phenomena the scaling problem will become less important. Parallel to the progress in the development of the computer hardware the application area of these codes will be extended.

The development of the Two-phase Flow CFD-codes is a great challenge for the analytical teams in the next decades and may contribute to the motivation of young scientists which are working in the field of nuclear technology.

NOMENCLATURE

Similarity Groups by Ishii and Kataoka

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>Flow area</td>
</tr>
<tr>
<td>d</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>f</td>
<td>Friction factor</td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
</tr>
<tr>
<td>K</td>
<td>Orifice coefficient</td>
</tr>
<tr>
<td>l</td>
<td>Axial length</td>
</tr>
<tr>
<td>u</td>
<td>Velocity (liquid)</td>
</tr>
<tr>
<td>x</td>
<td>Vapour quality</td>
</tr>
<tr>
<td>q''</td>
<td>Heat flux</td>
</tr>
<tr>
<td>α</td>
<td>Void fraction</td>
</tr>
<tr>
<td>ΔH_f</td>
<td>Latent heat</td>
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<tr>
<td>ΔH_sub</td>
<td>Subcooling</td>
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<tr>
<td>Δρ</td>
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<tr>
<td>ρ</td>
<td>Density of liquid</td>
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<tr>
<td>μ</td>
<td>Viscosity of liquid</td>
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Subscripts

<table>
<thead>
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<th>Definition</th>
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<tr>
<td>i</td>
<td>ith section</td>
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<tr>
<td>0</td>
<td>Reference constant</td>
</tr>
<tr>
<td>g</td>
<td>Vapour</td>
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Glaeser Correlation

- Bo: Bond number
- $d_{av}$: Downcomer average diameter
- Fr: Froude number
- g: Gravity
- L: Characteristic geometrical length
- $\Theta_{ECC-BCL}$: Angle between ECC injection leg and broken loop
- $\nu$: Kinematic viscosity
- $\rho$: Density

Subscripts:
- g: Vapour
- l: Liquid

REFERENCES


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