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Fluid-to-fluid modeling of natural circulation boiling loops for stability analysis

C.P. Marcel *, M. Rohde, T.H.J.J. Van der Hagen

Department of Physics of Nuclear Reactors, Delft University of Technology, Mekelweg 15, Delft 2629 JB, The Netherlands

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Abstract

Gravity driven flows may induce oscillations influencing the stability of natural circulation nuclear boiling water reactors. To experimentally study such phenomenon, a facility based on fluid-to-fluid downscaling modeling is proposed. New design criteria are developed for that purpose. It is found that a unique geometrical scale has to be used for all radial and axial dimensions. Moreover, the geometry and the time scaling are not independent each other. A Freon-based downscaled version of the economical simplified boiling water reactor (ESBWR) is designed and constructed based on the derived scaling rules. Experimental results show good agreement with numerical simulations regarding the static behavior and also the stability performance.

Keywords: Fluid-to-fluid scaling; Thermal–hydraulic stability; Boiling water reactors; Natural circulation loops

1. Introduction

In order to guarantee the safety of the next generation of nuclear reactors, special emphasis has been set to replace active systems by passive ones. In such line is the economic simplified boiling water reactor (ESBWR), which is a generation III+ nuclear reactor according to the generation IV classification. The ESBWR design eliminates the need for circulation pumps and associated piping and systems. Furthermore, the reactor was designed to provide large margins to instabilities [1]. This type of reactor however, has not been built yet and, therefore, its thermal–hydraulic stability was never demonstrated experimentally.

The knowledge regarding the interaction between the two-phase flow present in the reactor and the heat produced is still not complete. One of the most important reasons is that the calculations of the two-phase flow are still beyond current computational capabilities (see, for instance [2]). To fill this gap, a well instrumented system, designed to have a similar stability behavior to the ESBWR, was developed. Real reactor conditions, however, involve high power, high pressure and, particularly in the ESBWR case, large dimensions. To deal with this constraint, a fluid-to-fluid scaling approach was therefore followed. The work of Van de Graaf and Van der Hagen [3] was used as a starting point.

It needs to be emphasized that Van de Graaf and Van der Hagen [3] focused on the proper downscaling of the reactor core bundle. To achieve a successful similarity of the thermal–hydraulic stability performance of the reactor however, more attention has to be paid to the proper scaling of the facility in terms of the inertia and the friction distribution in the whole loop. For this reason, the work of Van de Graaf and Van der Hagen [3] is extended to cover a global fluid-to-fluid downscaling design (i.e. scaling each relevant section) that guarantees a similar stability performance for the original and downscaled system. Since dynamic similarity has to be achieved, the time scaling was analyzed in depth. Moreover, the main distortions caused by the use of fluid-to-fluid downscaling for stability studies are discussed and a way of diminishing their effect is also presented and tested numerically. Finally, the sensitivity of the geometrical downscaling to the operational pressure was also investigated.

* Corresponding author. Tel.: +31 15 278 3811.
E-mail address: c.p.marcel@tudelft.nl (C.P. Marcel).

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Nomenclature

Normal alphabet

A	cross sectional area (m^2)
C_0	distribution parameter (–)
cp	heat capacity (kJ/kg K)
D	diameter (m)
K	local pressure drop coefficient (–)
L	length (m)
f	frictional factor (–)
g	gravitational acceleration ($m\,s^{-2}$)
G_m	mass flux density ($kg\,m^{-2}\,s^{-1}$)
h	enthalpy ($kJ\,kg^{-1}$)
N	number (–)
M	mass flow rate ($kg\,s^{-1}$)
p	pressure ($kg\,m^{-1}\,s^{-2}$)
q	power transferred from fuel to coolant ($J\,s^{-1}\,m^{-1}$)
s	variable in the Laplace domain (s^{-1})
t	time (s)
$\bar{\vartheta}_{gj}$	weighted mean drift velocity ($m\,s^{-1}$)
T	temperature (°C)
X	scaling factor

Non-dimensional variables

N_{zu}	Zuber number number $N_{PCH} \equiv \frac{q_{tot}}{A_{Core}G_{m,0}h_{fg}}\frac{\rho_l-\rho_v}{\rho_v}$
N_ρ	density ratio number $N_\rho \equiv \frac{\rho_v}{\rho_l}$
N_{sub}	subcooling number $N_{sub} \equiv \frac{h_{l,sat}-h_{l,inlet}}{h_{fg}}\frac{\rho_l-\rho_v}{\rho_v}$
$N_{P\acute{e}}$	Péclet number $N_{P\acute{e}} \equiv \frac{G_{m,0}c_{P,l}D_h}{\lambda_l}$
N_g	geometry number $N_g \equiv \frac{D_h}{L_{Core}}$
N_f	Friction number $N_f \equiv f\frac{D_h}{L_0}$
N_{Fr}	Froude number based on $D_h N_{Fr} \equiv \frac{G_{m,0}^2}{\rho_{v,0}^2 g\cdot D_h}$
N_{we}	Weber number based on $D_h N_{We} \equiv \frac{(G_{m,0})^2\cdot D_h}{\rho_l\cdot\sigma}$

Greek symbols

α	void-fraction (–)
Υ	absolute friction factor (–)
λ	thermal conductivity (J/m K)
ρ	density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)
τ	time constant (s)
χ	vapor quality (–)

Subscripts and superscripts

*	dimensionless
^	Laplace transformed variable
< >	spatial average
0	characteristic
a	axial
Bundle	core bundle
Core	core
CHF	critical heat flux
DC	downcomer
driv	buoyancy driving force
exit	chimney exit
fg	difference between (saturated) vapor and liquid properties
g	geometry
h	hydraulic (diameter)
inlet	core inlet
l	liquid
loss	regarding drag forces
m″	mass flux
P	power
Press	pressure
r	radial
R-134	Freon R-134a
Chimney	chimney
rod	regarding fuel pin rod
sat	saturation
SV	separation vessel
TP	two-phase
t	time
tot	relative to the whole facility
v	vapor
water	water

As result of the scaling approach developed in this paper, the natural circulation GENESIS facility, which is a downscaled version of the ESBWR, was constructed. Finally, the GENESIS facility was used to test the scaling criteria shown in this work. The experimental results are compared with those performed with the ATHLET computer code and to some extent with results obtained with the TRACG code.

2. Scaling of the assembly

According to the characteristics of the specific problem, there are different scaling criteria for modeling the various two-phase systems characteristics, such as the average void-fraction, pressure drop and critical heat flux (see for instance the overview of Kakaç and Mayinger [4]). By non-dimensionalising the balance equations governing the problem, a number of dimensionless similarity groups can be found. This number, however, is larger than the number of parameters that can be adjusted in the design of the facility. This means a selection of the most important parameters (which in turn control the physics that is desired to be preserved) must be addressed.

In the present work, the so-called fluid-to-fluid scaling approach was used. This means that a fluid different from the original one was used in the downscaled system. A correct choice of such a fluid may allow a great reduction in power, pressure and temperature.

The flow inside a BWR assembly may vary from unsaturated single-phase flow to annular two-phase flow. In order to be able to design a scaled version of the ESBWR with a coolant different than water, scaling criteria are therefore necessary that cover all flow regimes present in the assembly. In the lower part of the assembly the coolant is not in thermal equilibrium. The development of the flow quality in this subcooled boiling regime and the required inlet enthalpy of the liquid can be scaled properly if the phase change number and the subcooling number are used as scaling parameters. Consequently, these parameters fix the development of the quality in the upper part of the assembly, where the coolant is in thermal equilibrium. Van de Graaf and Van der Hagen [3] found that the Froude number and a Weber number as given by Ishii and Jones [5], should be used as scaling parameters to ensure proper scaling of all flow regimes. It needs to be pointed out here that, by selecting a specific coolant, it is not possible to define externally the system set-up parameters such as scaling factors, pressure, temperature and power. The scaling simply fixes these parameters.

It has to be stressed that the approach recommended by Van de Graaf and Van der Hagen [3] shows results that are in agreement with those of Symolon [6], who performed a simulation of the slip ratios as a function of the void-fraction using a one-dimensional fully developed two-fluid model. In such analysis the similarity in the predicted slip ratios is excellent, except for the viscous bubbly regime. He also experimentally demonstrated that similar flow regime transition boundaries occur in Freon as in steam/water if the Weber and Froude numbers are kept the same.

3. Scaling procedure proposed for stability investigations

The scaling is based on the fact that two systems which can be represented by analogous differential equations should have the same type of solution, and thus the same physical behavior. Based on this idea, the mass, momentum and energy conservation differential equations together, with two more equations derived from the drift-flux model [3], are mathematically manipulated in order to find the intrinsic parameters and variables that define the problem.

The whole scaling procedure is summarized in Fig. 1, showing the most important steps that need to be followed.

From the manipulation of the balance equations, a number of dimensionless numbers were found. These dimensionless numbers are the density ratio N_ρ; the subcooling number N_{Sub}; the friction number N_{f}; the geometry number N_{g}; and the phase change number N_{PCH} [7,3,8].

These numbers need to be the same in both the facility and the reactor if similarity is to be achieved.

The drift-flux model parameters C_0 and $\bar{\vartheta}_{gj}$ (the distribution parameter and the weighted mean drift velocity, respectively) are assumed to correctly describe the flow transitions in the reactor and were therefore used to characterize the flow pattern [3]. To assure the same flow pattern in the facility as in the reactor (which is of great importance for a correct scaling) the equations describing the C_0 and the $\bar{\vartheta}_{gj}$ were therefore converted into their dimensionless form. In this way, two more scaling parameters arise, being the Froude dimensionless number, N_{Fr}, and the Weber dimensionless number, N_{We} [3].

In the present work Freon R-134a (CH_2FCF_3) was selected for the downscaling of the ESBWR, since its physical properties allow a great reduction in both the power and the pressure. Consequently, by selecting the liquid, all scaling parameters are quantified.

Looking further downwards in Fig. 1, three main branches arise from the scaling rules: in the first branch the operational point of the fluid (in the saturation line) is defined, in the second branch the geometrical scaling is shown, and in the last branch the scaling of the operational conditions is presented.

3.1. Defining the operational point

The starting point of the whole scaling procedure is the matching of the so-called density number N_ρ from which the operational point (namely nominal saturation pressure, P_{sat} and the nominal saturation temperature, T_{sat}) can be determined (see Fig. 1 left-hand branch). This matching gives a unique solution since the density number is a monotonical function of the pressure (along the saturation line). Thus, the dimensionless density number is

$$\frac{N_{\rho,\mathrm{R\text{-}134a}}}{N_{\rho,\mathrm{water}}} = 1 \rightarrow N_\rho = \frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}} = 5.03 \times 10^{-2}, \tag{1}$$

where the subindexes R-134a and water, refer to Freon R-134a and water, respectively.

As result it was found that the ESBWR operational nominal pressure of 7.1 MPa can be reduced to 1.14 MPa in the downscaled facility. Hence, the pressure scaling factor X_{Press}, is found to be

$$X_{\mathrm{Press}} = \frac{P_{\mathrm{R\text{-}134a}}|_{\mathrm{facility}}}{P_{\mathrm{water}}|_{\mathrm{ESBWR}}} = 0.16 \text{ (for water at 7.1 MPa)}. \tag{2}$$

Once the pressure is found, all the Freon fluid properties are known. A comparison between the water and the Freon fluid properties is shown in Table 1.

3.2. Scaling the geometry

In order to achieve the same flow pattern in the downscaled facility as in the ESBWR, the Weber and the Froude numbers need to be kept the same (see Fig. 1, second branch). From this requirement the core radial geometry scaling factor $X_{\mathrm{Core,r,g}}$ can be derived,

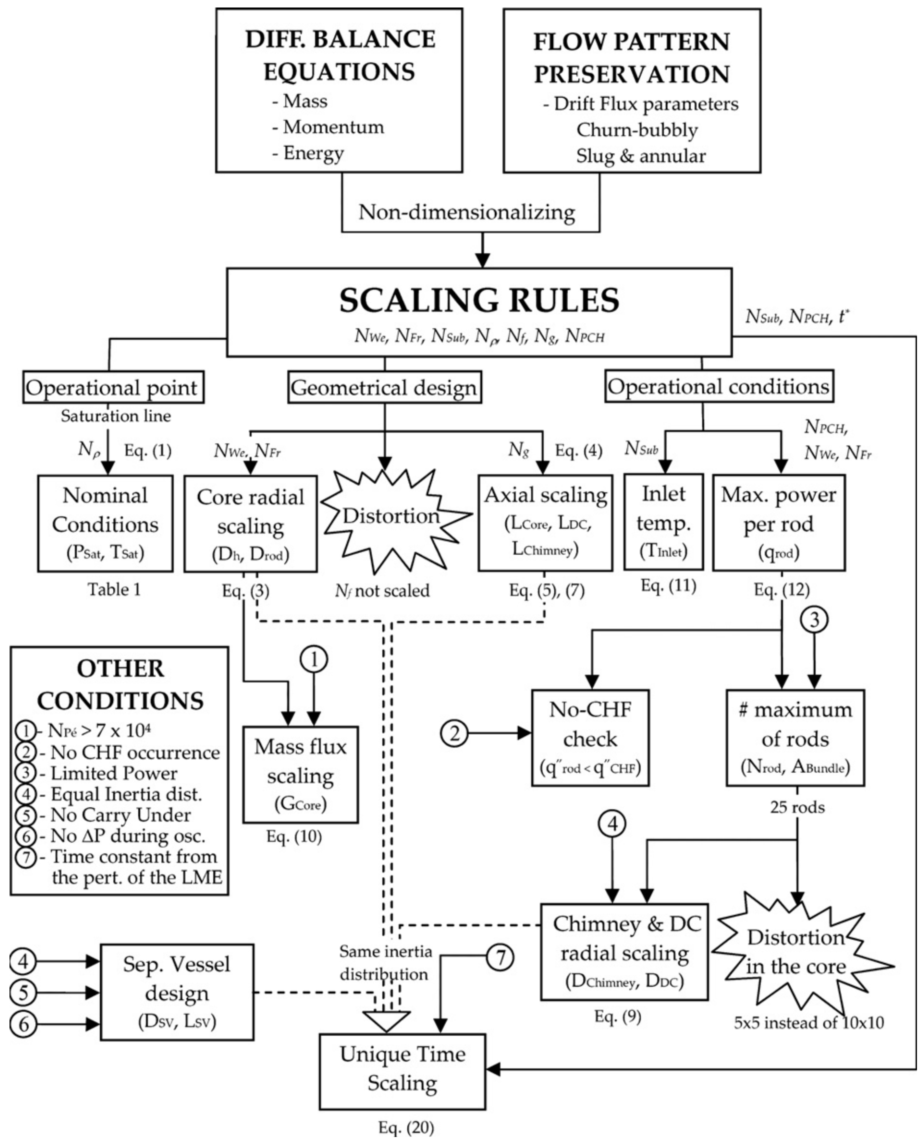

Fig. 1. Basic block diagram of the scaling procedure.

$$X_{\text{Core,r,g}} = \frac{D_{\text{h,R-134}}}{D_{\text{h,water}}} = \left(\frac{\sigma_{\text{R-134}}\rho_{\text{l,water}}}{\sigma_{\text{water}}\rho_{\text{l,R-134}}}\right)^{1/2} = 0.46. \tag{3}$$

From the dimensionless form of the momentum balance equation of the flow in the core, it can be seen that the radial and axial dimensions are related by the geometry number, N_{g} which needs to be kept the same for a proper scaling. Thus, the core axial and radial geometry scaling factors $X_{\text{Core,a,g}}$ and $X_{\text{Core,r,g}}$, respectively, also need to be the same. Consequently,

$$X_{\text{Core,r,g}} = X_{\text{Core,a,g}} = \frac{L_{\text{Core,R-134}}}{L_{\text{Core,water}}}. \tag{4}$$

In the downscaled facility the same balance of buoyancy-to-drag forces has to be achieved as in the reactor. Such balance can be found by integrating the steady state momentum balance equations within the loop. As a result of that, the following relation for the square of the dimensionless total mass flow rate, M^{*2}, which needs to be equal for the two systems, is found.

$$M^{*2} = \frac{\frac{L^*_{\text{DC}}}{N_{Fr}} - \frac{L^*_{\text{Core}}}{N_{Fr}}\left[N_\rho\alpha + (1-\alpha)\right] - \frac{L^*_{\text{Chimney}}}{N_{Fr}}\left[N_\rho\alpha + (1-\alpha)\right]}{\frac{1}{2A^{*2}_{\text{Core}}}\left[\left(N_{\text{f,Core,TP}} + \sum_j K_{j,\text{Core,TP}}\right) + \frac{A^{*2}_{\text{Core}}}{A^{*2}_{\text{Chimney}}}\left(L^*_{\text{Chimney}}N_{\text{f,Chimney,TP}} + \sum_j K_{j,\text{Riser,TP}}\right) + \frac{A^{*2}_{\text{Core}}}{A^{*2}_{\text{DC}}}N_{\text{f,DC}}L^*_{\text{DC}}\right]} \tag{5}$$

Table 1
Physical properties of saturated Freon R-134a and water at the operational pressure

Property	Freon R-134a[a]	Water[b]
Liquid density, ρ_l/kg m^{-3}	1128.3	738.23
Vapour density, ρ_v/kg m^{-3}	56.49	37.117
Saturation temperature, T_{sat}/°C	44.27	286.6
Latent heat, h_{fg}/kJ kg^{-1}	158.39	1499
Surface tension, $\sigma \times 10^3$/N m^{-1}	5.6	17.3

[a] Properties calculated at 1.14 MPa.
[b] Properties calculated at 7.1 MPa.

In the numerator, the Froude and density numbers, together with the void-fraction (determined by the phase change and subcooling numbers), are already kept the same in the downscaled facility and the reactor. In addition, the dimensionless lengths of all the sections need to be matched. This means that all lengths in the facility need to be downscaled following the same rule. Consequently, Eq. (3) has to be applied to all parts present in the downscaled facility. Especially the chimney section needs to be properly scaled since both the core and the chimney (and therefore the downcomer also) determine the driving head. The axial geometry scaling factor $X_{a,g}$, is therefore the same for all sections (see Fig. 1),

$$X_{a,g} = X_{Core,a,g}. \tag{6}$$

In a natural circulation loop, the mass flow rate M can be described by the loop momentum equation, which (in its dimensionless form) can be written as

$$\frac{dM^*(t)}{dt^*} = \frac{\Delta P^*_{driv}(t) - \Delta P^*_{loss}(t)}{\sum_i \frac{l^*_i}{A^*_i}}, \tag{7}$$

with $\Delta P^*_{driv}(t)$ being the driving force of the flow and $\Delta P^*_{loss}(t)$ the pressure losses [9]. From Eq. (7) it is clear that the inertia of the loop (playing an important role in the dynamics of the system) is determined by the summation in the denominator of all dimensionless length-to-area ratios present in the loop. Hence, to get the same dynamic response in the downscaled system as in the ESBWR, all radial dimensions in the facility have to be scaled by the same rule as the lengths [16]. Hence, a unique geometrical scaling factor X_g, exists for all dimensions of the facility.

$$X_g = X_{a,g} = X_{r,g} = \left(\frac{\sigma_{R\text{-}134}\rho_{l,water}}{\sigma_{water}\rho_{l,R\text{-}134}}\right)^{1/2}. \tag{8}$$

Another result of the matching of the Weber and the Froude numbers is the scaling rule for the mass flux (expressed by the mass flux scaling factor $X_{\dot{m}''}$)

$$X_{\dot{m}''} = \frac{G_{0,R-134}}{G_{0,water}} = \left(\frac{\sigma_{R-134}}{\sigma_{water}}\right)^{1/4}\left(\frac{\rho_{l,R\text{-}134}}{\rho_{l,water}}\right)^{3/4} = 1.007. \tag{9}$$

3.3. Scaling the operational conditions

To properly scale the quality profile in the heated section, the subcooling number N_{Sub}, and the phase change number N_{PCH}, need to be matched. The phase change number defines the power to be applied per rod (by means of the power scaling factor, X_P) and the subcooling number defines the Freon inlet temperature T_{in} (see the right-hand branch of Fig. 1). From these requirements, together with Eqs. (8) and (9) these dimensionless numbers are

$$N_{Sub}|_{facility} = N_{Sub}|_{ESBWR} = \frac{h_{inlet} - h_{sat}}{h_{fg}}\frac{\rho_l - \rho_v}{\rho_v} = 0.95 \rightarrow T_{inlet}|_{facility} = 39.8\,^{\circ}C\Big|_{R\text{-}134a}. \tag{10}$$

$$\frac{N_{PCH}|_{facility}}{N_{PCH}|_{ESBWR}} = 1 \rightarrow X_P = \frac{q_{facility/rod}}{q_{ESBWR/rod}} = \left(\frac{\rho_{l,water}}{\rho_{l,R\text{-}134a}}\right)^{1/4}\left(\frac{\sigma_{R\text{-}134a}}{\sigma_{water}}\right)^{5/4}\left(\frac{h_{fg,R\text{-}134a}}{h_{fg,water}}\right) = 0.023. \tag{11}$$

The phase change number together with the subcooling number defines the operational point in the stability plane [10], hence stability comparisons can be made between the downscaled facility and the ESBWR when these two numbers are the same.

As can be noted from Eq. (11), the scaling relation refers to the power *per rod*. Another external constraint, however, exists (related to the maximum available power for the experimental facility) which fixes the number of heating rods, N_{rod}, in the core section of the scaled facility (see Fig. 1, third branch). As can be seen from Eqs. (2), (9) and (11), the scaling rules do not define absolute quantities but relative quantities (e.g. hydraulic diameter of the core bundle, mass flux and power per rod). Moreover, the final radial dimensions of the sections (e.g. the bundle area, A_{Core}, the chimney diameter $D_{Chimney}$, and the downcomer diameter D_{DC}) and the mass flow rate are determined by the number of heating rods that can be used to operate the facility (see Fig. 1). In the particular case presented in this paper, the available power allowed to have a maximum of 25 downscaled ESBWR heating rods which were arranged in a 5×5 square lattice.

Other requirements that need to be fulfilled by the facility are: the critical heat flux, CHF phenomenon (see [11]) needs to be absent (condition 2 in Fig. 1) and vapor separation without the introduction of carry-under has to be achieved (condition 5 in Fig. 1). Furthermore, the Péclet number $N_{Pé}$, has to be larger than 7×10^4 in the facility (condition 1 in Fig. 1) in order to assure that the Weber and the Froude numbers correctly describe the flow. This requirement assures the void ejection is hydrodynamically controlled [12].

3.4. Time scaling

From the scaling equations, it follows that time is not a scaled parameter in the facility. Since we are interested in the dynamics of the reactor, the determination of the correspondence between the two times becomes an important issue. In this section, perturbation theory is used to derive the time scaling rule from the linearized momentum equations (LME).

The non-dimensionless version of Eq. (7) derived from the momentum balance equation of the whole loop is

$$\frac{\mathrm{d}M(t)}{\mathrm{d}t} = \frac{\Delta P_{\mathrm{driv}}(t) - \Delta P_{\mathrm{loss}}(t)}{\sum_i \frac{l_i}{A_i}}, \tag{12}$$

where the driving forces can be estimated by considering the void-fraction in the core plus the chimney section. This leads to

$$\Delta P_{\mathrm{driv}}(t) = \langle\alpha\rangle L_{\mathrm{tot}} \Delta\rho \cdot g, \tag{13}$$

where $\langle\alpha\rangle$ represents the average void-fraction over the assembly plus chimney sections and L_{tot} is the correspondent total length. The frictional pressure drop is modeled as $\Delta P_{\mathrm{loss}}(t) = a \cdot M^2$ where the parameter a originates from the requirement that $\mathrm{d}M/\mathrm{d}t = 0$ at the stable operating point.

The loop momentum balance equation is linearized by making use of the following set of equations.

$$\begin{aligned} \langle\alpha\rangle_{(\mathrm{t})} &= \langle\alpha\rangle_0 + \delta\langle\alpha\rangle_{(\mathrm{t})} \\ M_{(\mathrm{t})} &= M_0 + \delta M_{(\mathrm{t})} \end{aligned} \tag{14}$$

and the steady state momentum balance can be written as

$$a \cdot M_0^2 = \langle\alpha\rangle_0 L_{\mathrm{tot}} \Delta\rho \cdot g. \tag{15}$$

By Laplace transforming, the transfer function from void-fraction fluctuations to flow rate fluctuations can be derived. As result of this, the transfer function is found as

$$\frac{\delta\widehat{M}}{\delta\widehat{\alpha}} = \frac{M_0}{2\langle\alpha\rangle_0} \frac{1}{1 + s\tau}, \tag{16}$$

where $\widehat{M}$ and $\widehat{\alpha}$ are the Laplace transforms of M and α, respectively, and s the Laplace variable. The time constant of this transfer function is thus

$$\tau = \frac{M_0 \sum_i \frac{l_i}{A_i}}{2\langle\alpha\rangle_0 L_{\mathrm{tot}} \Delta\rho \cdot g}. \tag{17}$$

The time scaling, X_{t}, can now be determined by taking the ratio of the time constants, expressed in Eq. (17), for the facility and the reactor, thus

$$X_{\mathrm{t}} = \frac{\tau|_{\mathrm{facility}}}{\tau|_{\mathrm{ESBWR}}} = \left[\frac{\frac{A_{\mathrm{Core}}}{L_{\mathrm{tot}}} \sum_i \frac{l_i}{A_i}\Big|_{\mathrm{facility}}}{\frac{A_{\mathrm{Core}}}{L_{\mathrm{tot}}} \sum_i \frac{l_i}{A_i}\Big|_{\mathrm{ESBWR}}} \right] \frac{G_{\mathrm{m},0}|_{\mathrm{facility}}}{G_{\mathrm{m},0}|_{\mathrm{ESBWR}}} \frac{2\langle\alpha\rangle_0 \Delta\rho \cdot g|_{\mathrm{ESBWR}}}{2\langle\alpha\rangle_0 \Delta\rho \cdot g|_{\mathrm{facility}}}. \tag{18}$$

The term within brackets cancels out due to the geometrical scaling rules (see Eq. (8)). The mean void-fraction terms also cancel out since in the downscaled facility the void profile is kept the same as in the ESBWR (since this is one of the most important requirements of the scaling). By using the definition of the mass flux scaling factor Xm'', Eq. (18) can be expressed as

$$\frac{\tau|_{\mathrm{facility}}}{\tau|_{\mathrm{ESBWR}}} = X_{\dot{m}''} \frac{\Delta\rho_{\mathrm{water}}}{\Delta\rho_{\mathrm{R\text{-}134a}}} = X_{\dot{m}''} \frac{\rho_{\mathrm{water,l}}}{\rho_{\mathrm{R\text{-}134,l}}} \frac{(1 - N_{\rho,\mathrm{water}})}{(1 - N_{\rho,\mathrm{R\text{-}134}})}. \tag{19}$$

The operational point of the facility was chosen so the density number N_ρ is kept the same as in the ESBWR (see Eq. (1)). By using Eq. (9), the time scaling factor X_{t}, is therefore found as

$$X_{\mathrm{t}} = \frac{\tau|_{\mathrm{facility}}}{\tau|_{\mathrm{ESBWR}}} = \left(\frac{\sigma_{\mathrm{R\text{-}134}}}{\sigma_{\mathrm{water}}} \frac{\rho_{\mathrm{l,water}}}{\rho_{\mathrm{l,R\text{-}134}}} \right)^{1/4} = 0.68. \tag{20}$$

The last result can also be found by comparing the dimensionless time arising from the differential equations and from comparing the transit times defined as indicated by Zboray [13]. It can be concluded that for the scaling performed as described in this paper, a unique time scaling exists. Furthermore, the time scaling is independent of operational parameters (such as the power and the inlet temperature) defined by merely the physical properties of the two fluids. Moreover, Eq. (20) shows that the time is not scaled 1:1 but runs $1/0.68 = 1.45$ times faster in the downscaled facility than in the ESBWR.

By calculating the break frequency associated to the ESBWR time constant of the void-to-flow transfer function at nominal conditions, as expressed by Eq. (17), the following result is obtained

$$\begin{aligned} \tau|_{\mathrm{ESBWR}} &= \frac{M_0 \sum_i \frac{l_i}{A_i}}{2\langle\alpha\rangle_0 L_{\mathrm{tot}} \Delta\rho \cdot g} = \frac{12{,}000\,\frac{\mathrm{kg}}{\mathrm{s}}\ 3.2\,\frac{1}{\mathrm{m}}}{2 \times 0.7 \times L_{\mathrm{tot}} \cdot \Delta\rho \cdot g} \\ &= 0.23\ \mathrm{s} \rightarrow f|_{\mathrm{ESBWR}} \approx 0.7\ \mathrm{Hz}. \end{aligned} \tag{21}$$

This frequency is in the order of magnitude for the typical frequencies of BWRs type II oscillations (~1 Hz) and therefore cannot be neglected as other authors recommended (see [14]). Furthermore, the downcomer section contributes with roughly two thirds of the summation in the numerator, which means the preservation of inertia is important in order to achieve a correct scaling of the dynamical behavior.

By comparing Eqs. (20) and (8), it is found that a direct relation exists between the time scaling factor X_{t}, and the geometrical scaling factor X_{g}. This relation is

$$X_{\mathrm{t}} = X_{\mathrm{g}}^{1/2}. \tag{22}$$

An important implication of Eq. (22) is that the geometrical and temporal scaling is not independent in buoyancy driven systems. Hence, a scaling based on merely the core and the chimney sections (as performed by Kok et al. [15]) leads to an erroneous time scaling and therefore, an erroneous dynamic response.

It needs to be emphasized that the difference in the time speed is not a distortion but a result of the scaling and, therefore, does not need to be corrected for.

4. Analysis of the distortions

In the previous section, the scaling of the operational conditions, the geometry and the time was shown. As result of that scaling, the so-called 'distortions', appeared (see Fig. 1). The most important distortions are due to

– The friction dimensionless number N_f, not being properly scaled.
– A fuel bundle with a 5×5 rods arrangement instead of a 10×10 arrangement.

The influence of these distortions on the thermal–hydraulic stability of the system needs to be analyzed. Moreover, these distortions may need to be compensated in order to achieve the desired similarity between the scaled facility and the ESBWR.

4.1. Friction number not scaled

Using the geometry dimensionless number as scaling parameter implies that the friction number N_f may be different for the facility and the reactor [16]. This can be clearly seen when comparing the definitions of the geometry and the friction dimensionless numbers

$$N_g = \frac{D_h}{L_{Core}} \quad \text{and} \quad N_f = f\frac{D_h}{L_{Core}}, \tag{23}$$

where f is the single-phase friction factor (only the single-phase friction factor appears in the scaling rules since the homogeneous equilibrium model was used for describing the differential balance equations).

To analyze this distortion more accurately, the two-phase friction factor for the operational conditions, both for water and Freon, was determined by using the correlations suggested by Zhang and Webb [17] (developed for Freons) and Müller and Heck [18]. Fig. 2 shows that the friction factor is indeed not the same in the scaled facility and in the ESBWR (comparison has to be done at the same quality value).

As result of this difference, the downscaled facility has extra friction that plays a role in the stability of the system.

4.2. Smaller core fuel bundle (5×5 instead of 10×10)

The effect of the reduced number of rods in the bundle (see Fig. 1) is a higher core friction because of the increment in the wetted perimeter per rod.

4.3. Compensation of the distortions

The net effect of the aforementioned distortions is that a larger friction exists in the facility. This extra friction is particularly important in the core because of the high quality combined with the relatively small hydraulic diameter.

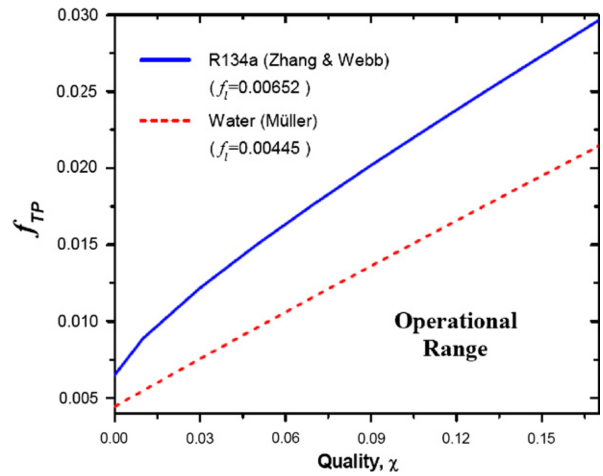

Fig. 2. Two-phase friction factor for water and Freon R-134a at their correspondent operational points in the ESBWR and the facility.

Marcel [19] showed that the stability of a natural circulation thermal–hydraulic system (in which the local restrictions are concentrated at the inlet and outlet of the channel, K_{inlet} and K_{exit}, respectively) is controlled by a dimensionless friction factor Υ defined as

$$\Upsilon = 2\frac{K_{inlet} + K_{exit}}{1 + K_{exit}}. \tag{24}$$

From the models implemented by these authors it is found that by preserving the scaling dimensionless factor Υ, the stability of the scaled facility and the ESBWR can be made similar by adjusting the chimney exit friction in such a way that Eq. (24) is kept the same for both systems.

To check the validity of the proposed correction a reduced order model [10] was used. In this analysis a value of 8% of core extra friction was assumed and later on *corrected* according to Eq. (24). Both results are then compared with the exact solution. The resulting thermal–hydraulic stability boundaries and their errors are shown in Fig. 3.

From the results of the reduced order model shown in Fig. 3, it can thus be concluded that the proposed method significantly diminishes the distortion caused by the extra core friction.

Although Eq. (24) was derived from a simplified model (the core friction located only at the inlet), its application in the downscaled version of the ESBWR is considered to be valid since the chimney section is very long and thus the core friction *distribution* (for the thermal–hydraulic stability) does not play an important role.

As can be seen in Fig. 3, ignoring the distortion caused by the core extra friction leads to a non-conservative determination of the stability characteristics of the ESBWR, since the stable region enlarges. By keeping the dimensionless friction using Υ the same, it can be assured that from the thermal–hydraulic stability point of view

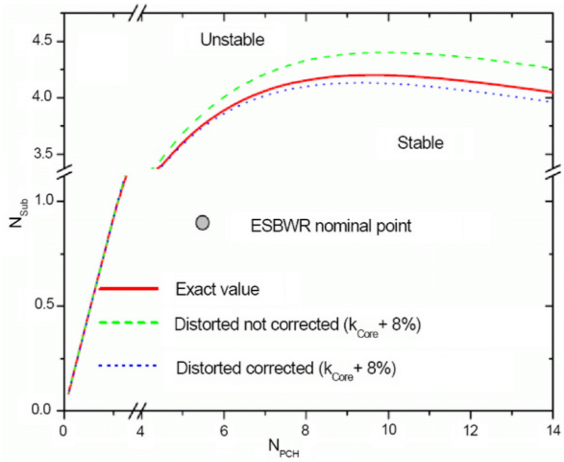

Fig. 3. The T–H stability boundaries (SBs) for three loop friction distributions: ideal case in which the friction is exactly downscaled (solid line); scaled case with no correction of the distortion (dashed line); corrected scaled system (dotted line).

the experimental results performed in the downscaled system will be slightly conservative.

4.4. Scaling sensitivity to the operational pressure

It may be of importance to study the stability performance of the ESBWR at a pressure different than the operational one, since a new method to control this reactor by changing the operational pressure is being considered. The downscaled facility, however, is designed to be operated at the point in which the density number is correctly matched (see Eq. (1)). For different pressures, the operational conditions (i.e. power and temperature inlet conditions) and geometry would need to be modified in order to scale the reactor in this new situation. The geometry of the facility, however, cannot be easily adjusted.

In order to investigate how the geometrical scaling, given by Eq. (8), should be modified when the operational pressure of the reactor is changed, Fig. 4 was constructed.

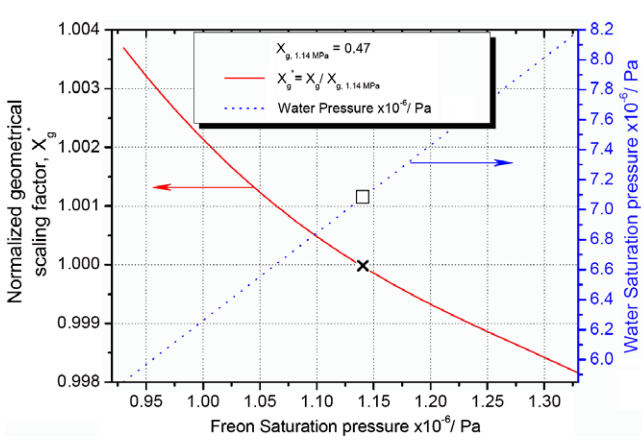

Fig. 4. Pressure relation between the ESBWR (water) and the downscaled facility (Freon R-134a). The resulting change in the geometrical scaling factor with respect of the original conditions (7.1 MPa in water) is also shown.

This figure shows the correspondence between the pressure in the ESBWR and the downscaled pressure in the facility. The figure has to be interpreted as follows: for a given reactor pressure at the right-hand side scale, the corresponding downscaled pressure is presented at the bottom scale (via the dotted line). The downscaled pressure can then be used to read the change in the geometrical scaling factor X_g, indicated by the left-hand side scale (via the solid line).

For instance, to investigate the scaling of the reactor at 6.4 MPa, the water-Freon saturation pressure line can be used to read the correspondent Freon operational pressure which in turn accounts to ~1.025 MPa. This Freon pressure is thus used to read the normalized scaling factor which in this example is ~1.0016.

Fig. 4 shows that, for a wide range of pressures, the change in the geometrical friction factor is less than 0.5% and therefore can be neglected. In other words, the stability of the ESBWR can be studied with a Freon R-134a based facility at a range of pressures without geometrical changes. Consequently, the change in the time scaling is also negligible. The new scaling factors defining the mass flux scaling, the power and the inlet subcooling, however, must be recalculated with the physical properties at the new pressure, according to Eqs. (9)–(11), respectively.

5. Results from the proposed scaling design approach

In order to analyze the proposed scaling design, the GENESIS facility was constructed according to the scaling rules developed in this paper. Fig. 5 shows a schematic view of this test facility.

The primary loop consists of a heated section, a chimney and a downcomer section. The vapor separation is done in the separation vessel which design assures that no carry-under occurs. The facility can be operated with natural or forced circulation. The heated section consists of a fuel bundle with 5 × 5 rods which represents a complete fuel bundle of the ESBWR. The core spacers and the tie plates are also located in the proper place. Numerous sensors located at different positions (thermocouples, capacitance void-fraction sensors, magnetic flowmeters and absolute and differential pressure sensors) allow characterizing the operational status of the facility (see [19] for a complete description of the GENESIS facility).

The results, obtained from the GENESIS facility, were compared with numerical simulations of the ESBWR by using the ATHLET system code [20] and the TRACG system code [21]. The results comprise the mass flux (which is an independent parameter) and the stability characteristics of the nominal point. In order to perform such a comparison, the same operational conditions, defined by the dimensionless phase change number, N_{PCH}, and the subcooling number, N_{Sub}, were used.

In Fig. 6 the obtained mass fluxes for different power conditions are shown.

In the ESBWR, core bypass channels are installed which were also included in the numerical simulation. These

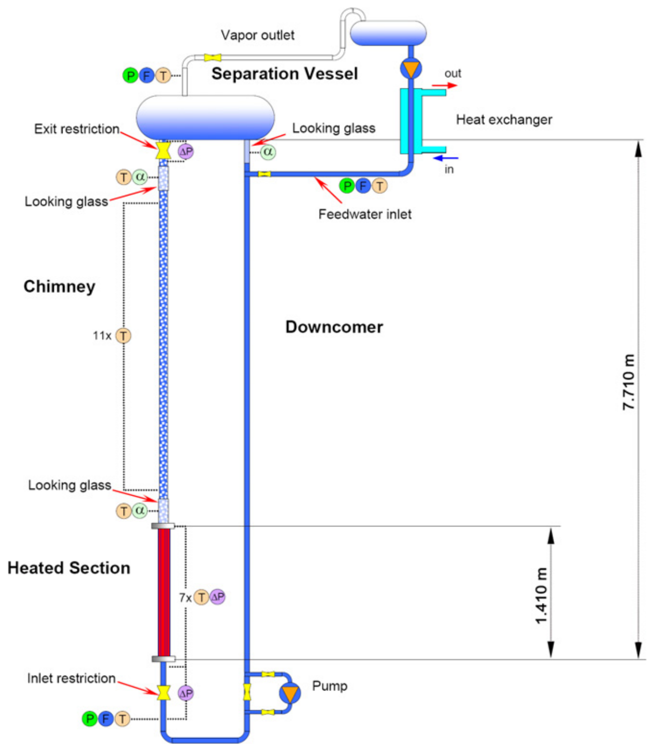

Fig. 5. Schematic view of the GENESIS facility (not to scale).

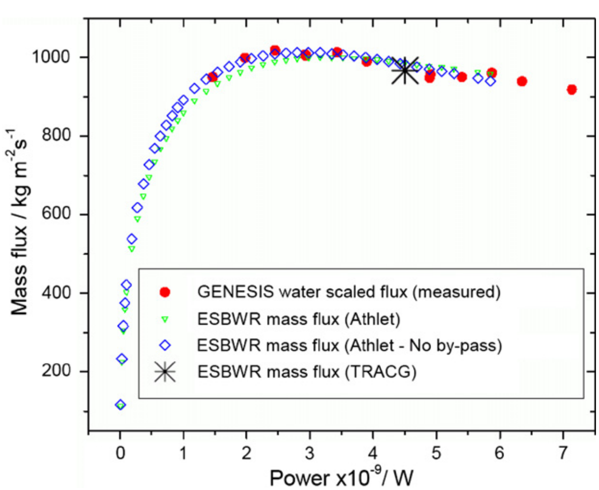

Fig. 6. The power-mass flux map as found in the numerical and experimental studies. The experimental GENESIS results have been rescaled to ESBWR scale.

bypasses, however, are not included in the facility due to the fact they do not significantly influence the stability. Nevertheless, for both cases, with and without the bypass, the resulting mass fluxes obtained from GENESIS and ATHLET show a very good agreement for the whole investigated range. As can be noted, the agreement between TRACG, ATHLET and GENESIS is also good for the nominal case.

The absence of experimental points at low power conditions is due to the difficulty to operate the GENESIS facility at low subcooling temperatures (close to the saturation point) since limitations exist on the maximum temperature at which the Freon can be introduced at the feedwater sparger position.

Table 2
Thermal–hydraulic stability characteristics for the nominal operational point

	GENESIS	ESBWR[a]	ESBWR[b]
Decay-ratio, DR (–)	0.12	0.11	–
Resonance frequency, f_{res}/Hz	0.11	0.13	0.083–0.17

[a] Obtained from numerical simulations performed in ATHLET code.
[b] Estimated from the typical period found for DWO (calculated as 1–2 times the raveling time through the channel) based on results obtained in TRACG code.

Besides the relation between the power and the mass flux, the thermal–hydraulic stability of the GENESIS facility and the ESBWR was investigated for nominal conditions. The resulting dynamics, obtained by slightly perturbing the steady state of the GENESIS facility running at nominal conditions, was used to extract the parameters which characterize its thermal–hydraulic stability. These parameters were the decay ratio DR, and the resonance frequency f_{res}. The same method was used regarding the numerical experiments performed in ATHLET code which allowed characterizing the ESBWR thermal–hydraulic stability performance. In addition to the GENESIS and ESBWR–ATHLET results, the expected natural frequency for density wave oscillations (DWO) was calculated from the TRACG results. The results of that study are presented in Table 2.

It is found that the experimental and numerical results show a good agreement for both the decay ratio and the natural frequency. The good agreement between the oscillation frequencies certifies the correct treatment of the time scaling proposed in Section 3.3. As a matter of completeness it can be mentioned that the resulting frequencies from both, ESBWR–ATHLET and GENESIS correspond well with the expected natural frequency estimated from the traveling time of the fluid through the hot channel (see [19]). This finding is in accordance with the expectable behavior of density wave oscillations (DWO).

6. Conclusions

The fluid-to-fluid scaling process for the simulation of the thermal–hydraulics of a natural circulation BWR has been revised and discussed in detail. Moreover, the importance of correctly scaling the inertia and the friction distribution has been shown. For stability investigations with fluid-to-fluid downscaled systems, the same geometrical scaling factor has to be used for the axial and radial dimensions of all the sections. If that rule is followed, the time in the downscaled facility is not scaled 1:1 with the time of the original system, but an explicit rule applies for that. Furthermore, a simple relation was found between the time scaling factor and the geometry scaling factor.

Scaling distortions are also discussed and a way of diminishing their consequences in the case of larger friction in the core was also presented. By using the proposed methodology, it was shown that core friction-related distortions can be sensibly reduced.

The sensitivity of the geometrical scaling factor with the pressure was also analyzed in order to determine whether the facility can be used to investigate the stability of the reactor at pressures far from the nominal pressure. It was found that the geometrical scaling factor is weakly dependent on the pressure for the Freon R-134a particular case. This result allows using the same facility for thermal–hydraulic stability studies in a wide range of pressures (6.0–8.0 water-MPa).

In order to experimentally validate the rules derived in this work, the GENESIS facility was designed and constructed. Finally, the steady state mass flux for different power conditions in the GENESIS facility was compared with results obtained by using a numerical model of the ESBWR reactor programmed in the ATHLET system code and in the TRACG system code. Furthermore, the stability characteristics of the experimental facility and the numerical models of the reactor at the operational point were examined. A very good agreement was found. The result of these investigations seems to confirm the validity of the downscaling methodology for stability analysis proposed in this paper.

In order to investigate the similarity between the downscaled system and the numerical results, a larger number of cases has to be compared. Moreover, the construction of complete stability maps is recommended.

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References

[1] Y.K. Cheung, B.S. Shiralkar, W. Marquino, Analysis of ESBWR startup in natural circulation, in: Proceedings of International Conference on Advances in Nuclear Power Plants, 2005 (Paper #5484).
[2] J.F. Offerein, L. Winters, (Eds.), 2004. Final Technical Report of NACUSP (Natural Circulation and Stability Performance of BWRs) Project, European Commission, Fifth EURATOM Framework Programme 1998–2002.
[3] R. Van de Graaf, T.H.J.J. Van der Hagen, Two-phase flow scaling laws for a simulated BWR assembly, Nucl. Eng. Design 148 (1994) 455–462.
[4] S. Kakaç, F. Mayinger, Two-phase Flows and Heat Transfer, vol. 1, NATO Advanced Study Institute, Hemisphere, Washington, 1977.
[5] M. Ishii, O.C. Jones Jr., Derivation and application of scaling criteria for two-phase flows, in: S. Kakaç, T.N. Veziroglu (Eds.), Two-Phase Flows and Heat Transfer, vol. 1, Hemisphere, Washington, 1977, pp. 163–185.
[6] P.D. Symolon, Scaling of two-phase flow regimes in a rod bundle with freon, Trans. Am. Nucl. Soc. 62 (1990) 705–706.
[7] R.T. Lahey, F.J. Moody, The Thermal–hydraulics of a Boiling Water Reactor, American Nuclear Society Publisher, 1993.
[8] C.P. Marcel, Development of the Scaling Laws for a Natural Circulation Loop, GE Proprietary Report, 2004.
[9] N.E. Todreas, M.S. Kazimi, Nuclear systems I Thermal Hydraulics Fundamentals, Taylor & Francis Ed, 1992.
[10] D.D.B. Van Bragt, Stability of natural circulation boiling water reactors: Part I – description stability model and theoretical analysis in terms of dimensionless groups, Nucl. Technol. 121 (1998) 40–51.
[11] I.L. Pioro, D.C. Groeneveld, S.C. Cheng, S. Doerffer, A.Z. Vasic, Comparison of CHF Measurements in R-134a Cooled Tubes and the Water CHF Look-up, 2001.
[12] P. Saha, N. Zuber, Point of net vapor generation and vapor fraction is subcooled boiling, in: Proceedings Fifth International Heat Transfer Conference, Tokyo, Japan, September, vol. 4, 1974, pp. 3–7.
[13] R. Zboray, An Experimental and Modeling Study of Natural-circulation Boiling Water Reactor Dynamics, PhD Thesis, Delft University of Technology, 2002.
[14] H.V. Kok, T.H.J.J. Van der Hagen, R.F. Mudde, Measurements of the void-fraction distribution in a simulated fuel assembly and the role of the void-fraction on the dynamics of a natural circ. loop, Ann. Nucl. Energ. 24-16 (1997) 1333–1347.
[15] H.V. Kok, T.H.J.J. Van der Hagen, R.F. Mudde, NURETH-7, Saratoga Springs, New York, 1995, pp. 2884-2894.
[16] C.P. Marcel, M. Rohde, Application of the Scaling Laws to the Design of a Natural Circulation Loop based on the ESBWR, GE Proprietary Report, 2005.
[17] M. Zhang, R.L. Webb, Correlation of two-phase friction for refrigerants in small-diameter tubes, Exp. Thermal Fluid Sci. 25 (2001) 131–139.
[18] H. Müller-Steinhagen, K. Heck, A simple friction pressure drop correlation for two-phase flow in pipes, Chem. Eng. Process. 20 (1986) 297–308 (Table. Int. J. Heat Mass Transfer 44, 73–88).
[19] C.P. Marcel, Experimental and Numerical Investigations on Coupled Neutronic-thermal–hydraulic Instabilities on Natural Circulation Boiling Water Reactors, Ph.D. Thesis, Delft University of Technology, 2007.
[20] A. Manera, Deliverable 2 (FZR) of the GENESIS Project, Revised Input Deck and Power Flow Map for ESBWR, GE Proprietary Report, 2005.
[21] B.S. Shiralkar, Personal Communication, 2005.