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Research Article

Use of the Natural Circulation Flow Map Circulation Systems Evaluation

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Abstract

The aim of this paper is to collect and resume the work done to bu engineering tool related to the natural circulation. After a brief des phase and two phase, the derivation of a suitable tool to judge the Finally, an extensive comparison among the NC performance of va is done to show a practical application of the NC flow map.

1. Introduction

The natural circulation (NC) is an important mechanism in sev behaviour is of interest to nuclear reactor design, operation, and true for new concepts that largely exploit the gravity forces for the the presence of a heat source and of a heat sink constituted in a n generators, respectively. In a gravity environment, with the cc generators, driving forces occur such that to generate suitable flov NC core power removal capability was only exploited for accider safety features of the plants, recently within the passive react importance having a large impact on the design phase.

The NC behaviour has been (and it is still now) object of several e
or characterization test in a test rig. In this view, a quite large dat
measurements from various facilities. The NC scenarios occurring
inventory were considered (reference is made to both single-phas
and analyzing data from the following PWR simulators: Semiscale,

In order to evaluate the natural circulation performance (NCP)
comes from the analysis of the trend of the core inlet mass flow r
rate and the residual masses have been normalised taking in
corresponding power level (typically ranging between 1 and 5%
experiment. Four main flow patterns were characterized depend
primary loop.

2. The Natural Circulation Flow Regimes

2.1. Single-Phase NC (SPNC)

SPNC regime implies no void occurrence in the upper plenum of th
be subcooled up to nearly saturated. Core flow rate is derived fror
Driving forces are the result of fluid density differences occurring
downcomer} and {core and ascending side of U-tubes}. Resistant f
along the entire loop. Resulting fluid velocities are sufficient for re
or forced convection heat transfer regimes: no film boiling conditio
the secondary side of SG is also a natural circulation system workin

SPNC may occur at any primary system pressure, consistently w
pressures range between 8 and 16 MPa with secondary pressu
expected from the NPP design that SPNC, provided the availabilit
decay heat from the core. Experimental database, including NPP te

2.2. Stable Two-Phase NC (TPNC)

TPNC regime occurs as a consequence of coolant loss from the
resistant forces increase when decreasing mass inventory of prima
of PWR, the former effect, that is, increase of driving forces, is pre
opposite occurs for larger decreases of mass inventories. The net
primary system inventory (when primary mass flow rate decr
convection, subcooled, and saturated heat transfer regimes occur
of SG. The average core void fraction is typically less than 30%,
reached without occurrence of thermal crisis in the considered pres

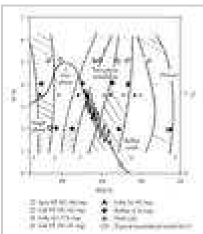

Figure 1: Characterization of natural circulati
system code calculations.

2.3. Siphon Condensation NC (SCNC)

The decreasing of NC driving forces, the small temperature differ

the occurrence of the countercurrent flow limiting phenomenon (C
at the origin of wide system oscillations of core inlet flow rate. Th
based on a natural circulation experiment performed in Lobi
condensation has been found also in other facilities.

At mass inventories of the primary system around 70% of the nor
transfer across U-tubes causes the release of almost all core ther
level builds up and is prevented to drain down by the steam-liquic
CCFL condition occurs. Therefore, liquid level rises in the U-tube
duration of the order of 10 seconds, the flow rate at the core inlet
the liquid level reaches the upper bend of U-tubes, the siphon effe
side of U-tubes and the reestablishment of core inlet flow rate. A
complex by the interaction of the several thousands of U-tubes th
tubes may stay at a different stage of the oscillation at the same
Suitable core cooling still can be achieved in these conditions.

2.4. Reflux Condensation (RCNC)

At “low” mass inventories of primary coolant and/or at low core
system including hot legs and steam generator entrance is low. W
that are not enough to cause CCFL. In these conditions, the liqui
side of the U-tubes may flow back to the hot leg and to the co
simultaneously in the hot legs. The mass flow rate at the core i
circulation path may establish between core and downcomer insic
and downward liquid flows occur at the core outlet. Core thermal
nucleate boiling heat transfer regime.

2.5. Dryout Occurrence

The terms “dryout occurrence” appear in the right part of Figure
lower than 40% of the nominal value. Dryout is caused by the cc
consequence, film boiling heat transfer regime is experienced w
temperature increases in various zones of the core, and the overa
to the fluid may become unstable. The system operation in these
point of view. It can be noted that the temperature excursion is
thermal power levels: the linear rod power plays a role in these c
MPa (nominal operation for PWR), “post-dryout” surface temper
tolerable for the mechanical resistance of the rod-clad material.

All the regimes cited above are summarized in Figure 1 which rep
vertical axis the percentage of the nominal core power (P) is re
primary circuit (RM) is reported on the horizontal axis.

3. The Natural Circulation Flow Map

The database gathered from ten experiments performed in the si
been used ([6, 7]) to establish a natural circulation flow map.

Table 1: Relevant hardware characteristic o
creation.

In all the considered ITF, NC experiments with similar modalities h in the previous chapter are experienced. The linear power of the power, and the primary system pressure constitute the main differ experiments. In relation to the primary side pressure, PKL expe roughly half of the value adopted in the other facilities. The rang (e.g., pipe diameter, system volume, number of the steam genera discussed here, and the identified differences are assumed to prod typical PWR when decay heat removal is concerned.

Measured values of core inlet flow rate (G, kg/s), core power (P, M and net volume of the primary system (V = const., m^3) have b map (NCFM). The diagram G/P versus RM/V has been preferred nondimensional quantities.

The experimental database from ITF (six ITFs, ten experiments) ar and 3, respectively. The envelope in Figure 3 is assumed to constit

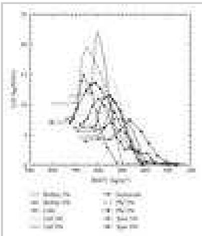

Figure 2: Natural circulation system behaviou PWR simulators.

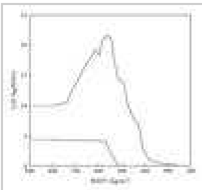

Figure 3: Natural circulation flow map achiev simulator.

A first demonstration of the use of the NCFM has been done in [8 ITFs, not used for setting up the database presented in Figure 2, and ITF can be drawn from Tables 2 and 3, respectively. The horizontal SG design. The ITFs are Pactel and RD14M (see Tab CANDU NPP, respectively. Their geometric layout is different fro loops equipped with HTSG are connected to the vessel, though configuration characterizes the CANDU design, that is, equipped wi

Table 2: Relevant characteristics of NPP consi

Table 3: PACTEL and RD14M.

Comparing the calculated data with the NCFM, authors concluded t

- (i) PWR equipped by OTSG have poor natural circulation per
- (ii) NPP designed around passive system concept showed a q
- (iii) Russian design reactors equipped by horizontal SG are al
- (iv) RD-14m database was not fully qualified (e.g., the docun

large deviation from the map.

The NCFM was used to characterize the behaviour of the CNA-I PH
mass inventory scenario [6]. The simulations have been perform
detail. The coarser one (SET I) was used as a basic set just to re
4). This permitted to verify that the trends known for most ITFs w
CNA-I behaviour, considering appropriate trips of some of its safet

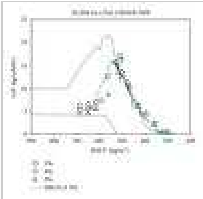

Figure 4: Natural circulation map for Atuch
SBLOCA.

4. Recent Use of the NC Flow Map

4.1. Application to the PSB-VVER Facility

As already showed by the previous examples (other can be g
advantageous tool to depict the NC capability in removing the cor
have been done that cover practically all the NPP types.

In Figure 5 (taken from [10]) it can be seen the use of the NCFM f
300. The experiment has been carried out in the frame of an
pressure are maintained constant, while the mass is stepwise dra
(in violet) are reported. The experimental data goes out from the
were not qualified in two-phase flow giving a wrong indication. H
suitability of the NCFM and on the other hand the good NC perforr

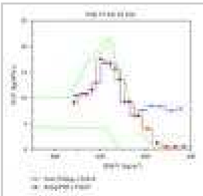

Figure 5: Natural circulation map for the PSB-

4.2. Revisiting the RD-14m Facility

In Section 3, the RD14m data were considered but achieving resul
calculation has been repeated fixing constant the core power an
stepwise reduced, following a typical way to perform such kind of I
LBLOCA test (B-9401) carried out in the framework of an IAEA pr
in Figures 6 and 7), two main conclusions can be drawn.

(i) The CANDU facility seems not so suitable for NC status
NCFM reasonably resumes the SG NC, it does not consider any
of its definition.

(ii) Figure 7 shows that in the CANDU installation other type
seems relevant from the core power removal point of view. T
greater than 500 kg/m^3, where the NCFM predicts low flow
the core power) the dryout is not experienced.

Regarding the latter point (i.e., the channel to channel NC mode)
over power versus time of two different horizontal channels. It ca
mass flow rate (i.e., the water follows the normal flow path enter
the channel), the other is cooled by water circulating in the oppo
core flow rate (sum of the core channels mass flow rate) reaches t

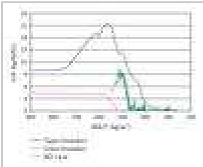

Figure 6: Natural circulation map for the RD-1

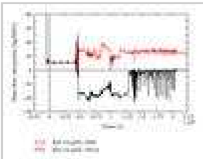

Figure 7: Channel-to-channel natural circulati

4.3. Consideration of BWR Data

The last use of the NCFM regards the consideration of boiling wa
(BWR) and calculation results (RBMK).

Figure 8 reports the typical power-flow map of a BWR in which t
power in NC mode is roughly 40% with a core flow rate of 25%.

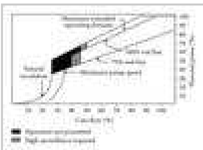

Figure 8: Typical BWR power-flow map.

In Figure 9 the BWR data are reported into the NCFM (green dots
map: full power condition (green square) at full pump speed, 25%
It can be seen that the points are practically aligned along a l
confirming the suitability of the BWR to work in NC mode. Value
conditions in PWR simulators are experienced in BWR but with a
performance in core removable power typical of PWR is not prese
its nominal power.

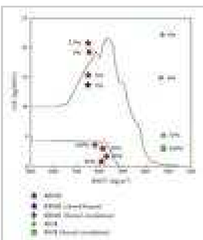

Figure 9: BWR and RBMK data and compariso

Again in Figure 9 it can be seen also the RBMK data. Those calcula
use of a qualified nodalization developed and tested during an E
come out when calculated data are put inside the NCFM and compa

(i) The RBMK data stay almost aligned at various power lev
(ii) The full power point of both boiling water reactors (v (practically) same G/P ratio, but differs by a factor of two in type (vessel type versus channel type reactor), the differen primary side (PS) mass of the two steam drums used in the RE
(iii) The G/P ratio remains comparable between the two reac
(iv) Deviation from the consideration of the item above is ex header and the suction header is closed (blue star in Figure 9 core power. The former case has an important negative impa case seems to represent the last possible NC operational point point.
(v) When power level around 3% is considered, the two re lower mass flow rate in the RBMK enhancing a better performa

5. Conclusions

A system scaling study was the precursor of this work in which tl tool aimed at evaluating the NC performance of an NPP. The NCFM PWR simulators.

Recently, the use of the NCFM has been extended to practicall experimental data available after an NC experiment carried out a 14m data after its nodalization qualification; BWR and RBMK comp

Once more, the NCFM results in a very helpful tool to judge the N be noted that the NCFM is suitable to catch the SG NC type henc channel-to-channel circulation experienced in the RD-14m. Consid been derived, other applications may regard support on scaling a and validation of computational tools.

As mentioned above, this engineering tool has been directly derive a theoretical and generalized relationship between the system in objective of a future research work.

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