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Research Article

Use of the Natural Circulation Flow Map for Natural Circulation Systems Evaluation

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The aim of this paper is to collect and resume the work done to build and develop, at the University of Pisa, an engineering tool related to the natural circulation. After a brief description of the different loop flow regimes in single phase and two phase, the derivation of a suitable tool to judge the NC performance in a generic system is presented. Finally, an extensive comparison among the NC performance of various nuclear power plants having different design is done to show a practical application of the NC flow map.

1. INTRODUCTION

The natural circulation (NC) is an important mechanism in several industrial systems and the knowledge of its behaviour is of interest to nuclear reactor design, operation, and safety. In the nuclear technology, this is especially true for new concepts that largely exploit the gravity forces for the heat removal capability. The NC takes place due to the presence of a heat source and of a heat sink constituted in a nuclear power plant (NPP) by the core and the steam generators, respectively. In a gravity environment, with the core located at a lower elevation than the steam generators, driving forces occur such that to generate suitable flow rate for removing nuclear fission power. While the NC core power removal capability was only exploited for accident situations basically to demonstrate the inherent safety features of the plants, recently within the passive reactor concept the NC performance assumes major importance having a large impact on the design phase.

The NC behaviour has been (and it is still now) object of several experiments aimed at addressing issues like scaling or characterization test in a test rig. In this view, a quite large database has been created collecting the experimental measurements from various facilities. The NC scenarios occurring for different values of the primary system mass inventory were considered (reference is made to both single-phase and two-phase natural circulation) by gathering and analyzing data from the following PWR simulators: Semiscale, Spes, Lobi, Bethsy, Pkl, and Lstf [1].

In order to evaluate the natural circulation performance (NCP) of the mentioned facilities, significant information comes from the analysis of the trend of the core inlet mass flow rate and the primary loop mass inventory. The flow rate and the residual masses have been normalised taking into account the volume of each facility and the corresponding power level (typically ranging between 1 and 5% of the nominal core power) utilized in the selected experiment. Four main flow patterns were characterized depending upon the value of the mass inventory of the 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 the system. Therefore, coolant at the core outlet will be subcooled up to nearly saturated. Core flow rate is derived from the balance between driving and resistant forces. Driving forces are the result of fluid density differences occurring between {descending side of U-tubes and vessel downcomer} and {core and ascending side of U-tubes}. Resistant forces are due to irreversible friction pressure drops along the entire loop. Resulting fluid velocities are sufficient for removing core power in (subcooled) nucleate boiling or

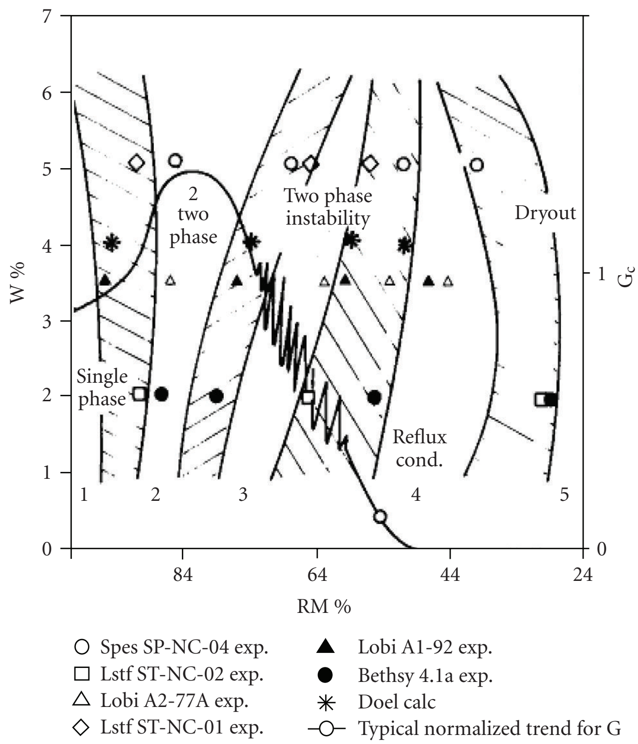

FIGURE 1: Characterization of natural circulation flow regimes based on experimental data and system code calculations.

forced convection heat transfer regimes: no film boiling condition is experienced in the core. It may be noted that the secondary side of SG is also a natural circulation system working in two-phase conditions.

SPNC may occur at any primary system pressure, consistently with SG pressure. However, typical primary system pressures range between 8 and 16 MPa with secondary pressure close to the nominal operating condition. It is expected from the NPP design that SPNC, provided the availability of SG cooling, is capable to remove the nuclear decay heat from the core. Experimental database, including NPP tests, confirms this capability.

2.2. Stable two-phase NC (TPNC)

TPNC regime occurs as a consequence of coolant loss from the primary system. Owing to this, both driving and resistant forces increase when decreasing mass inventory of primary system. Assigned the typical geometrical layout of PWR, the former effect, that is, increase of driving forces, is prevalent at small decreases of mass inventories. The opposite occurs for larger decreases of mass inventories. The net result is a "peak" in core mass flow rate versus primary system inventory (when primary mass flow rate decreases) as can be observed in Figure 1. Forced convection, subcooled, and saturated heat transfer regimes occur in the core. Condensation occurs inside the U-tubes of SG. The average core void fraction is typically less than 30%, whereas at the outlet values around 50% can be reached without occurrence of thermal crisis in the considered pressure range.

2.3. Siphon condensation NC (SCNC)

The decreasing of NC driving forces, the small temperature difference across U-tubes of the steam generators, and the occurrence of the countercurrent flow limiting phenomenon (CCFL) at the entrance of U-tubes (e.g., see [2]) are at the origin of wide system oscillations of core inlet flow rate. This phenomenon has been investigated in [3, 4] and based on a natural circulation experiment performed in Lobi facility in [5]. However, evidence of the siphon condensation has been found also in other facilities.

At mass inventories of the primary system around 70% of the nominal value, the efficiency of the condensation heat transfer across U-tubes causes the release of almost all core thermal power in the ascending side of U-tubes. Liquid level builds up and is prevented to drain down by the steam-liquid mixture velocity at the tube entrance, that is, the CCFL condition occurs. Therefore, liquid level rises in the U-tubes till reaching the top. During this period, typical duration of the order of 10 seconds, the flow rate at the core inlet is close to zero hence the core boiloff occurs. Once the liquid level reaches the upper bend of U-tubes, the siphon effect occurs and causes the emptying of the ascending side of U-tubes and the reestablishment of core inlet flow rate. A new cycle starts. The phenomenon is made more complex by the interaction of the several thousands of U-tubes that constitute a SG tube bundle. Different groups of tubes may stay at a different stage of the oscillation at the same time, also causing flow reversal in the tube bundle. 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 power, the steam velocity in the upper part of the system including hot legs and steam generator entrance is low. Weak interactions occur at the steam-liquid interface that are not enough to cause CCFL. In these conditions, the liquid that is condensed or entrained in the ascending side of the U-tubes may flow back to the hot leg and to the core. Stratified countercurrent steam and liquid flow simultaneously in the hot legs. The mass flow rate at the core inlet is close to zero, although a "minor" natural circulation path may establish between core, and downcomer inside the vessel. However, upward two-phase mixture and downward liquid flows occur at the core outlet. Core thermal power can be removed by boiloff in the saturated nucleate boiling heat transfer regime.

2.5. Dryout occurrence

The terms "dryout occurrence" appear in the right part of Figure 1, when primary system mass inventory is roughly lower than 40% of the nominal value. Dryout is caused by the combination of low flow and high void fraction. As a consequence, film boiling heat transfer regime is experienced with low coefficient for heat transfer. Rod surface temperature increases in various zones of the core and the overall process of thermal power transfer from fuel rods to the fluid may become unstable. The system operation in these conditions

Table 1: Relevant hardware characteristic of the PWR simulators considered for the NCFM creation.

Item	1 Semiscale Mod2A	2 Lobi Mod2	3 Spes	4 PKL-III	5 Bethsy	6 Lstf
Reference reactor and power (MWt)	W-PWR 3411	KWU-PWR 3900	W-PWR 2775	KWU-PWR 3900	FRA-PWR 2775	W-PWR 3423
No. of fuel rod simulators	25	64	97	340	428	1064
No. of U-tubes per SG	2/6	8/24	13/13/13	30/30/60	34/34/34	141/141
Internal diameter of U-tubes (mm)	19.7	19.6	15.4	10.0	19.7	19.6
Actual Kv	1/1957	1/589	1/611	1/159	1/132	1/48

is not acceptable from a technological point of view. It can be noted that the temperature excursion is strongly affected by primary system pressure and thermal power levels: the linear rod power plays a role in these conditions. At primary system pressure around 15 MPa (nominal operation for PWR), "post-dryout" surface temperature jumps may be as low as a few tens of Kelvin, tolerable for the mechanical resistance of the rod-clad material.

All the regimes cited above are summarized in Figure 1 which reports both experimental and calculated data. On the vertical axis, the percentage of the nominal core power (P) is reported, while the residual mass inventory in the primary circuit (RM) is reported on the horizontal axis.

3. THE NATURAL CIRCULATION FLOW MAP

The database gathered from ten experiments performed in the six integral test facilities (ITFs) listed in Table 1 has been used ([6, 7]) to establish a natural circulation flow map.

In all the considered ITF, NC experiments with similar modalities have been performed, and the NC regimes discussed in the previous chapter are experienced. The linear power of the fuel rod simulators, the fraction of nominal core power, and the primary system pressure constitute the main differences for the boundary conditions of the considered experiments. In relation to the primary side pressure, PKL experiments have been performed at a pressure value roughly half of the value adopted in the other facilities. The range of design and operational parameters of the ITF (e.g., pipe diameter, system volume, number of the steam generators, heat losses to the environment), not explicitly discussed here, and the identified differences are assumed to produce an envelope for any expected NC situation in a typical PWR when decay heat removal is concerned.

Measured values of core inlet flow rate (G, kg/s), core power (P, MW), primary system fluid mass inventory (RM, kg), and net volume of the primary system (V = const., m^3) have been used for setting up the natural circulation flow map (NCFM). The diagram G/P versus RM/V has been preferred for the NCFM over other possible choices including nondimensional quantities.

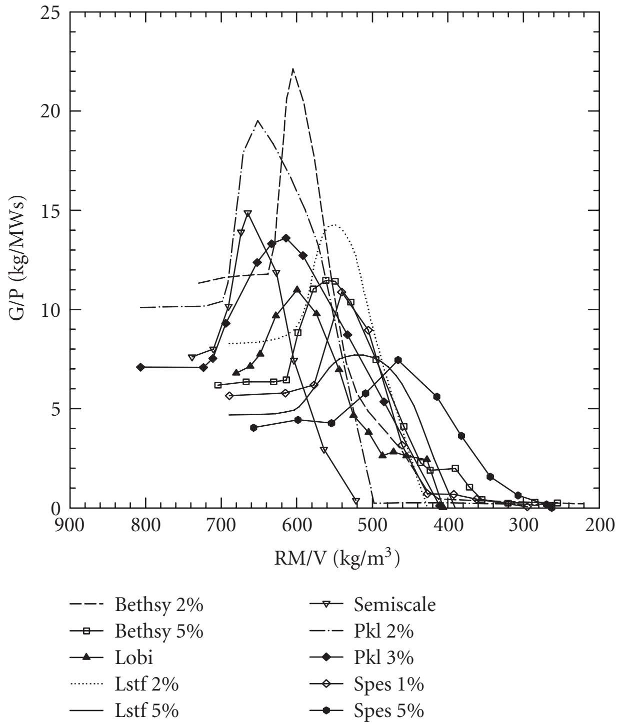

Figure 2: Natural circulation system behaviour measured in ten experiments performed in six PWR simulators.

The experimental database from ITF (six ITFs, ten experiments) and the envelope of the curves are given in Figures 2 and 3, respectively. The envelope in Figure 3 is assumed to constitute the NCFM of PWR at core decay power.

A first demonstration of the use of the NCFM has been done in [8], where seven commercial NPP systems and three ITFs, not used for setting up the database presented in Figure 2, have been analyzed. Main characteristics of the NPP and ITF can be drawn from Tables 2 and 3, respectively. The considered NPP include U-tube, once through and horizontal SG design. The ITFs are Pactel and RD14M (see Table 3) experimental simulators of WWER-440 and CANDU NPP, respectively. Their geometric layout is different from those

Table 2: Relevant characteristics of NPP considered for the application of the NCFM.

	PWR	PWR	PWR	WWER-1000	EPR	AP-600	EP-1000
Nominal power (MWt)	1877	870	2733	3000	4250	1972	2958
Primary system volume (m^3)	167	150	330	359	459	211	339
SG type	U-tubes	U-tubes	Once-through	Horizontal	U-tubes	U-tubes	U-tubes
No. of loops	2	4	2	4	4	2	3
No. of pumps	2	4	4	4	4	4	6
Nominal mass inventory (Mg)	108	108	224	240	307	145	227
Nominal core flow (kg/s)	9037	3150	17138	15281	20713	8264	14507
Pressurizer and SG pressure (MPa)	15.6 6.	14.0 3.1	15.0 6.4	15.7 6.3	15.5 7.2	15.5 5.5	15.8 6.4

Table 3: PACTEL and RD14M.

	Pactel (original)	Pactel (with CMT)°	RD14M
Reference reactor and power (MWt)	WWER-440 1375	WWER-440 1375	CANDU 1800
No. of rods	144	144	70
No. of SG	3	3	2
SG type	Horizontal	Horizontal	U-tubes
Actual Kv+	1/433	1/462	1/378

°CMT = core makeup tank.
+Definition introduced for database in Table 1.

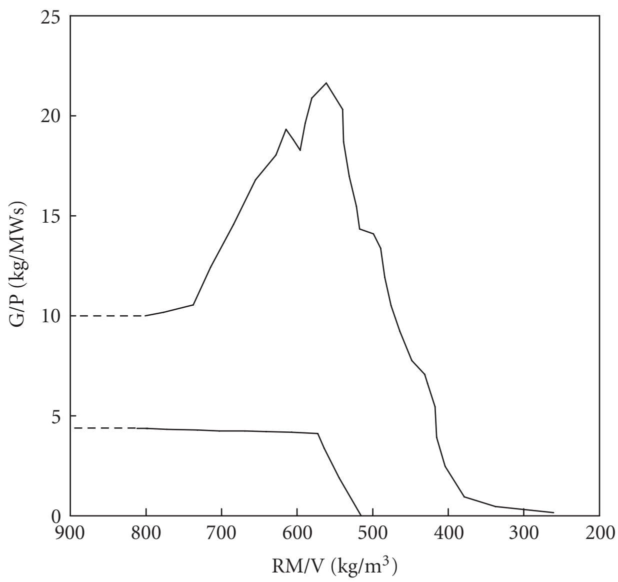

Figure 3: Natural circulation flow map achieved from the envelope of measured curves in PWR simulator.

of a PWR. In the case of WWER-440, six loops equipped with HTSG are connected to the vessel, though only three are simulated in Pactel. Horizontal core configuration characterizes the CANDU design, that is, equipped with UTSG.

Comparing the calculated data with the NCFM, authors concluded that

(i) PWR equipped by OTSG have poor natural circulation performance;

(ii) NPP designed around passive system concept showed a quite extend SPNC even at low mass inventory;

(iii) Russian design reactors equipped by horizontal SG are also suitable for NC mode;

(iv) RD-14m database was not fully qualified (e.g., the documentation was not so exhaustive), this brought to a large deviation from the map.

The NCFM was used to characterize the behaviour of the CNA-I PHWR NPP in NC flow conditions, in a reduced primary mass inventory scenario [6]. The simulations have been performed using three different nodalizations of increasing detail. The coarser one (SET I) was used as a basic set just to represent a plant layout similar to a PWR (see Figure 4). This permitted to verify that the trends known for most ITFs working in similar situations give an envelope to the CNA-I behaviour, considering appropriate trips of some of its safety systems.

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 got from, e.g., [8, 9]), the NCFM constitutes an advantageous tool to depict the NC capability in removing the core power. Starting from this point more applications 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 for a VVER-1000 simulator whose scale factor is 1 : 300. The experiment has been carried out in the frame of an OECD project in which the core power and the SG pressure are maintained constant, while the mass is stepwise

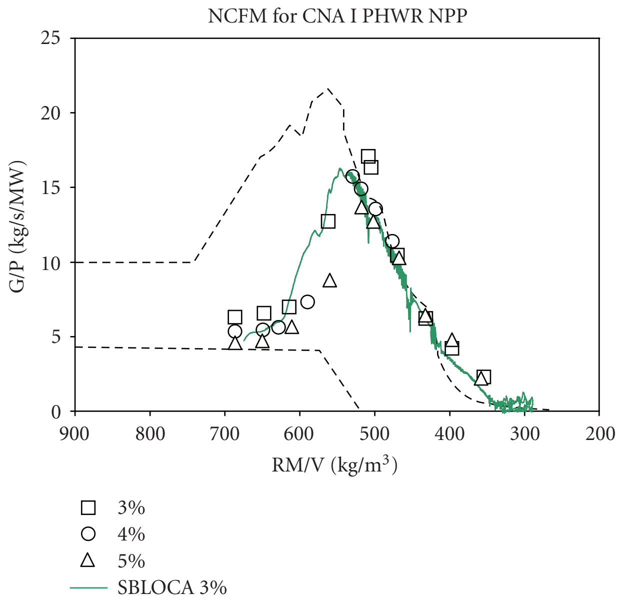

FIGURE 4: Natural circulation map for Atucha-I at different core power level and in case of SBLOCA.

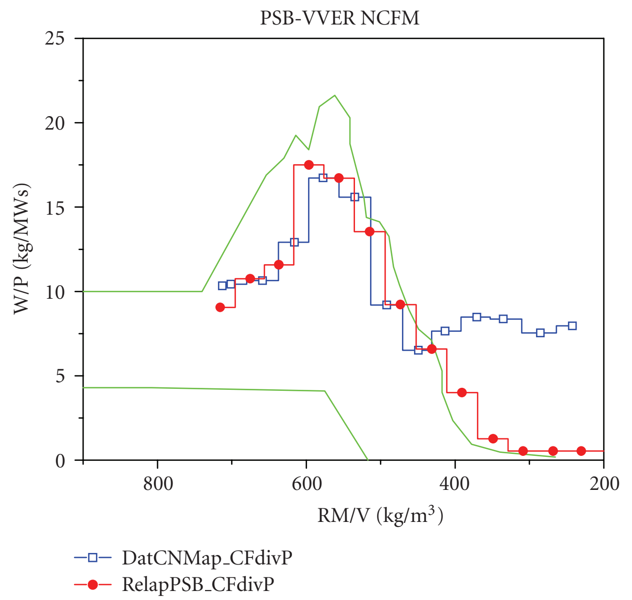

FIGURE 5: Natural circulation map for the PSB-VVER experimental and calculated data.

drained. Both measured (in blue) and calculated date (in violet) are reported. The experimental data goes out from the map because the flow rate measurement systems were not qualified in two-phase flow giving a wrong indication. However, the calculation confirms on one hand the suitability of the NCFM and on the other hand the good NC performance of the VVER reactor type.

4.2. Revisiting the RD-14m facility

In Section 3, the RD14m data were considered but achieving results far from what expected by the NCFM. Recently, a calculation has been repeated fixing constant the core power and the SG pressure, while the primary side mass is stepwise reduced, following a typical way to perform such kind of NC test. The nodalization had been qualified against LBLOCA test (B-9401) carried out in the framework of an IAEA project [11]. Analyzing the code results (summarized in Figures 6 and 7), two main conclusions can be drawn.

(i) The CANDU facility seems not so suitable for NC status (Figure 6). However it should be noted that the NCFM reasonably resumes the SG NC, it does not consider any other mechanism simply because they are outside of its definition.

(ii) Figure 7 shows that in the CANDU installation other type of NC are present. The channel to channel mode seems relevant from the core power removal point of view. This behaviour explains why even at value of RM/V greater than 500 kg/m^3, where the NCFM predicts low flow condition (hence degraded capability in removing the core power) the dryout is not experienced.

Regarding the latter point (i.e., the channel to channel NC mode), Figure 7 reports the ratio channel mass flow rate over power versus time of two different horizontal channels. It can be seen that once one core channel has positive mass flow rate (i.e., the water follows the normal flow path entering from the inlet and going out from the outlet of the channel), the other is cooled by water circulating in the opposite path. This means that only a part of the total core flow rate (sum of the core channels mass flow rate) reaches the SG to be cooled.

4.3. Consideration of BWR data

The last use of the NCFM regards the consideration of boiling water reactor type coming from plant measurement (BWR) and calculation results (RBMK).

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

In Figure 9 the BWR data are reported into the NCFM (green dots and green square). Four points are present in the map: full power condition (green square) at full pump speed, 25%, 4%, and 3% of the nominal power (green dots). It can be seen that the points are practically aligned along a line that marks the RM/V of the considered plant confirming the suitability of the BWR to work in NC mode. Values of G/P comparable to what measured in TP-flow conditions in PWR simulators are experienced in BWR but with a RM/V ratio almost halved. The degradation of the performance in core removable power typical of PWR is not present in BWR that in turns can be operated at 25% of its nominal power.

Again in Figure 9 it can be seen also the RBMK data. Those calculated values (red and blue stars are obtained by

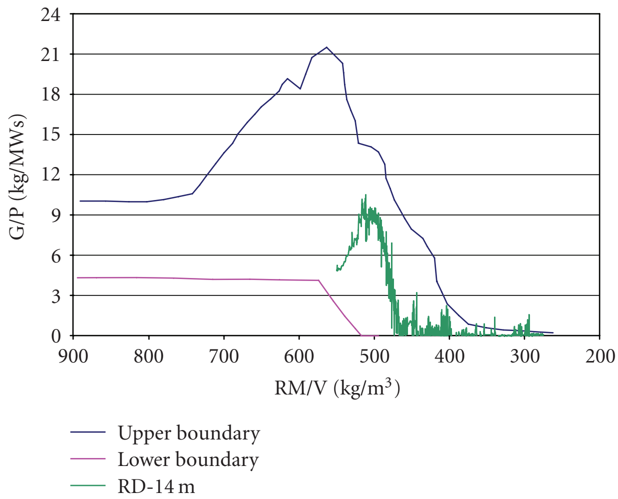

Figure 6: Natural circulation map for the RD-14m calculated data.

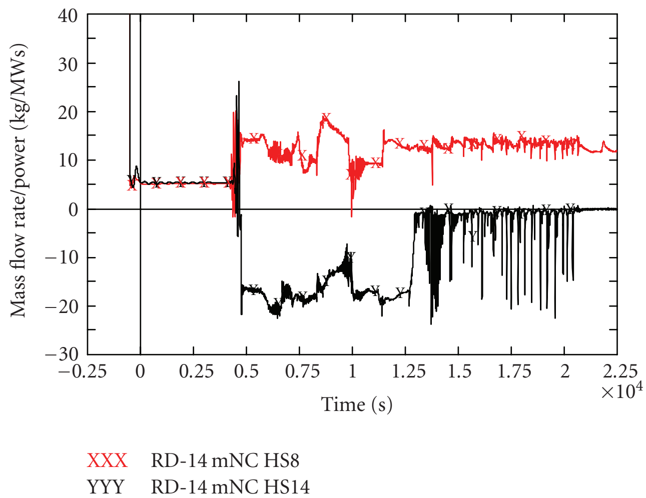

Figure 7: Channel-to-channel natural circulation mode for the RD-14m calculated data.

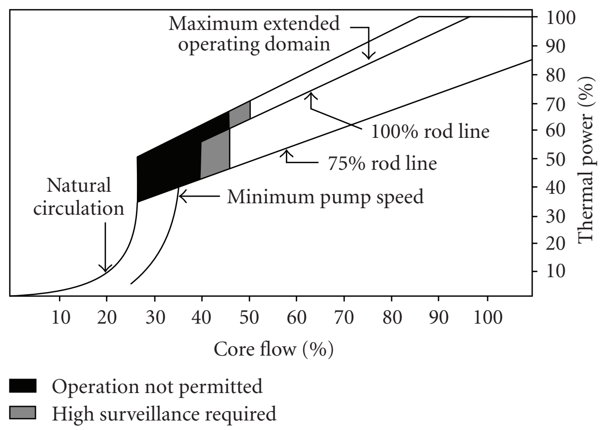

Figure 8: Typical BWR power-flow map.

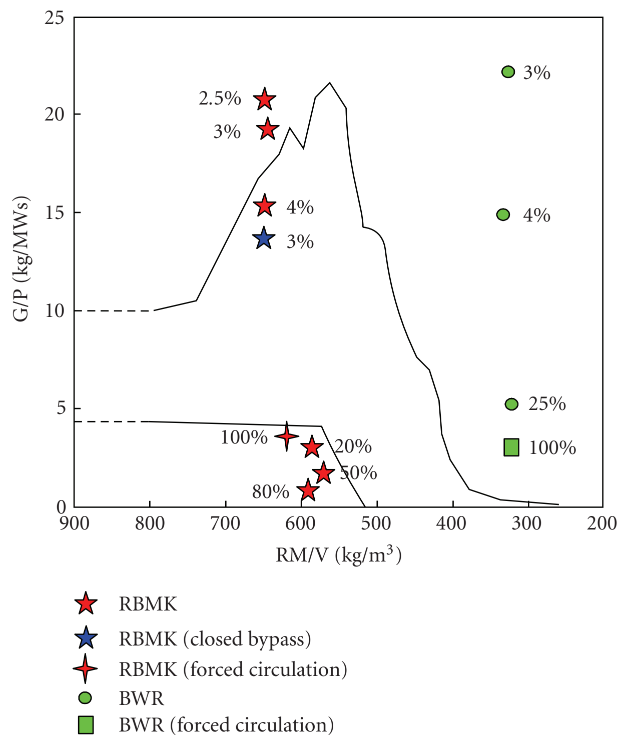

Figure 9: BWR and RBMK data and comparison with the NCFM.

the use of a qualified nodalization developed and tested during an EC funded project [12]. The following consideration come out when calculated data are put inside the NCFM and compared with BWR values.

(i) The RBMK data stay almost aligned at various power levels as occur in the BWR.

(ii) The full power point of both boiling water reactors (western and eastern project type, resp.) has the (practically) same G/P ratio, but differs by a factor of two in the RM/V ratio. This stresses the diverse project type (vessel type versus channel type reactor), the different nominal point of work, and the impact on the primary side (PS) mass of the two steam drums used in the RBMK as separator.

(iii) The G/P ratio remains comparable between the two reactors at various power levels up to 4%.

(iv) Deviation from the consideration of the item above is experienced, when the bypass between the pressure header and the suction header is closed (blue star in Figure 9) and when the power level is 20% of the nominal core power. The former case has an important negative impact on the NC performance of the RBMK; the latter case seems to represent the last possible NC operational point for the RBMK, lower than the BWR corresponding point.

(v) When power level around 3% is considered, the two reactors behave in a different way: it can be seen a lower mass flow rate in the RBMK enhancing a better performance of the BWR with a low void fraction.

5. CONCLUSIONS

A system scaling study was the precursor of this work in which the main objective was the setup of an engineering tool aimed at evaluating the NC performance of an NPP. The NCFM was created gathering experimental data from six PWR simulators.

Recently, the use of the NCFM has been extended to practically all types of reactor: VVER-1000 by the use of experimental data available after an NC experiment carried out at the PSB-VVER test rig; CANDU revisiting the RD-14m data after its nodalization qualification; BWR and RBMK comparing measured and calculated data, respectively.

Once more, the NCFM results in a very helpful tool to judge the NC performance of different reactor types. It should be noted that the NCFM is suitable to catch the SG NC type hence not able to deal with other NC type, such as the channel-to-channel circulation experienced in the RD-14m. Considering the characteristic and the way the NCFM has been derived, other applications may regard support on scaling analysis, design and/or optimization of NC system, and validation of computational tools.

As mentioned above, this engineering tool has been directly derived from the analysis of experimental data. However, a theoretical and generalized relationship between the system inventory and the flow per unit power could be the objective of a future research work.

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