Investigation of Three-Dimensional Effects on Natural Circulation Nuclear Reactors: Chimney Recirculation

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ABSTRACT

This paper explores the intricate interplay of three-dimensional effects on the operational dynamics of nuclear reactors employing natural circulation. Specifically, attention is directed towards reactors featuring a long chimney, also called riser, in which upward movement of hot fluid happens, together with a downflow with lower temperature in the surrounding downcomer. The study delves into the potential occurrence of recirculation phenomena within the chimney and the consequential risk of cold fluid ingress into the core region. Such occurrences may precipitate in instabilities including the neutronic-thermal hydraulic feedback. Recirculation in the chimney is affected by core power, which also determines natural circulation flow inside the vessel. In this work, we consider single phase flow including the presence of subcooled void and two-phase flow in the core region which are typical respectively of PWRs (Pressurized Water Reactors) and BWRs (Boiling Water Reactors). The performed study is preliminary considering that no experimental data is available, and the system code RELAP5-3D is used instead of a more powerful CFD code, perhaps more suited in case of single-phase conditions.

***Keywords**: natural circulation, 3D-effects, RELAP5-3D, recirculation, chimney*

1 INTRODUCTION

1.1 Small Modular Reactors

In recent years, the imperative for decarbonization and achieving energy independence has become increasingly pressing. Nuclear power clearly stands out as a pivotal player in addressing these challenges. However, the landscape of large-scale nuclear power plants in many Western economies has been marred by cost overruns and a lack of political will to pursue a renaissance in this sector. Private investors are often inclined towards renewable technologies due to subsidies and the relatively rapid return on investment they provide. However, it is widely acknowledged that in an electrical grid, baseload energy sources play a crucial role in its stability, a requirement that intermittent renewables are unable to meet, especially considering the limitations of current energy storage technologies, which are generally incompatible with seasonal electricity storage.

Consequently, there has been a growing interest in the concept of leveraging mass production in the nuclear power sector, with a focus on small-scale, factory-built reactors. This approach promises expedited construction schedules and reduces initial capital outlay, while giving the possibility to account for baseload energy production. It's worth noting that the decision to increase the size of nuclear reactors 60-70 years ago was primarily driven by economic factors, namely economies of scale and neutron economics. Only time will reveal which scale choice proves more advantageous. Still, SMRs (Small Modular Reactors) could offer unquestionable deployment opportunities concerning the installation in remote locations and regions with small energy grids. However, this study does not primarily focus on the economic aspects of SMRs, but rather on some technical characteristic potentially relevant for the ones working in NC (Natural Circulation). Among SMRs, being reactors with a power output up to 300MWe, the water-cooled, water-moderated types, drawing upon almost 20,000 years of LWRs (Light Water Reactors) operational experience, are the closest to realization. Here, we are going to focus primarily on iPWRs (integral Pressurized Water Reactors) and BWRs.

1.2 Thermal-hydraulic phenomena: tree-dimensional effects

Water-cooled nuclear reactors are complex systems that operate under conditions presenting continuous challenges to their materials, structures, and components, in particular during postulated accidents, but also during normal operation and transients, potentially more so for new designs. Accident or transient scenarios in water-cooled reactors are analysed through identification and prediction of thermal-hydraulic phenomena. Extensive research over the past three decades has identified more than 100 phenomena [1] that can characterize accident scenarios in these reactors. In the following, we will mention three-dimensional flow behaviour in key components.

In water-cooled reactors, most two-phase flow phenomena are inherently three-dimensional and unsteady, such as the interactions between droplets and the surrounding gas field.

Three-dimensional phenomena significantly influence local thermal hydraulics in flow passages of the primary system, such as the upper plenum, core, and downcomer in a PWR. For instance, mixing and condensation during ECCS (Emergency Core Cooling System) injection lead to complex three-dimensional distributions of velocity, temperature, and void fractions. One-dimensional models often simplify these effects, potentially affecting the accuracy of their predictions. In PWRs, ECCS water injection through hot legs creates complex flow paths that impact core cooling. Similarly, in BWRs, parallel channel flow regimes during accidents can lead to varying flow conditions across the core, influencing cooling effectiveness.

Understanding these multidimensional phenomena is essential for improving the accuracy of thermal-hydraulic models and enhancing the safety and performance of nuclear reactors. [2]

1.3 Chimney recirculation

In the present study we have performed scoping calculations regarding a potentially “new” thermal hydraulic phenomenon characterizing LWRs designed to work under natural circulation. We will refer to this phenomenon as “Chimney recirculation” (CR).

LWRs designed to work in NC present a long chimney in such a way to enhance the driving force and increase the primary flow rate, typically weak in absence of pumps.
Therefore, a situation is created in which, for a relatively long path, hot fluid rises along the chimney, while transferring some heat to the colder fluid moving downward in the downcomer. It may happen that, the cooling of the peripheral rising fluid, especially during but not limited to low power (low flow) conditions, could be such to create a three-dimensional recirculation loop internal to the chimney itself. Such a loop may cause flow instabilities and may lead to the entering of relatively cold fluid in the core upper region, with consequent reactivity implications.

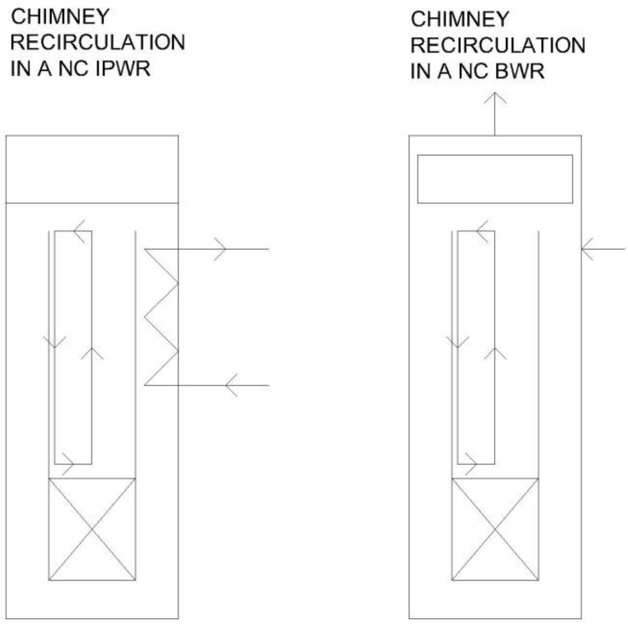

Figure 1. Schematic of the recirculation loop in a natural circulation iPWR on the left and BWR on the right. The recirculation loop is internal to the chimney itself.

2 SIMPLIFIED NODALIZATIONS

2.1 Introduction

To investigate the CR in both one and two-phase flow, two simplified nodalizations have been developed, nodalization 1 and nodalization 2, and they can be schematized as shown in Figure 2. and Figure 3., respectively. In both nodalizations, in order to isolate the recirculation phenomenon and to avoid feedback and interferences with other effects (flow instabilities in the iPWR HCSGs (Helical Coil Steam Generators) or in the BWR core for instance), chimney and downcomer have been separated, meaning that in each of them the flow has been imposed separately, so they’re not part of a loop. The chimney is realized by dividing it into two standing pipes, one which models the inner region and the other the outer one. Only the outer region is thermally connected to the downcomer. In this way we may expect flow to go upward in the inner one and eventually downward in the outer one, for buoyancy related reasons. Also, in nodalization 1, the two standing pipes are put into communication only at the bottom and the top, meaning that crossflow is not allowed across their height. In nodalization 2 instead, each volume of the inner pipe is cross connected to the corresponding volume of the outer pipe.

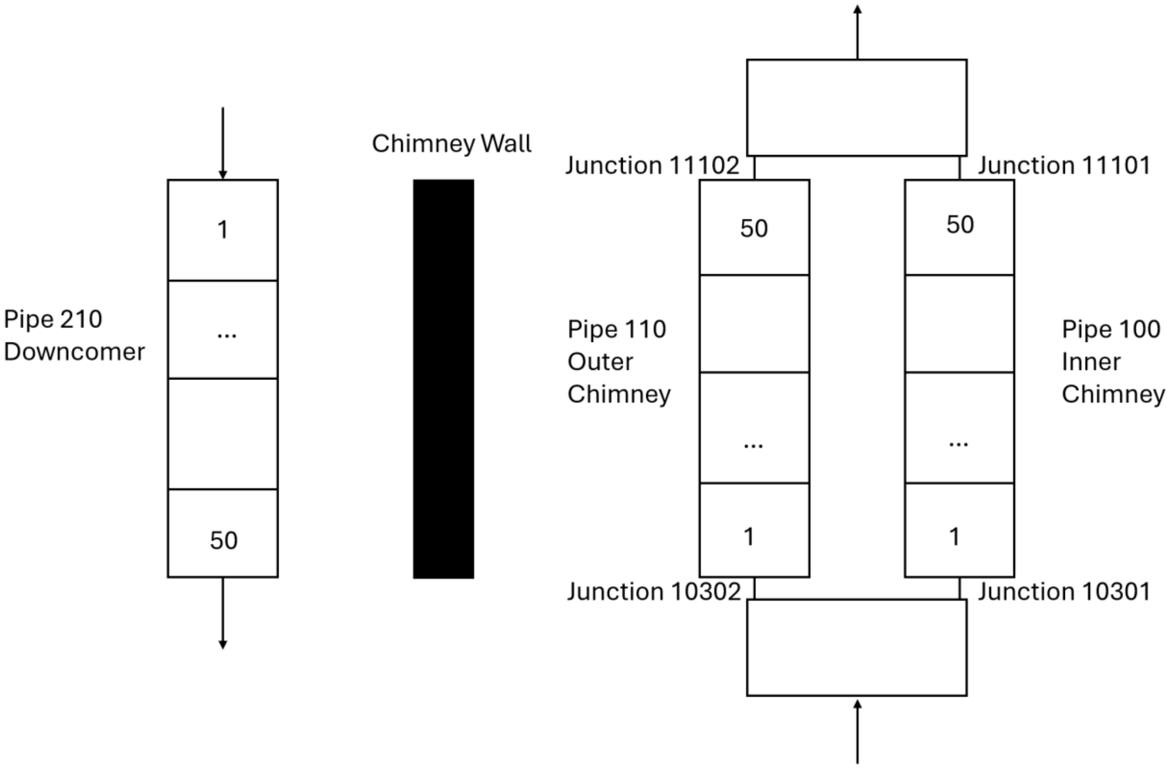

Figure 2. Schematic of nodalization 1. No cross-junctions across inner and outer chimney.

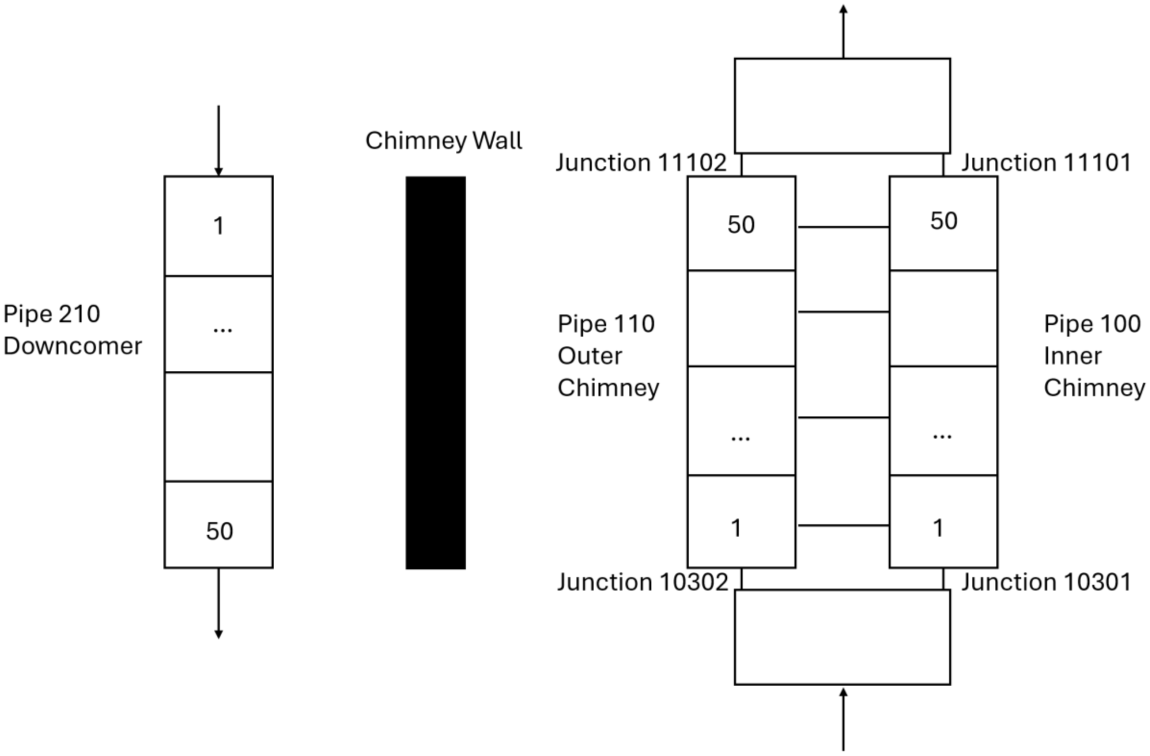

Figure 3. Schematic of nodalization 2. Inner and outer chimney are interconnected by cross junctions.

2.2 iPWR-like geometrical and flow related properties

The iPWR-like geometry is inspired to a NC 160MWth iPWR. The chimney was supposed to be 10m long with a 1.5m inner diameter. The DC (Downcomer) outer diameter has been fixed to 2.5m and they are separated by a stainless-steel wall having 1cm thickness. The DC HD (Hydraulic Diameter) has been supposed to be 1cm (same order of magnitude of the distance between HCSG tubes). Each volume is 20cm long.

For what concerns the fluid and flow properties, pressure has been fixed to 130bar, the DC inlet temperature to 285°C, consistent with a reasonable primary average temperature, and the riser inlet temperature to 315°C.

The riser flow rate at full power has been supposed to be around 590kg/s, consistent with values found for a 160MWth iPWR in [3]. Flow rates below 15% nominal power have simply been linearly extrapolated to zero starting from 280kg/s for 15% power, which would be the design flow at that power [3]. For what concerns the DC flow, it has been fixed to 280kg/s. This has been done to reduce the impact of the temperature increase for the flow flowing downward in the downcomer itself, since in reality, because of the presence of the HCSGs, the temperature would decrease; with this approach it increases but only of a few degrees, even when the flow in the chimney is the nominal one. Another simplification to be noted is that the riser inlet temperature has been kept fixed, while in reality, if the system is set up to operate at fixed primary average temperature, the core outlet temperature would increase when power increases. These assumptions can be justified by keeping in mind that the objective of the present analysis is not to accurately predict the eventual recirculation phenomena, but to assess their potential to happen.

2.3 BWR-like geometrical and flow related properties

The BWR-like geometry is inspired to a NC 900MWth BWR. The chimney was supposed to be 15m tall with a 3.5m inner diameter. The DC outer diameter has been fixed to 4m and they are separated by a stainless-steel wall with 1cm thickness. Each volume is 30cm long.

For what concerns the fluid and flow properties, pressure has been fixed to 72bar, the DC inlet temperature to 270°C, consistent with a reasonable core inlet temperature, and the riser inlet quality to 15% in saturation conditions.

Flow rates have been linearly extrapolated towards zero supposing the flow at full power around 1800kg/s.

3 ONE PHASE RECIRCULATION

3.1 One phase recirculation, nodalization 1

By using nodalization 1, we obtain the following trends for recirculation related quantities, being the recirculation flow rate (G chimney), the heat exchanged through the chimney wall (Q chimney), put in relation between themselves and with the imposed primary flow (G core) and correspondent core power (Q core).

The recirculation flow rate is defined as the mass flow rate flowing (downward) in junction 11102, where this junction can be identified in Figure 2 and 3.

From Figure 4. we can see that the power exchanged through the chimney wall sees a saturation effect, meaning that it increases up to 2MW from 1% to 5% power, and then it stays about constant till 100% power. From Figure 5. we can notice that we have a peak in G chimney around 5% power. From Figure 6. we can conclude that the recirculation flow rate can be even higher than the primary flow rate for low power conditions, according to the adopted nodalization. Sensitivity studies on the repartition of the riser flow area have shown that Q chimney is pretty much independent on it, but the some does not hold for the recirculation flow rate. For instance, if we assign to the outer chimney only 10% of the riser flow area, then the recirculation flow rate drops to 1/3 of the one obtained with the 50-50 repartition used as reference.

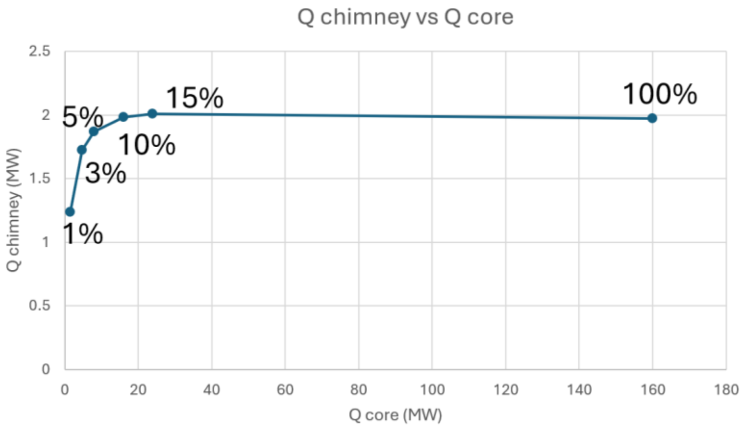

Figure 4. Nodalization 1, one phase flow. Power exchanged through the chimney wall vs Core power. Corresponding core power in % is also indicated on the graph.

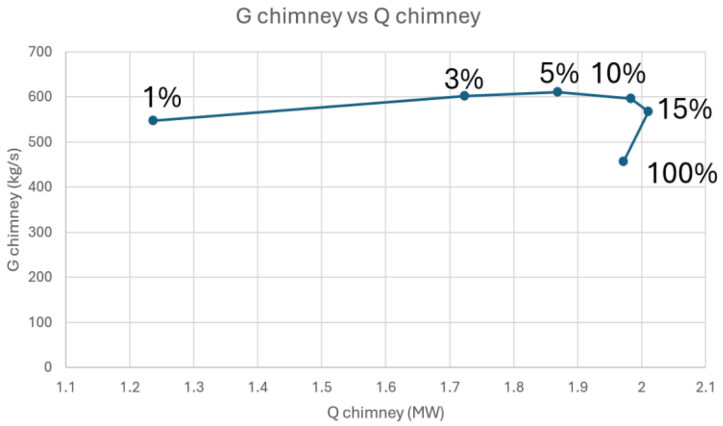

Figure 5. Nodalization 1, one phase flow. Recirculation flow rate vs Power exchanged through the chimney wall. Corresponding core power in % is also indicated on the graph.

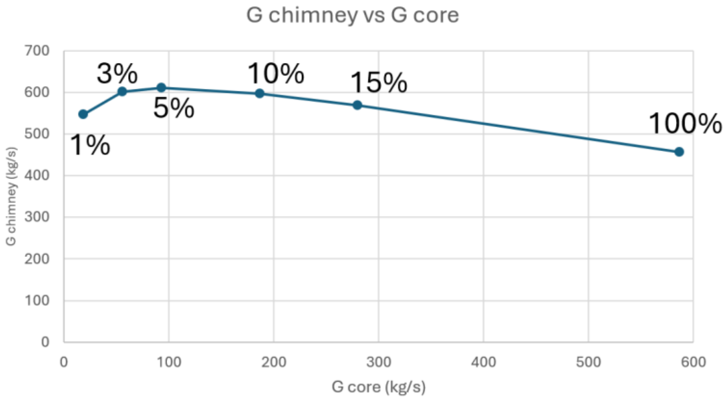

Figure 6. Nodalization 1, one phase flow. Recirculation flow rate vs Primary flow. Corresponding core power in % is also indicated on the graph.

3.2 One phase recirculation, nodalization 2

Studies performed by using nodalization 2, a nodalization that allows cross flow at intermediate elevations along the riser height, have shown the possibility for the recirculation loop to affect only the upper part of the chimney, as visible from Figure 7 and Figure 8.

In fact, we can notice that starting from 10% power, while on top of the riser we get both ascending and descending flow (Figure 8), at the bottom we only see ascending flow (Figure 7). Therefore, the recirculation loop affects only the upper part of the riser and closes because of cross junctions flow. For instance, at 15% power the recirculation loop occupies the upper half of the chimney, while at 100% power it's located in the top 20% of the riser height. This can be explained by considering that at higher flow rate, the increased inertia of the ascending column is such to counter more and more the downward gravity driven flow. This concept can be schematized as shown in Figure 9. Moreover, it's worth noting that with the adopted nodalization, the recirculation flow rate is much larger than the one obtained with nodalization 1, as can be inferred from Figure 8, where at 15% power the recirculation flow rate is around 2000 kg/s, about 7 times the primary flow rate.

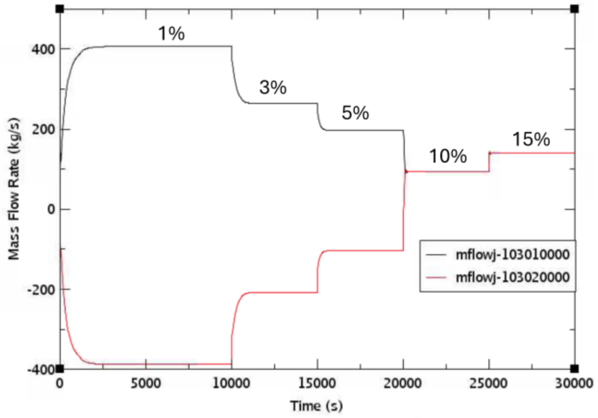

Figure 7. Nodalization 2, one phase flow. Flow rate in the bottom inner junction (10301) and in the bottom outer junction (10302) as a function of power, indicated in % of the nominal one.

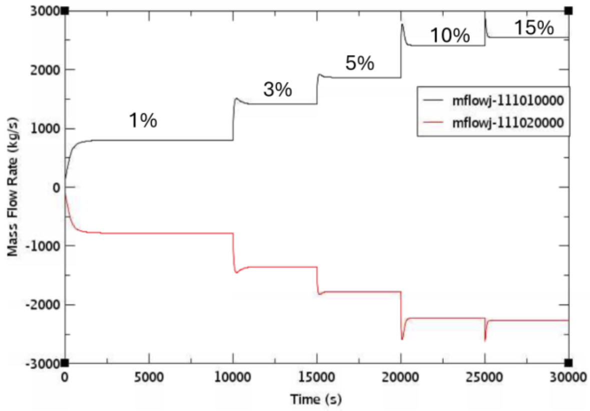

Figure 8. Nodalization 2, one phase flow. Flow rate in the top inner junction (11101) and in the top outer junction (11102) as a function of power, indicated in % of the nominal one.

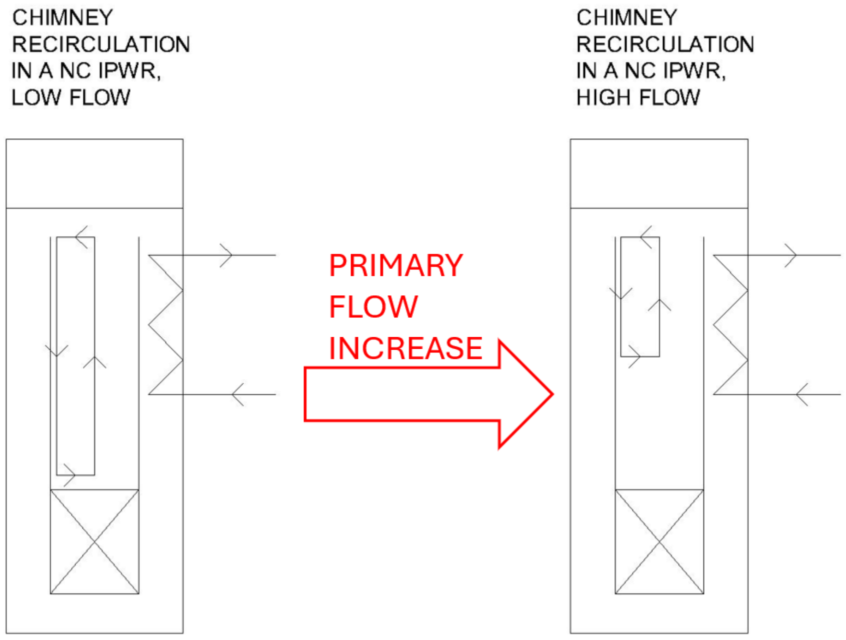

Figure 9. Schematic of the position of the recirculation loop in an iPWR for different power/primary flow levels.

4 Two phase recirculation

4.1 Results

In BWR conditions, regardless of the adopted nodalization, the recirculation flow reaches the bottom of the chimney. In Figures 10, 11 and 12, the relationship between relevant parameters previously introduced are reported, as obtained for nodalization 1. We can see that higher the primary flow rate and the core power, higher are the recirculation flow rate (Figure 11 and 12) and power exchanged through the chimney walls (Figure 10). The same trend is encountered for nodalization 2, but the recirculation flow rate is even higher in that case.

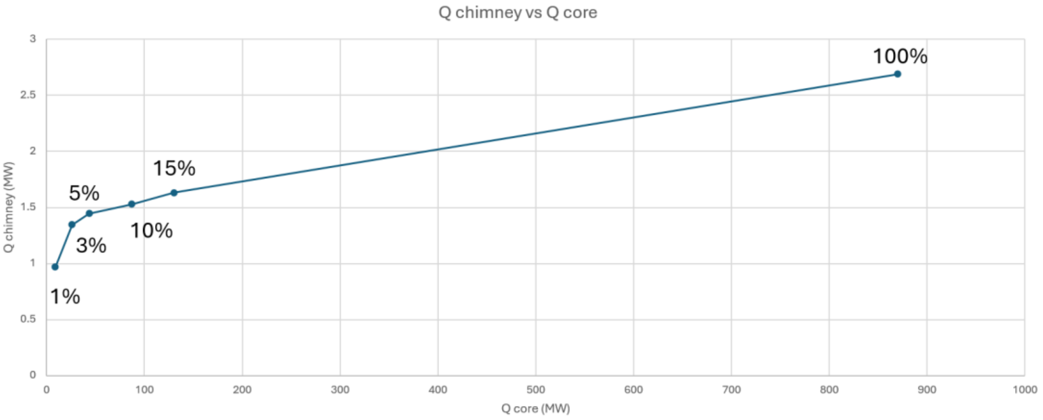

Figure 10. Nodalization 1, two phase flow. Power exchanged through the chimney wall vs Core power. Core power in % is also indicated on the graph.

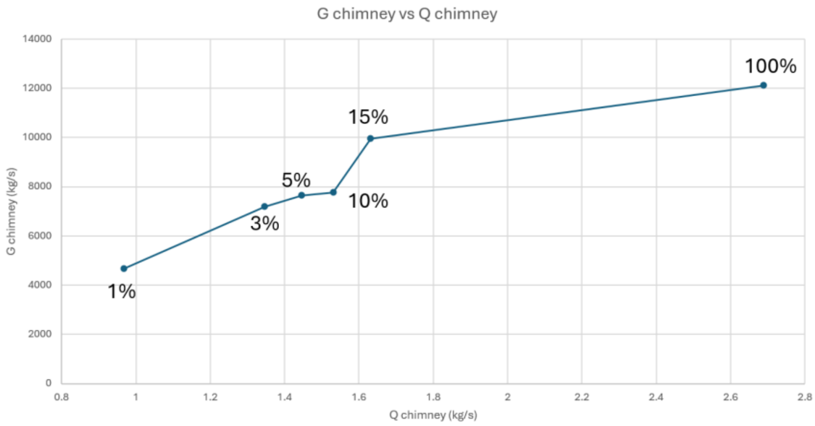

Figure 11. Nodalization 1, two phase flow. Recirculation flow rate vs Power exchanged through the chimney wall. Core power in % is also indicated on the graph.

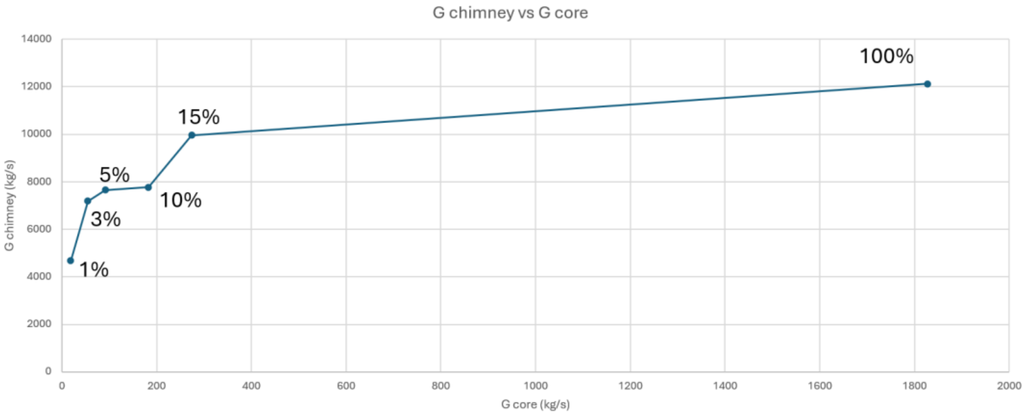

Figure 12. Nodalization 1, two phase flow. Recirculation flow rate vs Primary flow. Core power in % is also indicated on the graph.

5 IPWR RECIRCULATION

5.1 Snapshot on the reference iPWR design

The reference design is vaguely inspired to the NuScale design [3] even though this study does not claim to mirror the NPM (NuScale Power Module) normal operation characteristics nor its response to operational transients or accidental conditions. Anyway, in the following a description of the NuScale design itself will be given.

The design of the NuScale reactor [3] features an integral power module housing the reactor core, two HCSGs, and a pressurizer within the reactor vessel. The RPV (Reactor Pressure Vessel) is enveloped by a CNV (Containment Vessel), partially submerged in a pool serving as the ultimate heat sink for long-term decay heat removal. The primary system flow is driven by natural circulation. Safety systems are fully passive obviating the need for emergency diesel generators.

The reactor pressure vessel is a cylindrical steel vessel with an inside diameter of approximately 3m and an overall height of approximately 18m, designed to withstand an operating pressure of approximately 12.8 MPa. A flanged lower portion facilitates refuelling access.

The reactor's pressurizer system maintains coolant pressure through a pair of heater bundles installed above the pressurizer baffle plate and a spray provided by the chemical and volume control system. A steel pressurizer baffle plate integral with the RPV provides a barrier between the saturated water in the pressurizer and the RCS (Reactor Coolant System). The pressurizer baffle plate is integrated with the upper steam plenums, has 8 flow holes having a 10cm diameter each to allow surges of water into and out of the pressurizer, and it acts as a thermal barrier.

The core configuration for the NPM consists of 37 fuel assemblies and 16 CRAs (Control Rod Assemblies).

The fuel assembly design is like a standard 17x17 PWR fuel assembly. The only significant differences are that the fuel assembly is nominally half the height of a standard fuel assembly and is supported by five spacer grids. The fuel is uranium dioxide, with gadolinium oxide as a burnable absorber homogeneously mixed within the fuel in select rods. The U-235 enrichment is less than 4.95 percent. A seamless M5R fuel rod cladding encapsulates the fuel pellets which are cylindrically shaped with a spherical dish and chamfer at each end. Each fuel rod has an internal spring system which axially restricts the position of the fuel stack within the rod. The fuel rods are pressurized with helium.

The CRAs are organized into two banks: a regulating bank and a shutdown bank. The regulating bank is used during normal plant operation to control reactivity. The shutdown bank is used during normal shutdown. All 16 CRAs are inserted for scram events. The individual rods contain B4C pellets in the upper portion of the rod, and AIC absorber in the tip of the rod.

The core is surrounded by a stainless-steel heavy neutron reflector.

Differently from most of the other iPWR designs having many small HCSGs, NuScale features two large HCSGs whose helix is intertwined along the riser assembly axis. This allows symmetrical inlet core temperature even in the case in which only one of them is operating. They are composed by 1380 tubes in total with an average length of about 24m, and an inner diameter of about 1.3cm. Each SG tube is comprised of a helix with bends at each end that transition from the helix to a straight configuration at the entry to the tubes' sheets. In normal operation they produce steam at 35bar, 307°C with a moisture content smaller than 0.1 percent. The feed and steam plena comprising a single SG are configured 180 degrees apart and a total of four feed and four steam plena are located 90 degrees apart around the RPV. [3,6]

5.2 Guidelines in setting up the nodalization

The general guidelines for setting up the nodalization have been derived from the RELAP5-3D code manuals. [7,8]

As a rule of thumb in the primary system nodalization, volumes lengths have been kept between 10 and 50cm, mainly around 20cm for the primary circuit but their length can reach 2m in the steam line region. Also, it has been tried, when possible, to keep the ratio length/hydraulic diameter greater than 1 and homogeneous for the system. In fact, having all the nodes with the same Courant limit, would allow the selection of an optimized maximum time step, beneficial both from the point of view of computational time and numerical accuracy.

In the primary system, as well as in all the natural circulation loops modeled in this work, the "slice nodalization" technique is implemented to enhance the code's ability to replicate natural circulation phenomena. This approach involves dividing mesh cells into different nodalization zones at the same elevation, each with identical cell lengths. By doing so, errors stemming from the position or elevation of the cell nodalization centre, which could impact calculated data accuracy, particularly in the presence of natural circulation regimes, are mitigated. These errors stem from the computation of the gravitational contribution to the momentum equation of physically parallel volumes situated at points with varying elevations. Consequently, they aggregate to form a kind of spurious pump effect. Without employing the "slice nodalization" technique, these errors must be considered, especially as they amplify with the use of larger nodalization cells. However, employing a "fine nodalization" can alleviate this issue. While the impact of this error on results is generally less significant in simulations of forced circulation regimes, adopting the "slice nodalization" technique may necessitate nodes of smaller lengths, potentially leading to increased numerical errors and computational time. [9] This is for instance true in the present work, where the part of downcomer parallel to the core, is characterized by relatively short nodes.

The 1380 helical tubes of the reference iPWR are divided into four groups and are connected to the four feedwater headers and four steam plena.

In the RELAP5-3D nodalization, each one of these four groups of tubes is modeled by a single pipe. Each pipe is characterized by an equivalent flow area, an average length, an estimated pitch angle and a hydraulic diameter equal to the geometric one. In this phase, it was deemed not necessary a reduction of the HD in the tubes because of the arbitrarity of the singular pressure drop at the tubes' inlet.

At each tube's inlet, a flow restrictor is present to increase pressure drops and to avoid DWOs (Density Wave Oscillations) for full power conditions. To simulate this feature, an arbitrarily large k-factor has been placed at the inlet junction of each of the tubes.

The heated diameter has been reduced to increase the HTC (Heat Transfer Coefficient). It has been checked that the order of magnitude of the HTC is the same as the one provided by correlations available in literature. [10,21]

5.3 Sketch of the primary side nodalization

In Figure 13, as sketch of the primary side nodalization used for steady state qualification is shown.

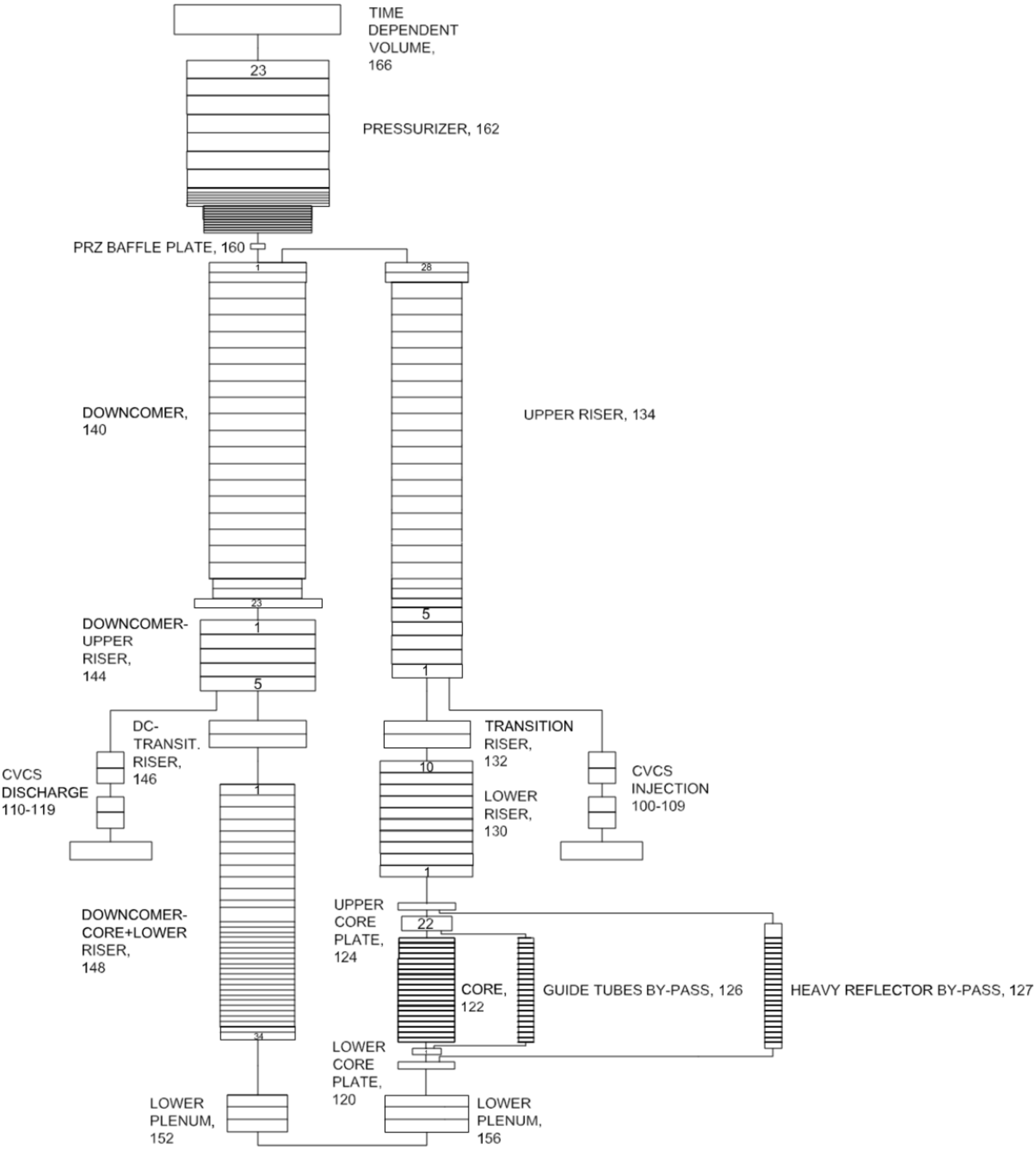

Figure 13.Sketch of the primary side nodalization used for steady state qualification.

5.4 Qualification of the nodalization in steady state

In Table 1., a comparison between some relevant parameters as reported in the reference documentation [3], and the data obtained by using RELAP5-3D is presented.

Table 1. Steady state in natural circulation: main parameters comparison

Parameter (unit)	Reference [14]	RELAP5-3D
Core thermal power (MW)	160	160
Average linear power density (kW/m)	8.2	8.2
Primary pressure (MPa)	12.755	12.755
Primary flow rate (kg/s)	587	586
Bypass flow (%)	7.3	7.2
T cold primary (˚ C)	258	260
T hot primary (˚ C)	314	313
T average primary (˚ C)	284	286
Core delta T (˚ C)	56	53
Subcooling at core outlet (˚ C)	16	17
Secondary flow rate (kg/s)	67	67
SG inlet temperature (˚ C)	149	149
SG outlet temperature (˚ C)	307	311
SG outlet pressure (bar)	34.5	34.5
SG outlet superheat (˚ C)	65	69

5.5 Nodalizations used to investigate the chimney recirculation in the reference iPWR

To realize a nodalization able to predict CR, the riser has been divided into an inner and an outer region, analogously as what has been described in paragraph 2.1. Therefore, two different nodalizations have been obtained, nodalizations 3 and 4, the first without and the second with cross junctions in the riser, as shown respectively in Figure 14 and Figure 15.

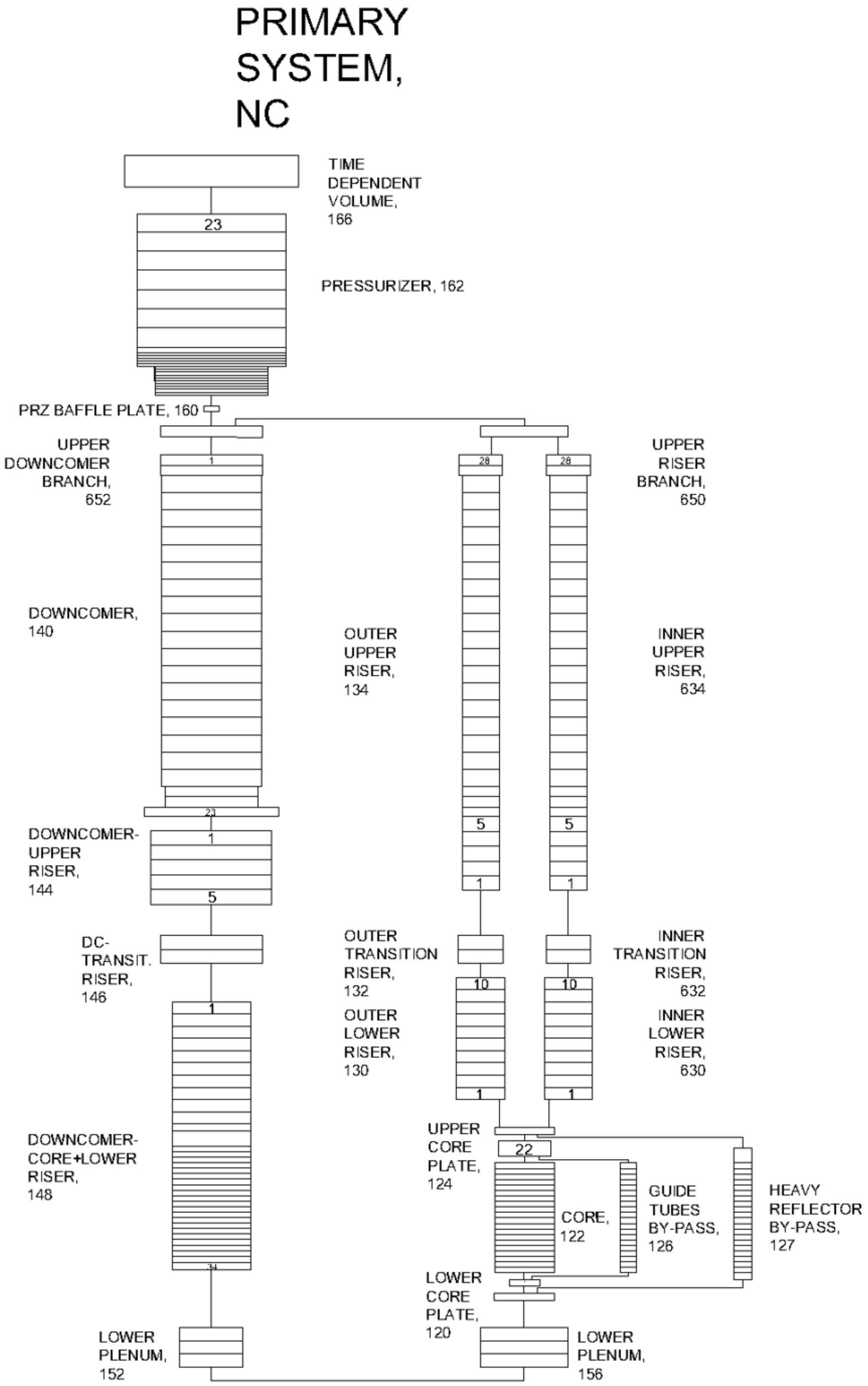

Figure 14. Nodalization 3: iPWR nodalization with outer and inner chimney connected only at the top and at the bottom.

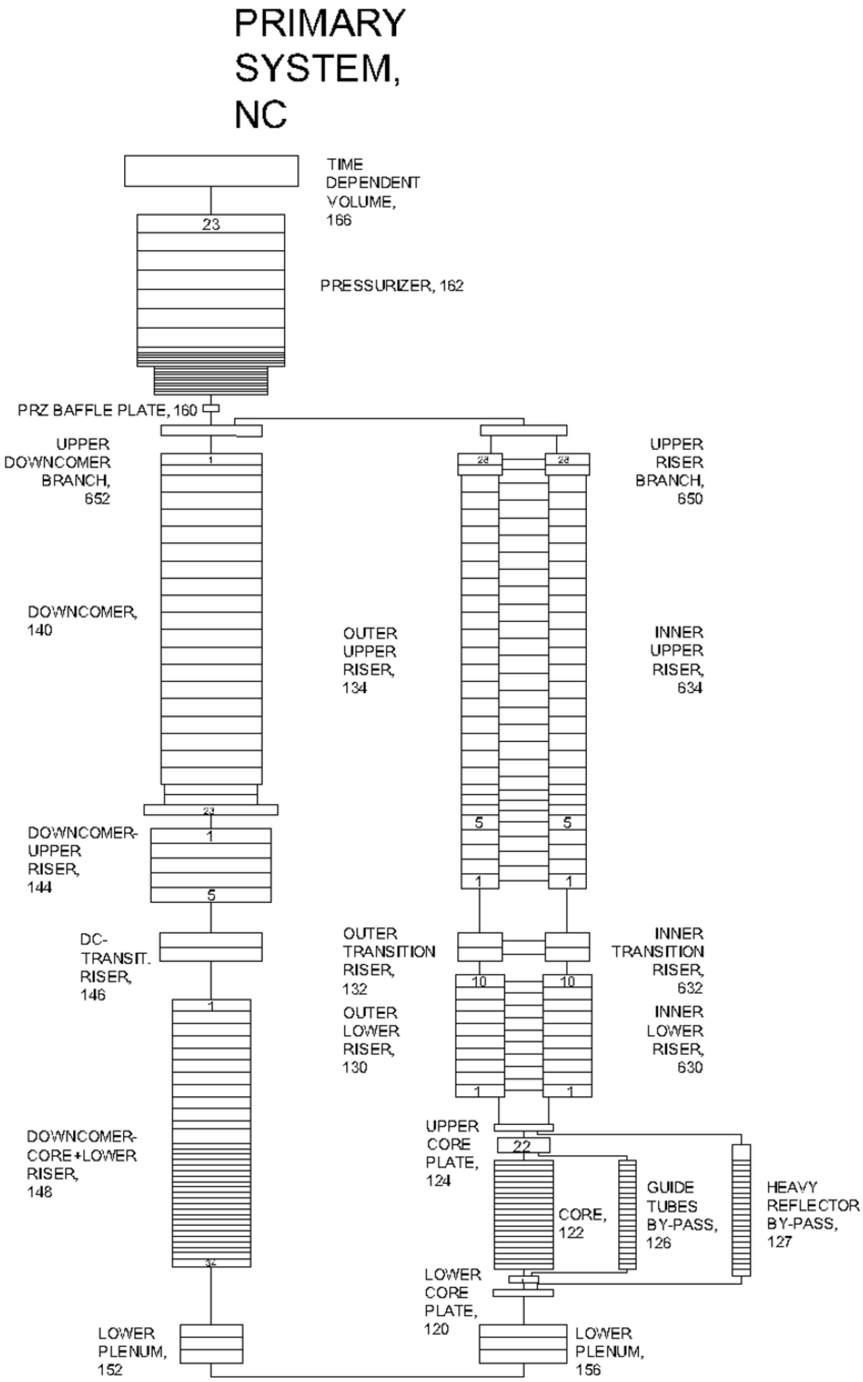

Figure 15. Nodalization 4: iPWR nodalization with outer and inner chimney connected by cross-junctions.

5.6 Results

Three sets of calculations have been performed. Each set employs the same nodalization, either nodalization 3 or 4, and three power levels have been analyzed per set: 1%, 15%, 100% of the nominal power. At 1% and 15% power, the secondary pressure and flow rate have been tuned to moderate the DWOs affecting the HCSG for low power conditions, therefore the primary average temperature is lower than the one we have for full power conditions.

In all the cases a common response has been obtained, meaning that when nodalization 1 is adopted, a recirculation flow of roughly 100kg/s is obtained and the colder stream reaches the region above the core.

When nodalization 4 is utilized, again a recirculation loop is established, but regardless of the power level it stays localized in the upper part of the chimney. The bottom boundary of the recirculation loop moves upward when primary flow is increased.

Even though this may not have effects on reactivity feedback, it may still have structural mechanics implications or trigger unstable behaviors.

In Figure 16. we can see the flow rate in the ascending branches for nodalization 3, 100% power. The power exchanged through the chimney wall is about 580kW.

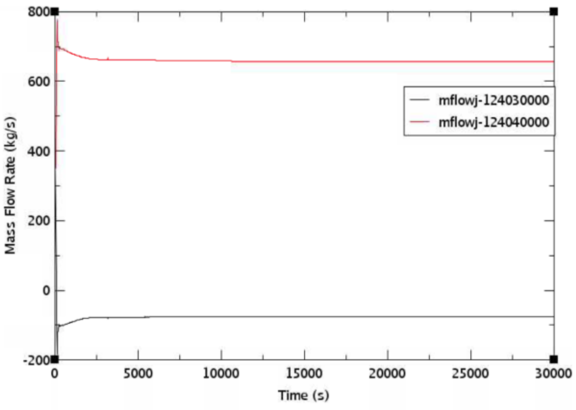

Figure 16. Flow rate in the two ascending junctions at the riser bottom for 100% power, nodalization 3.

While, from Figure 17 and 18, we can understand that for nodalization 4, full power, the recirculation loop is located on the upper portion of the riser. The recirculation loop height is about 1.5m and the power exchanged across the wall is about 640kW. The differences between this result and the results seen in paragraph 3 are due to several factors between the two models such as different temperature profiles and different hydraulic and heated diameter in the downcomer, plus also a slightly different geometry for the chimney itself.

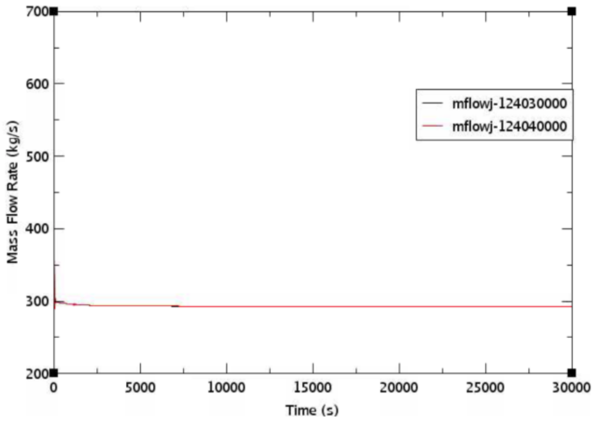

Figure 17. Flow rate in the two ascending junctions at the riser bottom for 100% power, nodalization 4.

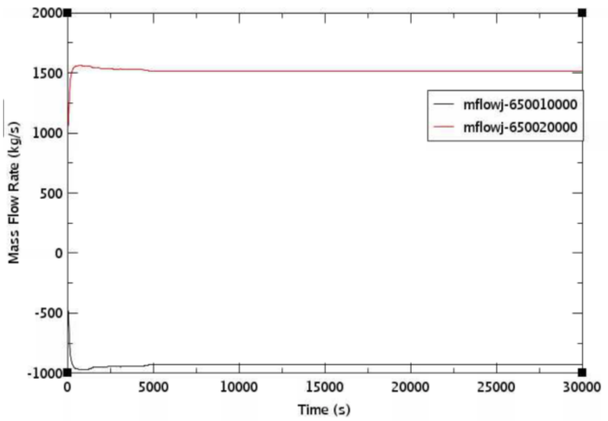

Figure 18. Flow rate in the two descending junctions at the riser bottom for 100% power, nodalization 4.

6 CONCLUSIONS

Several simulations have been performed through RELAP5-3D to investigate three-dimensional recirculation phenomena in the chimney of NC LWRs through simplified nodalizations, in such a way to isolate the phenomenon itself.

To do so, the riser has been modeled by dividing it into an inner and an outer region, where only the outer region has been put in contact with the riser wall and therefore been allowed to exchange power with the fluid in the downcomer. In this way, a gravity driven downward flow in the riser periphery has been obtained.

Sensitivity studies on the modeling of the riser itself for different power levels have been conducted, and the location of the recirculation loop as well as the power exchanged through the chimney wall have shown dependencies on the nodalization adopted. Nevertheless, the phenomenon has always been detected.

Furthermore, we’ve simulated this phenomenon thanks to a nodalization representing the complete primary system of an iPWR. Also in this case, the recirculation loop has been obtained, and depending on the adopted nodalization it can span the whole chimney, or it can be limited to the upper region of the riser.

Moreover, when cross junctions are used to connect riser outer and inner regions, the location of the recirculation loop has shown to move upward when power increases, because of the increased inertia of the ascending flow.

Of course, the qualification level of the performed analysis is not proven in quantitative terms and these calculations are preliminary scoping calculations. Nevertheless, recirculation in the chimney of NC reactors may occur and may have an impact on system performance.

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