Experimentally investigating the influence of the feedwater sparger position on the stability of the boiling water reactor facility GENESIS

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Abstract

In this bachelor project research is done on the influence of the position of the feedwater sparger on the stability of a natural-circulation boiling water reactor (BWR). This is done by doing numerous experiments on the BWR facility GENESIS, in which a sufficient number of different feedwater inlets are created. It has been found that the stability of the BWR shows periodic behaviour and that for different feedwater inlet positions minima and maxima in the decay ratio exist. One of the so called stable points is situated close to the reactor core inlet of the facility. Since this location is not realizable the next minimum is considered which is located 7 meters further away from the core inlet. This behaviour of the stability is easily understood by relating the sparger to core inlet distance to the phase at which the temperature oscillations reach the boiling boundary. If this phase reaches appropriate values then the stability is positively influenced. In this case it is found that the 7 meter position corresponds to a phase of about 360 degrees and that the oscillations are in phase with the core inlet oscillations which causes the low decay ratio.

Introduction

Nuclear reactors have always been and always will be a hot topic. With all the discussion going on about sustainable energy, safety of reactors and the most efficient way of producing energy nuclear reactors are an important and interesting topic to investigate. This thesis, performed as part of a Bachelor Project at the Physics of Nuclear Reactors research group, evolves around this topic and focuses, in particular, on one type of reactor: the natural-circulation boiling water reactor (BWR).

The natural-circulation BWR is just one of many different reactor types. The obvious characteristic of this type of reactor is that the reactor coolant is allowed to boil inside of the reactor core and that this boiling forces the coolant to circulate due to simple convection, instead of the usual pumps that are implemented. This fact makes the BWR an efficient but, most of all, safe construction.

In these types of BWRs, due to the complex feedback mechanisms taking place inside of the reactor, different kind of instabilities occur. One of these instabilities is caused by temperature fluctuations at the core inlet. Previous research done by Zboray [5] et al. , based on numerical models and experimental data of the reactor facility DESIRE, has shown that the position of the feedwater sparger has a significant influence on this instability and that by changing the position the stability can be altered. An important conclusion is that the phase (dependent on the position) at which the temperature oscillations reach the core inlet with is directly linked to the stability. Since Zborays methods were limited and in DESIRE unsufficiently high flow rates could be reached due to the small cross sections of the downcomer a new facility was created. This facility, called GENESIS, is a scaled down version of the newest type of BWR (the ESBWR). Marcel has followed up Zborays research with measurements on this facility in which three different feedwater inlets were created. With this he was able to verify Zborays prediction that the phase is indeed the instability determining characteristic and that the reactor is the most stable at the reactor core inlet where this phase is zero[3].

To further investigate this stability influence, and possibly find more minima and maxima in the instability, 10 additional inlet positions have been added to the facility. The goal of this bachelor project is to do measurements on all 13 inlets, when the reactor is running at nominal power, and thus to gain important extra knowledge on the influence of the feedwater sparger position.

Chapter 1

Theory

1.1. Introduction

As this thesis covers the stability of the BWR and this stability is determined by the (feedback) system taking place first a brief description of this subject is given. Secondly we will look at the theory behind stability analyses and the general usage of correlation functions. Conclusively, in this chapter and the next, we will look at the reactor itself - how it works and why the position of the feedwater sparger has such a major influence - and how we want to handle the main subject. [1]

1.2. Signals & Systems

Signals describe a wide variety of physical phenomena. The representation of the signal depends on the nature of the signal and its environments, but generally speaking a signal describes the variations, of some particular form, of the physical phenomenon.

For instance the power of a reactor can be described by a signal by plotting the magnitude of the power for a given time period. From this one can obtain the characteristics of the process like its maximum value, its period (if its periodic) or another variable one finds interesting. Thus by doing this or by creating a different mathematical representation of physical phenomena one can try to understand the physical behaviour at work.

Most of the time there is not only one signal but an input and an output signal. If this situation occurs one can also consider a system which contains the information of how the input and the output are linked to each other.

What basically happens in a system is explained by the following picture:

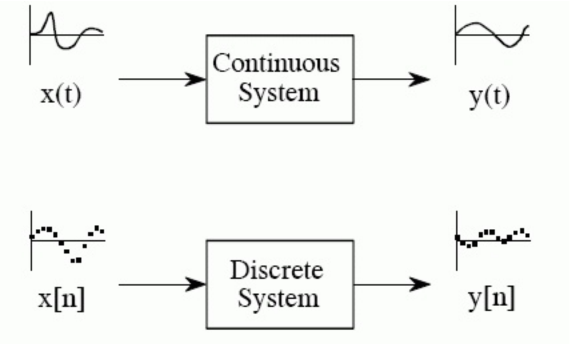

Figure 1.1. Simple representation of a system and its effects

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[1] The theory in this chapter is gotten from the following sources: [1, 4, 6]

A (continuous or discrete) signal enters a system. This system posesses numerous characterics which can influence the input signal. This results in an output signal that in most cases differs from the input signal. In most of the cases treated in this thesis a periodic and continuous signal enters a system and leaves the system with a certain change in frequency, phase, or amplitude. Mathematically speaking an input signal $x(t)$ enters a system G and an output signal $y(t)$ comes out:

$$x(t) \rightarrow y(t)$$

An example of a first-order system with input and output is:

$$\frac{dy}{dt} + ay(t) = bx(t)$$

Here $x(t)$ is the input signal, $y(t)$ is the output signal and a and b are constants.

1.2.1. Transfer functions

Because a system contains so much important information about the process at work numerous different analytic methods can be applied to it. One of them is determining the transfer function: another type of mathematical representation of the relation between input and output of the system, but this time in terms of frequency. This representation allows having a different viewpoint of the system and gives us new and easier achievable information. Besides that it makes it more efficient to work with large systems with many different physical processes. All this is caused by the simplifying nature of the transfer function that just looks at the two important parameters: the frequency and the phase.

In the frequency domain we can write the input-output system:

$$Y(\omega) = G(\omega)X(\omega) \tag{1.1}$$

Here $G(\omega)$ is the transfer function and $X(\omega)$ and $Y(\omega)$ the input and output signals respectively. The transformation to this domain from the time domain is most often called the Fourier transform or Laplace transform. The transfer function $G(\omega)$ highlights the relation between input and output at the different frequencies. Since in this project the instabilities are caused by oscillations and are periodic every instability exists at a different frequency and can be looked at seperately. The transfer function thus offers the possibility to look at the most important system: the relation between the feedwater and the main stability.

1.2.2. Feedback systems

A feedback system is a system that is used to control itself. The general explanation is that the output signal of a system is used and added (fed back) to the input signal. Feedback processes are usually found in complex systems such as the one this thesis is dealing with. In this case the origin of the feedback lies in the way that the different characteristics within the system are all linked to eachother. When for instance one of the physical parameters is fluctuating it causes another one to fluctuate and the other way around. The following picture might make the definition of the feedback clear:

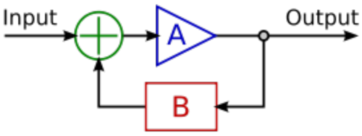

Figure 1.2. A feedback system

In this picture one can see that a certain input enters a system, is amplified by a certain transfer fuction A, and that following this the output is fed back (with a certain multiplication factor B that can be positive or negative) to the input. This induces a total input-output system in which the definite output is determined by the nature of the feedback B.

Often the feedback is used to stabilize a system: when the amplitude of the output, without feedback, would be growing the feedback causes it to grow less or even to fully stabilize. This is called negative feedback.

The opposite can also happen and a feedback system might have a destabilizing effect: positive feedback. Usually the type of feedback depends on how the phases and amplitudes of the input and the output are related to eachother. If for example two sine functions that are out of phase by 180 degrees get added to eachother the maxima and minima exactly cancel eachother.

1.3. Stochastic signal analysis

Signals that are less clear and show some sort of unpredictable nature of which the physical nature is not easily determinable are described by using random variables and stochastic processes. One of the reasons for this different approach lies in the fact that these types of signals are difficult to reproduce. When the same signal is measured at a different time or location the signal might be disturbingly different due to random unwanted influences like temperature fluctuations or noise. Of course the physics remain the same and the relevant information can still be deduced from the signal, albeit in a different way and a method has to be found to distill the signal.

For instance one can interpret the signal as random noise and not describe it by parameters like its amplitude but by a probability density function that characterizes the probability that a certain value will result. This creates a better way to analyse these signals. The following subsections will treat the two main analyzation techniques used in this project.

1.3.1. Auto-correlation.

Auto-correlation function

To understand what the nature of a signal is one can compare signal values at certain times to those at other instants. From this a dependence can be deduced and it is described by the auto-correlation and auto-covariance function. The correlation is calculated as the average product of two signal values (of the same signal) which are a time instance τ apart. What can be deduced from this function is the timelag between the signal and its shifted versions.

The auto-covariance (COV) is related to the auto-correlation (ACF) function as the ACF is just the normalized COV:

$$ACF_x(\tau) \equiv \frac{COV_x(\tau)}{COV_x(0)} = \frac{< x(t)x(t+\tau) >}{\mu} \tag{1.2}$$

Here μ is the maximum of the COV. One can see that the ACF is actually a particular representation of the signal and that signal properties can be obtained from it. What the ACF is used for is detecting the average duration of disturbances in the signal.

Auto-power spectral density

The auto-power spectral density (APSD) is the frequency representation of the ACF (or actually the COV). It too is a continuous function but this time in the frequency domain. When the APSD is calculated the resonance frequency of the signal can be found.

The APSD gives the power that is present in a certain frequency band so the higher the power at a frequency is the more that frequency is dominant in the signal. This fact is used in the project to find what physical process would be of main interest. The APSD can be calculated from the COV by Fourier transforming it:

$$APSD_x(\omega) = \mathcal{F}(COV_x(t,\tau)) \tag{1.3}$$

Where the Fourier transform is:

$$\mathcal{F}(x) = \int_0^T x(t)e^{-j2\pi\omega t}$$

The APSD can efficiently be used as proper signal analysis as it gives the the distribution of the signal in parts. Every dominant frequency(band) it shows can have its corresponding transfer function and the most dominant one might just be the driving force of the entire system. To actually do something with the transfer function we conclusively have to look at cross-correlation.

1.3.2. Cross-correlation

Cross-correlation function

This function (the CCF) is basically the same as the ACF except that it gives the correlation between one signal and another signal. It can give some added insight in the relation between two different variables located within the system and it is defined as:

$$CCF_{xy}(\tau) \equiv \frac{COV_{xy}(\tau)}{\sqrt{COV_x(0)COV_y(0)}} = \frac{< x(t)y(t+\tau) >}{\sqrt{\mu_x \mu_y}} \tag{1.4}$$

Here the μ_x and μ_y are the respective maxima of the two signals. When this CCF is zero the signals are said to be uncorrelated; they have no influence on one another. When the CCF exhibits a peak at a certain timelag τ this usually means there is a disturbance in one signal that needs time τ to influence to the other signal. This means that CCF analysis can be used for transit time estimation.

1.3.3. Noise analysis

The theory of correlation is often used in noise analysis. Input signals that contain noise can efficiently be used to gather important information about the system and its transfer function. Important for this type of analysis is that the input signal can be interpreted as white noise (noise that contains all frequencies) in order that responses to all frequencies are equally considered.

In the case of this white noise we can determine the transfer function from the APSD (and thus the ACF) because the input and output signals are related like this:

$$APSD_e \cdot |G|^2 = APSD_x \tag{1.5}$$

Here $APSD_e$ is the APSD of the noise. Because it is white its value is just 1 and equation 1.5 reduces to:

$$|G|^2 = APSD_x$$

Thus from the APSD the transfer function and in turn the characteristics of the system can be determined. Noise analysis also ensures that the signals used are reliable since all possible influences (frequencies) are considered.

1.3.4. Decay Ratio estimation

As the entire system is characterized by its ACF the ACF can be used to determine the stability. This stability can be calculated by means of the decay ratio (DR). Since the system of interest is present at a certain frequency it has some sort of oscillating influence. As most physical systems are stable this influence damps out.

To calculate the amount of damping the DR is used. The DR is the ratio of two consecutive maxima of the ACF[2]. If the DR is equal to 1 the ACF stays constant over time. If it is higher than 1 it is unstable and when it is lower than 1 it is stable. Let us consider an example:

If the ACF is described by the following function:

$$y(t) = e^{at} \cdot cos(bt) \tag{1.6}$$

then a provides the information about the amount of damping and b the information about where the maxima are located. The DR is then calculated as follows:

$$DR = \frac{cos(b(t+T)) \cdot e^{a(t+T)}}{cos(bt) \cdot e^{at}} = e^{aT}$$

As $T = 2\pi/b$ it follows that

$$DR = e^{\frac{2\pi a}{b}} \tag{1.7}$$

This theory is the main analyzation technique used in this project to determine the stability. In this project a method is found to represent the ACF as a function that looks like equation 1.6 in order to easily find the DR.

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[2] Given that a second-order system is used. A higher-order system has a different behaviour of its maxima and there is no straightforward way of finding its maxima and thus its DR.

1.4. Physics of the natural-circulation boiling water reactor

1.4.1. Basic natural-circulation principle

BWRs are reactors in which water is heated to produce steam that is sent to turbines to produce energy. For this process to occur the fluid has to flow around in a loop. This flowing is important because not only does it make the steam reach the seperation vessel (and the turbines), it also creates the possiblity to use the reactor fluid itself as the coolant.

Natural- circulation BWRs also use this principle but the water is forced around by convection instead of pumps. This aspect has been made possible by forcing the water to flow by density differences only; an effect that always occurs and makes this version of the BWR that much safer. Not only is it safer cause active components (like the pumps) are absent it also is very stable because of the negative feedback of the flow-void coupling.

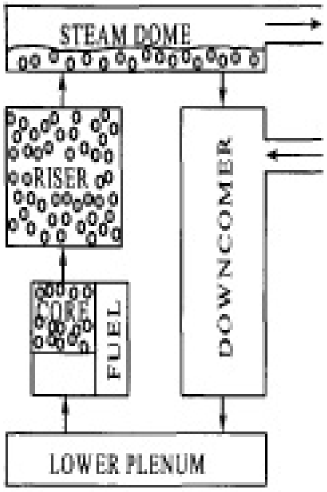

Figure 1.3. Schematic view of a BWR [5]

The main principle behind the BWR starts at the reactor core. In the reactor core heat is produced by nuclear fission reactions in as many as 700 fuel assemblies. The heat that is produced is transferred to the coolant (water) that enters the core below saturation temperature. During its rise through the core the boiling begins at the boiling boundary and from that point more and more void gets created. When the water, which now is a mixture of fluid and vapour, leaves the core at the core outlet it spends some time in the riser, also known as the chimney. Then at the top it reaches the seperation vessel and the damp leaves the main circulation loop to power the steam turbines.

The remaining fluid flows forward without void and enters the downcomer. This is basically what forces the natural-circulation process the most because the removal of the void causes a significant density difference between the fluid in the core plus riser section and the downcomer. This also explains the purpose of the riser section: it increases the flow distance and therefore the flow by quite a margin.

Meanwhile, during its fall through the downcomer, the fluid is joined by the feedwater of which the main purpose is to cool the hotter downcoming fluid and to conserve the mass in the system. This feedwater is the vapour that, after it has been used in the turbines, has been condensed and it re-enters the main circulation at a constant temperature.

The downcoming fluid, now with a lower enthalpy due to the feedwater, arrives at the core inlet and the entire process repeats itself.

Within this entire process of circulating fluid and of inserted feedwater exists a very complex system of feedback mechanisms that determine the overall stability.

Our interest is the exact influence the input of the feedwater has on the stability so the main void-flow feedback will not be explained in detail. Still a brief description can be helpful.

1.4.2. BWR instabilities

There are three classes[3] of instability present in the natural-circulation BWR of which it has been shown that the thermal-hydraulic effects cause the most important instability. The effects of the thermal-hydraulics are due to the density wave oscillations in the core and the riser. If for instance the flow at the core is increased (due to a perturbation in power or temperature) this causes the coolant to spend less time in the core and thus less vapour to be created. This lower amount of vapour then causes the flow to decrease as opposed to the original increase of flow[4]. As can be seen this is a negative feedback process and it is the reason the BWR is unconditionally stable.

1.4.3. Feedwater inlet influence

Why does the feedwater inlet position change the performance of the BWR? Not only is there the thermal-hydraulic system there is also added (possibly negative) behaviour of the reactor due to the insertion of feedwater. To explain this behaviour let's have a look at the flow at the feedwater sparger position. Because in the core the saturation enthalpy has been reached, and because the pressure over the channel is sufficient, the enthalpy at the sparger position is basically constant. The flow on the other hand is fluctuating due to all the different characteristics of the system.

Now the feedwater point can be seen as something similar to the reactor core section, the only difference being that now the coolant is being cooled by the feedwater. What happens is that if the coolant flows past the inlet position, with a relatively high flow, the enthalpy is perturbed. If it flows relatively slow this effect is amplified and the fluid is cooled more than when the flow is higher. So if a simple oscillatory flow reaches the feedwater inlet what follows is an enthalpy oscillation of the same frequency. This oscillation then travels to the core inlet and has its added influence on the stability of the reactor.

For this effect the traveltime (transport delay) of the enthalpy oscillation (the downcoming flow) is very important. For one certain distance between feedwater inlet and core inlet (one inlet position) the oscillation reaches the core with a certain phase delay. When this phase delay is exactly $k \cdot 360$ degrees the enthalpy is maximal at the feedwater inlet (high flow) and the

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[3] The other two are related to the neutronics of the reactor and are of no interest in this project.

[4] This is a very short explanation. For more information on this instability, the neutronics and/or reactor dynamics have a look into [5] and [3].

enthalpy it reaches the core inlet with is also maximal. If on the other hand the phase delay, for a different inlet position, is not exactly $k \cdot 360$ degrees then the coolant will reach the core inlet with a different value (out of phase with the flow) than it originally had at the feedwater inlet (in phase with the flow) and it has an amplifying or damping effect on the feedback mechanism.

Chapter 2

Experimental setup

2.1. Introduction

To determine the stability of the BWR and the influence the feedwater inlet has on this stability the experimental facility GENESIS was created. This chapter treats the overall properties of GENESIS and the analyzation methods used to identify the stability.

2.2. GENESIS

The newest type of natural-circulation BWR is the Economic Simplified Boiling Water Reactor (ESBWR) and this reactor has been taken as the reference reactor. Because it does not exist yet an experimental facility has been created in the form of GENESIS.
Because it is not efficient to make an experimental facility with water as the coolant the ESBWR has been scaled down. Instead Freon R-134a (CH_2FCF_3) is chosen.

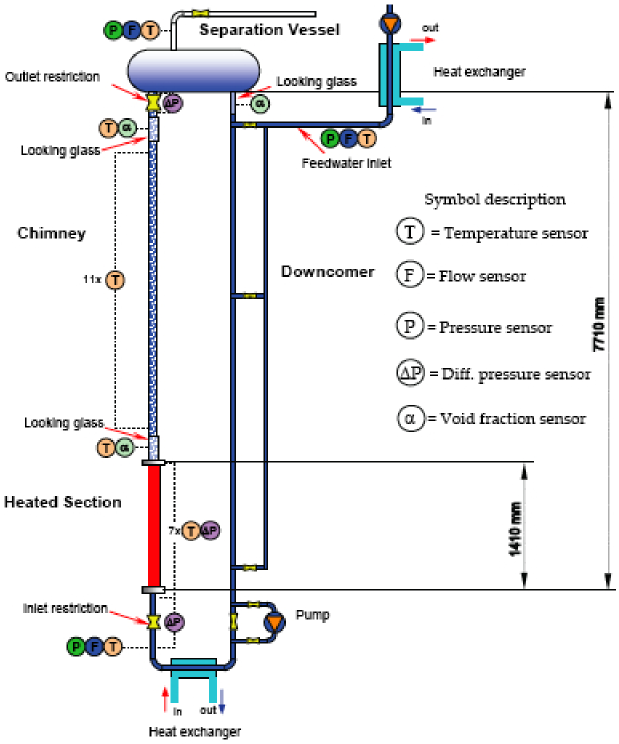

Figure 2.1. The GENESIS facility with three feedwater inlets. The current facility has 13 inlets.[3]

Figure (2.1) shows a schematic view of the GENESIS facility. Being about 10 meters high in total it is obvious that the facility is smaller than the proposed ESBWR that will be about 20 meters.

The facility has the same two circulation loops as the ESBWR. The primary loop starts at the reactor core (the heated section). In here the Freon will flow due to natural-circulation and move through the chimney section, past the seperation vessel and re-enter the core through the downcomer section. In the seperation vessel *all* the vapour is caught (no carry-under in the downcomer) and, through the secondary loop in which it is condensed and stored in a buffer vessel, led back into the primary loop by means of the feedwater inlet.

In the entire facility numerous measurement devices are installed to observe all the processes taking place in the reactor. The most important ones are the magnetic flowmeters, the pressors sensors, the capacitance void-fraction sensors and the thermocouples located at a sufficient amount of positions. Some of the sensors are not only used to characterize the operational status but also to maintain the safety. Linked to the pressure sensor at the seperation vessel is a regulator that regulates the pressure drop over the riser exit valve. When the reactor is running especially this pressure has to be kept constant because if it is the reactor is running at nominal conditions.

To be certain these nominal conditions are reached and maintained (this is wanted because the ESBWR of course would be running under the same condition) the feedwater inlet flow can also be adjusted to sustain the mass balance in the system. To be able to do measurements with Freon of different temperatures (defined by the subcooling number) at the core inlet the feedwater temperature too can be adjusted by means of the heat exchanger.

2.2.1. Thermal-hydraulic instability

GENESIS has been created to offer numerous ways of characterizing the physics at work in a ESBWR. In this project, as has been said, the main matter of interest is the thermal-hydraulic instability and especially the feedwater inlet position influence on this instability.

2.2.2. The feedwater inlet(s)

To determine the stability influence of the position of the feedwater inlet GENESIS has also been given the possibility to change this position. As many as 13 different inlet positions have been created starting from 215 mm from the heating core to all the way at the top of the downcomer about 10 meters higher up.

The Freon that is led through the inlet is, thanks to the condenser and heat exchanger, kept at roughly the same temperature. As has been said the feedwater pump too can be adjusted and can be set at a choseable constant feedwater flow. This makes way for making a solid analysis of the GENESIS stability.

2.3. Signal analysis

2.3.1. The frequency content

To identify what types of influences there are within the system the APSD of the signals will be calculated. As most signals (the temperature, the mass flow or the pressure) are all linked to eachother through the entire feedback system it should be sufficient to look at one of the signals only. Here most analysis is aimed at the mass flow since it is one of the determining parameters of the feedback. To be sure the correct signals are being used the signal analysis will be performed on not only this signal but also on others, but it is expected that it should not make a major difference.

As it is known most dominant frequencies in the system are not especially high and will correspond to the overall velocities in the system (which should be in the order of meters per second in a facility in the order of about 10 meters). This means it is most efficient to filter the various signals with a low pass filter and to look at frequencies in the order of about 0.1 Hz. (more information about the actual procedure undergone will be supplied in the next chapter).

When used hopefully the PSD will show peaks at different resonance frequencies and also possibly show a dominant frequency. The frequencies will most likely correspond to the thermal-hydraulic instabilities (although other influences like a pump frequency might also show) and it will offer important information about the contents of the system.

2.3.2. Determination of the stability: the decay ratio

While determining the frequency content only offers the possibility to understand which instabilies actually exist inside of the reactor the next procedure will provide the most important goal of this project: *finding the stability performance of the BWR for different feedwater inlet positions.*

In order to do this auto-correlation calculations will be executed to find out information about the behaviour of the instabilities. For this again mainly the mass flow signal will be used. Conclusively with MATLAB the ACF will be calculated. The ACF will show an oscillating signal in which all dominant frequencies present in the system are contained. This is all that is needed to determine the amount of stability.

Since it is difficult to directly calculate the DR from this signal Marcel has created a script which distills the important DR from the ACF. The undergone procedure is mentioned in Appendix A.

2.3.3. Stability influence

Hopefully the previous analysis shows just how stable GENESIS is. To understand what actually causes the instability and how it performs in different circumstances the CCF is used. For this analysis two different signals have to be used, for instance the mass flow and the temperature inside of the core. The CCF could then show that a certain timelag is present inside of the system and if it changes for different presets (here of course the position of the feedwater inlet) then this can give more insight in the situation. The CCF can then be compared to the ACF and together they can be used to draw the final conclusions of the thesis.

Chapter 3

Results

3.1. Experimental results with 13 feedwater inlet positions

3.1.1. STABILIZED case

In order to achieve a more elaborate conclusion on the influence of the feedwater inlet position measurements are performed on as 13 different inlet positions. First, research is done on the the DRs for all the different feedwater inlets. Here stability measurements are conducted for a stable situation, where the chimney outlet valve friction is small (this will be called the STABILIZED case) and resembles the ESBWR outlet friction. General information about the settings used can be found in Appendix C.

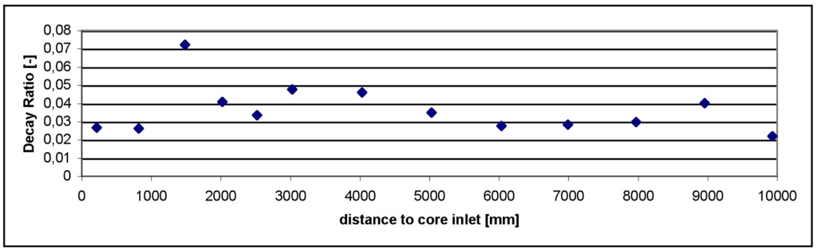

Figure 3.1. Decay Ratios of GENESIS for a minimal riser exit friction. As can be seen the facility is extremely stable for all inlets

Figure (3.1) shows the DR of the facility plotted against the feedwater sparger distance $l_{sp,in}$ to the core. A slight change in DR for changing distance is noticeable. One can see that there is some sort of periodicy which is probably related to the phase. Besides, eventhough it might just be caused by inaccuracies, it seems the DR is noticeably highest at distances between 1 and about 4 meters. All in all the DR of the reactor is very low for all conditions and one can conclude that the reactor is very stable and that just after one period (about 10s) the instability oscillation is damped almost completely. On the other hand a general conclusion on the feedwater position influence can not be made since the spotted periodicy could be coincidental and could be linked to uncertainties in the measurements (Appendix A).

3.1.2. DESTABILIZED case

To ensure more reliable results can be gotten the chimney outlet friction has been increased by closing the outlet valve (by a small margin). This increases the pressure drop over the valve by about a factor of 10 and it destabilizes the reactor [3]. It makes way for more accurate DR analysis since the DRs will be of a lot higher value (to just under 1) and due to this the relative uncertainty in the DR will be lower.

For this purpose two measurement series have been performed at equal conditions. In the next table and graph the general results are included.

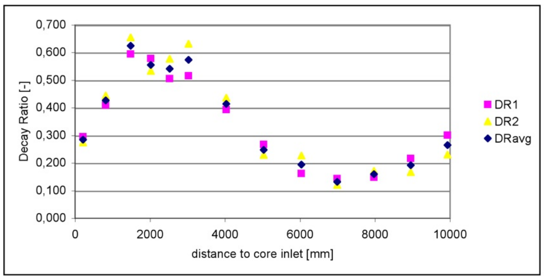

Figure 3.2. Decay Ratio plotted against sparger to core inlet distance. Two measurement sets are used together with their average

As can be seen clear periodic behaviour is spotted. In the region from the third inlet ($\approx 1,5$m) to the sixth inlet (≈ 3m) the DR is maximal but a new maximum in instability is located around the thirteenth inlet (≈ 10m). This verifies the presumption that the instability of the reactor indeed is periodic and that an ideal feedwater inlet position exists that is not located directly at the core inlet. It seems that the lowest minimum in DR is located at 7m instead of 0m.

To understand this behaviour (why exactly is it maximal or minimal at these values?) the DR is plotted against against Zborays interpretation of the phase delay[2]:

$$\phi = -2\pi \cdot f_{res} \cdot \tau_d \tag{3.1}$$

Here f_{res} is the resonance frequency and τ_d the time delay (or transit time) from feedwater inlet to the core inlet. τ_d is directly proportional with the distance $l_{sp,in}$ and thus the phase delay is determined by this distance. In the following table the various parameters are included.

Table 3.1. Measurement data for the DESTABILIZED case. The * is located at the disputable datapoints considering the DR itself.

$\#$	$l_{sp,in}[mm]$	$\tau_d[s]$	$f_{res}[Hz]$	$DR_1[-]$	$DR_2[-]$	$DR_{avg}[-]$	$\phi[°]$
1	215	0.20	0.129	0.295	0.274	0.284	-4.63
2	820	0.768	0.127	0.409	0.445	0.427	-31.3
3*	1485	0.93	0.121	0.595	0.654	0.625	-40.6
4*	2020	1.46	0.116	0.578	0.533	0.556	-61.1
5	2520	2.03	0.110	0.506	0.578	0.542	-81.0
6	3030	2.51	0.108	0.516	0.632	0.574	-97.4
7	4030	3.50	0.103	0.393	0.436	0.415	-130
8	5029	4.71	0.103	0.267	0.229	0.248	-174
9	6034	5.62	0.102	0.163	0.226	0.194	-206
10	6994	6.61	0.105	0.144	0.121	0.132	-250
11	7969	7.6	0.109	0.148	0.171	0.160	-302
12	8955	8.43	0.108	0.217	0.167	0.192	-329
13	9931	9.31	0.114	0.301	0.180	0.266	-383

No obvious dependence of the DR on the phase can be seen. Still as the distance and thus the phase changes the DR does that too and the maxima correspond to phases of roughly 50 and 400 degrees (the second maximum is to be expected shortly after the thirteenth inlet since periodicity is very probable). The minima are found at 4.6 degrees (probably fully minimal at 0°) and ≈ 270 degrees. The bad correspondence in the phase period of the maxima (350°) and minima (270°) probably lies in the third and fourth datapoints[1]. If we take the sixth inlet as the possible maximum then the phase difference with the second maximum comes closer to the phase difference of the minima, although the correspondence is still not optimal. Still it is presumable that the measurements on the sixth inlet are surely more accurate.

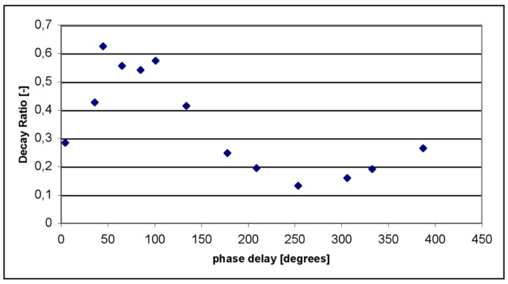

Figure 3.3. The average DR versus the phase delay.

Nonetheless, the maxima and minima have no logical phase at all. It could be that because the traveltime of the downcoming coolant is longer some of the influences get shifted. This can also be seen in the change of resonance frequency for increasing $l_{sp,in}$ as pictured in Figure (3.4). Due to unknown influences this frequency drops (and it even seems that the frequency too has periodicity). This would cause an influence on the DR that cannot be ignored.

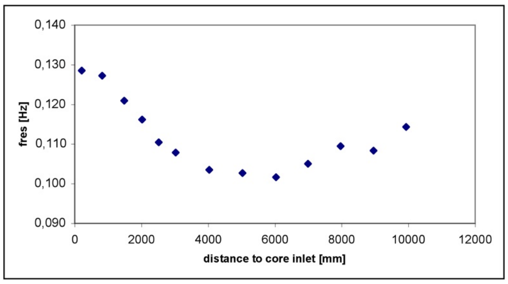

Figure 3.4. The resonance frequency versus the distance to core inlet.

It could also be that for the the other part of equation 3.1, the transit time, a correction must be made. Till now the transit time from feedwater

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[1] More on the uncertainties of the measurements is found in Appendix B and chapter 4.

inlet to the core inlet is taken, but expecting the enthalpy perturbation to already have an influence on the feedback right there might be incorrect. This presumption might be caused by the nature of the numerical models used by Zboray and Marcel [3, 2] in which the 1ϕ part of the core (before the boiling boundary) is considered as one node and the transit time thus as practically instantaneous. Looking at the boiling boundary as the reference position seems more logical because the feedback is based on the interaction of the enthalpy oscillations and the void fraction and the latter is just located at the boiling boundary. Since this boiling boundary is located fairly above the beginning of the heated section this might have a severe influence on the DR-plot as it would shift the graph to the right.

By calculating the cross-correlation between the *tc_1* and the *tc_2* temperature measurement data the average velocity of the one-phase (1ϕ) coolant inside the core can be found: $v_c = 0.5 \pm 0.1$ m/s. Taking a boiling boundary position of roughly 0.75 meter (at about halfway in the core) we get an extra transit time of about $1.5s$. Now the DR versus the corrected phase is replotted in Figure (3.5):

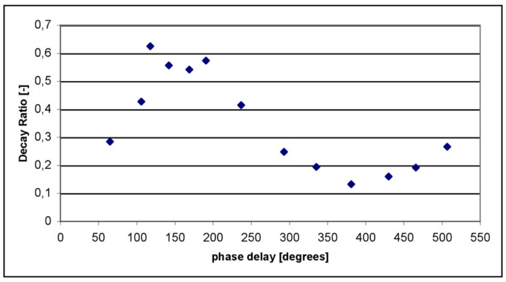

Figure 3.5. The average DR replotted versus the corrected phase delay.

The locations of the maxima now correspond to the prediction nicely. The maximum values are located exactly at about 180 degrees (and the second one might just be 360 degrees further on) and the minimum is located at the expected 360 degrees. The phase periods also agree and this seems an accurate result. Still it must be taken into account that the above calculations have notable uncertainties and that the calculation of the transit time to the boiling boundary position is an estimate. All in all it can be said that uncertainties exist in the total analysis but that the qualitative result definitely gives something useful.

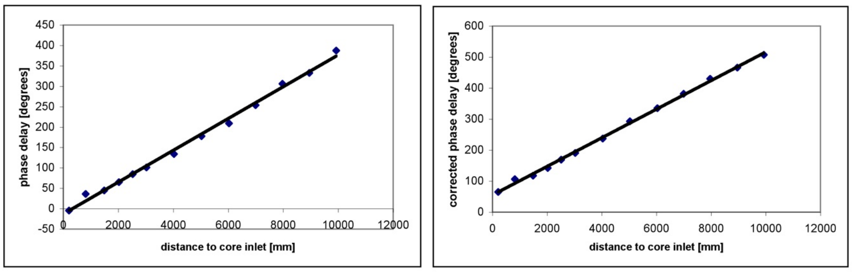

Figure 3.6. The original and corrected phase delay versus the distance to the core inlet.

In the above figures the distance is plotted against the phase delay. This also opts for the corrected phase delay as the phase cannot be zero at the core inlet since the heated section (let alone the boiling boundary) does not start exactly at this position. When extrapolated the corrected phase delay reaches zero at ≈ -50cm , about the place of the boiling boundary.
Another important aspect that can be distilled from the DR figures (3.3) to (3.5) is that for increasing distance (or phase) the DR gets smeared out. This can easily be assigned to the fact that, for increasing distances, the perturbations of the enthalpy become weaker due to turbulent dispersion. It is expected that for even larger distances the coolant will reach the core inlet at a basically constant temperature and that therefore the feedwater influence is gone. This also leads to the probablity that a certain constant DR is reached for increasing distances and it looks like it will be in the range of 0.3 to 0.4. It means that the DR is oscillating around this equilibrium value and that the feedwater can thus both stabilize and destabilize the system. Nevertheless the closer (and more realistic) positions should be considered and especially the minimum located at 7 meters is an interesting option.

Chapter 4

Conclusions

4.1. General conclusions

It has been shown that that the position of the feedwater sparger has a significant influence on the stability of the ESBWR facility GENESIS. By calculating the DR with the help of stochastic analysis proper conclusions can be made concerning this feedwater influence. It can be attributed to the fact that the distance from the feedwater sparger to the boiling boundary determines a certain phase delay which, as it changes, influences the overall stability. Minima in DR, that correspond to positions of the feedwater sparger that make the reactor as stable as possible, are located at phase delays of about $k \cdot 360$ degrees. Maxima, which should be avoided, are located at $(2k-1) \cdot 180$ degrees and correspond to situations where the out-of-phase nature of the feedback amplifies the instability by quite a large factor compared to the minima. These conclusions are obtained from the phase lag that is induced by the transit time from feedwater inlet to the boiling boundary position and not as was previously assumed from the feedwater inlet to the core inlet. Although quite some (quantitative) uncertainties exist in this conclusion a qualitative fact is that the ideal feedwater inlet position is located at about 7 meters from the core inlet (in the GENESIS facility) and that the general influence on the stability shows some sure periodic behaviour. The other positions where the DR is minimal this periodicity invokes are located either too close (unsafe) to the core or too far away (unrealistic) from the core.

4.2. Future work

Not all of the research was accurate. In order to draw some more definite conclusions on the feedwater influence extra and more elaborate measurements have to be done, especially on the effect of the boiling boundary. More important might however be to do some measurements at different conditions. Since in this situation the void reactivity feedback was inexistant it is interesting to see how the feedwater influences relate to these feedback mechanisms, especially since the resonance frequencies differ for these situations and in reality these mechanisms are of course present.

There is also the possibility to do some extra measurements on different feedwater positions since in the facility there exists a bypass (the heat exchangers). This would make the distance to the core for all inlets a few cm longer. All in all it is probably most important that the effect of the feedwater inlet position should be translated to real reactors like the ESBWR itself. Changed geometries of the real reactor can cause characteristics like the mass flow and the temperature oscillation wavelength to significantly change. Besides, in industrial reactors there might be added chaotic behaviour and (turbulent) diffusion could have a bigger (added) influence on the performance. Also the connection of the feedwater sparger to the downcomer should be included in the discussion. Surely considering the fact that a proper conclusion could not be deduced from the STABILIZED case it remains to be seen if the feedwater stability is really that prominent in the ESBWR.

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Appendix A

Noise analysis and DR estimation

To encertain that the analyzed signal can be used for noise analysis white noise is added to the power. Added to the noise are some random perturbations (of about 10%) of the total power that are used to amplify and clarify the instabilities. These perturbations were manually performed about every minute during a total measurement time ranging from 30 to 100 minutes.

On these noisy and perturbed signals correlation analysis has been performed in order to determine the DR.

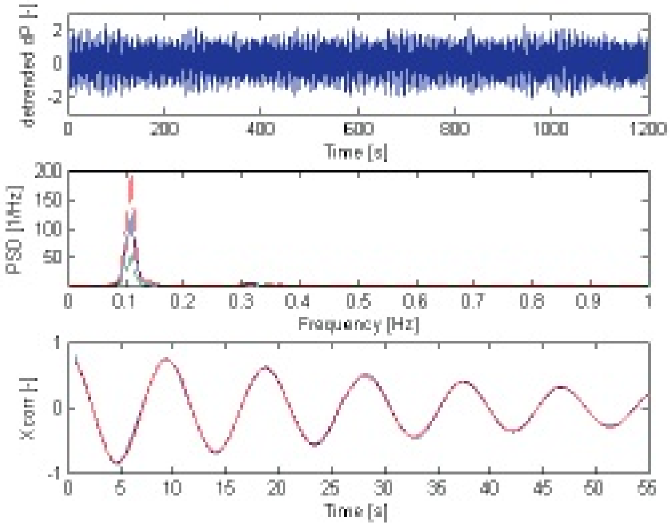

Figure A.1. Procedure followed to calculate the DR by using noise analysis techniques [3]

For the analysis during this project the auto-correlation of the (detrended and normalized) main flow has been used. During this process the PSD of the signal has also been determined as can be seen in the second graph in Figure A. This PSD (DESTABILIZED case) clearly shows the resonance frequency of the main instability (located at about 0.1 Hz).

This resonance frequency has been used to help MATLAB fit the auto-correlation (and to gain extra knowlegde). For this fit a third order model is used. The one used in this project differs slightly from Marcels model, but the general principle is the same.

$$y = b_1 e^{b_4 t} cos(b_5(t - b_2)) + b_3 e^{b_6 t} \tag{A.1}$$

When fitted the values of b_4 and b_5 can be used to calculate the DR:

$$DR = e^{2\pi b_4 / abs(b_5)} \tag{A.2}$$

In order to calculate the timelag from feedwater sparger to core inlet (and from the core inlet to the boiling boundary) the cross-correlation of respectively the main flow and core inlet temperature *tc_1* and of *tc_1* and *tc_2* is determined. The resulting ACF shows a clear peak at the time constant of interest (0 to 10 seconds for the first, and about 0.2 s for the second)

Appendix B

Uncertainties in the measurement data

DR estimate uncertainties

For the calculated DR some uncertainties exist. First of all there is the general uncertainty in the analysis of the signal. For every time a measurement is performed at equal conditions the values of the DR can differ by a certain margin. For the STABILIZED case this margin was quite high as the calculated DRs could differ up to 50% (about 20% on average). Since the difference in DR between subsequent measurements (the maxima and minima differ by a factor 2) was not extremely high to begin with as seen in Figure (3.1) this made the calculations highly inaccurate since any value could just as well be due to measurement errors.

Therefore the DESTABILIZED case has been made. Here the difference between subsequent measurements of the DR (the maxima and minima differ by a factor 6) is a lot bigger compared to the relative measurement errors.

Auto-correlation fit uncertainties

In order to calculate the actual DR MATLAB has been used to fit the autocorrelation. Since this applies to simple data the determination of the uncertainty is easily calculated.

For the DR the following uncertainties were calculated:

Table B.1. Uncertainties in the three calculated DRs

#	$u(DR_{stable})$	$u(DR_1)$	$u(DR_2)$
1	0.003	0.003	0.003
2	0.003	0.004	0.024
3	0.003	0.005	0.018
4	0.002	0.004	0.008
5	0.002	0.003	0.022
6	0.003	0.002	0.018
7	0.001	0.002	0.020
8	0.003	0.002	0.003
9	0.003	0.002	0.004
10	0.005	0.004	0.006
11	0.019	0.002	0.005
12	0.002	0.004	0.004
13	0.002	0.003	0.005

Phase estimate uncertainties

As the phase is obtained from the timelag that in turn is obtained from the cross-correlation of the main flow and the temperature at the core inlet (further on also with the second cross-correlation used to estimate the coolant velocity inside the core) this phase has a many added uncertainties. This uncertainty however cannot easily be calculated. Still these values were mainly used to roughly estimate the various parameters and to obtain some qualitative results. In both cases many measurements were done to verify the validity of the results, and both times the measured values were of the same order. Therefore most of the results appear to be valid.

Appendix C

Facility conditions

During the final measurements GENESIS was found in one particular condition. The conditions during the measurements of DR_1(Table 3.1) were as follows:

Table C.1. Facility conditions during the measurements of DR_1. All values have been averaged over the entire measurement duration. The $dp_{exitvalve}$ for the STABILIZED case could not easily be determined as it was very small but it was in the orders of several $mbar$. The average mass flow for this case was found to be about 0.55 kg/s.

#	$dp_{exitvalve}[mbar]$	$M_{c,i}[kg/s]$	$T_{c,i}[°C]$
1	110.9	0.393[1]	37.7
2	108.9	0.465	37.4
3	111.1	0.464	37.4
4	108.6	0.461	37.1
5	106.0	0.460	37.3
6	106.3	0.460	36.9
7	106.2	0.461	36.8
8	107.1	0.462	36.8
9	107.0	0.467	36.9
10	108	0.468	37.0
11	108.3	0.469	36.9
12	109.6	0.470	37.2
13	110.9	0.470	37.4

Other conditions:

- the measurement time: $1800s$ for all final measurements, 3600 and $7800s$ for measurements that were used to show the validity of the 1800s measurements and $600s$ for practise measurements and so on
- the feedwater temperature T_{fw} that was in the heat exchanger set to be exactly $9.1°C$. This was the setting which was set and it was kept constant. In reality the feedwater temperature was not exactly constant but fluctuated a little (but quite slowly) and it was found to have no extreme influence. Marcel has found the facility to be about as stable for all different subcooling numbers [3] (and thus for the feedwater temperature.)