J Biochem Tech (2020) Special Issue (1): 134-148
ISSN: 0974-2328

# Investigation of Ledinegg Instability in Natural Circulation of Closed Loop with Supercritical Water as Working Fluid

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Received: 12 August 2019 / Received in revised form: 07 December 2019, Accepted: 15 December 2019, Published online: 25 January 2020


## Abstract

The Supercritical Water Reactor (SCWR) is one of the six types of nuclear reactors proposed by the Generation IV International Forum (GIF), based on the technology of light-water reactors. SCWRs are designed to remove heat from the core using the natural circulation system, which is usually done by active pumps. This will make the reactors safer. Since conditions in quasi-critical regions are complicated for fluid like water, and the results of experiments and analyzes indicate discontinuities or extreme changes in the various physical properties of water, in this study, generally speaking, by describing the circulation system in supercritical conditions, the types of instabilities that occur in the system are investigated. Also, attempts were made to calculate the instabilities as much as possible for operating conditions. In reality, the problem is much more complicated, and this thesis briefly examines the quality of a natural circulation system. Ultimately, the Ledinegg instability areas were found, but their precise positions were not predicted in the stability map. This thesis focuses on the natural circulation system of the supercritical water reactor.

**Key words:** Supercritical water, Natural circulation, Nuclear reactor, Ledinegg Instability

## Introduction

*Supercritical water*

A state of water, in which liquid and liquid properties are present, is called the supercritical state. The water reaches this state when both pressure and temperature are above the critical point. The critical point of the water is 373.946 °C and 22.064 MPa. Generation IV International Forum with supercritical water reactor is generally fixed at 25 MPa, and therefore the liquid state or supercriticality of water in them depends only on temperature. The water that flows into the core is 280 °C, where the state of water is liquid. As the water is heated in the core, the heat from the critical point rises and reaches the supercritical state. These reactors are considered as single-phase systems due to the lack of phase change.

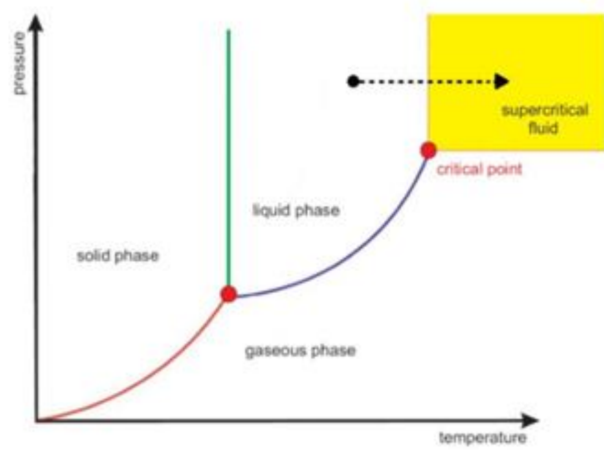


**Figure 1.** Water phase diagram.

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*Natural circulation with supercritical water*

From an engineering point of view, the transfer of a fluid into a closed cycle is called circulation. When such a transition occurs without the need to design an initial stimulus and only due to the gradient of density along the path under the influence of volumetric force, it is natural circulation. Gebhart (1973) designed a natural circulation flow to describe the upflow in an environment covered by surfaces (such as the tube through which the flow passes).

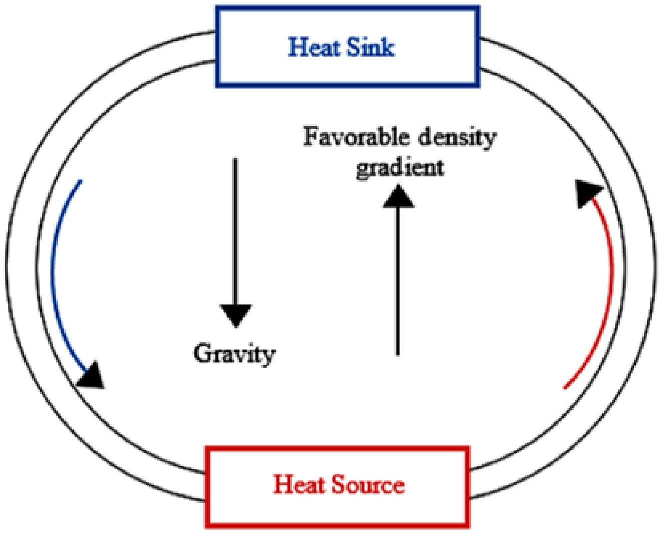



**Figure 2.** Natural circulation.

The most recognizable feature of the natural systems is the sensitivity to working conditions and the ability to instability, often due to the flexible pairing between the flow and the temperature fields. There is also a lower circulation rate, compared with the cycles with the primary circulator, as well as other features such as momentum and viscosity (considering inertia effects insignificant). Accordingly, the flow field is an implicit function of many parameters that affect the geometry of the cycle, boundary conditions, and spatial conditions.

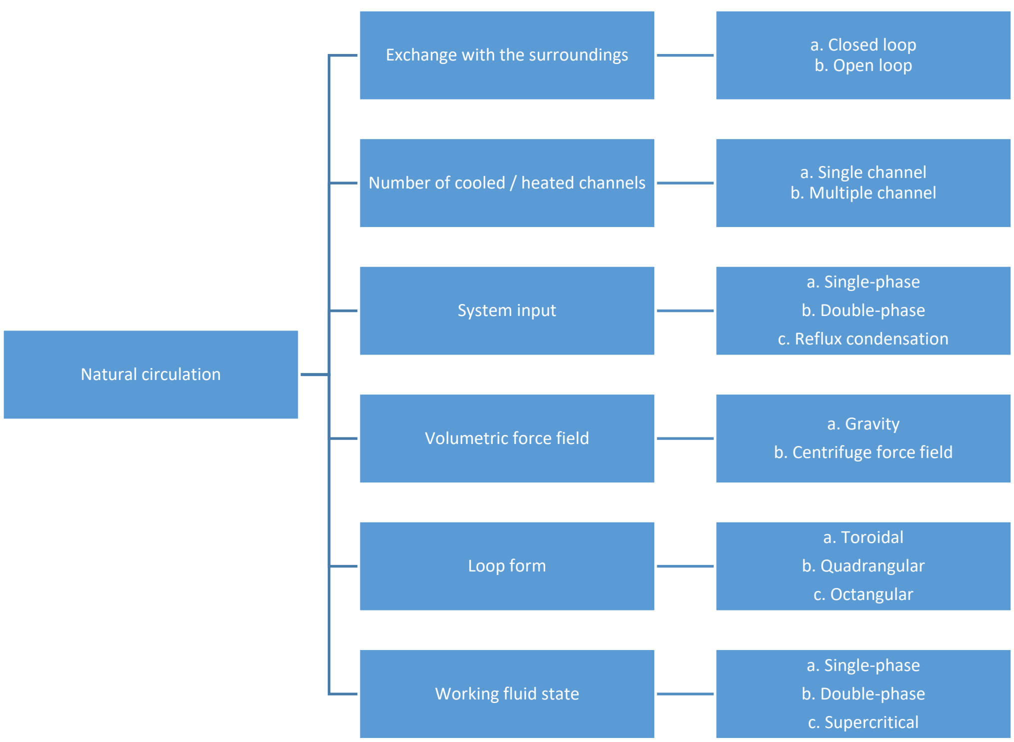



**Figure 3.** Characteristics affecting natural circulation.

The natural circulation in a water cycle is that relatively cold water (280°C) enters the core from the downflow part. The water is heated in the core. In fact, when the temperature exceeds 368-440 °C, it has passed the quasi-critical temperature and the water density is reduced from about 552 kg/m$^3$ to about 145 kg/m$^3$. As a result, after the fluid passes the quasi-critical temperature, its density decreases sharply, and then the fluid enters up-flow from the heart. Up-flow is placed in the upper part of the core to improve circulation.

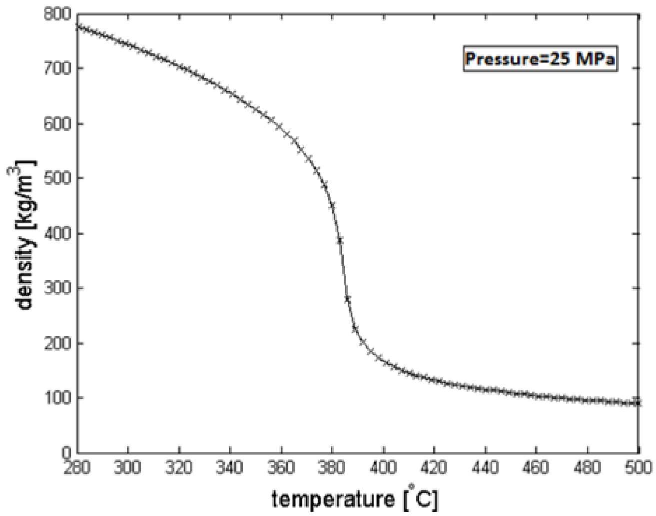



**Figure 4.** Water density in terms of temperature at 25 MPa. The pressure drop occurs around the quasi-critical temperature (384.9 °C) (NIST 2011) (van Bragt and van der Hagen, 1998).

*The Supercritical Water Reactors*

The development of SCWRs on a world scale as a clean energy source is very important. The supercritical water reactor (SCWR) is one of six conceptual designs that are a part of the international effort of Generation IV to develop the efficiency and safety of proliferation-resistant nuclear reactors (physical protection plan). Using supercritical water, the output temperature can be significantly increased. Most designs have a temperature of 500 °C and a pressure of 25 MPa. This will increase efficiency (up to 42-45%), which is much higher than the current nuclear reactor (about 33%). According to the initial information provided in GIF, SCWRs have a power output of about 1000 MW, and their thermal efficiency is about 11% higher compared to today's light water systems, which is about 33%, reaching about 44%. (Amborisini and Shahrabi 2008). In addition to higher efficiency, more focus is needed on reactor safety. New reactors (Generation IV) with supercritical water (Fig. 5) have the potential to overcome this problem. When natural circulation is established, there is no need to control the circulation of the pumps, and the normal circulation will present a more secure form in an emergency (GIF R&D Outlook for Generation IV Nuclear Energy Systems 21 August 2013). In these conditions, the pumps are still in use.

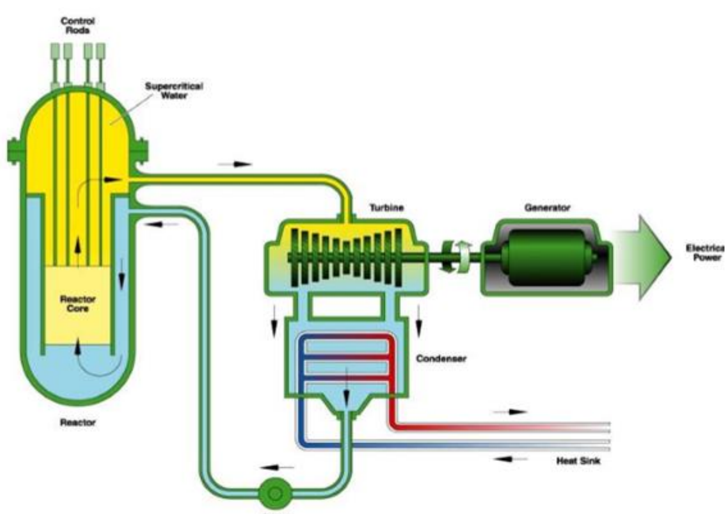



**Figure 5.** Supercritical water reactor scheme (GIF 2014).

*Stability issues*

In recent decades, there has been much research on the stability of water cycles in boiling-water reactors. Since there is a comparable deductible density drop with a two-phase flow system in the circulation of supercritical water, there is an underlying thought that instabilities of the density wave oscillations are also present in these supercritical systems, except that there is only one phase here. This research examined the response of the supercritical water circulation system to disturbances and investigated if there are any instabilities in boiling-water reactors. When a system is exposed to a disturbance, it can respond in two ways: one possibility is that the disturbance decreases over time and the mass flux rate returns to its original state (steady mass flux); the second possibility is that the disturbance can increase over time (grow) and causes oscillations with the growing amplitude. This issue is not welcome because an unstable mass flux can have unwanted results. It should be noted that the progress of the amplitude over time is shown by the reduction ratio. The relaxation ratio is a base number in time exponential function. This ratio is greater than one (unit) for an unstable system and smaller than one (unit) for a stable system.

The following figure shows two examples of amplitude oscillations after disturbance, one with a relaxation ratio smaller than unit and the other larger than the unit.

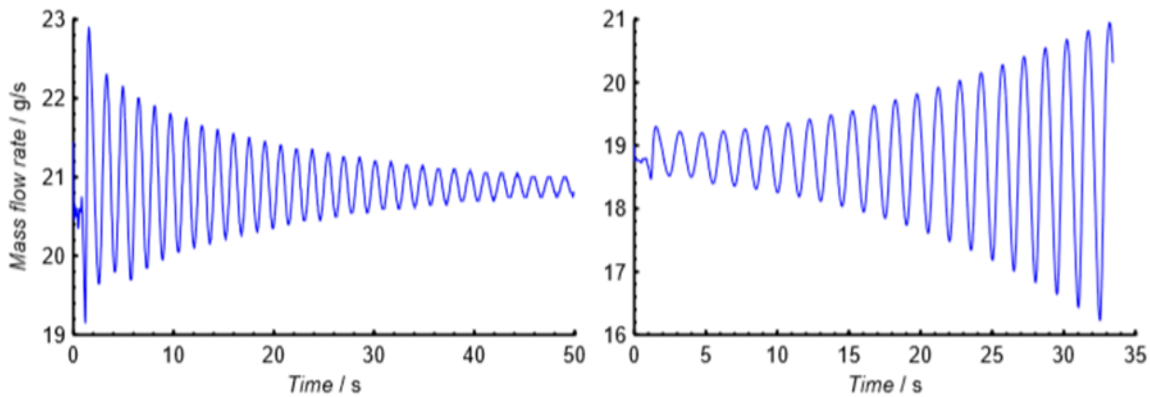



**Figure 6.** Stability examples: the left is a stable oscillation, while the right is unstable oscillation.

Water, in addition to cooling, is also used as a retarder. Water, after an unstable mass flux, can lead to unstable power. Also, oscillations in mass flux can lead to fatigue or even damage to the reactor components and complicate the safety issue (Jane and Rezvan-Odin, 2008). In addition, the flow rate may be so low that the mass flux cannot cool the heart, and thus the reactor components are overheated.

There are several types of instabilities that can occur in a supercritical water circulation system. Van Bragt (1998) showed that there is a variety of instabilities in a boiling-water reactor.

Dynamic instabilities can be solved by a time-dependent approach. There are also static instabilities that are solved by constant state equations. This researcher distinguished between two types of dynamic instabilities. The first type occurs at a low frequency and is caused by a drop in the pressure due to gravity, while the second type instability has a higher frequency and is generated by the loss of normal frictional pressures.

Boure et al. (1973) divided static instabilities into three classes. The basic static instability is one of them. Ledinegg instabilities are related to this class. This instability is, in fact, a sudden change in mass flux to a higher or lower value (Ortega, 2009). In a pumped water circulation system, these changes occur in flux when the pressure in relation to the mass flow rate of the pump intersects at several points with the compressive properties of the circulating water. An unstable mass flux can change its flux rate quickly to a different rate to create stability, although in this thesis, due to flow, there is no pumping natural circulation.

## Research background

Using supercritical water, the complexity of auxiliary systems and power plant components and the cost of investment reported by Bognorno and McDonald (2003) are reduced. However, natural loops can become unstable in certain operating conditions (e.g. high power and low flow rates). Boure et al. (1973) presented the classification of different types of instability. A static instability can be described using stable state equations. In this case, a small change in flow conditions will lead to a new stable state. For dynamic instabilities, such as density wave oscillation (DWO), stable state equations for predicting system behavior, even the threshold of instability, are not insufficient. In such a situation, there are numerous solutions to the governing equations. The system moves from one solution to another, driven by feedback mechanisms. March-Leuba and Rey (1993) provided a detailed explanation of the DWO and feedback mechanisms that are driven by inertia and friction interaction for thermohydraulic modes. In a nuclear reactor, there is another feedback mechanism: neutron feedback. Condensation connects fluid to energy production through modulation performed by water molecules. This causes the amount of decomposition and then heat generated at the reactor core to be directly related to the neutron density. This illustrates the result of very complex behavior, as shown by Van Brett and Van Harden (1998) for ESBWR. Yi et al. (2004) reviewed the experimental data on natural critical loops in the open literature for US SCWR design. Most published results on the stability of supercritical currents are numerical, and they are a single authorized system (Ambrosini and Sharabi, 2008) or an ideal loop geometry (Jain and Uddin, 2008; Sharma et al., 2010). Lomperski et al. (2004) made an experimental study on a supercritical rectangular $CO_2$ loop. They reported the data for a stable state. These findings were not consistent with Jain's (2005) numerical work because they found the boundary of stability at very low power. The purpose of this study was to examine the boundary of HPLWR stability in natural circulation. A scale adjustment was designed and built for this purpose. The neutronic feedback was artificially done, and the time delay between the power generation and the thermal flux of the wall was modeled using a fixed fuel time.

T'Joen and Rohde (2012) designed another laboratory instrument and started their experiments on that. This instrument uses Freon 23 as the working fluid. Freon 23 has similar properties with water around the quasi-critical point, except that this point is obtained at a temperature of 33 °C and a pressure of 5.7 MPa. In this study, the neutronic-thermohydraulic coupling was considered. Therefore, it led to the emergence of unstable areas for specific operating conditions.

Due to the lack of experimental data on the stability of a supercritical loop in the open literature, these data can act as an important standard for existing codes.

*The proposed model*

The qualitative behavior of a supercritical water circulation system was investigated using a model that is available in most circulation studies in one-phase and two-phase quadrangular systems.

An important feature of this model is its core, which is simplified by a single channel with a hydraulic diameter and a constant current cross-section, located on top of it, known as upflow. The water enters the buffer zone after passing through the upflow. The buffer represents systems that absorb heat from the cooler, such as heat exchangers and turbines.

Finally, a downflow, whose geometric characteristics are like the core and upflow, returns water to the core.
The various cooling properties around the quasi-critical enthalpy show a strongly non-linear behavior.

To do this, using accurate data and estimates is necessary. To check the natural flow, the core (heater) and buffer (cooler) were divided into a number of nodes. Then, in order to obtain a stability map using the two operational parameters related to the ratio of power to mass flux and temperature (enthalpy), we considered the system in a different way, so the heart is once divided into two nodes and once into a node to express the undercritical and supercritical conditions separately.

In the meantime, we examined the wall effect, that is, we consider a wall for the core to initially enters it, then heat is transferred to the fluid by assigning the heat transfer relationship.

In this research, considering that we reach quasi-critical enthalpy or not, the core was modeled as one and two nodes alone. A model in which the core has one node is a model in which the cooling temperature does not reach the quasi-critical enthalpy, and a model in which the core has two nodes, indicates the arrival of the cooling temperature to a quasi-critical enthalpy. The single-node model is referred to as the low enthalpy model, and the two-node core model is referred to as the high enthalpy model. Two other nodes are for the core walls. The length of the wall nodes is proportional to the length of the core nodes. The static heat generated through the wall is transmitted to the cooling channel. As a result of the thermal inertia of the wall, heat transfer to the channel is dependent on time. In the high thermal model when conducting (conductive heat transfer), the wall nodes exchange heat between themselves and thus form closed-loop feedback.

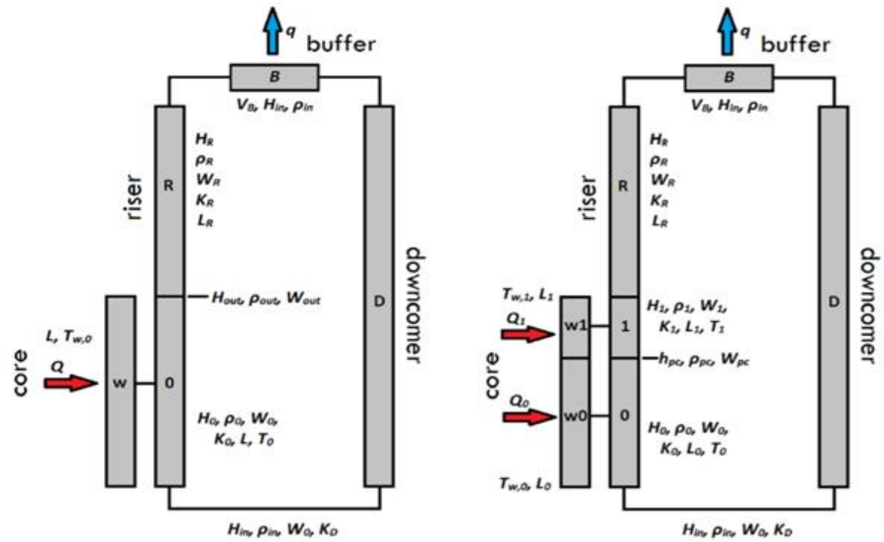



**Figure 7.** A water loop model

*Equations of state and model simplification*

When the pressure is constant throughout the system, water density can only be considered as a function of enthalpy. The system should operate at a constant pressure of 25 MPa, but due to the loss of pressures caused by gravity and friction, this amount cannot remain constant throughout the system. Changes in the equation of state with pressure variations are negligible.

We tried to act more like a real reactor. Since we kept the system at a constant pressure of 25 MPa, we could have a density in terms of enthalpy. Since the special volume is inversely related to the density, we can write the state equation in the form of special volume to be a function of enthalpy and density. In order to investigate and draw up an instability map under different conditions, especially when considering the effect of indirect heat transfer on the wall, by assigning the thickness to the heart wall, we consider the state equation as follows:

$$V = V(p,h) \tag{1-1}$$

However, we wrote the above relation using the most accurate approximation as follows. Using the equation of state, special density and volume variables in the preceding equations can be replaced with enthalpy. In this section, the approximation of the two regions was used to obtain the equation of state. Before the quasi-critical point, the density was approximated by a linear function, and after the quasi-critical point, the volume is approximated by a linear function, in such a way that in the low enthalpy region, the density is linearly reduced, and in a large enthalpy region, the special volume, which is a reversal of the density, increases linearly.

The slopes of these linear functions are $C_1 = 4 \cdot 7877 \cdot 10^{-4}$ and $C_2 = 0 \cdot 80 \cdot 10^{-8}$ , respectively. The equations are as follows:

$$\begin{cases} \frac{1}{\rho_{pc}+C_1(H_i-h_{pc})} \ (H_i < h_{pc}) \\ v_{pc} + C_2\left(H_i - h_{pc}\right) \ (H_i \geq h_{pc}) \end{cases} \tag{1-2}$$

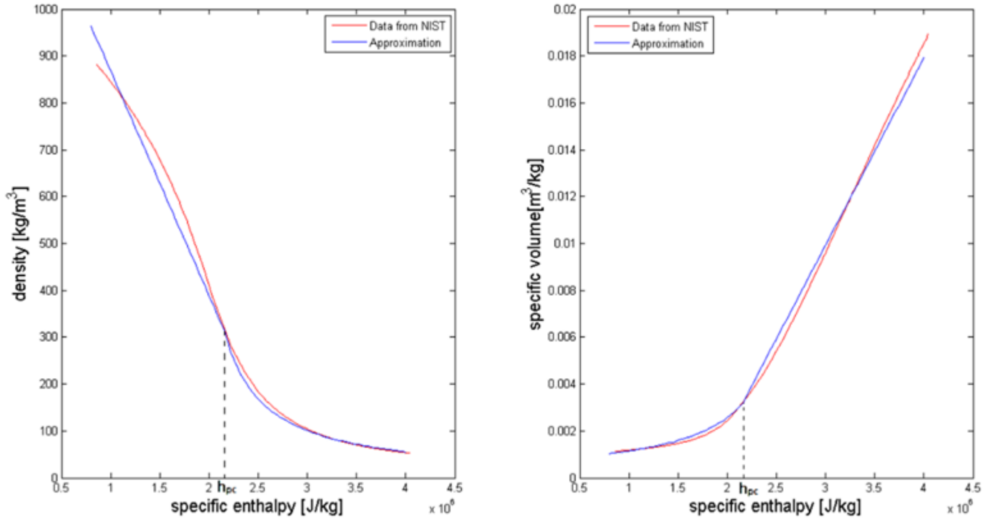



**Figure 8.** Approximation of the special volume of the equation of state. The left-hand side of the linearized density of the enthalpy model is low and the right-hand side of the special linearized volume of the enthalpy model is high.

If we compare the above approximations with the following values obtained from the XSteam code, we see that there is no difference in the values obtained.

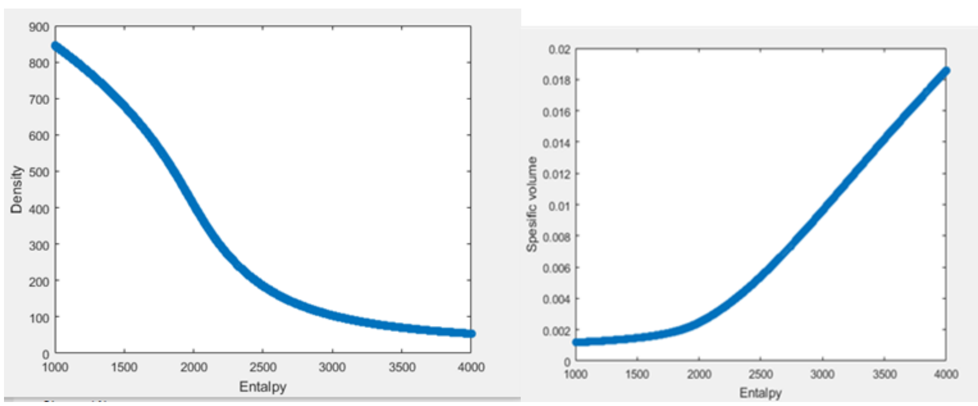



**Figure 9.** Equation of state from XSteam. The left is the density in terms of enthalpy and the right is a special volume in terms of enthalpy.

In addition, the temperature is estimated using quadratic functions in both regions. Since these functions seem necessary for making the linearization simpler, it is considered that the approximation and derivative of both are continuous in a quasi-critical enthalpy. The temperature approximation is performed using the following equation:

$$T_i = \alpha_i(H_i - h_{pc}) + T_{pc} \qquad (2\text{-}2)$$

In this equation, the specific water heat coefficient is determined at a quasi-critical point (389 °C and 25 MPa). The constant value is for the low enthalpy region and the value $a_1 = 1.0 \times 10^{-10}$ is for the high enthalpy region. In Fig. 2.3, the temperature graph is plotted in terms of enthalpy. We have already said that the special heat is dependent on enthalpy. The gradient of this graph is the reverse of the special heat.

$$a_0 = -1.1 \times 10^{-10} KJ^{-2}$$

It should be noted that the enthalpy and temperature are one-to-one in some way, and therefore, the enthalpy can be written unambiguously as a function of temperature.

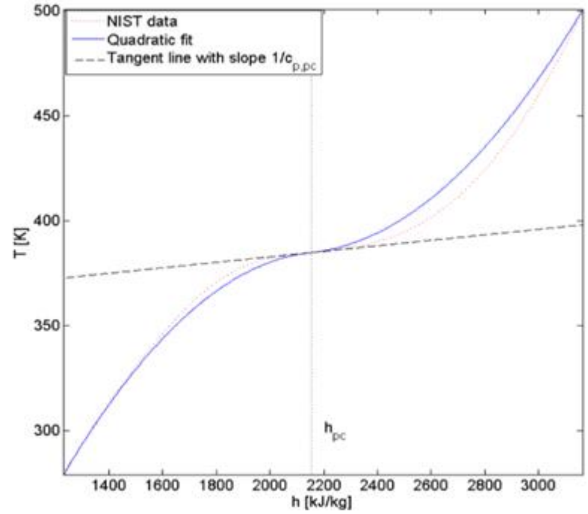



**Figure 10.** Temperature approximation from the equation of state. The red line is related to the data of NIST (2013).

Finally, the thermal conductivity was modeled. The approximation of thermal conductivity for simplicity reasons should essentially follow the behavior of the actual thermal conductivity. In the enthalpy region, the thermal conductivity is reduced by an approximation of the linear function and in the upper enthalpy region with an exponential function.

$$\lambda_{f,0} = -\beta_0 H_0 + \lambda_{f,b,0} \tag{2-3a}$$

$$\lambda_{f,1} = \lambda_z e^{-\beta_1 H_1} + \lambda_{f,b,1}$$

As can be seen, the equations require up to 5 values. To avoid the ambiguity surrounding the quasi-critical enthalpy, again, like the temperature approximation, the parameters are chosen so that the thermal conductivity and gradient around the quasi-critical enthalpy are continuous. The gradient and the values of the linear approximation with the experimental data are small in most of the enthalpy region. This issue gives a parameter for free discussion, which is the same asymptotic horizontal of the relaxed exponential function.

$\beta_0$=-3.2711×$10^{-7}$$Wm^{-1}K^{-1}J^{-1}kg$;   $\beta_1$=1.3694×$10^{-6}$$kgJ^{-1}$;

$\lambda_{f,b,0}$=1.0133 $Wm^{-1}K^{-1}$;   $\lambda_{f,b,1}$=7.0154×$Wm^{-1}K^{-1}$;   $\lambda_z$=4.5553$Wm^{-1}K^{-1}$

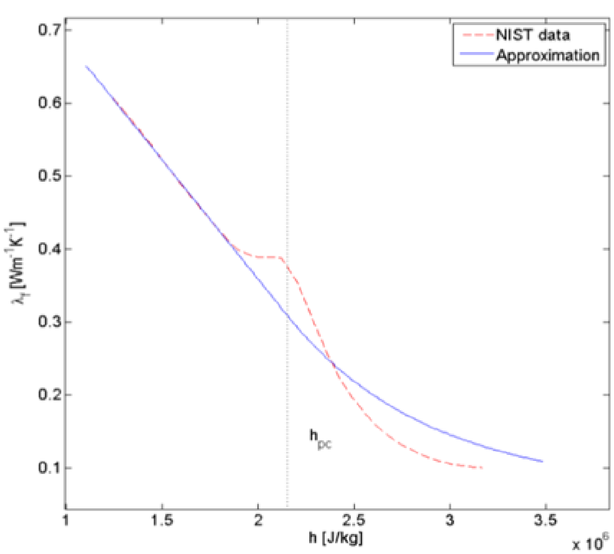



**Figure 11.** Thermal conductivity approximation (Red dotted line relates to NIST 2013 data).

## Results

*Ledinegg instability*

Some stability maps for different design parameters are very similar to the previous findings by Gaido (1991). This led to the idea that Ledinegg instabilities are also present in the sustainability maps of our supercritical water research reactor. Gaido (1991) analytically examined the sustainability problem for parallel boiling-water channels as well as a heated lonely channel. In the figure below, two stability maps are presented, one by Gaido (1991) for a boiling-water channel alone, and another similar. In fact, it is the stability map of the supercritical fluid loop without upflow in this study.

The dimensionless number in these two studies differs in a certain coefficient and can be compared with each other. The ripped straight line refers to the boundary of the unstable Ledinegg region.

In order to make our shape looks like the considered shape, apart from the need to remove the upflow to simulate the conditions of a single channel, we have to make changes in the volume of the buffer and the ratio of the area of the wall to the area of the channel and the coefficient of pressure drop.

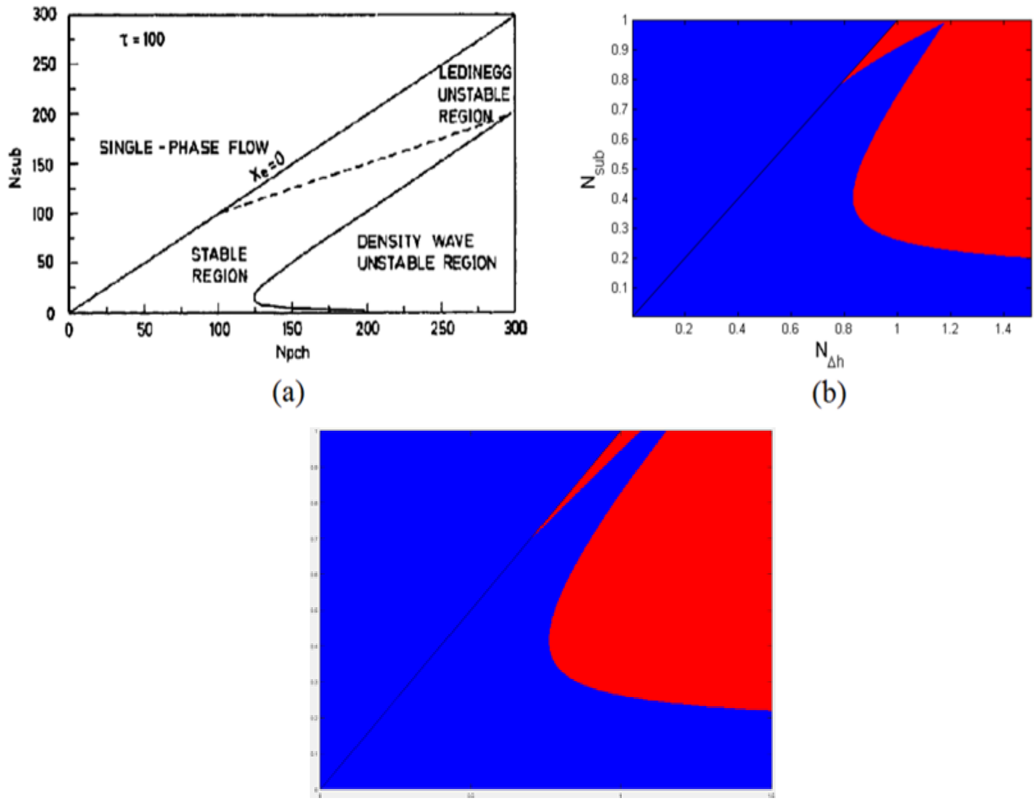



Fig. 12 is the left-hand side is the single-channel heat map. τ is the friction parameter, and the line represents the boundary between the single-phase and the two-phase current (Gaiduo 1991). The left-hand side is the stability map similar to that of the Gaido work, which is written by the code, in which the upflow is eliminated and the volume of the buffer is halved, the wall area is ten-folded, and the amount of friction coefficient is doubled.

To check operationally if Ledinegg instabilities are present here, we need to make some changes to the code and get the flow rate graph in terms of power characteristics and analyze it. We can also obtain a graph of gravitational pressure drop in terms of power to explain unstable mass flows.

*Investigation of DWO (density wave oscillation) instabilities*

The DWOs analysis for the natural circulation system was done using the initial conditions and boundary conditions. Boundary conditions are described in the stable state solution, and the stable state solution is used as an initial condition for transient prediction. Then, time-dependent survival equations are solved to determine the transient response. The transient response at the selected operational point indicates a stable, unstable or stable condition. While in disturbance, the system is referred to as "stable" if the system is back to the previous state or another state of equilibrium. If the system with oscillating amplitudes throughout the loop, this system is called a "stable margin". If the system is oscillating with the amplitude of growth along the loop, the system is "unstable." At first, the working pressure is 25 MPa and we were in supercritical or dense state conditions.

Input heating power is initially considered to be 117.5 $kw/m^2$. In this case, we see a neutral stability. In power above this value, we see that the mass flux increases ascending and creates a state of instability. However, in lower thermal power, for example, at 110 $kw/m^2$ mass flux reaches a stable state of 34.18 kg/s.

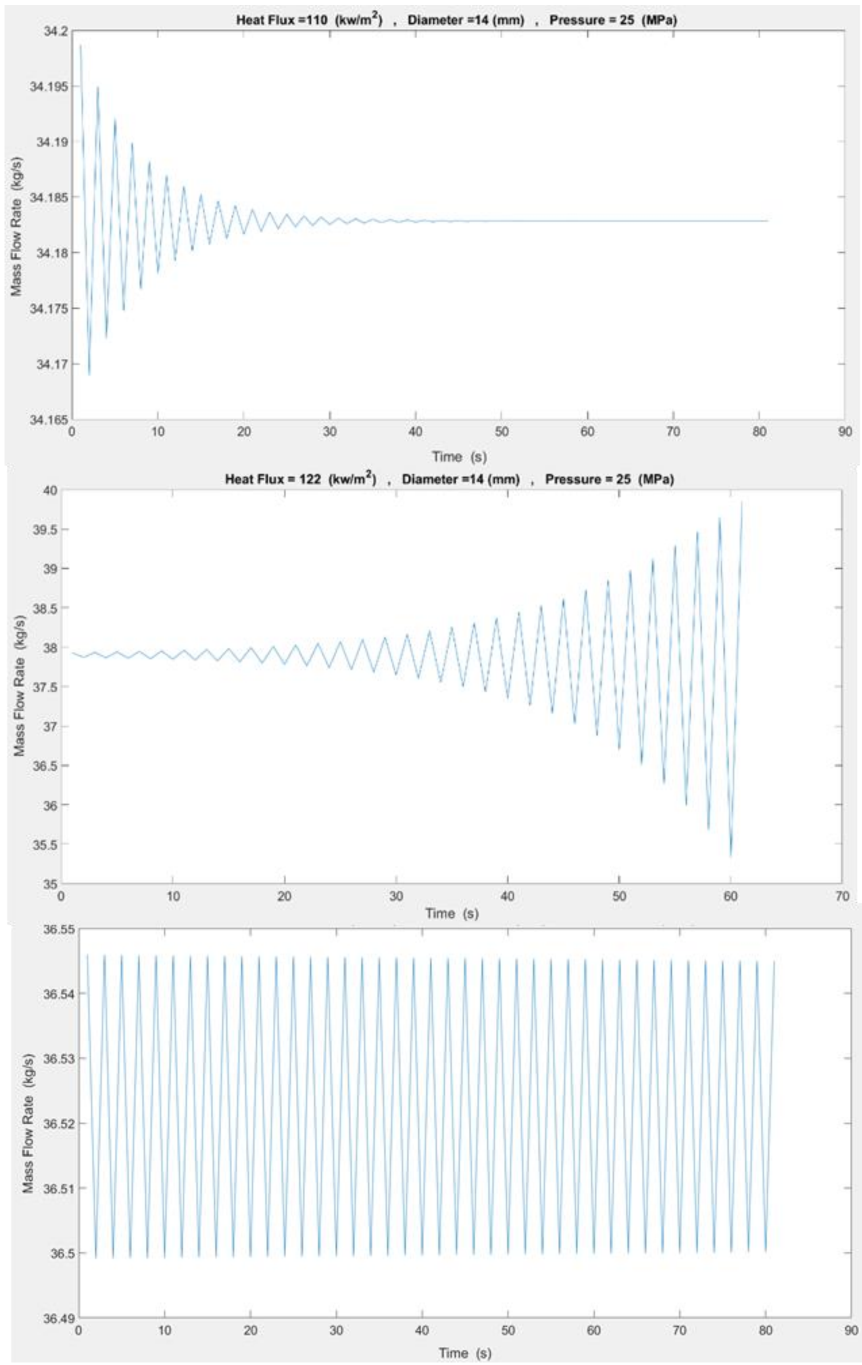


**Figure 13.** Fluid mass flow diagrams over time in different heat fluxes

If we reduce the pressure of the system, the mass flux condition changes, so that, as shown in the figures below, the mass flux reaches a value of 26.1 kg/s.

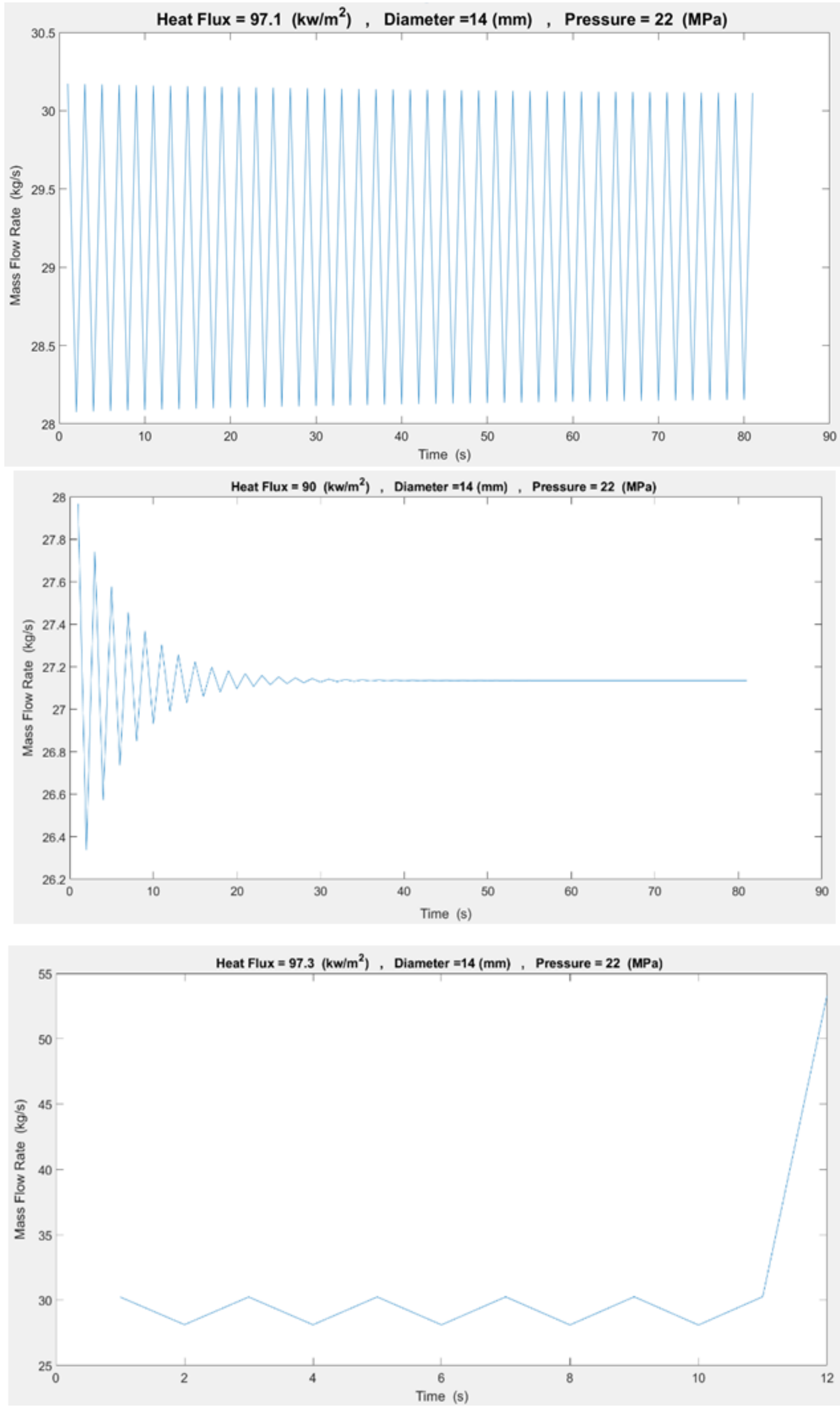



**Figure 14.** Fluid mass flow diagrams of fluid over time in different heat fluxes

Also, at a pressure below 20 MPa which is below the critical point pressure, the mass flux reaches a stable value at 20 kg/s, as shown in Figure 15.

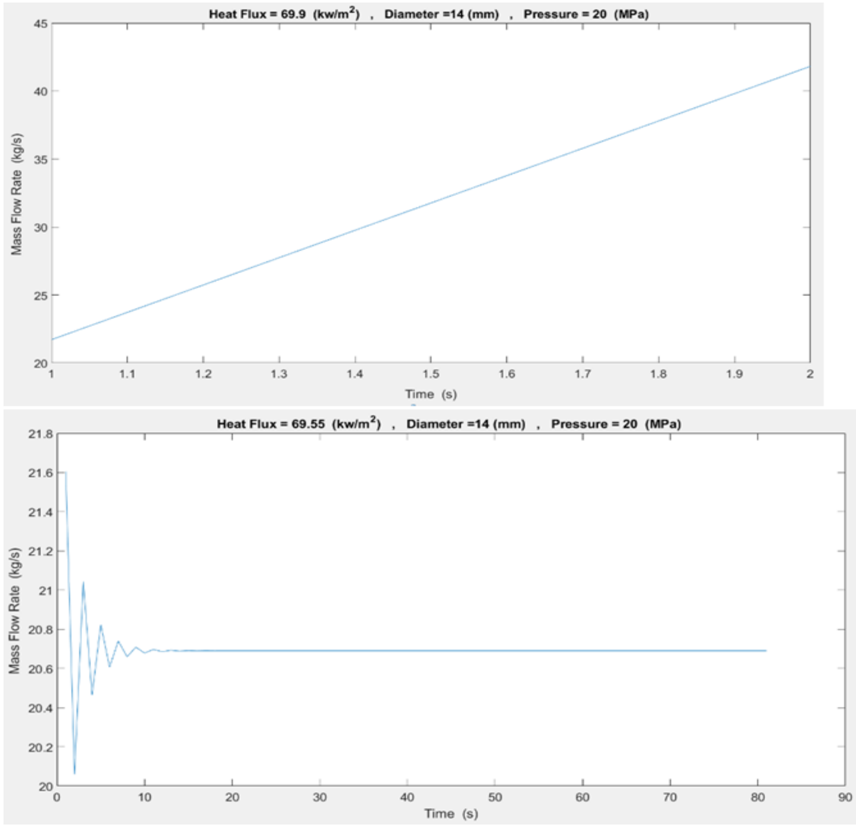



**Figure 15.** Fluid mass flow diagrams over time in different thermal fluxes

At 16 MPa, the mass flux reaches a stable value at 12.1 kg/s.

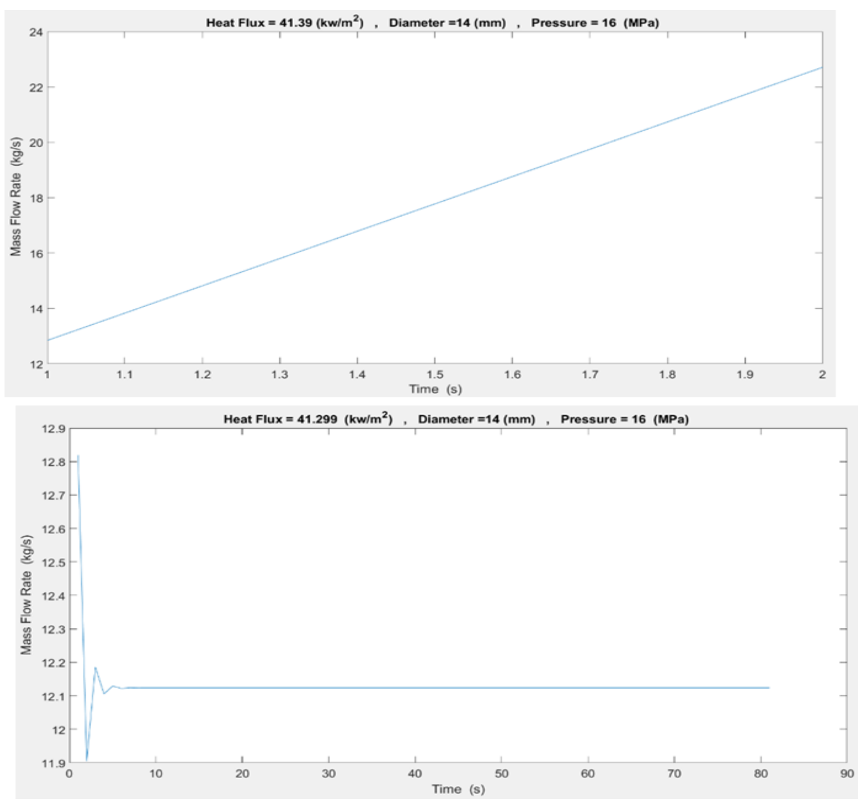
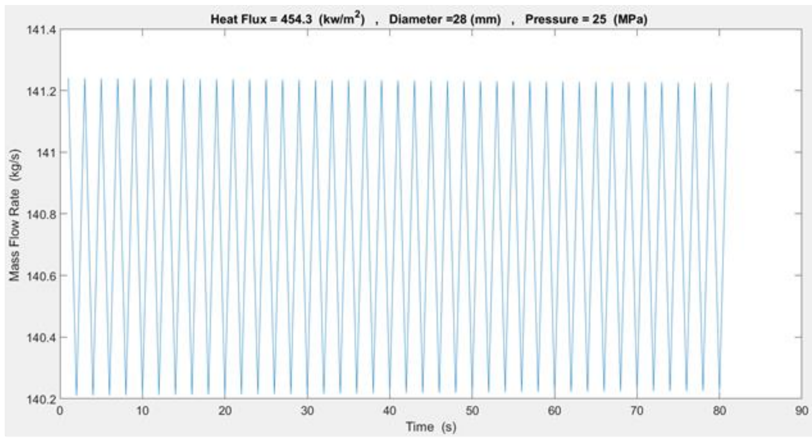


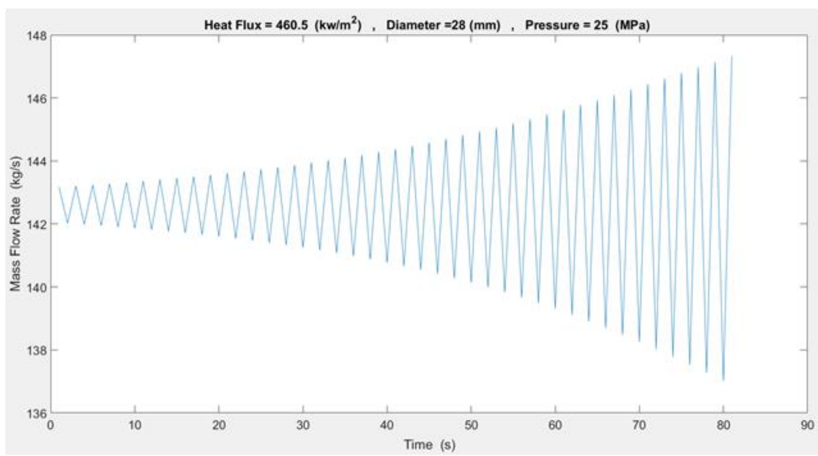
**Figure 16.** Fluid mass flow diagrams over time in different thermal fluxes

As it has been observed, with a decrease in system pressure, the mass flux becomes stable in lower quantities. In fact, in the supercritical (quasi-critical) pressures we will have more stable mass flux.

The work done above was a constant consideration of the parameters affecting the system, including the hydraulic diameter of the system. Given the fact that the hydraulic diameter is considered to be constant throughout the system, changing the diameter makes it be changed everywhere else.

In the next step, considering a constant pressure of 25 MPa and a heat output of 117.5 kW, we increase the hydraulic diameter from 14 mm to twice the value, i.e. 28 mm.



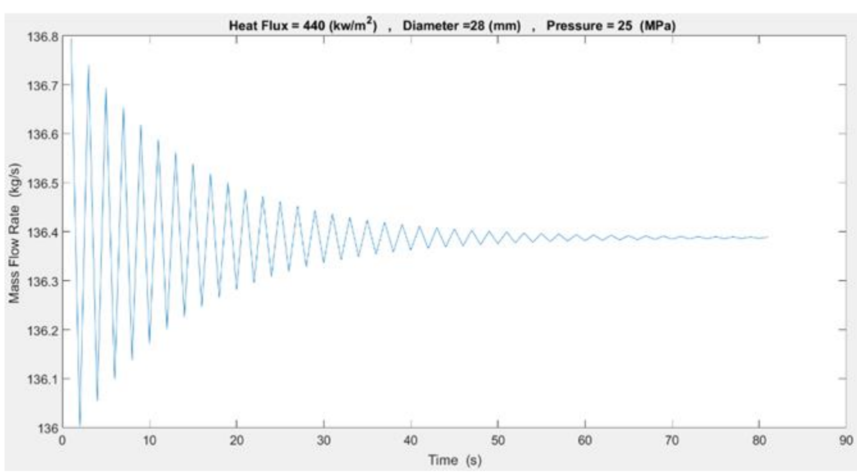



**Figure 17.** Fluid mass flow diagrams over time in different thermal fluxes with twice the hydraulic diameter

Due to the increase in diameter, we need a multiple of 136.4 kg/s in order to reach a stable mass flux. In fact, with the increase in the diameter of the hydraulic, the system's stable state occurs in higher mass fluxes.

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