EXPERIMENTAL STUDY ON A NATURAL CIRCULATION DRIVEN HPLWR

C. T'Joen[1], M. Rohde[1]
[1] Delft University of Technology, Delft, The Netherlands

Abstract

The large density change through the core of a supercritical water reactor could be used as the driving force for circulating the coolant. To study such a natural circulation system, a scaled experimental setup was developed using Freon R23. This paper presents the first power-flow measurements for single core heating as well as 3 core heating (HPLWR power distribution) indicating that natural circulation occurs. A numerical model was developed to further study the impact of geometric and system parameters. This model shows good qualitative agreement with the experiment. By further refining the proposed model to include the pressure drop over the heat exchanger, a better quantitative agreement could be obtained.

1. Introduction

To obtain a higher thermal efficiency, a light water reactor based on supercritical water (the SCWR, Super Critical Water Reactor) has been proposed as part of the GenIV platform. Using supercritical water would also result in a simpler construction as there is no more need for steam dryers or separators. The estimated efficiency varies between 42 and 45% depending on the details of the proposed system. During the past decades a number of core designs been developed: a Japanese design [1], a Korean design [2], a US design [3], Canadian CANDU designs [4] and most recently a European design (the HPLWR, High Performance Light Water Reactor) [5-6]. These designs differ considerably with regard to the fuel assemblies, flow layout and moderators that are used. The HPLWR [5-6] is remarkable as it consists of a three-pass core layout (Fig. 1A) combined with water rods for moderation. The system operates at 25 MPA, with an inlet and exit temperature of 280 °C and 500 °C respectively. Between the passes mixing plena are used to reduce peak cladding temperatures. Recently Vogt et al. [7] presented a PWR concept using supercritical water in the primary loop as a first step in using supercritical water in a nuclear reactor with an exit temperature of 380°C.

As is well known, supercritical fluids experience strong changes in fluid properties near the pseudo critical point, as illustrated in Fig 1B. In the HPLWR e.g. the density varies between 780 kg/m³ at the inlet and 90 kg/m³ at the outlet with a sharp change near the pseudo critical temperature. This strong density change could be used as the driving force in a natural circulation system resulting in an inherently safer reactor as large feed water pumps can be omitted. Using natural circulation for improved safety of a nuclear system is not new. It has been suggested for the ESBWR boiling water reactor [8]. This design was built on a small scale at Dodewaard, the Netherlands, and operated for decades. These natural circulation systems, however, may show additional instable modes at low power and at low pressures (e.g. flashing events during the startup of the ESBWR [21]). This indicates a need to study the stability behavior of such systems for a wide range of operational conditions. To this end a setup has been designed to examine the stability behavior the proposed natural circulating HPLWR experimentally.

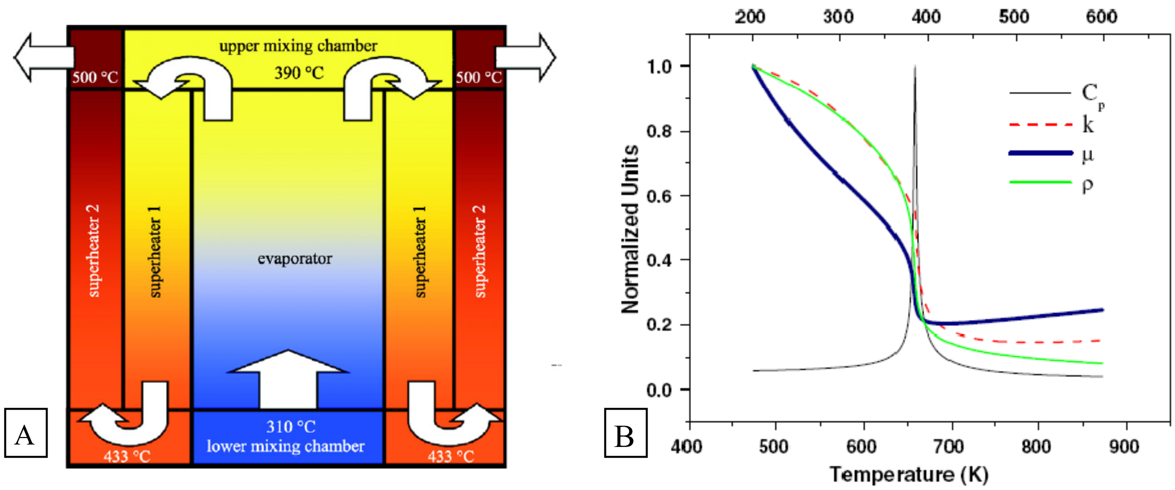

Figure 1 A: Three pass core arrangement proposed for the HPLWR (Fischer et al. [5]), B: normalized fluid properties for water at 25 MPa for a range of temperatures

Different methods exist to determine the stability of such systems. In most cases numerical tools are used which describe the system through a set of non-linear coupled differential equations, see e.g. [9-10]. These equations are solved to determine the steady state solution first and then by either performing transient simulations [10] or by using e.g. Laplace transformation [11], or through eigenvalue analysis of the linearized set of equations, the stability of the system can be determined. In order to benchmark these results, experimental data is required on both the steady state and stability behaviour. These experimental data also allow to assess the validity of certain assumptions (e.g. pressure independence of substance properties, neglecting non linear terms…). To avoid excessive costs due to the material (high pressure) and power requirements of the actual proposed reactor system, scaled versions are mostly used. This has been done at the Delft University of Technology for the ESBWR using the GENESIS facility [8]. The experimental data served as a benchmark for numerical codes [12].

2. Scaling the HPLWR: DeLight

In order to design a scaled version of the proposed HPLWR, the governing equations (conservation of mass (Eq. (1)), momentum (Eq. (2)) and energy (Eq. (3)) and the equation of state (Eq. (4))) of the system should first be considered. These are shown here with G, h and P as the system variables in a one-dimensional form (z as coordinate). These equations describe the flow through a channel (representing a single fuel assembly) with a given hydraulic diameter. For this study the fuel assembly design proposed by Hofmeister et al. [13] was considered. This design consists of a central water box surrounded by 40 fuel pins spread in 2 rows (8mm outer diameter) with a pitch of 1.15 mm, resulting in a hydraulic diameter of 5.67 mm. Note that different forms of the proposed equations are used throughout literature: Ortega Gómez et al. [14] also use the mass flux, but Jain and Uddin [10] and Ambrosini [9] use the velocity as a variable. Jain and Uddin [10] also preserved the coupling between the energy and impulse equation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \qquad (1)$$

$$\frac{\partial G}{\partial t}+\frac{\partial}{\partial z}\left(\frac{G^2}{\rho}\right)=-\frac{\partial p}{\partial z}-g\rho\sin\theta-\frac{G^2}{2\rho}\left[\frac{f}{D_h}+C_j\delta\left(z-z_j\right)\right] \tag{2}$$

$$\frac{\partial\rho h}{\partial t}+\frac{\partial(Gh)}{\partial z}=\frac{q''P_h}{A} \tag{3}$$

$$\rho=f(h) \tag{4}$$

Rohde et al. [15] describe the scaling procedure and derive a number of scaling factors based on the selected scaling fluid. This was done by making the equations (1-4) non-dimensional by using a reference enthalpy and density (evaluated at the pseudo-critical point) and by introducing a characteristic length scale (length of the core), mass flux (steady state mass flux through the core). This results in the appearance of the Froude number in the momentum conservation equation and the phase change number in the energy conservation equation. Because the influence of the pressure on the density value is much smaller than that of the enthalpy, and the pressure drop over the core is limited, it was chosen to neglect the influence of the pressure on the density (Eq. (4)). Ambrosini [9] uses a similar procedure to render the equations non-dimensional and study the relationship between the occurring non-dimensional numbers for boiling fluids and supercritical fluids. Using this proposed scaling of the fluid properties, he was also able to show a surprising similarity between different fluids (water, ammonia, R23 and CO2), [16]. Using the NIST property database [17] a large number of fluids were compared. Based on the power scaling factor, the resulting temperature and pressure requirement as well as safety (flammability), Freon R23 was selected as the scaling fluid. This resulted in a pressure of 5.7 MPa and a pseudo-critical temperature of only 33°C. The non-dimensional fluid properties agree well with water, with a maximum deviation of 8% for the density, see Rohde et al. [15]. Some relevant pseudo-critical fluid properties and scaling values are indicated in Table 1. Through linear stability analysis (using eigenvalues) of a single heated channel with supercritical water and of its scaled R23 counterpart, it was shown that the scaling rules result in the same stability behavior, confirming the proposed scaling procedure and fluid selection, Rohde et al. [15]. Important to note is that in the scaling procedure an arbitrary constant Cf was introduced to scale the overall friction distribution of the channel. It was shown that this does not affect the stability of the system and it allows having a different radial and axial length scaling. Otherwise the scaled hydraulic diameter is only 1 mm, which would result in excessive pressure drop at the considered mass fluxes. By varying Cf a more optimal scaled design was conceived with a 6 mm tube.

Table I. Comparison of selected pseudocritical properties of H_2O and R23, the resulting scaling rules as derived by Rohde et al. [15]

	R23	H_2O	Scaling	
Pressure (MPa)	5.7	25	Length	0.191
Temperature (°C)	33.2	385	Diameter	1.06
Density (kg/m³)	537	317	Power	0.0788
Enthalpy (kJ/kgK)	288	2153	Mass flux	0.74
Core inlet temperature (°C)	-21	280		
Core exit temperature (°C)	105	500		

3. DeLight experimental facility

Based on the derived scaling rules an experimental facility has been constructed at DUT, named 'DeLight' (Delft Light water reactor facility). A schematic drawing is shown in Fig. 2A and some of the dimensions are listed in Table II. The loop is constructed using stainless steel tubing (6mm ID for the core sections, 10 mm ID for the riser and downcomer). The total height of the loop is 10 m. Up to 18 kW of heating (twice the scaled power requirement) can be added in 4 sections (3 cores and the moderator channel which mimics the water rod presence). Heating is done electrically (providing a uniform heat flux boundary) by sending a current through the core tubes (up to 600A per core element using Delta SM15-200 power units). The power rating of each core can be controlled individually, as the power distribution in the HPLWR core is non uniform, with the evaporator accounting for 53% of the total power produced. Each core is electrically insulated from the rest of the setup using a PEEK ring mounted in between 2 flanges. Valves are mounted between the core sections, at the inlet and exit of the core and at the exit of the riser. These can be used to introduce local friction values in the system, such as inlet systems or the plena mimicking actual reactor designs. It is well known that these local friction values can have a significant effect on the stability of a system, see e.g. [9-12]. To provide a stable pressure level, a buffer vessel is present at the top of the loop which has a moveable piston (Parker Series 5000 Piston Accumulator) connected to a nitrogen gas cylinder. By positioning this piston higher or lower the pressure level in the loop can be set at 5.7 MPa. Two heat exchangers (HX in Fig. 2) are mounted in series at the top section of the loop to extract the heating power and to set the inlet conditions. The first one uses cooling water and cools R23 to 17°C. The second is an evaporator with R507a in which R23 is cooled down to a minimum temperature of -25°C. Due to the differential thermal expansion of the core sections (wall temperatures can reach over 200 °C) and the other parts of the loop, the tubes are connected to the wall using moveable spacers which contain 2 prestressed springs. The bottom connection between the different core sections is made from a flexible tube of woven steel.

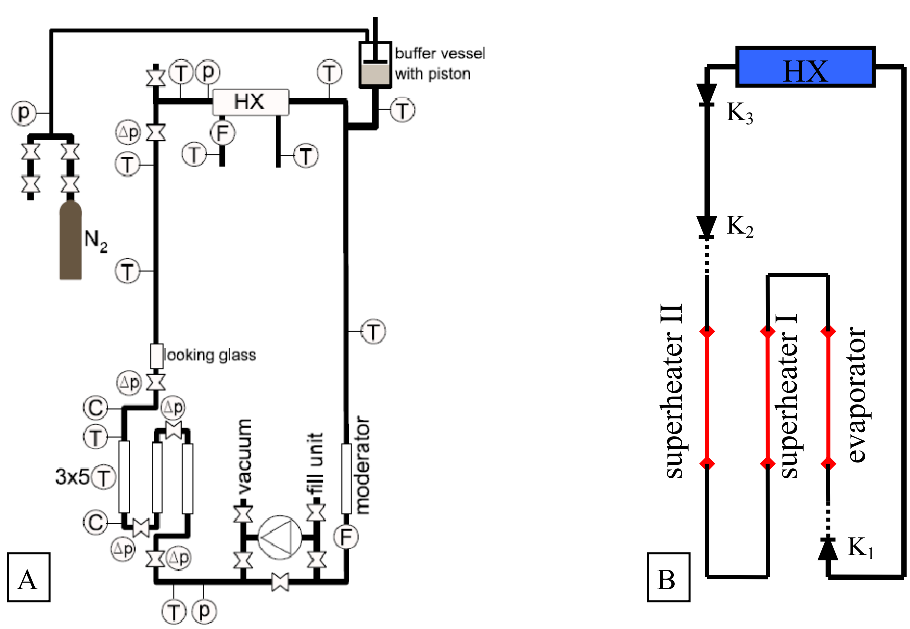

Figure 2 A: Schematic overview of the DeLight setup as constructed at DUT, B: numerical model used for the steady state simulation of DeLight (not drawn to scale)

Table II Comparison of the dimensions and operational parameters of the HPLWR and DeLight.

	HPLWR	DeLight
Core average mass flux (kg/m²s)	1665	1232
Power per fuel pin (kW)	114	9
Hydraulic diameter (m)	0.00562	0.006
Core length (m)	4.2	0.8

4. Experimental results: mass flow rate

The described loop has been constructed and testing is currently underway. As a first set of test cases natural circulation was induced through the setup under supercritical conditions and at low power conditions. Only the first heat exchanger was used, setting the inlet temperature of the core to 17°C. Because of the high mass flow rate of the water on the secondary side of this heat exchanger (up to 0.5 kg/s) this inlet temperature could be controlled with good accuracy. The inlet pressure varied between 56 and 58.5 bar. In these initial experiments only 2 cores were used separately: the evaporator (upward flow) and superheater 1 (downward flow). The results are shown in Fig 3. As can be seen, increasing the power results in a higher flow rate. But as the power increases the density of the flow reduces, resulting in higher fluid velocities and an increase in the flow friction. This will eventually result in a lower mass flow rate at higher power rating, resulting in the typical power flow curve of a naturally circulating system. The data suggests a maximum flow rate around 3.5 kW when using only superheater 1 as power input, and a maximum around 2.5 kW when using the evaporator as power input. At higher power the two curves start to deviate slightly, which is due the difference in the friction for these scenarios. Heating in the evaporator results in a longer length of the system which experiences high velocities and friction. Two different series were measured with the evaporator as heater on different days (whereby the setup was depressurized at night) showing good agreement.

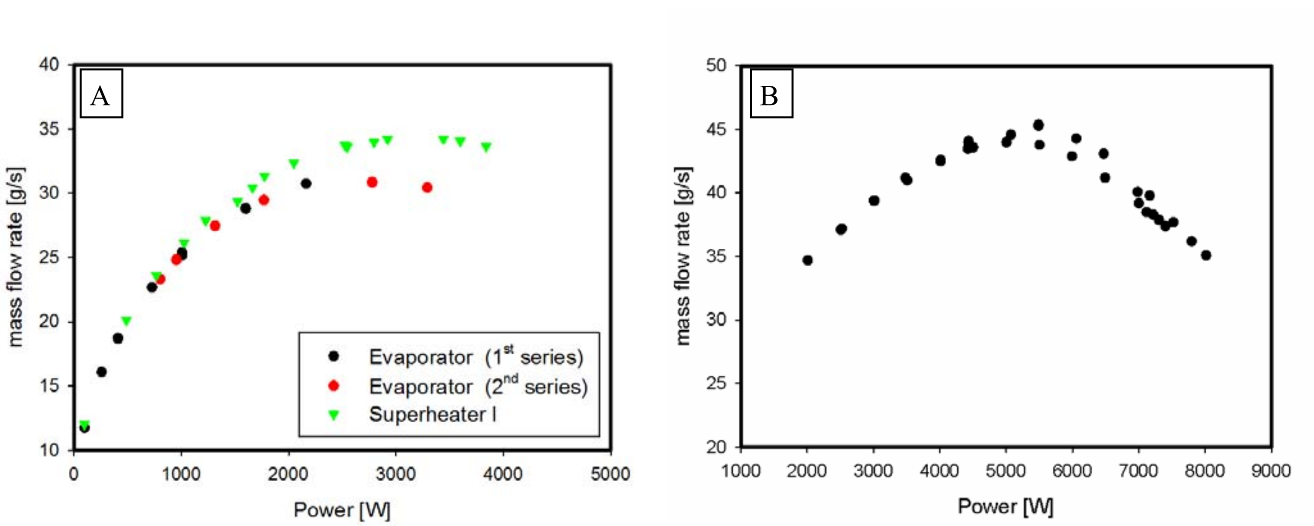

Figure 3 A: mass flow rate measurements of the DeLight setup operating at low power using two cores separately, B: mass flow rate measurements of the DeLight setup operating using three cores and the HPLWR power distribution.

As a second series of test measurements all three cores were used at the same time imposing the power distribution proposed for the HPLWR (53% on the evaporator, 30% on superheater I and

17% on superheater II, [5-6]). These measurements were done with both heat exchangers operational, thus cooling the R23 to a temperature between -6°C and -4°C. During these measurements it was found that the second heat exchanger (evaporator using R507a) failed to reach the required capacity. Discussion with the manufacturer showed this could be due to the interaction of the Freon R23 with internal seals, and a solution has been devised and will be implemented soon. The measured flow rates are shown in Fig. 3B. The expected power-flow trend is clearly visible, with an initial increase in the flow rate as power rises due to the increased gravitational head, followed by a decrease in the flow rate at higher power as the friction becomes dominant with the higher velocities. It should be noted that the inlet temperature was not the same for all these data points, as the power increases, the inlet temperature follows (due to the mentioned heat exchanger issues). This results in the scatter at higher power. However, the results are promising, showing that the system is able to operate in natural circulation mode up to higher powers.

5. Numerical modelling of the DeLight setup

Next to the experimental setup, a numerical model has been developed which will be used to study the steady-state and stability behaviour of the system in more detail. This code will allow for studying the effects of specific parameters in more detail which cannot be easily changed in the experimental setup (e.g. heat flux distribution, variation of the wall friction, location of the heating…). The experimental setup is also constrained to a certain range of power, mass flow rate (imposed by a pump or by the overall friction in the system) and inlet temperatures due to safety reasons and material/constructional limitations. The experimental data will provide a benchmark for this code. As an additional benchmark the code will be compared to other published results for similar systems.

5.1 The model for DeLight

The code is a 1D model of the experimental loop. The considered geometry is that of DeLight, but simplified, as shown in Fig 2B. Initially only 3 local frictions are considered: the valve at the inlet of the core (K_1), the valve at the outlet of the core (K_2) and the valve on top of the riser section (K_3). The heated sections are indicated in red (uniform flux boundary). The 2 heat exchangers are combined as 1 single unit with a given length, and this heat exchanger is set to extract exactly the same amount of power as the three heated sections add to the flow.

The proposed model is simulated using Comsol©. This is a finite element analysis software environment for the modelling and simulation of so called 'multi-physics' problems where different phenomena interact. Standard modules exist to add e.g. 1D flow and heat transfer problems, but for the proposed system the basic 1D PDE coefficient mode was used whereby the full system equations are added to the model, and Comsol acts as the solver. To this end, the equations had to be rewritten in a slightly different form from Eqs. (1-3) to Eqs. (5-7). This procedure was required to make the equations fit in the predefined Comsol PDE coefficient structure. Important to note is that to this end the static pressure p was transformed into the dynamic pressure P in the momentum equation (Eq. (8)), to result in a form with only one spatial partial derivative. Ortega Gómez et al. [14] used the same set of equations in Comsol to study the stability of a single channel with a supercritical fluid. To determine the wall friction factor f, the Haaland relationship [18] was used, this is an approximation of the more exact but implicit Colebrook equation for fully turbulent friction factors in a tube.

$$\frac{\partial h}{\partial t} = \upsilon^2 \frac{\partial G}{\partial z}\left(\frac{\partial v}{\partial h}\right)_p^{-1} \tag{5}$$

$$\frac{\partial G}{\partial t} = -\frac{\partial P}{\partial z} - \frac{g}{\upsilon}\sin\theta - \frac{G^2\upsilon}{2}\left[\frac{f}{D_h} + C_j\delta\left(z - z_j\right)\right] \tag{6}$$

$$\frac{\partial h}{\partial t} + G\upsilon\frac{\partial h}{\partial z} = \frac{q"P\upsilon}{A} \tag{7}$$

$$p + G^2\upsilon = P \tag{8}$$

By neglecting the coupling between the momentum and energy conservation equation, it is easier to solve the set of equations. As only steady state cases are considered here, the time derivatives are set to zero. A first guess is made for the mass flux; this value is used in the energy equation to determine the enthalpy profile in the loop. At this point the substance properties are known within the loop (being only a function of h). The friction factors can then be evaluated allowing for the momentum equation to be solved. Local friction values (valves and bends) are implemented as short tube sections (5 cm) similar to their actual physical length in DeLight. In these tube sections the effects of gravity and wall friction are neglected, to clearly separate these effects from the local friction.

Because there are two different tube diameters used in the loop, DeLight was modelled as 2 separate systems which are coupled using ‘periodic conditions’ (indicated as dotted lines in Fig. 2B). The first system contains the three heated sections and the interconnecting tubes, and has a diameter of 6 mm. The second system contains the riser, downcomer, bottom section and the heat exchanger as well as all the valves with a diameter of 10 mm. The heat exchangers are modelled as a single tube. The periodic boundary conditions used to couple the exit and inlet of the two systems are the preservation of the mass flow rate, the static pressure and the enthalpy. By doing so, no pressure difference is imposed onto the loop, in other words, there is natural circulation.

To define the substance properties, the NIST Refprop database was used. The density and viscosity at 5.7 MPa were determined as a function of the enthalpy over a wide range of temperatures (-65°C to 400 °C). The data points were carefully spread over the selected data range, concentrating more near the pseudo critical point to capture the sharp change. To determine the derivative of the specific volume with respect to the enthalpy as a function of enthalpy, the central difference approximation was used on a fine mesh of tabulated values. At the lowest and highest temperatures the mesh had to be made coarser due to the limited accuracy at these conditions in order to get a smooth dataset. These data points were then used to determine a series of splines which covered the entire range and which were then added to the code. A comparison between the density and viscosity data from the NIST Refprop data base between -20 °C and 100 °C evaluated every 0.05 °C shows a maximum difference of 0.2% compared to the spline interpolations. An example of such a spline is shown in Fig. 4. Ortega Gómez et al. [14] studied the effect of various approximations to define supercritical fluid properties (e.g. a two or three region model), and they found that this has a significant impact on the results. This was also reported by Jain and Corradini [19] who found that a very small change in the equation of state near the pseudo critical point had a very significant impact on the computed eigenvalues. Therefore great care was taken to ensure the fluid properties are well defined.

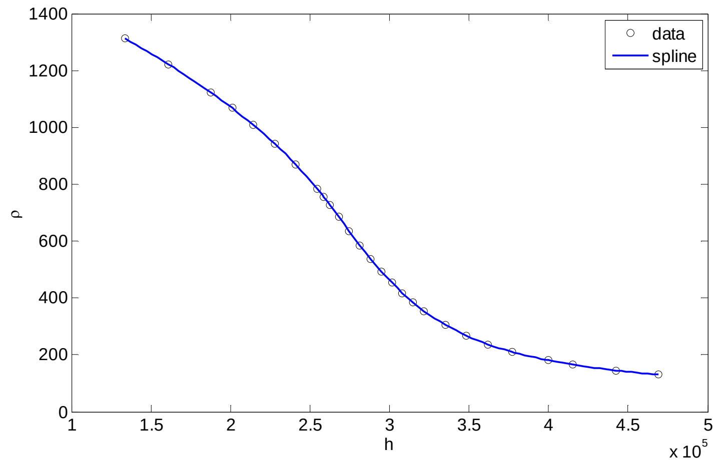

Figure 4: the density-enthalpy spline (blue line) and the original dataset (black circles), R23

5.2 Qualitative assessment of the code

To provide an initial numerical benchmark of the code, two different loop systems from open literature were considered, being the loop presented by Chatoorgoon [20] and by Jain and Uddin [10]. Both loops were constructed in the same code frame and simulated using the same boundary conditions. Chatoorgoons [20] loop uses supercritical water at 25 MPa with an inlet temperature of 350 °C, and Jain and Uddin [10] used supercritical CO_2 at a pressure of 8 MPa with an inlet temperature of 25°C. For both water and CO_2 similar splines were built as for R23. The friction relationships were slightly different. Chatoorgoon used a set of three fixed f values, depending on the location in the loop, thus removing the impact of the Reynolds number in the computations, whereas Jain and Uddin used a different frictional relationship (Mc Adams). The results are shown in Fig 5 A and B. As can be seen there is a very good agreement between the steady state results for both these codes. The difference for the Chatoorgoon case is less than 1.5% and less than 4% for the Jain case. These small differences are attributed to possible differences in the substance properties and some ambiguity as to how the local friction values were treated in theses codes.

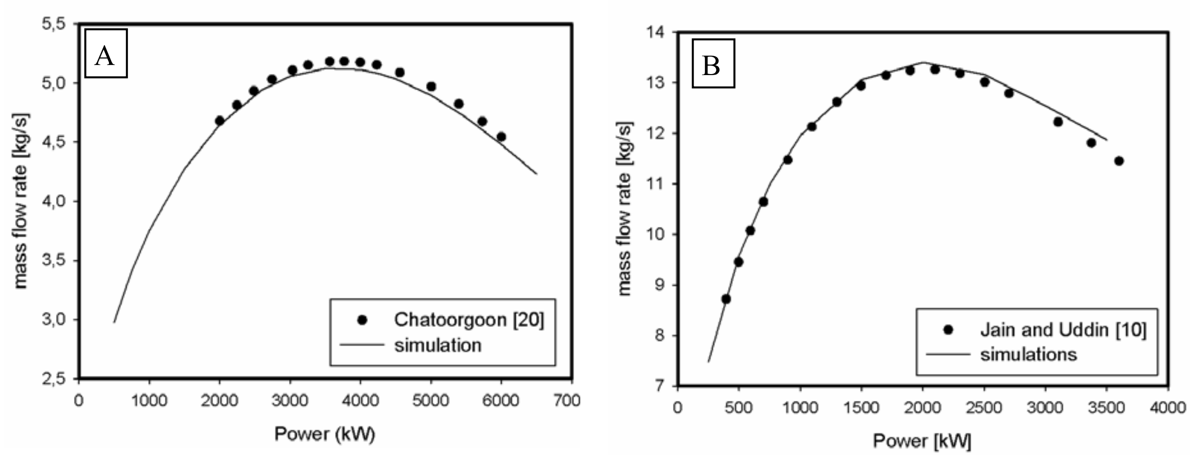

Figure 5: comparison of the simulated power-flow curve (line) to two data sets from open literature (black dots): A – Chatoorgoon [20], B – Jain and Uddin [10]

The Comsol code makes use of a set of 'shape functions' which need to be selected for the meshed elements. There are different types available, and their order can be selected freely. A comparison of the steady state results showed that there was no significant impact in using lower or higher order shape functions (2nd to 5th order all gave the same end result), nor was there any effect of using different types of shape functions. The following results were all obtained using 4th order Lagrange shape functions.

5.3 DeLight simulations

By using the benchmarked code a number of simulations were performed for the DeLight setup. The effect of various parameters on the steady state mass flow rate as well as the accuracy of the proposed DeLight model were studied. A grid independency study was performed, showing that grid cells smaller than 5 cm result in a well converged result. In the segments with a local friction, a minimum of 3 cells was imposed and in the remainder of the system the maximum grid size was set to 5 cm. Figure 6A shows a comparison of the natural circulation mass flow rate at different power when heating is applied by just one core and this for the three different core sections. The shown data series are for an inlet temperature of 20 °C. As can be seen, shifting the heating from the evaporator to superheater I or superheater II results in a significant increase of the mass flow rate, especially at higher powers. The maximum of the power flow curve also shifts to higher powers. This is due to a reduction of the friction in the loop as a smaller section experiences the high velocity. These trends agree well with the experimental results, but as shown in Fig. 6A the simulations overestimate the experimental data. This indicates that the code underestimates the friction in the loop. As a first addition, the pressure drop of the bends was added using local friction values (K = 0.5). The results for the evaporator are shown in Fig. 6B. Adding the pressure drop of the bend lowers the power flow curve and slightly shifts the maximum to lower power. This data still overestimates the experimental data. Changing the surface roughness ε from 4e-7 (reported value by the manufacturer) to 3e-6 (value used by Ortega Gómez et al. [14] for similar tubes (10.91 mm ID)) results in a significant decrease of the power flow map. A further possible addition to the model is adding a pressure drop correlation for the heat exchangers as a function of the flow rate. However these data have to be determined experimentally as no such correlations exist for heat exchangers under supercritical conditions. These results are promising and indicate that with experimental input for the heat exchanger friction a fully benchmarked code could be obtained.

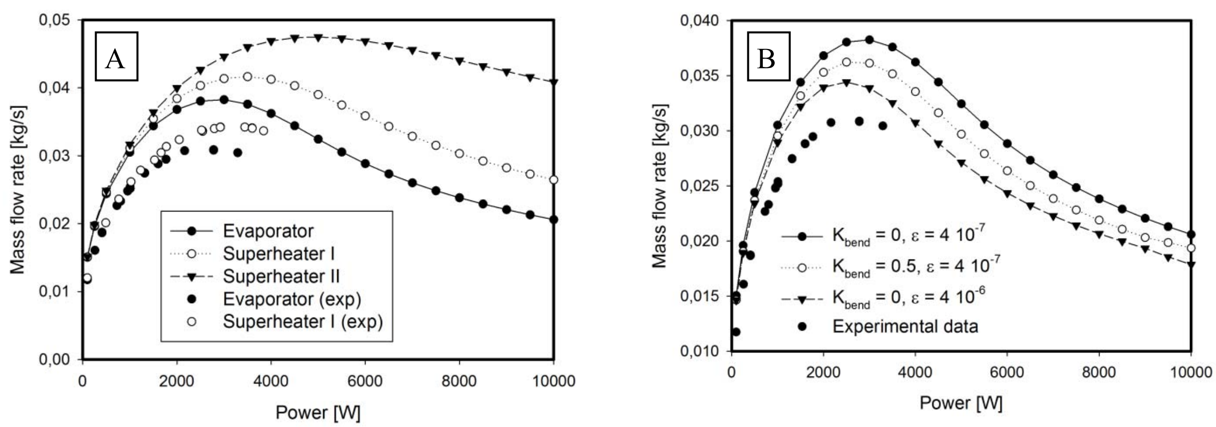

Figure 6. A: comparison of the simulated power-flow curves for single core heating on different cores to the experimental data. B: comparison of the experimental data when heating only the evaporator to different friction scenarios, T_{in} = 20°C.

Figure 7 shows the impact of the inlet temperature on the mass flow rate when using just the evaporator as heating element. As can be seen, reducing the inlet temperature increases the natural circulation flow rate, as the gravitational head increases. The maximum flow rate also shifts towards higher powers. This is beneficial for the setup as it results in lower core exit temperatures at higher powers. The used scaling procedure resulted in a power requirement of 9 kW to simulate the HPLWR conditions, and a core inlet temperature of -21 °C. The computed power flow map for the DeLight setup operating under HPLWR power distributions (53%, 30%, 17%) but without any local friction is shown in Fig. 7B. The red line indicates the nominal operating conditions. Considering the findings for the single core heating which showed that the maximum location of the power-flow curve is slightly overestimated, it is expected that the nominal operation condition of the DeLight loop will be within the frictionally dominated regime. The curve indicates that the margin for operation at higher power is considerable, though limited to say a factor of 1.3 to prevent a too sharp reduction of the mass flow rate.

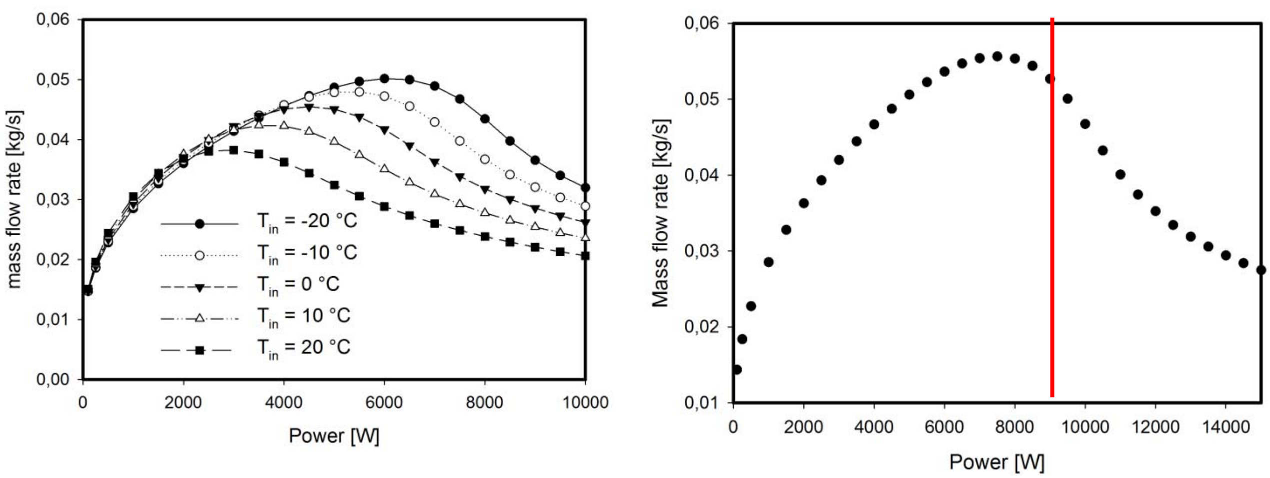

Figure 7. A: impact of the inlet temperature on the power flow curve when heating using the evaporator only, B: predicted power-flow for the DeLight setup using the HPLWR power distribution, T_{in} = -20°C.

6. Nomenclature

A	flow surface area [m²]
C	local friction value [-]
D_h	hydraulic diameter [m]
f	friction coefficient [-]
G	mass flux [kg/m²s]
H	enthalpy [J/kg]
p	static pressure [Pa]
P	dynamic pressure [Pa]
P_h	heated perimeter [m]
q”	heat flux [W/m²]
Re	Reynolds number [-]
t	time [s]
z	spatial coordinate [m]
ε	surface roughness [m]
θ	angle [°]
ρ	density [kg/m³]
υ	specific volume [m³/kg]

7. Conclusions

This paper presents an overview of the development of the experimental DeLight facility and the initial power-flow measurements. This facility is a scaled version of the HPLWR core, intended to operate at natural circulation conditions. The experimental results show that natural circulation was obtained in the system. To further study the impact of different geometric parameters, a numerical model was developed within the Comsol© environment. The details of the model and the initial benchmarking results are presented. A comparison of the results to the experimental data showed good qualitative agreement, capturing the trends in the single core power-flow measurements. An analysis of the results showed that by adding more information on the friction of the heat exchangers could result in a better quantitative agreement.

8. Acknowledgements

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