Preliminary natural circulation data of a scaled HPLWR experiment

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Abstract. The HPLWR is the proposed European design of a reactor based on supercritical water, as part of the GEN-IV research platform. The large change of the water density when flowing through the core could be used as the driving force for natural circulation, resulting in an inherently safer design. It is well known that such natural circulation loops are prone to instabilities in particular at high power and low flow conditions. To study the potential of natural circulation and the stability of such a loop (three-pass core) an experimental facility, DeLight, was built at the Delft University of Technology. This facility is a scaled down version of the HPLWR using Freon R23 as scaling fluid. This paper describes the setup and some preliminary measurements of natural circulation. As part of the EU THINS project a new test section is being developed for DeLight in collaboration with NRG for detailed velocity measurements.

1. Introduction

It is well known from thermodynamics that increasing the heater outlet temperature in a thermal cycle will result in a higher thermal efficiency (Carnots law). This has driven the development of power stations world wide, pushing the turbine inlet temperature and pressure higher, starting from about 500°C, 180 bar during the 70s to current units operating at 300 bar, 600-650°C. New units, so called 'ultrasupercritical power stations' are in development to operate at 360 bar with a turbine inlet temperature of 700°C and higher. These are expected to become operational past 2020. Modern coal fired power stations have a thermal efficiency of up to 45% and if a combined cycle is used the most advanced units just fall short of 60%. Compared to these numbers the thermal efficiency of the nuclear reactors currently in operation (BWR and PWR at about 33-34%) and even the more advanced units under construction (Gen III+, EPR is rated at 37-38%) is low. This is due to the lower pressure and temperature used in these cycles (150 bar, 315°C for a PWR) which is related to the stringent safety criteria, neutronics, thermohydraulic interactions and material properties.

To increase the thermal efficiency, a light water cycle based on supercritical water (SCWR, SuperCritical 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. Over the course of the past decades a number of core designs have finalized, including a Japanese design [1], a Korean design [2], a US design [3] and most recently a European design [4]. These designs differ considerably in fuel assemblies, flow layout and moderators which are used… The European design (HPLWR, High Performance Light Water Reactor) [4] is remarkable having 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. Between the passes mixing plena are used to reduce peak cladding temperatures.

As is well known, supercritical fluids experience strong changes in fluid properties. This is illustrated in Fig 1B. The density varies between 780 kg/m³ and 90 kg/m³ with a sharp change near the pseudo critical point. This strong density difference could be used as the driving force for natural circulation which would result in an inherently safer reactor without the need for large feed water pumps. Using natural circulation for improved safety of a nuclear system is not a new idea, but it has not seen any commercial application. So far only one design, the ESBWR [5], has actually been constructed in a small size at Dodewaard, the Netherlands operating for decades. These natural circulation systems however can become unstable under specific operational conditions (e.g. high power and low flow rate). This indicates a need to study the stability boundary of such systems, which lead to the research presented in this paper. The goal of this study is to examine the stability boundary of the HPLWR experimentally. To this end a setup has been designed, which will be described further on.

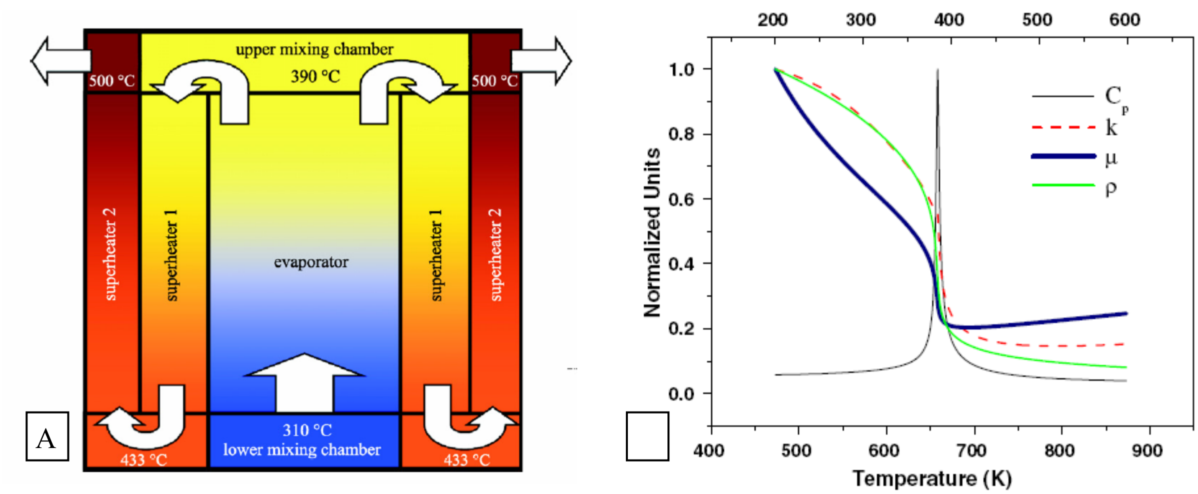

FIG 1. A: Three pass core arrangement proposed for the HPLWR (Fischer et al. [4]), B: normalized fluid properties for water at 25 MPa for a range of temperatures

Different methods exist to perform stability research on natural circulation loops. In most cases numerical finite element tools are used which describe the system through a set of non-linear coupled equations, see e.g. [6]. These equations are solved to determine the steady state operation after which perturbation theory is applied to describe the linear stability behaviour (through e.g. Laplace transformation, eigenvalues…). In order to benchmark these numerical codes, experimental data is required on the steady state and stability behaviour. To this end experimental facilities are required which simulate the proposed system. To avoid excessive costs due to the material and power requirements of the actual system, a scaled version should be used. This has been done at the Delft University of Technology for the ESBWR using the GENESIS facility [5]. The experimental data was used as a benchmark for numerical codes [7].

2. Scaling the HPLWR

In order to design a scaled version of the HPLWR the governing equations (conservation of mass, momentum and energy and the equation of state) of the system should first be considered. Rohde and Van der Hagen [8] describe the scaling procedure through the non-dimensional equations and derive a number of scaling factors based on the choice of a scaling fluid. After comparison of a large number of different fluids, Freon R23 was selected as the scaling fluid based on the power requirement, the temperatures (the pseudo-critical temperature is only 33°C), the pressure (5.7 MPa) and safety (non flammable). The non-dimensional fluid properties agree well, with a maximum deviation of 8% for the density, [8]. Some relevant pseudo-critical fluid properties and scaling values are indicated in Table 1. Through linear stability analysis (using eigenvalues) of a channel with supercritical water and of its scaled R23 counterpart, it was shown that the scaling rules result in the same stability behaviour, confirming the proposed scaling procedure and fluid selection, Rohde et al. [9].

Table I. Comparison of selected pseudocritical properties of H_2O and R23, the resulting scaling rules as derived by Rohde and Van der Hagen [8]

	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 setup

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 boundary of a system. 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.

The loop contains a large number of sensors to closely monitor the thermohydraulics. At the top and bottom absolute pressure drop sensors are presents (p symbol in Fig. 2, ± 0.15%). Each valve is combined with a differential pressure drop sensor (Δp symbol in Fig. 2, ±0.5%, ±200/500 mbar) to measure the local pressure drop. The different core sections each contain 5 type K thermocouples to measure the local fluid temperature as it passes through the core (T symbol in Fig. 2, ± 0.1K). These thermocouples also have to be insulated electrically from the core to prevent the feed current passing through them. This was also done using PEEK rings, as shown in Fig. 2B. The individual thermocouple channels were calibrated carefully using 3 reference thermocouples which were calibrated over the entire temperature range by a certified body. As shown in Fig. 2 additional thermocouples are placed in the riser and downcomer section, as well as on the secondary side of the heat exchangers to monitor the heat removal. The R23 mass flow rate is measured using a coriolis meter (F symbol in Fig. 2, ± 0.25%, including a density measurement: ±0.005 kg/m³). Apart from the core sections the entire setup is insulated using Armacell© (25 mm thick) to reduce any heat loss to the exterior. A magnetic rotor pump is present in the loop, but a bypass can be set to allow for natural circulation, as shown in Fig. 2.

The data acquisition system consists of a PC with one National Instruments PCI-6259 data acquisition card, connected to a National Instruments SCXI-1001 rack with two SCXI-1102B 32-channel amplifiers. This system is used for monitoring the experimental setup and for recording sensor signals. The measured and processed data are displayed on the PC screen which allows for continuous monitoring. Up to 64 multiplexed signals are recorded with a sampling rate of 1000 Hz for further analysis. Additionally, seven signals (three temperature values, two pressure values, and the measured R23 and cooling water flow rate) from the facility are connected to a separate stand-alone data acquisition system with a National Instruments NI-6035 DAQ card. This system is used for safety monitoring and will shut down the power supplies if one of the signals exceeds prescribed limits.

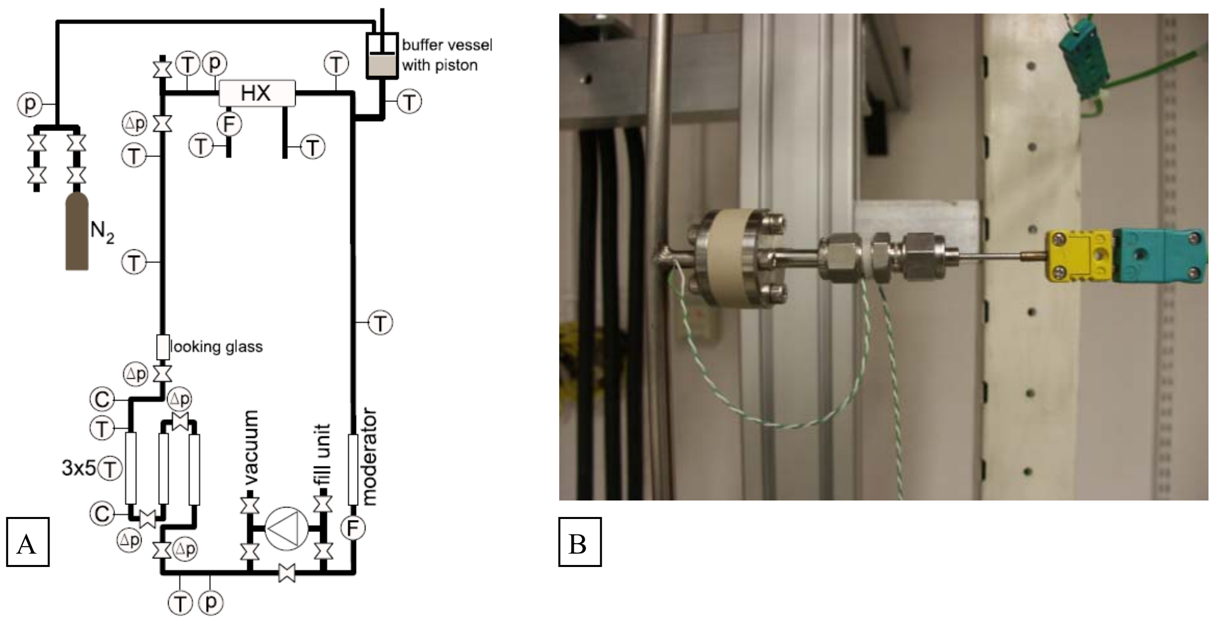

FIG. 2. A: Schematic overview of the DeLight setup as constructed at DUT – B: detailed construction of the thermocouple connection in the core section showing the electric insulation.

4. Results

The described loop has been recently finalized and initial testing is currently underway. As a first set of test cases natural circulation was induced through the setup under supercritical conditions but only 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).

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

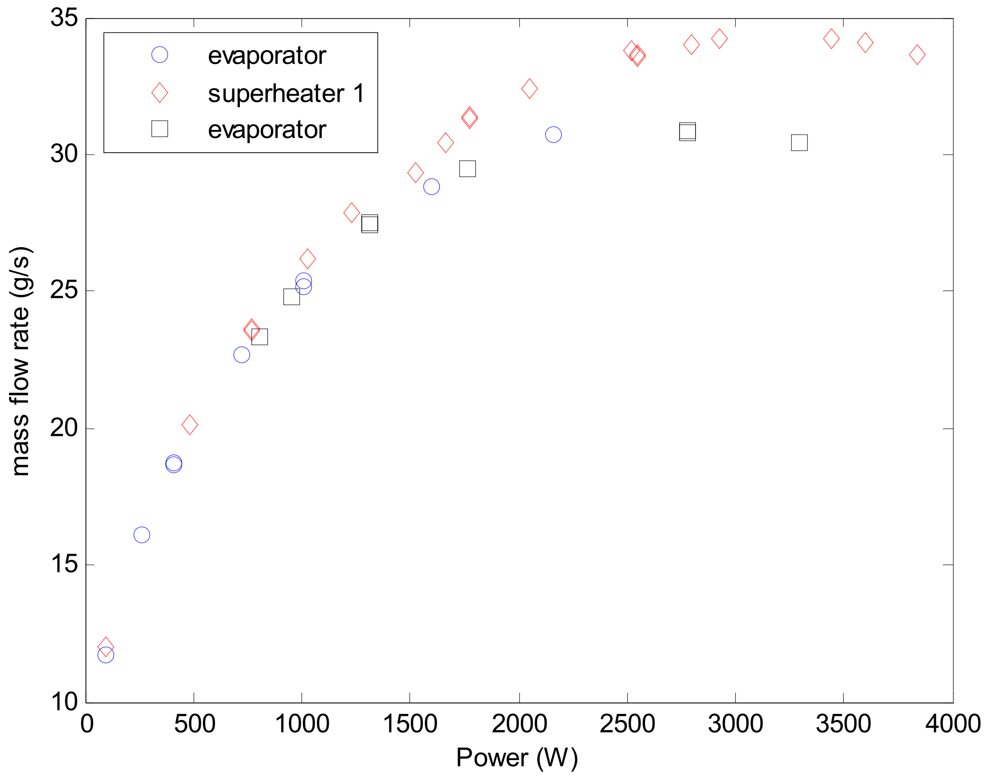

FIG. 3. Initial mass flow rate measurements of the DeLight setup operating under natural circulation at low power using two cores separately.

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 this already occurs around 3.5 kW when using only superheater 1 as power input, and around 2.5 kW when using the evaporator as power input. At higher power the two curves start to deviate slightly, which might be due to the difference in orientation relative to gravity. Two different series were measured with the evaporator as heater on different days (whereby the setup was depressurized at night) showing good agreement.

5. Future work: THINS project

Recently the THINS project (FP-7, ThermoHydraulics of Innovative Nuclear Systems) was launched in which the thermohydraulics of different Gen-IV designs including the SCWR are studied experimentally and numerically. In this project a large consortium consisting of more than 20 institutes (research centers, universities and industries) from EU (19) and non-EU (2) countries will collaborate. The research program is aimed at the development and validation of new physical models, improvement and qualification of numerical engineering tools and their application to innovative nuclear systems. Specifically for the SCWR, research is conducted in the area of single phase mixed convection and single phase turbulence in a heated annulus to provide benchmark data for numerical simulations. To this end the DeLight facility will be modified in order to perform detailed local velocity measurements in single phase turbulent flow. The design of the modified test setup is done in collaboration with NRG using numerical simulations, as described below.

6. Design of the THINS test setup: CFD analyses

The objective of the THINS experiments in the DeLight facility is to study supercritical turbulent flow and in particular the Heat Transfer Deterioration (HTD) phenomenon. Fig. 4A gives a schematic view of the proposed annular test section. Supercritical R23 flows upwards through the annular channel, opposed to gravity. The first 7 m of the channel are unheated to provide a hydrodynamically developed turbulent flow at the inlet of the test section. The test section consists of an electrically heated rod placed in the center of the annulus using thin strut spacers. These spacers are kept thin to reduce their impact on the flow. The distance between the measurement location and the nearest upstream spacer is at least 50 hydraulic diameters, ensuring their impact will have dampened out. A uniform heat flux is imposed on the rod surface through current heating. Wall temperatures are measured at different positions using thermocouples soldered onto the surface. At the center of the test section, as indicated in Fig. 4A, the local fluid temperatures are measured as well as the local velocity profile over the annular section. The fluid temperatures will be measured using thermocouples. The velocities will be measured using Laser Doppler Anemometry (LDA). To this end optical access is provided. By preheating the R23 in the core sections of the DeLight facility, the inlet temperature of the test section can be set to a value close to the pseudo-critical point. The added heating power of the heating rod will then be used to increase the temperature to a desired point at the measurement plane, varying from well below to above the pseudo-critical value. Precisely in this temperature range the local fluid velocity and wall temperature will be measured to study the turbulent flow and heat transfer in detail.

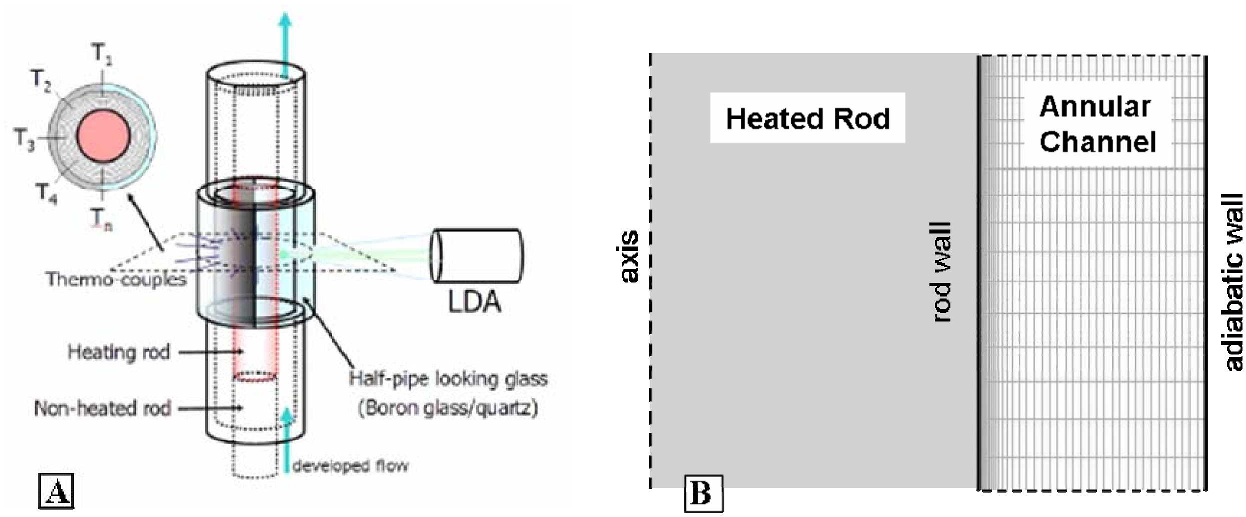

FIG. 4. A: Schematic representation of the annular test section to be applied for studying supercritical turbulent flow in the DeLight facility at DUT – B: Schematic drawing of the geometry and mesh applied in the pre-test CFD analyses performed by NRG.

In support to the design of the annular test section, pre-test CFD analyses are performed to identify suitable ranges for the input parameters (mass flow rate, inlet temperature and rod power) to study HTD using R23 under supercritical conditions. Previous studies [10, 11] showed that HTD, and the changes in the flow structure that are associated with it, occur close to the heated wall. Therefore, it is also important to identify the measurement resolution required to capture the characteristics of HTD in the annular test section with CFD analyses and assess the technical feasibility of the THINS experiments.

The numerical analyses are performed with the commercial CFD code Fluent 6.3. Following Palko and Anglart [12] and Visser et al. [11], the SST k-ω turbulence model with enhanced wall treatment is employed to investigate the characteristics of HTD. Buoyancy is included in the transport equations of the SST k-ω model to account for the effect of gravity. A two-dimensional rotationally symmetric geometry is employed to model the heated annular channel. The applied mesh consists of hexahedral cells and is strongly refined near the heated rod wall such that the viscous and thermal boundary layers are well resolved. The mesh obeys $y^+ < 0.2$ at the heated rod wall (recommended by Koshizuka et al. [10] and Roelofs and Komen [13]) and includes more than 10 cells within the viscosity affected region ($Re_t < 200$), which is in agreement with the mesh guidelines provided by Fluent [14]. A coarser mesh is applied at the adiabatic outer wall. Sensitivity analyses showed that the numerical results obtained with this mesh were mesh independent. A schematic drawing of the considered geometry and mesh is shown in Fig. 4B. R23 is modeled as an incompressible, single phase fluid under steady, isobaric, turbulent flow conditions. The temperature dependent properties of R23 are obtained from the NIST database [15] and implemented in the CFD model using a piecewise linear approach. To ensure good accuracy the interpolation points were spread closer together in the region where the gradients are stronger.

CFD analyses are performed at 5.7 MPa (the operating pressure of the DeLight facility) for an annular channel with a hydraulic diameter of 5 mm and height of 4 m. In order to investigate the effect of the input parameters, analyses are performed with different values of the mass flux, inlet temperature and heat flux. A mass flux of 200 kg/m^{2}s, inlet temperature of 0 ºC and heat flux of 20 kW/m^2 are found to be suitable input parameters for studying HTD using R23. At these settings HTD is predicted at an elevation of 0.8 to 1.8 m along the heated rod wall, which is characterized by a region of high temperature at the rod wall shown in Fig 5A. In order to determine the characteristic length scale of the HTD phenomena, the radial profiles of flow velocity and density are observed at a height of 1m (inside the region of HTD) in the annular channel. Fig 5B shows the part of these radial profiles within a distance of 0.3 mm from the heated rod wall. Strong changes in flow and fluid properties are predicted close to the heated rod. These CFD results indicate that measurements within a distance of 0.1 mm (or less) from the heated rod may be required to capture the characteristics of HTD.

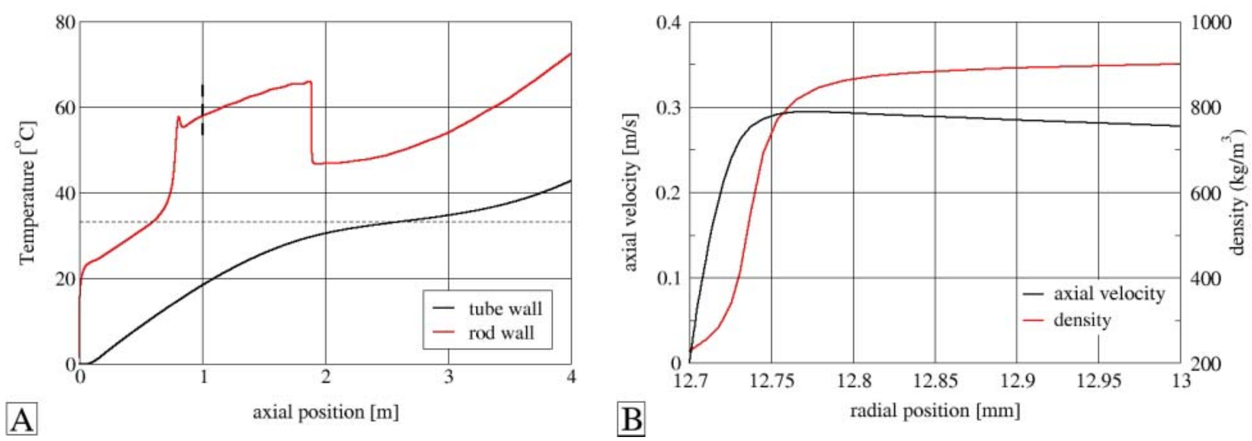

FIG. 5. CFD results for the annular test section at a mass flux of 200 kg/m^{2}s, inlet temperature of 0 ºC and heat flux of 20 kW/m^2. – A: Calculated temperature profiles along the adiabatic tube wall and heated rod wall of the annular test section. HTD is predicted from 0.8 ~ 1.8 m – B: Radial profiles of flow velocity and fluid density close to the heated rod (located at a radial position of 12.7 mm) in the annular test section at 1 m height.

7. Conclusions

In this paper the design and construction details of the DeLight facility are presented. This facility is aimed at studying the possibility of using natural circulation to drive the flow in the HPLWR. In particular the large density difference over the core might induce instabilities which should be avoided. The facility is a scaled version of the HPLWR geometry, including the three pass layout. A scaling fluid, Freon R-23, is used to allow for operation at more moderate temperature and pressure compared to water. This paper also presents some preliminary measurements of natural circulation. As part of the EU THINS project a new test section is currently being developed for DeLight in collaboration with NRG for detailed velocity measurements.

8. Acknowledgements

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