Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 43 (2013) 254 – 263

Physics Procedia

The 7th International Topical Meeting on Neutron Radiography

Study on the properties of supercritical water flowing in a closed loop using dynamic neutron radiography

Márton Balaskó[*,a], László Horváth[a], Ákos Horváth[a], Attila Kiss[b] and Attila Aszódi[b]

[a]Hungarian Academy of Sciences,Centre for Energy Research, 29-33 Konkoly Thege Miklós street, 1121 Budapest, Hungary
[b]Budapest University of Technology and Economics, Institute of Nuclear Techniques, 9. Muegyetem rkp., 1111 Budapest, Hungary

Abstract

This paper describes the first steps of the realization of a natural circulation loop cooled by supercritical water. The thermal hydraulics of supercritical water is not fully understood. The thermal hydraulic phenomenon in the loop is intended to be measured by thermocouples, absolute and differential pressure transducers, flow meter and simultaneously visualized by dynamic neutron radiography techniques. The structure of the loop, the measurement techniques applied and the data acquisition system will be presented in details.

Keywords: High temperature; high pressure; supercritical water; dynamic neutron radiography; thermohydraulics; natural circulation loop

1. Introduction

The supercritical water (SCW) as working fluid is widely used in the technical life for example during supercritical water extraction or oxidation technologies [1], in supercritical fossil fired boilers, etc. Because of the advantageous thermal features of this fluid, it has been considered as a possible coolant for advanced nuclear reactors. In the 1960's and 1970's very intensive research has been done for Supercritical Water pressure cooled Reactor SCWRs [2], [3], [4], [5], [6], [7], then a twenty years long pause came. At the beginning of 1990's the interest for SCWR has resuscitated and extensive research has started in Europe, U.S., Canada, Russia, Japan, South Korea, China, etc. The SCWR [8] is one of the six worldwide developed Generation IV [9] nuclear reactor concepts. The specialty of the SCWR concept is that the pressure of the coolant (light water) is higher (25 MPa) than its critical value (22.1 MPa), and the outlet water temperature of the reactor is well above (500°C) the critical temperature (374ºC). The concept is based on the design of present Light Water Reactors and the commercial supercritical – ultra supercritical boilers. Whereas the two above mentioned technical bases currently are in daily use, there are unresolved challenges and questions about the SCWR concept. For example: need of new high temperature resistance structural materials [10], questionable role of the

[*] Corresponding author. Tel.: +36-1/392-2222; fax:+36-1/395-9162.
E-mail address: balasko@aeki.kfki.hu.

1875-3892 © 2013 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and/or peer-review under responsibilty of ITMNR-7
doi:10.1016/j.phpro.2013.03.029

hyper-compressibility at supercritical conditions [11], and the specific heat transfer regimes: normal, enhanced, deteriorated and regenerated heat transfer under certain supercritical conditions [12], [3], [6] and [13]. This ongoing research investigates the different heat transfer regimes assisted by combined measurement techniques of temperature, pressure, mass flow rate (conventional) and dynamic neutron radiography (for simultaneous visualization).

In this research the authors have been dealing with the study of the properties of SCW since 2005 at the Dynamic Radiography Station (DRS) of the Budapest research reactor (10 MW) [14], [15]. Indeed, the main interest of supercritical water is that its density can be controlled between gas-like and liquid-like values by varying its pressure and temperature. The Dynamic Neutron Radiography (DNR) has given a possibility to observe the changing of the density of the water in extreme conditions [23]. Firstly, a special sample holder (GR-5H) was designed from titanium alloy with full-length heating system, see Fig. 1. Flow did not occurred in this sample holder but the transition from sub-critical state to supercritical state could be demonstrated and visualized [15].

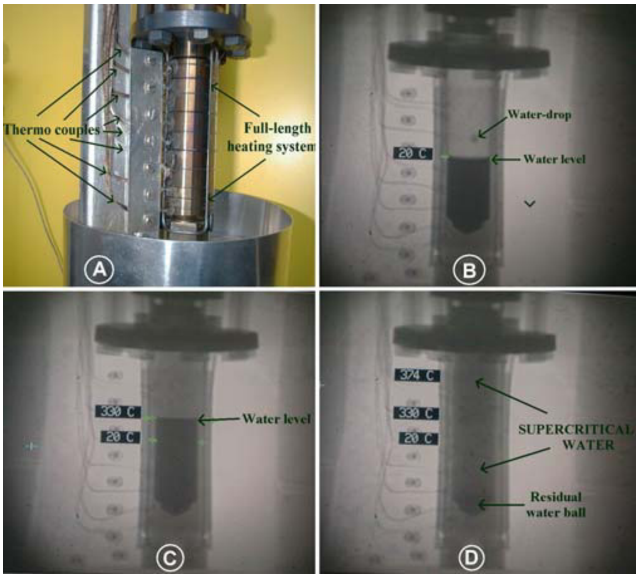

Fig. 1. (A –D). Production of the super critical water for the uniform temperature distribution [15], which was measured by eight thermo-couples.
Fig. A : GR-5H sample holder with full-length heating for study of the behaviour of supercritical water by Dynamic Neutron Radiography
Fig. B : The Dynamic Neutron Radiography picture of the GR-5H sample holder with water on 20 ^{0}C (water drop is visible on the inside wall of the sample holder).
Fig. C : Increasing water level in the GR-5H sample holder on 330 ^{0}C by Dynamic Neutron Radiography – above the water level the vapour phase contains of more moisture then in figure B.
Fig. D : Supercritical water in the GR-5H sample holder on 374 ^{0}C by Dynamic Neutron Radiography (Exception on the bottom of the hole. It contains a little residual water ball).

After the success of the static sample holder, it seemed reasonable to continue this research with a closed loop cooled by natural circulation of SCW.

2. Aspects of the thermalhydralic concept

Since the 1930's more than 500 experiments have been performed dealing with supercritical fluids, mainly with water SCW [13]. The main disadvantage of these experiments is that very limited number of information has been recorded for the different distribution of thermal hydraulic variables. For example, the distribution of wall temperature along the heated length has been often recorded with a typical 50÷200 mm distance between thermocouples. This resulted a coarse resolution of wall temperature though very step increase of wall temperature has been reported under deteriorated heat transfer conditions [2], [4], [5], [6]. Many other variables and their distribution have not been measured during the above mentioned experiments, for example the distribution of fluid temperature, velocity, density and other material properties in the radial or axial direction. It means that the limited resolution of measurements has bounded the possibility of the research on the thermal hydraulics of SCW. The above mentioned high pressure and temperature conditions of SCW has also made these experiments more complicated, because there is no any structural material which is transparent and can stand the high pressure and temperature. That is why the visualization of SCW flow is a big challenge [24].

In the last two decades, the computational fluid dynamic technique has undergone a significant development. Nowadays, the performance of such codes enables the detailed 3D modeling of the thermal hydraulics of SCW. The results are very promising (see [16], [17]), but validation is still needed [18]. The application of DNR simultaneously with conventional measurements seems a very powerful tool for both to validate the CFD calculations and discover more details of the thermal hydraulics of SCW.

Considering the need of simplicity, as a first step, a natural circulation loop cooled by SCW has been designed based on the successful previous attempts published in literature [19], [20]. This loop essentially is a many times bended closed pipe with two horizontal (one lower and one upper) and two vertical (one hot leg and one cold leg) parts. The lower horizontal (preheater) and hot leg (heater) is heated. The structure of the loop can be seen on Fig. 2. That is the reason why a big density difference occurs between the hot and cold leg. This density difference drives the natural circulation flow.

In the future, the application of forced circulation is intended in the loop and this circumstance has been considered during the design of the loop. The main goal is the investigation of natural circulation of SCW but the possibility of modification to forced flow has been ensured in the construction.

3. Experimental facility

The investigation was obtained at the DRS of the Budapest research reactor (10 MW). The main parameters of the DRS are the following: the neutron flux is $8X10^{7}$ n cm^{-2} sec^{-1}, the gamma dose rate is 8.5 Sv/h , the Cd ratio is 8, when the L/D ratio is 170. Neutron radiation passing through the object is converted into light by a scintillator screen, and the light is detected by a LLL tv camera. Radiography images are displayed on a monitor, stored by S-VHS and DVD recorders for further analysis. At the DRS the sensor of the LLL tv camera is a vidicon tube with built in imaging-intensifier. Its type is TV1122. The single frame exposure time of the camera is 40 msec and its sensitivity is 10^{-4} lux. This registration speed and sensitivity are available to study the medium speed motion of the water in the loop.

4. Investigated object

The investigated object is the ANCARA (MTA KFKI **A**EKI-BME **N**TI Budapest Super**C**ritical w**A**te**R** test f**A**cility) natural circulation loop.

The study of water in the supercritical regime means high load on the material of the loop. Materials of good corrosion resistance and of high strength at high temperature (above 400 ^{0}C) were selected, as it was published in [21, 22]. The safe measurement conditions and the integrity of the loop were verified by a stress analysis calculation based on the equivalent tensile stress, or Huber-Mises-Hencky yield criterion.

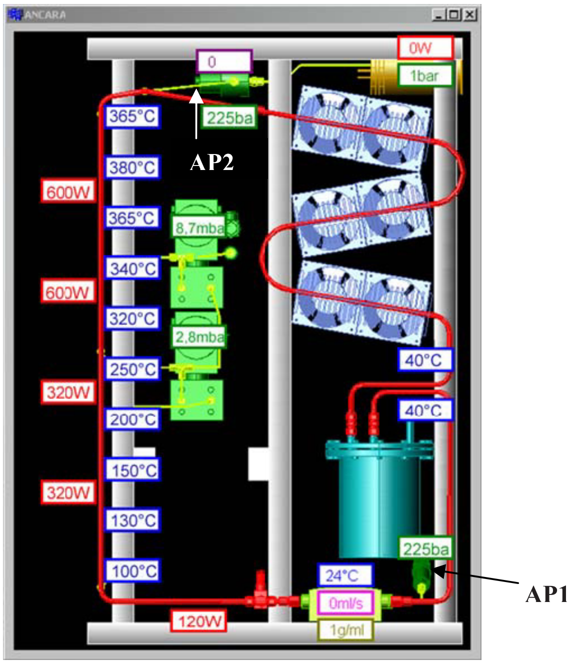

Fig. 2. The construction of the ANCARA loop: Sematic view in the data acquisition software.

The loop is essentially a bended closed pipe with many different measurement equipment mounted on an aluminium alloy frame (see Fig. 2.). The pipe was made of stainless steel which inner diameter (ID) is 5, outer diameter (OD) is 8 mm. This ID is in the same order of magnitude as the equivalent diameters in an individual cooling channel of a fuel assembly in a current SCWR design. The loop consists of more pipe parts with a total length of 5,2 m. Each pipe part connects to another part by weld or to an equipment by a Swagelok type pipe connection. The total volume of the closed loop is 102.1 cm^3.

In the following, the description of each equipment will be presented started from the lower right corner of the loop. The direction of this description coincides with the flow direction.

Two UNIK 5072 – TD – A3 – CC – H0 – PE type absolute pressure transducer measures the absolute pressure in the loop. Their accuracy is 0.04%. The positions of these two transducers can be seen on Fig. 2. at the lower and upper horizontal part (both of them (AP1 and AP2) show 225 bar absolute pressure).

Left to the lower UNIK-5072 there is a SITRANS F C 300 type mass flow meter (MFM) made by SIEMENS (see Fig. 3.). This mass flow meter operates by the Coriolis theory. This equipment measures simultaneously the density and temperature of the fluid and the mass flow rate (or the volume flow rate).

The last equipment in the lower horizontal part is the preheater (PHE, see Fig. 3.). This is an unique manufactured type heater which is identical with the four heaters in the vertical hot leg. Its total heating power is 500 W per unit. Its heating coil is 1NcI20 type made by Thermocoax.

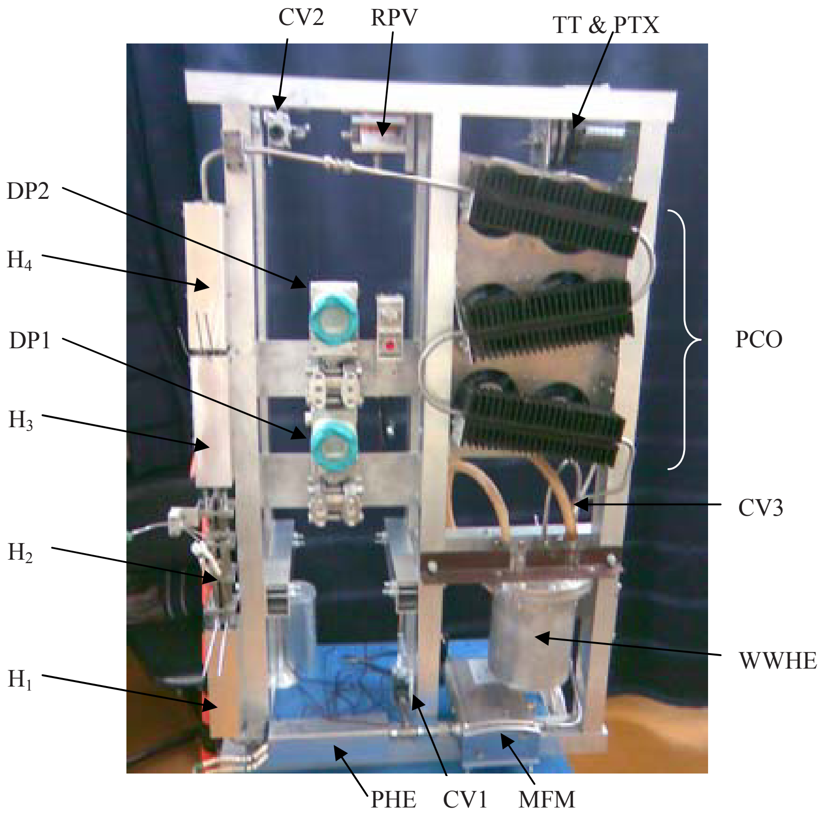

Fig. 3.: Picture of the semi-final state of the ANCARA loop

The hot leg heated by the above mentioned four heaters (H_1-H_4, see in Fig. 3.) with a total heating power of 2000W (4 x 500 W). The temperature distribution on the outer wall of the hot leg was measured by ten “K” type thermocouples. The distance between two thermocouples was 110 mm (see in Fig. 2.).

The length of the hot leg is approximately 1 m where the pressure drops are measured by two SITRANS P DSIII 7MF4533-1DB32-2AA6-Z A01 type differential pressure transducers made by SIEMENS (see Fig. 3.). The first one (DP1) measures the differential pressure between the start and middle point of hot leg. The second one (DP2) measures the differential pressure between the middle and end point of hot leg (see Fig. 3).

To reach the SCW state the high purity water has been heated from room temperature above the critical temperature. In the meantime the fluid expands and its pressure increases. This is how the pressure is controlled but if the heating power is not sufficient (higher than needed) then fast blow down possibility would be needed. To realize this function an electrically controlled blow down valve has been installed at the beginning of the upper horizontal part (see Fig. 2., where 0 means the valve is fully closed). This valve is a 30-041-A024 type magnet valve (reduce pressure valve ~ RPV, see Fig. 3.). Its shortest opening time is 0.1 s. The water blow down through this valve is collected in a tiny tank (TT) which total volume is 55 cm^3. This tank has its own heating capability which enables water feed back to the loop. The pressure in this tank can be measured by a PTX 1400 absolute pressure transducer (PTX, see Fig. 3.).

There is a three pass active air-cooled pre-cooler (PCO) at the upper part of the cold leg. This pre-cooler consists of cooling ribs actively cooled by two ventilators per each pass. This configuration is from commercial PC technique (see Fig. 2. and 3.).

Downstream from the pre-coolers there is a crosscurrent water-water heat exchanger (WWHE) contained by a stainless steel tank (see Fig. 2. and 3.).

Downstream from the WWHE there is a PB491021 type valve (CV3, see Fig. 3.). Its function is controlling the mass flow rate. This valve is controlled by an electrical motor.

For the necessary vacuum and high purity water charge processes two PB491021 type valves (CV1 and CV2) have been installed in the loop at the bottom and upper horizontal parts.

5. Measurement

The aim of the DNR investigation was to give visual information about the behavior of the SCW in the loop. Before the starting of the DNR investigation a cleaning and filling up procedure have to be done. The whole tube system with the all miscellaneous equipment and TT is cleaned by a vacuum pump. At the end of the cleaning procedure the TT is separated from the other parts of the loop by the RPV. Latter the pump is separated from the loop by the CV2. After CV1 is opened the water fills up the loop from bottom to the top. At the end of the filling up procedure the CV2 is opened to verify the water level. Finally, all valves are closed and the DNR measurement can start. The first period of the heating procedure (0 – 10 minutes) was applied for the verification of the upper limit of

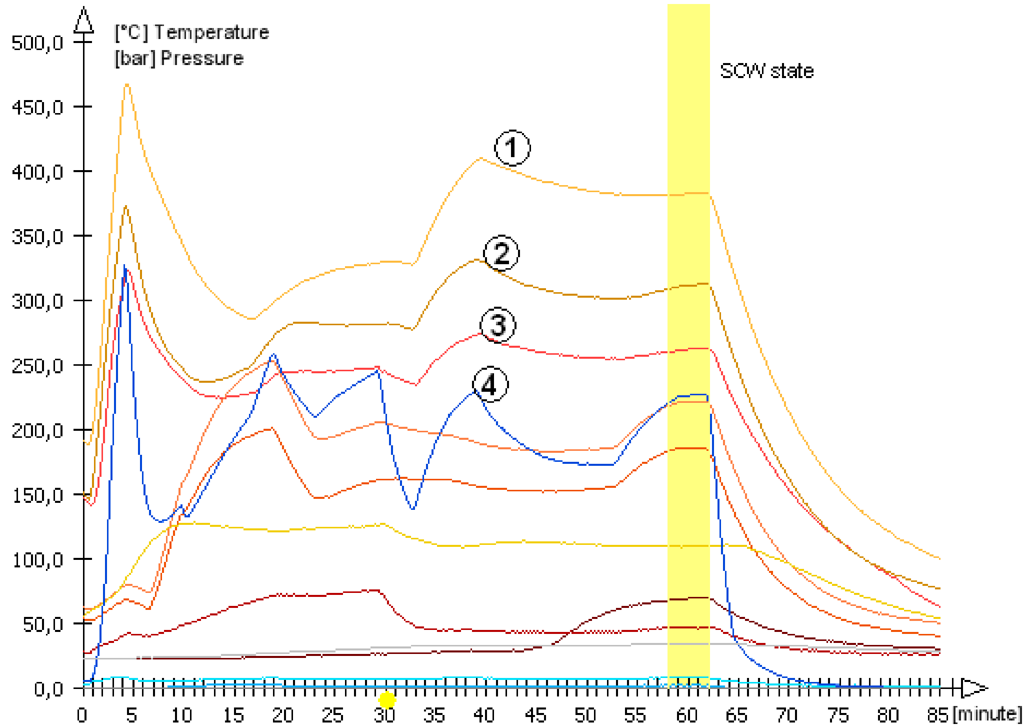

Fig. 4. Simplified parameters of the measurement process

the temperature and the pressure (450 °C and 30 MPa). It was success as it is visualized in Fig.4. which is contained of a simplified version of the original registered parameters. The running time of the measurement is written on the horizontal coordinate in minutes. The temperature and the pressure are written by the vertical coordinate in °C and bars with nominally same values. The highest curve (1) is described by the temperature of H_4 on the middle part, the next (2) is in down stream the temperature of H_3 on the middle part, the next (3) is in down stream the temperature of H_2 on the middle part, the next (4) is in down stream the pressure on the AP2. The further curves are negligible now. The heating power was changed between 1,1 and 1,9 kW. The SCW state was stabilized between 58 and 63 minutes.

It should be noted that the sensors of the pressure measurements are covered by a high thickness complex, sandwich style biological shielding (boron-carbide, cadmium and lead) against the damage of the high level scattered radiation. Regarding the reduced territory of our interest (because the dimension of hot leg is limited – only a vertical tube) the neutron beam was reduced by an additive complex shielding also.

The whole procedure was recorded on S-VHS video and on DVD. Simultaneously the temperatures, absolute and differential pressure values, the mass flow rate, heating powers were registered together in an in-house developed data acquisition software.

The measurements on the ANCARA loop has been just started. That is why some preliminary results can only be seen in Fig. 5. – Fig. 8. The Fig.5. shows the DNR picture of the upper part of the hot leg at the middle of H_4 heating element on room temperature. The light intensity on the line between the two yellow crosses (shown on Fig. 5. and 7) can be seen on Fig. 6. The light intensity was analysed by a QUANTEL CRYSTAL SAPPHIRE type picture analyzer. When the temperature of the water on 25 °C in the Fig. 6. a little valley is observable between the two walls of the tube of the hot leg. The right curve is written by the little gap of the complex shielding elements (Cd and Pb).

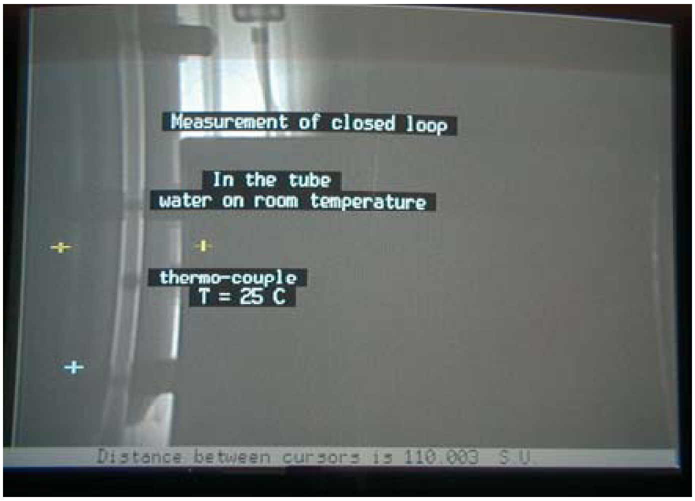

Fig. 5. DNR picture of the upper part of the hot leg at the middle of H_4 heating element on room temperature. The two yellow cross indicates the post process line shown Fig. 6.

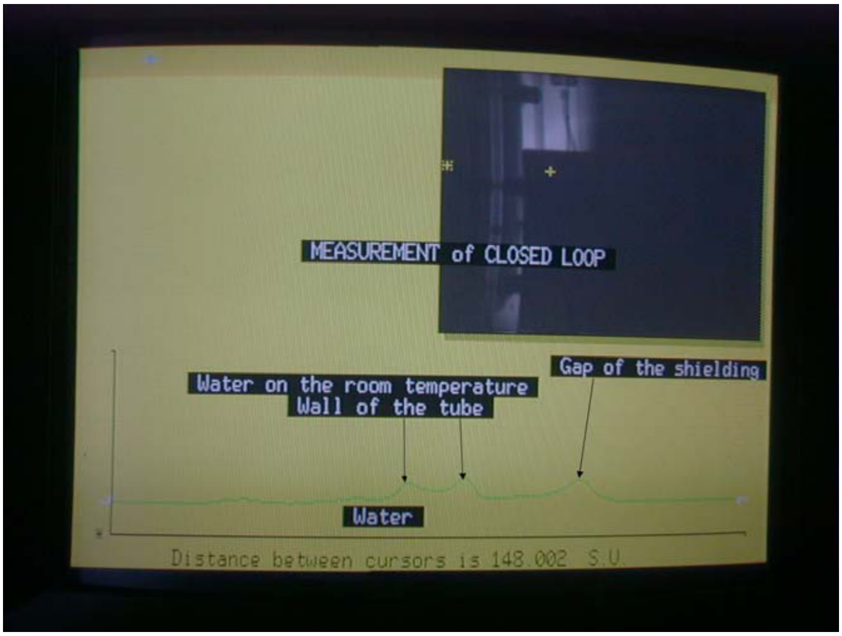

Fig. 6.: The light intensity between the yellow crosses shown Fig. 5 on room temperature

Latter when the temperature and the pressure increased above the critical values (374 °C and 22,1 MPa) of the water the closed loop extended its dimensions the hot leg moved away to left direction a little as it is visible on the DNR picture in Fig.7. The distribution of the light between the two crosses is visible in Fig. 8. The deep of the valley between the wall of the hot leg reduced its deep. It is meaning the SCW density is lower then the water on room temperature. The amplitude of the right curve is increased by the dilatation motion of the hot leg, because the gap became wider then previously.

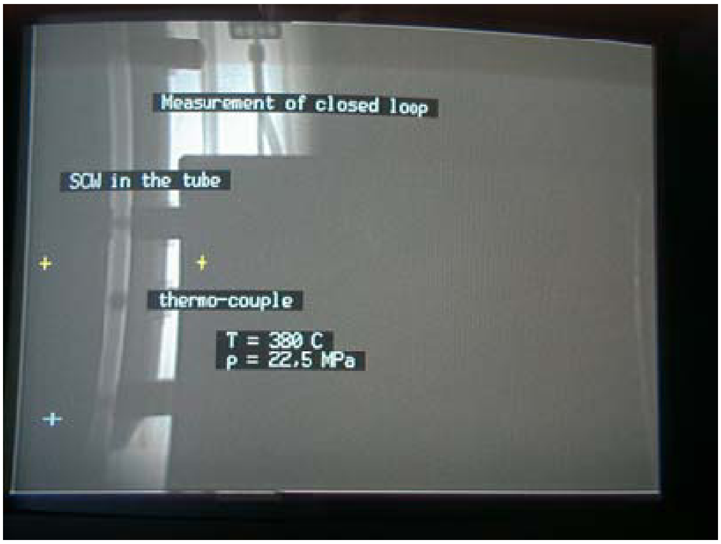

Fig. 7. DNR picture of the upper part of the hot leg at the middle of H_4 heating element on SCW state.

The two yellow cross indicates the post process line shown Fig. 8.

Finally we have to mention some difficulties of this work. When the closed loop was produced we had to make some compromises. The limited motion capability of the remote controlled moving mechanism for DRS hindered to use the optimal exposure position of DNR. We were not able to apply the shaft of the neutron beam as the central of the hot leg. We had to use the left part of the beam as you could see in Fig.5 and Fig. 7. These effects are visible in Fig.6 and Fig. 8. because the peaks of the wall of the tube are not symmetric. By the way this effect made the barrel form distortion of the hot leg in the Fig. 6 and Fig. 8. but it is not so bad for the evaluation work. We will modify the structure of the remote controlled moving mechanism.

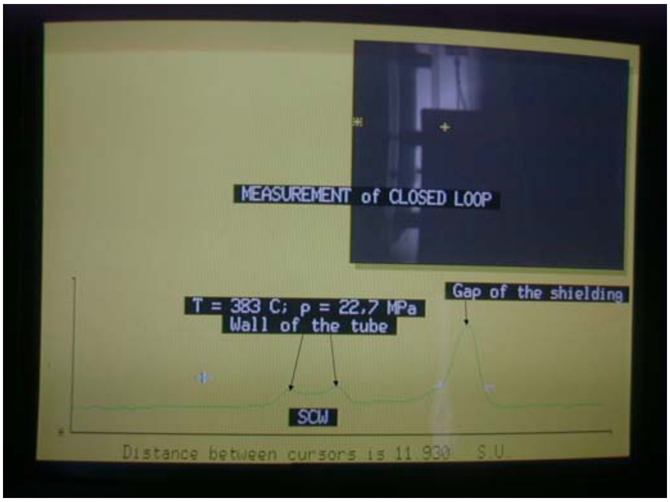

Fig. 8. The light intensity between the yellow crosses shown Fig. 7. on SCW state

6. Conclusions

Description of the design of the ANCARA natural circulation loop and some preliminary results have been presented in this paper. The detailed investigation for the thermal hydraulics of the natural circulation flow of SCW has now been enabled. The temperature- and pressure tests of the loop were success. We will develop more details of the arrangement of the measurement for the better effect of the SCW.

Acknowledgements

This project was partly supported by the New Hungarian Development Plan (Project ID: TÁMOP-4.2.2.B-10/1--2010-0009). This work was supported by NUKENERG project which was funded by National Innovation Office (2006-2012) also.

References

[1] M. Bazargan, and M. Mohseni, Algebraic Zero-Equation versus Complex Two-Equation Turbulence Modeling in Supercritical Fluid Flows, *An International Journal of Computers and Fluids*, Accepted manuscript on 22 February, (2012).

[2] M.E. Shitsman, Impairment of the heat transmission at supercritical pressures, *High Temperatures*, Vol. 1, pp. 237-244 (1963).

[3] H. S. Swenson, J. R. Carver, C. R. Kakarala, Heat Transfer to Supercritical Water in Smooth-Bore Tubes, *Journal of Heat Transfer*, Vol. 87, pp. 477-484 (1965).

[4] J.W. Ackerman, Pseudoboiling heat transfer to supercritical pressure water in smooth and ribbed tubes, *J. Heat Transfer, Trans.ASME92 (3)*, pp. 490–498 (Paper No. 69-WA/HT-2, pp. 1–8) (1970).

[5] A.P. Ornatskij, L.F. Glushchenko and S.I. Kalachev, Heat Transfer with Rising and Falling Flows of Water in Tubes of Small Diameter at Supercritical Pressures, *Thermal Engineering*, Vol. 18(5), pp. 137-141 (1971).

[6] K. Yamagata, K. Nishikawa, S. Hasegawa, T. Fujii, S. Yoshida, Forced Convective Heat Transfer to Supercritical Water Flowing in Tubes, *International Journal of Heat and Mass Transfer*, Vol. 15, pp. 2575-2593 (1972).

[7] J. D. Jackson and J. Fewster, Forced convection data for supercritical pressure fluids, *HTFS* 21540 (1975).

[8] Y. Oka, and S. Koshizuka, Conceptual Design of a Supercritical-pressure Direct-cycle Light Water Reactor, *Nuclear Technology*, Vol. 103, Iss. 3, pp. 295-302 (1993).

[9] U.S. DOE, A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, *Issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum*, December (2002).

[10] K. Ehrlich, J. Konys, L. Heikinheimo, Materials for High Performance Light Water Reactors, *Journal of Nuclear Materials*, Vol. 327, Iss. 2-3, 1 May, pp. 140-147 (2004).

[11] B. Zappoli, Influence of Convection on the Piston Effect, *International Journal of Thermophysics*, Vol. 19, pp. 803-817 (1998).

[12] W. H. McAdams et al., Heat Transfer to Superheated Steam at High Pressure, *TRANS. ASME*, Vol. 72, pp. 421-428 (1950).

[13] I. L. Pioro, R. B. Duffey, Experimental heat transfer in supercritical water flowing inside channels (survey), *Nuclear Engineering and Design*, Vol. 235, pp. 2407-2430 (2005).

[14] M. Balaskó, L. Horváth, Á. Horváth and P. Tóth, Study of the behavior of supercritical water by Dynamic Neutron Radiography, *Proceedings of 4th International Symposium on Supercritical Water-Cooled Reactors*, March 8-11, 2009, Heidelberg, Germany, Paper No. 01#.

[15] M. Balaskó, L. Horváth, Á. Horváth, P. Tóth, B. Schillinger and M. Mühlbauer, Comparison of the special properties of supercritical water by thermal – and cold dynamic neutron radiography, *Proceedings of The 5th Int. Sym. SCWR (ISSCWR-5)*, Vancouver, British Columbia, Canada, March 13-16, 2011, Submission number: 30.

[16] A. Kiss, E. Laurien, A. Aszódi, Y. Zhu, Numerical simulation on a HPLWR fuel assembly flow with one revolution of wrapped wire spacers, *Kerntechnik*, 2010/04, Page 148-157.

[17] Zhang, G., et al., Experimental and numerical investigation of turbulent convective heat transfer deterioration of supercritical water in vertical tube. *Nucl. Eng. Des.* (2012), http://dx.doi.org/10.1016/j.nucengdes.2012.03.026

[18] A. Kiss, A. Aszódi, Summary for Three Different Validation Cases of Coolant Flow in Supercritical Water Test Sections with the CFD Code ANSYS CFX 11.0, *Nuclear Technology*, Volume 170, Number 1, Pages 40-53, April 2010.

[19] M. Sharmaa, D.S. Pilkhwala, P.K. Vijayana, D. Sahaa, R.K. Sinhab, Steady state and linear stability analysis of a supercritical water natural circulation loop, *Nuclear Engineering and Design,* 240 (2010) 588–597.

[20] V. Chatoorgoon ∗, A. Voodi, D. Fraser, The stability boundary for supercritical flow in natural convection loops Part I: H2O studies, *Nuclear Engineering and Design*, 235 (2005) 2570–2580.

[21] M. Balaskó, L. Horváth, Á. Horváth, L. Kammel, P. Tóth, G. Endrőczi, „Investigation of the behaviour of supercritical water in the model of 4th generation nuclear reactor by combined nde methods"EUR 23356 EN- 2008, 441- 448,Proc. Sixth International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components,8-10 October 2007, Budapest, Hungary, EUR 23356 EN- 2008, pp 441-448.

[22] M.C. Bellisent-Funnel, "The structure of supercritical heavy water as studied by neutron diffraction", J.Chem.Phys.,107(8) (1997) pp 2942-2949.

[23] M.Balaskó, L. Horváth, Á. Horváth, P. Tóth, Study of the behaviorof super critical water by dynamic neutron radiography, Nucl. Instr. and Methods Phys. Res. A 605 (2009) 138-141 pp.

[24] Takami, S., Sugioka, K-I., Tsukada, T., Adschihiri, T., Takenaka, N., Saito,Y. „Neutron radiography on tubular flow reactor for hydrothermal synthesis: In situ monitoring behavior of supercritical water and room temperature water", Journal of Supercritical Fluids, volume 63, issue , year 2012, pp. 46 - 51