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Validation of RELAP5 model of experimental test rig simulating the natural convection in MTR research reactors

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التحقق من صلاحية نموذج ريلاب–5 لجهاز تجريبى يماثل دائرة الحمل الحرارى الطبيعى فى مفاعلات إختبار المواد

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فى محاولة لفهم تطور الحمل الحرارى الطبيعى فى مفاعلات إختبار المواد ذات السريان الصاعد بعد فقدان مصدر الكهرباء فقد تم بناء جهاز تجريبى يماثل دائرة التبريد بالحمل الحرارى الطبيعى فى هذا النوع من المفاعلات. فى هذا الجهاز التجريبى تم تمثيل قلب المفاعل بقناتي تبريد لهما مقطع مستطيل ويحيط بكل منهما سخان كهربى يمكن التحكم فى قدرته الكهربية. هذه القنوات مزودة بوسيلة لقياس توزيع درجات الحرارة فى كل من سائل التبريد وأسطح التسخين. هذه القياسات التجريبية تم نشرها بمعرفة الثلاثة مؤلفين الأوائل.

إستكمالا للدراسة التجريبية فإن هذه الورقة تقدم دراسة تحليلية للسلوك الهيدروحرارى للجهاز التجريبى بإستخدام الكود الحسابى المعروف بإسم ريلاب–5. هذه الدراسة مكونة من جزئين: الجزء الأول يدرس مدى صلاحية نموذج ريلاب–5فى محاكاة السلوك الهيدروحرارى من خلال مقارنة نتائج ريلاب–5 مع القياسات

التجريبية، والجزء الثانى يقدم نتائج ريلاب–5 لبعض البارامترات الأخرى التى لم تقاس فى التجارب العملية.

أوضحت النتائج أنه على الرغم من الضعط المنخفض الذى تمت عنده التجارب، وهو الضغط الجوى، إلا أنه يوجد توافق نوعى بين نتائج ريلاب–5 والقياسات الحرارية للجهاز التجريبى وخاصة تلك المتعلقة بإنعكاس سريان سائل التبريد فى القناة ذات القدرة الأقل ومايصاحبها من إرتفاع فى درجة حرارة سطح التسخين. على الناحية الأخرى فإنه يوجد إختلاف كمى بين نتائج ريلاب–5 وتلك المقاسة وضح ذلك فى تدنى قيم ريلاب–5 الخاصة بدرجة الحرارة القصوى لسطح التسخين عن تلك المقاسة. هذا الإختلاف يرجع إلى عدة أسباب منها أن درجات الحرارة المقاسة هى لخط التماثل داخل جدار القناه وليست للسطح، عدم اليقين من الحالة الأولية التى بدأت منها التجارب، وكذلك حزمة المعادلات المستخدمة داخل ريلاب–5 فى حساب معامل إنتقال الحرارة والتى تناسب الضغوط العالية أكثر مما تناسب الضغوط المنخفضة.

Abstract

In an attempt to understand the buildup of natural circulation in MTR pool type upward flow research reactors after loss of power, an experimental test rig was built to simulate the loop of natural circulation in MTR reactors. In this test rig the reactor core is simulated by two electrically heated, rectangular parallel channels. The channel's coolant and surface temperature at different operating conditions were measured. The measurements and their interpretation were published by the first three authors.

In the present article the thermal hydraulic behavior of the test rig is complemented by theoretical analysis using RELAP5 system code. The analysis consisting of two parts; in the first part RELAP5 model is validated against the experimental measurements and in the second part the other non-measured hydraulic parameters are presented and analyzed.

In spite of the low pressure of the test rig, the results show that RELAP5 Mode 3.3 qualitatively predicts the thermal hydraulic behaviour and the accompanied phenomenon of flow inversion in such facilities. Quantitatively, there is a difference between the predicted and measured values especially the surface temperature of channel's wall. This difference may be return to the uncertainties in initial conditions of experimental runs, the position of the thermocouples which buried inside the heat structure, and the heat transfer package in RELAP5.

Introduction

The design goals of research reactors involve sufficient margins against critical phenomena such as the critical heat flux and the flow instability in addition to not critical but undesirable phenomena such as the onset of nucleate boiling and the flow inversion. Therefore, an analysis for the reactor safety covering all operational and accident conditions is usually prepared in the design phase. The codes used in safety analysis especially for nuclear power reactors underwent a rigorous process of validation and verification [1]. Some of these codes, such as RELAP5, are extended to cover the low pressure installations such as research reactors [2-8]. Such codes still require more applications on such low pressure facilities for the purpose of their validation.

This paper is the second part of a study handled the flow inversion in upward flow MTR pool type research reactors immediately after pump coast down. In the first part, an experimental work consisting of built up of a test rig simulating the cooling loop after pump coast down aims to study the effect of environmental and operating conditions on the buildup of core natural convection [9]. The present paper complements the first one and introduces theoretical simulation and analysis for the test rig with using RELAP5 MOD3.3 thermal hydraulic system code. The analysis consisting of two parts; in the first part RELAP5 model is validated against the measured values and in the second part the other didn't measured hydraulic parameters are predicted and analyzed.

Reference reactor

The reference reactor is an MTR plate type fuel upward flow research reactor. During normal operation the core is cooled by forced circulation loop and after shutdown or at low reactor power the core is cooled by natural circulation. The new designs of such reactors use upward flow core cooling to avoid the flow inversion after pump coast down which present in downward flow designs. In addition, some engineering safety features are implemented to improve the reactor safety such as install of long chimney above the core and raise the position of the natural convection valves. The schematic diagram of core cooling system during the different cooling modes is shown in Figure 1. The main reactor data are tabulated in Table 1.

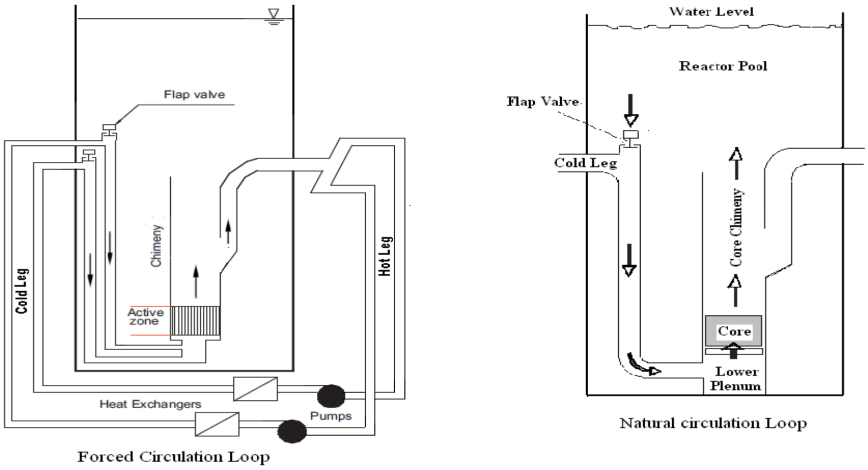


Fig 1. The cooling loops during the forced and natural regimes

Table (1) Reference MTR Research Reactor data

Property	Value	Property	Value
Core nominal power (MW)	22	Chimney height (m)	3.55
Channel flow width (cm)	7.0	Flapper valve level (m)	5.8
Channel heated width (cm)	6.40	Core inlet temperature (^{o}C)	40.0
Channel thickness (cm)	0.27	Core outlet temperature (^{o}C)	50.0
Core active length (cm)	80.0		
Pool height (m)	10.4		

The phenomenon under study

By looking to Fig. 1, after loss off electrical power, the secondary side lost, the reactor is shutting down and the core flow decayes according to the inertia of pump flyweel up to the opening of the natural connvection valve. At the opening time, the cold leg is full of hot water coming from the hot leg, where the secondary side lost, and the core is full of cold water coming from the cold leg. Under this condition the core natural convection starts to build up to remove the decay heat from the core. As seen from the right part of Fig. 1, the core natural convection may be start downward or upward according to the coolant temperature in each of the core and cold leg sides.

Test rig and experimenta runs description

The above mentioned phenomenon has been studied experimentally with a test rig constructed in the Thermal Hydraulic Laboratory at the Egyptian Nuclear and Radiological Regulatory Authority. As shown in Fig. 2, It consists of a vertically oriented test section (1) consists of two electrically heated rectangular channels made from stainless steel plates, 2 mm in thickness, extended between upper and lower plenums. The channel's cross section is 7.0 x 0.4 cm^2 and 85 cm acive length. The upper plenum is connected to a refrigerant coold water tank (4) through a vertical pipe (15) simulating the core chimeny. The lower plenum is connected to electrically heated water tank (5) through a vertical pipe (9) simulating the core return pipe. Many copper-constantan thermocouples are axially distributed on the coolant channels and its heating walls.

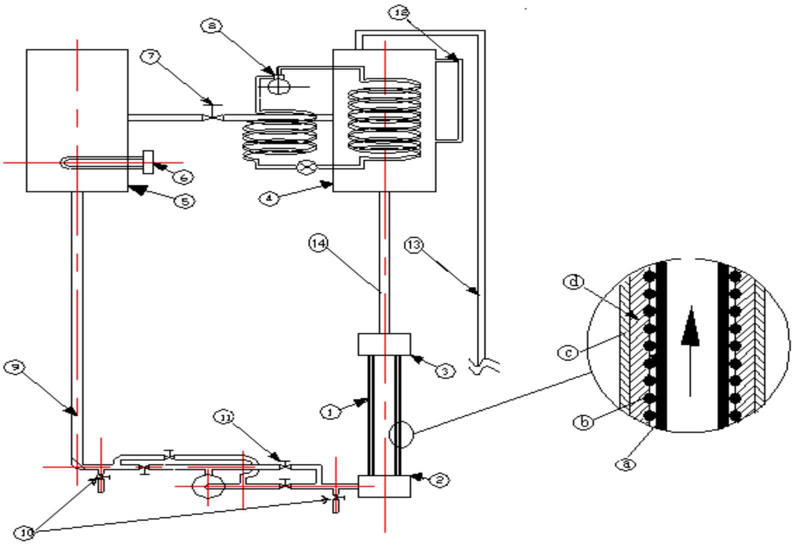


Figure 2. Schematic diagram of test rig

1- Test Section
  a) Channel wall
  b) Electric heater
  c) Insulation
  d) Cover
2- Lower plenum
3-Upper plenum
4- Cold tank
5- Hot tank
6- Electrical heater
7- Valve
8- Cooling circuit
9-Hot left pipe
10- Drain
11- Valve
12- Water level indicator
13- Water supply
14- Cold right pipe

Three growps of experimental runs are performed, in each growp only one of key parameters is changed; the key parameters are channel's power, left coulmn temperature, and right coulmn temperature. In each run, the channel's coolant and wall axial temperature distribution are measured and recorded on a PC computer through a data acquisition system. One of these experimental groups is used in the present study for code validation. This group consisting of four runs at left coulmn temperature of 283, 293, 303, and 313 K. The other key parameters are constant at; channel's power 1000 and 500 Watts and the right column temperature 323 K.

Brief discription of the experimental runs

Before the beginning of an experimental run a preparation procedure is implemented to nearly create a situation similar to that encountered in the reference reactor during the loss off power. Intially, the temperatures in tanks 4 and 5, Figure 2 is adjusted at a prescriped value. The drain valves 10 are opend to fill the left and right column with water at the prescriped temperature and then closed. The channel's heaters are started for nearly 15 minuts befor opening the manual valve 11 to start the experimental run. Each run continues for nearly 300 second. After nearly 250 second from the initiation of the run, the channel's heater power is manually decreased gradually untill stoped at the end of the run. All of these conditions are considered in RELAP5 simulation.

Test rig nodalization

For the purpose of RELAP5 calculations, the nodalization shown in Fig. 3 and the accompanied input deck are used to accurately simulate the test rig. The test section is represented by two vertical pipes 104 and 114, each one accompanied with a heated structure 800 and 900 respectively. The lower and upper plenums are represented by two branches 100 and 120. The left column is represented by a branch 250 connected to a vertical pipe 260. The right column is represented by a branch 150 and a vertical pipe 130.Different pipe sections intervened with globe valves 310 and 330 connects the lower branch 100 with pipe 260. The time dependent volumes 195 and 295 represent the boundary conditions. The initial conditions of each component are put accurately as possible in the experimental runs.

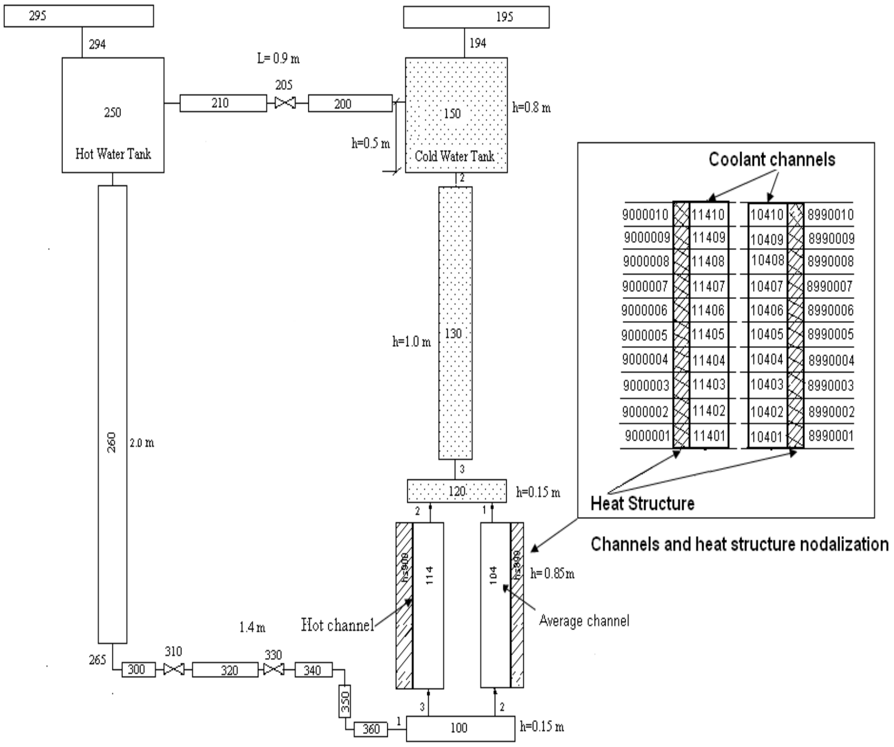


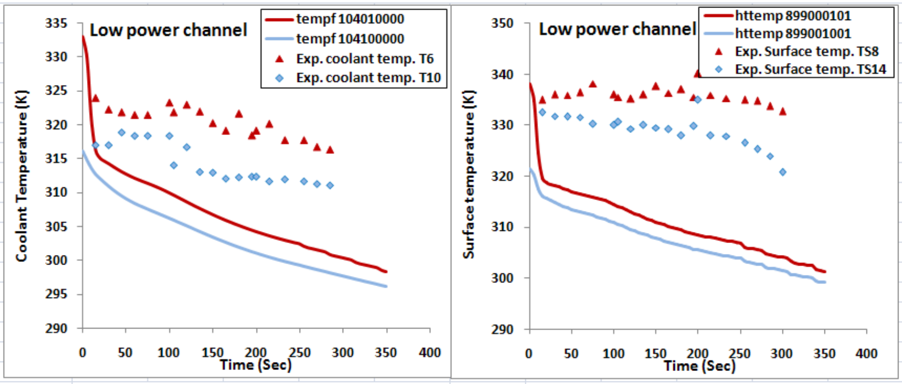
Fig. 3 Test rig nodalization

The results displayed her consisting of two sections. In the first section, comparison between RELAP5 results and the experimental measurements is introduced. In the second section, RELAP5 results of the unmeasured parameters such as the flow rates through the channels are introduced.

Model validation and nodalization qualification.

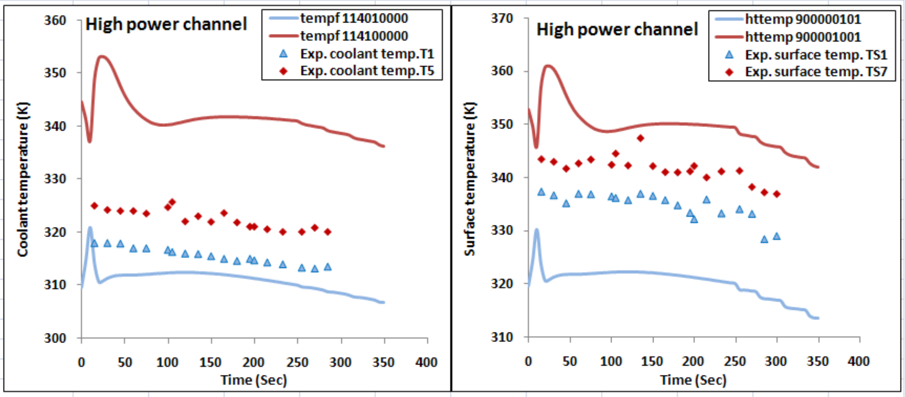
The experimental runs mentioned previously are simulated using RELAP5 and the results are compared with the corresponding measured values as shown in Figures 4-7. To avoid the complexity in the figures, the comparison is focused on the temperature changes at the lower and upper ends of the channels. Therefore, the measurements of channel's coolant temperatures at lower and upper ends are T_1-T_5 and T_6-T_{10} of low and high power channels respectively. The corresponding measurements of channel's wall surface temperatures are T_{S1}-T_{S6} and T_{S7}-T_{S14}. The code runs start with channel's heaters on and the control valve 310 off for nearly 900 second, after that the control valve is opened during the remained runs time (350 second). The total runs time is 1250 seconds. The zero time appears on the figures corresponding to the moment at which the control valve 310 is opened; the other valves are normally open.

Figures 4 and 5, show the channels coolant and surface temperatures at their lower and upper ends for right column temperatures of 283 and 293 K respectively. Generally there is a difference in the temperature values predicted by RELAP5, continuous lines, and the experimental measurements, dots shape. On the other hand, from of coolant temperature, it is obvious that there is an agreement between RELAP5 and the measurements regarding the direction of flow as downward flow in the low power channel (LPC) and upward flow in the high power channel (HPC), where the coolant temperature at the lower end is higher than that at the upper end of LPC and the vice versa in HPC.



(a) LPC coolant temperature

(b) LPC surface temperature

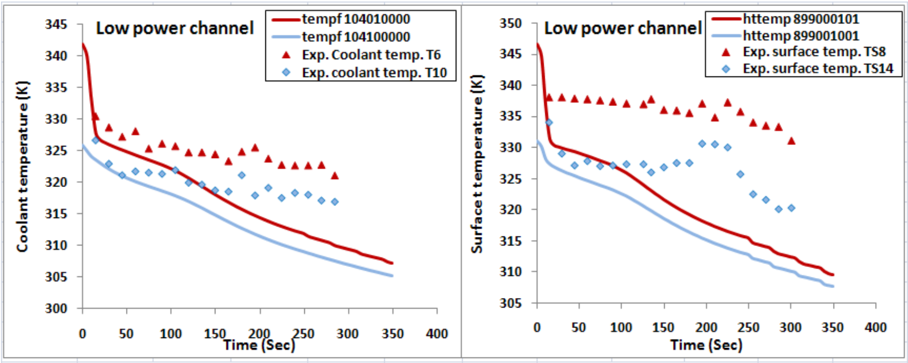


(c) HPC coolant temperature

(d) HPC surface temperature

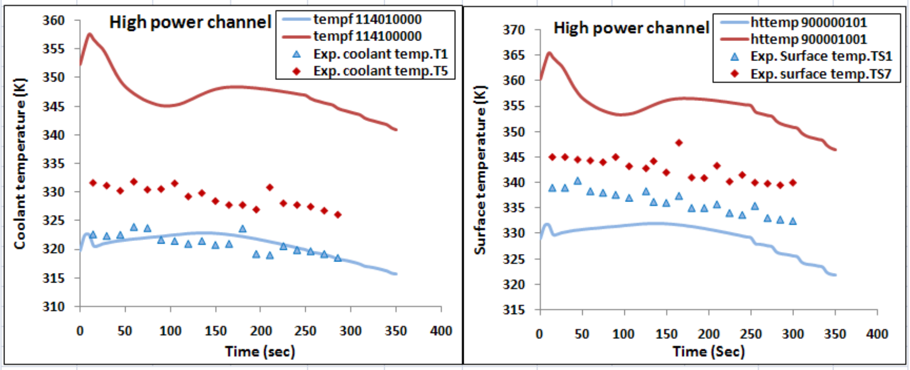
Figure 4, Comparison between RELAP5 and experimental measurements of coolant and surface temperatures at inlet and outlet of high and low power channels for right column temperature of 283 K

Also, the same behaviour appears on the wall's surface temperature in the two channels. The deviation between the RELAP5 results and experimental measurements decreased with increasing the right column temperature, especially in the low power channel, as shown in Figure 5.



(a) LPC coolant temperature

(b) LPC surface temperature

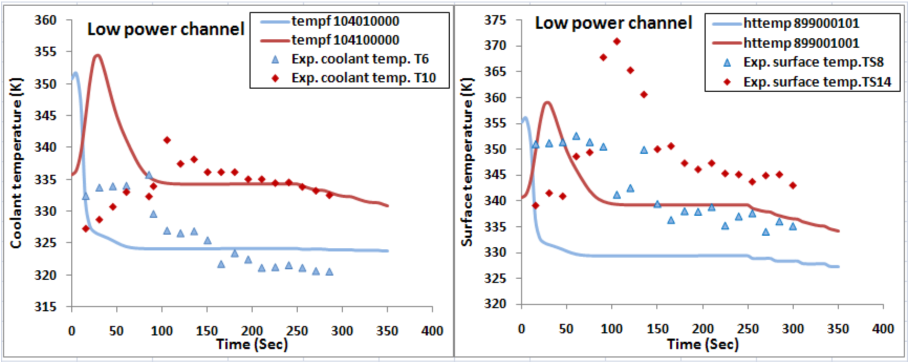


(c) HPC coolant temperature

(d) HPC surface temperature

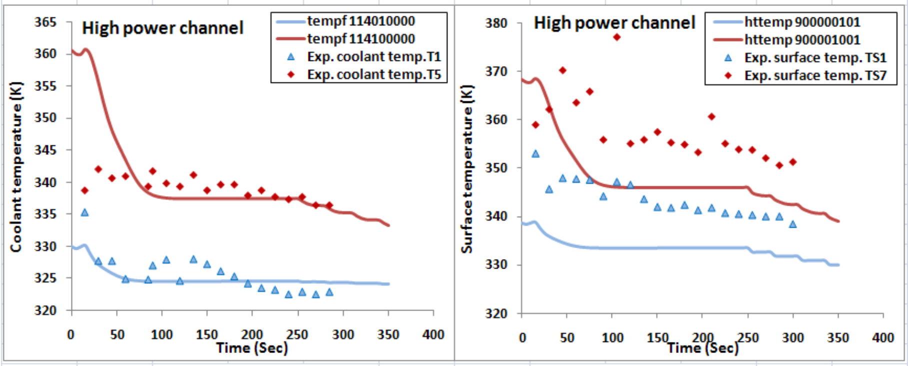
Figure 5, Comparison between RELAP5 and experimental measurements of coolant and surface temperatures at inlet and outlet of high and low power channels for right column temperature of 293 K

Figure 6 shows the comparison at right column temperature of 303. There are three observations on the results. Firstly, RELAP5 predicts the occurrence of flow inversion in low power channel, in agreement with the experimental measurements. This inversion appears in inverse of coolant temperature at the upper and lower ends of LPC. Secondly, RELAP5 predicts the increase in coolant and surface temperature accompanying that inversion, in agreement with the experimental measurements, in spite of the over predictions in the maximum coolant temperature and the under prediction in the maximum surface temperature. This may be returns to the heat transfer package in RELAP5 or to the position of the thermocouples which are embedded into the walls. Thirdly, the predicted surface temperature in HPC does not affected by the flow inversion in LPC in disagreement with the measurements.



(a) LPC coolant temperature

(b) LPC surface temperature

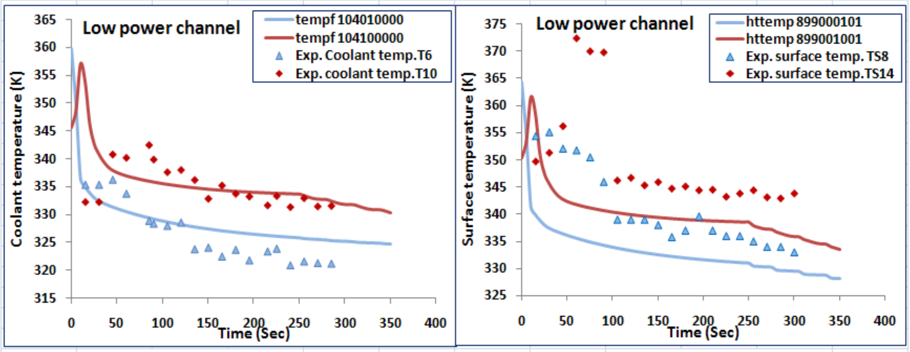


(c) HPC coolant temperature

(d) HPC surface temperature

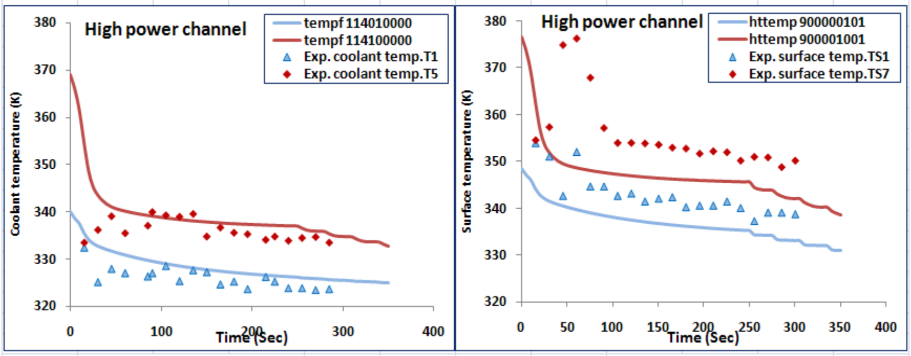
Figure 6, Comparison between RELAP5 and experimental measurements of coolant and surface temperatures at inlet and outlet of high and low power channels for right column temperature of 303 K

At right column temperature of 313 K, Figure 7, the results show nearly the same qualitative behaviour likes that at 303 K but the deviation between the measured and predicted values decreased. The flow inversion in low power channel occurs earlier than that at 303 K. Also, the effect of flow inversion on the HPC which appears in the measurements as increase in its surface temperature, does not predicted in the RELAP5 results.



(a) LPC coolant temperature

(b) LPC surface temperature



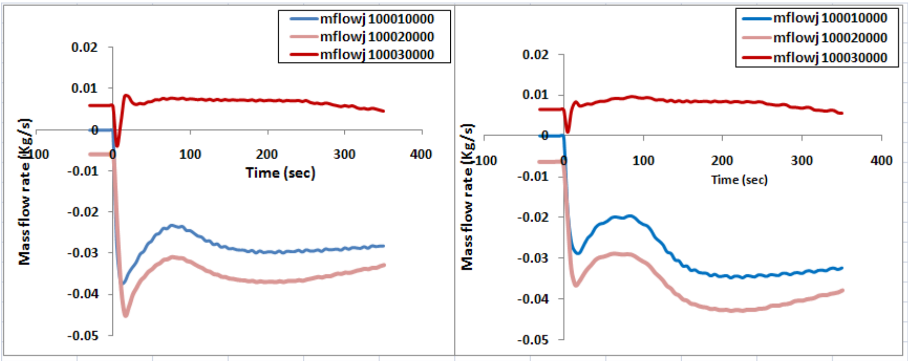
(c) HPC coolant temperature

(d) HPC surface temperature

Figure 7, Comparison between RELAP5 and experimental measurements of coolant and surface temperatures at inlet and outlet of high and low power channels for right column temperature of 313 K

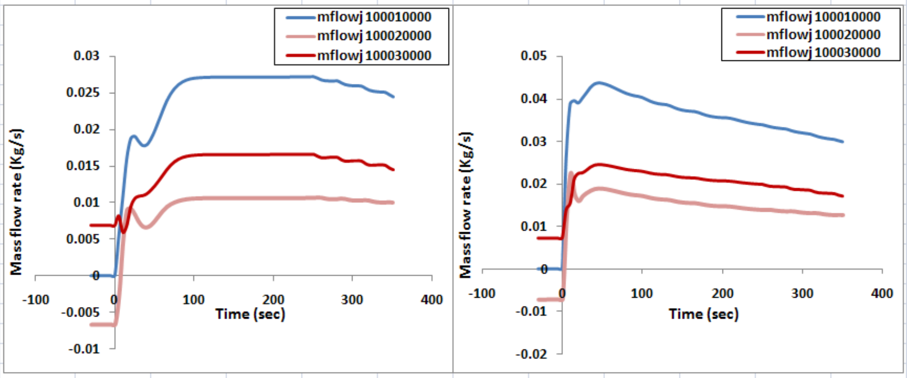
Other analytical results

One of the important parameters which cannot be measured but assist in understanding the thermal hydraulic behaviour of the test rig is the coolant flow rate. Figure 8 shows the flow rate in the three junctions connected to branch 100 at right column temperatures of 283, 293, 303 and 313 K. These junctions are 100010000, 100020000, and 100030000 which connected to the left column, LPC and HPC respectively. They summarize the flow rates in the different parts of the test rig. Time zero in the figures is the opening time of control valve 310. Figure 8 (a), shows the results at right column temperature of 283 K. Before 0.0 s, the flow in HPC or junction 100030000 is upward, in LPC or junction 100020000 is downward, and in left column or junction 100010000 is zero. This means that before opening valve 310 there is a natural circulation loop between the two channels, referred to an internal circulation loop. After opening of valve 310, another circulation loop is created between the left and right columns, referred to an external circulation loop. This loop enhances the downward flow in the LPC without significant effect on the HPC. This means, the heating rate in HPC is sufficiently enough to create internal bouncy forces contradict the driving force in the external circulation loop. This behaviour persists at right column temperature of 293 K as illustrated in Fig. 8 (b).



(a) right column temp. (283 K)

(b) right column temp. (293 K)



(c) right column temp. (303 K)

(d) right column temp. (313 K)

Figure 8, The mass flow rate in left branch, low power channel, and high power channel at different right column temperature

At right column temperature of 303 K, Figure 8(c), there is a different behaviour. After the opening of valve 310, the flow in the two channels becomes upward, i.e. the heating rate in LPC can convert its flow direction from downward to upward. This means that only one natural circulation loop exists, the external loop, and the flow rate in junction 100010000, equals to sum of the mass flow rate in the two channels. This behaviour also appears at right column temperature of 313 K, Fig. 8 (d).

Conclusion

In spit of the low operating pressure of the test rig, the results show that RELAP5 Mode 3.3 qualitatively predicts the thermal hydraulic behaviour and the accompanied phenomenon of flow inversion. Quantitatively, there is a difference between the predicted and measured values especially the heat structure surface temperature. This difference may be returns to uncertainties in the initial conditions of the experimental runs and on the other side to the heat transfer package in RELAP5.

References

1. A. Alessandro, F. D'Auria,"Thermal-Hydraulic System Codes in Nuclear Reactor Safety and Qualification Procedures", Science and Technology of Nuclear Installations, Volume 2008, ID 460795, 2008.

2. W. L. Woodruff, N. A. Hanan, R. S. Smith, J. E. Matos," A Comparison of the PARET/ANL and RELAP5/MOD3 codes for the analysis of IAEA Benchmarke transients", Proceeding of the International Meeting on Reduced Enrichment for Research and Test Reactors, pp. 1-11, Seoul, Republic of Korea, October 7-10, 1996.

3. A. Khedr, M. Adorni, F. D'Auria," The effect of code user and boundary conditions on the RELAP calculations of MTR research reactors", Nuclear Technology & Radiation Protection, Vol. 1, pp. 16-22, 2005.

4. Gee Yang Han and KwiSeok Ha," Modifications and Assessment of RELAP5/MOD3.2 for HANARO Thermal-Hydraulic Safety Analysis," Journal of the Korean Nuclear Society, Volume (34) 5, pp. 455-467, October,2002.

5. A.R. Antariksawan, J. Zmitkova, M.Q. Huda, C.M. Allison, T. Liu, J. K. Hohorst," Validation of RELAP/SCDAPSIM/MOD3.4 for research reactor applications", 13th International Conference on Nuclear Engineering, Beijing, China, May 16-20, 2005.

6. M. Adorni, A. Bousbia-salah, F. D'Auria,"Application of Best Estimate Thermalhydraulic Codes for the Safety Analysis of Research Reactors", International Conference of Nuclear Energy For New Europe, Portorož, Slovenia, Septemper 18-21, 2006.

7. P.A.L. Reis, A.L. Costa, C. Pereira, M.A.F. Veloso, A.Z. Mesquita, H.V. Soares, G.P. Barros," Assessment of a RELAP5 model for the IPR- R1 TRIGA research reactor", Annals of Nuclear Energy, Vol. 37, pp. 1341-1350, 2010.

8. A.L. Costa, P. A. L. Reis, C. Pereira, M.A.F. Veloso, A.Z. Mesquita, H.V. Soares," Thermal hydraulic analysis of the IPR-R1 research reactor using a RELAP5 model", Nuclear Engineering and Design, Vol. 240, pp.1487-1494, 2010.

9. A. Khedr, E.A. Abdel-Hadi, K. A. Talha and S. H. Abdel-Latif, "Experimental Study of flow inversion in MTR upward flow research reactors", PP 226-236, KERNTECHNIK 79 (2014) 3.

10. Salah El-Din El-Morshedy, "Prediction, analysis and solution of the flow inversion phenomenon in a typical MTR-reactor with upward core cooling". Nuclear Engineering and Design, Vol. 241, pp 226-235, 2011.

11. H. A. Khater, K. A. Talha, A. M. El-Fara," Experimental Validation of a Thermal Hydraulic Model for ETRR-2 During Loss of Off Site Power," 12th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Pennsylvania, Sep. 30-Oct. 4, 2007.