Experimental Study of MTR Core Cooling after Pump Coast-Down
In MTR pool Type Research Reactors

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ABSTRACT

This study presents experimental investigations on core cooling of MTR pool type research reactor at later stages of pump coast down. The study aims to clarify the effect of the reactor pool temperature on the core cooling during these stages. Test rig is designed and built to simulate the MTR core cooling loop at later stages of pump coast down and after the opening of the natural convection valve. The core is simulated as two channels, one represents the core hottest channel and the other represents the average or less power channel. Each channel consists of two aluminum plates heated by electrical heater uniformly distributed on the plate’s outer surfaces. Due to the expected shallow core flow at later stages of Pump coast down, the analysis is based on measuring the temperature distribution through the coolant and plate’s inner surface. The measurements are taken at different reactor pool and return pipe temperatures. Also some measurements are taken at different channel powers. The experimental results show that at this stage of shallow flow the flow direction in the core channels depends on the reactor pool and return pipe temperature. Sometimes an upward flow is established in the two channels and in others the flow is upward in hot channel and downward in colder channel. Also, for power ratios \( P_{av}/P_{hot} \) less than one, the inner circulation between the channels is more susceptible in spite of the high temperature difference between the reactor pool and return pipe temperature. In addition, the comparison with the theoretical results shows that there is a good agreement between RELAP5 results and the obtained experimental results.

Key Words: Research Reactors/Thermal Hydraulic/Flow Inversion/Natural Convection

INTRODUCTION

One of the engineering safety futures in the new designs of research reactors is the High Level of Penetration Points (HLPP) of cold and hot legs to the reactor pool with respect to the core level. This safety future was considered to avoid the core uncover during the loss of coolant accidents and also to enhance the buildup of natural circulation after reactor shutdown. In MTR pool type upward core cooling Research Reactors (RRs) this future creates a situation in which two long vertical columns of coolant at different temperatures are connected to the core, as shown in Fig. (1). This situation has a great effect on the build up of the natural circulation after pump coast down. Basically, the upward forced circulation core cooling is used in RRs to avoid the flow inversion which accompany downward core cooling reactors after shutdown. In downward core cooling reactors, the flow reversal or flow inversion usually occurs after a period of nearly zero core flow, where the buoyancy force becomes high enough to invert the core flow and establish the upward natural circulation \cite{1}. In upward flow reactors, the flow reversal does not normally occurs but if it happens it will usually lasts for a limited period and re-reverse its direction to upward flow, i.e. there is a double
inversion. This second inversion requires more heating for core contents (coolant and fuel). Therefore this phenomenon is not desirable in the upward flow research reactors.

An example of situations in which the double inversion may occur in the upward flow reactor is the reactor scram after a short period of operation due to the loss of power supply. In this case, after the opening of the Natural Convection Valve (NCV), a long column of water above the core colder than the cold leg is established. These situations enhance the downward flow through the core before the buoyancy force becomes large enough to re-invert the core flow to upward direction again. Also create flow disturbance between the core channels, i.e., downward flow in cold channels and upward flow in hot channels.

![MTR Core Cooling](image)

**Fig. (1): MTR Core Cooling.**

The flow inversion in downward flow research reactors after pump coast down and during the build up of natural circulation is handled by many authors [2-7]. Most of these published works were focusing on the safety margin in the clad temperature and Onset of Nucleate Boiling (ONB) during the flow inversion. Due to the abnormality of flow inversion in upward flow research reactors a limited work has been handled it [8, 9].

The aim of this work is to investigate experimentally the core cooling at later stage of pump coast down and the establishment of natural circulation. At this stage, the buoyancy force has a great value in the establishment of natural circulation. Therefore, the dominant parameters considered are the coolant temperature in the core return pipe, the reactor pool temperature, and the heating power in the core. Consequently, a test rig has been built to simulate the core cooling loop during this stage. The core is represented by two rectangular channels electrically heated, one of them at high power and the other at low power. To measure the temperature distribution, a group of thermocouples are distributed along the heated plate and coolant channel length. For comparison with theoretical calculations, RELAP5 mode 2 is used to nodalize this test leg and simulate its thermal hydraulic behaviour.
THE EXPERIMENTAL TEST RIG

An experimental test rig was designed and constructed as shown in Figure (2.1). This test rig consists of a vertically oriented test section (1) simulating the reactor core. This section contains two electrically heated channels extended between upper and lower plenums. The upper plenum is connected to a cold water tank (4) through a vertical pipe (15) that simulates the core chimney. The water temperature in tank (4) is changed through a cooling circuit (8). The lower plenum of the test section is connected to hot water tank (5) through a vertical pipe (9) simulating the core return pipe. An electrical heater (6) is inserted in the tank (5) to change its temperature. To establish a closed cooling loop the two tanks are connected through a ball valve (7). The cooling channels have the same dimensions as the core channels. The dimensions of the other rig's components, especially the heights, are controlled by the laboratory heights and not typical to the corresponding RR's components.

Fig. (2.1) Schematic diagram of the test apparatus

1- Test section  
2- Lower plenum  
3- Upper plenum  
4- Cold tank (pool)  
5- Hot tank (hot leg)  
6- Electric heater  
7- Valve  
8- Cooling circuit  
9- Hot vertical pipe  
10- Drain  
11- Pump  
12- Valve  
13- Water indicator  
14- Water supply  
15- Cold vertical pipe

Fig.(2.2) Channel heating

1- Channel plate  
2- Electric Heater  
3- Insulation  
4- Cover
Measuring Devices and Instrumentation

Fourteen calibrated copper-constantan thermo-couples were used to measure the channel heated plate surface temperature, seven thermocouples per channel. The thermocouples junctions were embedded inside grooves of 0.7 mm depth created on the rear surface of the plates as shown in Figure (3). Also, ten thermocouples were used to measure the coolant temperature distribution inside the heated channels, 5 in each channel. Those thermocouples are installed inside the channels through holes created in channels side plates as shown in Fig. (4). Two additional thermocouples were installed; one in the test section upper plenum and the other in the test section lower plenum. Due to the expected shallow coolant flow rate through the rig, measuring flow rate devices are not installed.

The electric control circuit built here consists of a control panel, which has five switches, three for electrical heaters, one for Refrigeration cycle and the last for flow initiation pump. The rig instruments are connected to a fast data acquisition system thermo couple input /out put (32-channels) which allows data acquisition at time intervals reach to 1ms.
RELAP5 MODEL

For comparison with theoretical analysis, the test rig shown in Figure (2) is nodalized and a RELAP5 input deck is prepared to simulate the thermal hydraulic behaviour at the same boundary and initial conditions used in the experimental study. The typical dimensions of rig's components (heights and cross sections) are used in the preparation of RELAP5 input deck. The channels heating power is considered axially uniform.

Case 1: The effect of the pool temperature ($T_c$):

In this case, the coolant temperature in the vertical pipe (9) (Figure 2.1), denoted $T_h$, is stabilized at 50 $^\circ$C through the electric heater (6) and the drain (10). The heating power at the hot channel is adjusted and maintained twice that at the average channel. The average channel power is 500 W and the hot channel power is 1000 W, i.e. $P_h/P_a=1/2$. The temperature at the vertical pipe (15), denoted $T_c$, is changed in steps from 10 $^\circ$C to 40 $^\circ$C and at each step the channels inlet and outlet temperatures is measured. Fig. 6 shows the channels temperature difference ($D=T_{out}-T_{in}$) for four runs at $T_c$ 10, 20, 30, and 40 $^\circ$C. It is found that with increasing $T_c$ the driving force that contradict the build up of natural circulation decreases, consequently the negative temperature difference on the average channel which appears in Figs 6a & 6b changed to positive temperature difference in Figs 6c &6d. This means that the flow direction in the average channel changed from downward flow to upward flow.

Also, as $T_c$ becomes sufficiently lower than $T_h$ an internal circulation between the channels builds up with somewhat high flow rates. This interprets the smaller temperature differences in Figs 6a & 6b than those in Figs. 6c & 6d. But with increasing $T_c$, the contradicting forces decreases to values comparable with the buoyancy force. Therefore, a weak upward natural circulation build in through the channels and the test rig pipes results in an increase in the channels temperature difference shown in Figures (6c) & (6d). These figures show also that the results predicted by RELAP5 code for this case under the same initial and boundary conditions are in good agreement with the experimental results.

Case 2: The effect of core returns coolant temperature ($T_h$):

At the same channels power and constant $T_c$ equal to 20 $^\circ$C, four runs are executed at $T_h$ varying from 30 $^\circ$C to 60 $^\circ$C in equal steps of 10 $^\circ$C. This temperature range of $T_h$ is expected to occur in the cold leg of the core cooling system of a research reactor during the loss of offsite power. The measured temperature difference on each channel during these runs is shown Figure (7). At low $T_h$ the temperatures in left side still higher than but comparable with that in right side of the test rig. This condition creates weak natural circulation and results in high temperature difference on the channels, as shown if Figures (7a) & (7b). With increasing $T_h$ the density in the left side decreases more and higher opposite forces to natural circulation is created. Therefore, an inner circulation between the channels is initiated. As shown in Figures (7c) & (7d), this inner circulation builds up an upward flow in the hot channel and downward flow in the average or colder channel. Also as shown on the Figures the RELAP5 results are in good agreement with the corresponding experimental results.

Case 3: The effect of the channel's power ratio

To study the effect of power ratio on the build up of natural circulation, four runs are executed at constant $T_c$ and $T_h$. At $T_c$=20 $^\circ$C and $T_h$=50 four power ratios ($P_h/P_a$) equal to 1, 1/2, 1/3, and 1/4, are considered. The experimental results are shown in Fig. (8) and the theoretical results of RELAP5 are shown in the same figure. In Fig. 8a at power ratio equal to one, the temperature difference at the two channels is negative. This means that, the difference in coolant density between the left and right sides is sufficient to enforce the flow in the two channels in downward direction. With increasing the hot channel power or decreasing the average or colder channel power an inner circulation between the two channels is established in which an upward flow is built in the hot channel and downward flow in the colder channel. Under the conditions considered, there is no an upward natural circulation established in the two channels.
Fig. (5) RELAP5 input Nodalization.
(Fig. 6) The effect of pool temp. \(T_c\) on the channel's temp. difference at power ratio =1/2 and retrans pipe temp. \(T_h\)=50 °C
(Fig. 7) The effect of retrans pipe temp. \( T_h \) on the channel's temp. difference at power ratio = 1/2 and pool temp. \( T_c \) = 20 °C
(Fig. 8) The effect of power ratio on the channel's temp. difference at pool temp. \( T_c = 20^\circ C \) and retran pipe temp. \( T_h = 50^\circ C \)
CONCLUSIONS

An experimental test rig is built to study the establishment of natural circulation at later stages of pump coast down after opening of the natural convection valve in MTR pool type research reactors. The rig consists of a test section connected to two long pipes one simulates the core return pipe and the other simulates the core chimney. This test section simulates the reactor core and consists of two channels, one at higher power than the other. This work is focused on studying the effect of return pipe temperature, the reactor pool temperature, and the channels power on the build up of core natural circulation. Also, a theoretical analysis by RELAP5 code for the proposed cases is performed and the results are compared with the corresponding experimental results.

The experimental study shows that the configuration of the core cooling system has a great effect on the build up of core natural circulation. After reactor shutdown and after the opening of the natural convection valve, the build up of natural circulation will depend in addition to the power distribution between the channels on the reactor pool and return pipe coolant temperatures. At low reactor pool temperature and at high return coolant temperature an inner circulation between the core channels in which an upward flow in the hot channel and downward flow in the colder channels is established. This inner circulation disappears when the pool temperature moves toward the return pipe coolant temperatures. The comparison with the theoretical results predicted by RELAP5 shows that there is a good agreement between the theoretical and experimental results for all the cases considered.

NOMENCLATURE

T<sub>c</sub>  Pool temperature  °C
T<sub>h</sub>  Hot leg temperature  °C
DTh  Coolant temp. difference in the hot channel  °C
DTav  Coolant temp.difference in the average channel  °C
Relap5 Cal.  From Relap5 code calculation
Exp.  Experimental Results

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