13th International Conference on Nuclear Engineering
Beijing, China, May 16-20, 2005
ICONE13-50213

ANALYSIS OF METASTABLE REGIMES IN A PARALLEL CHANNEL SINGLE PHASE NATURAL CIRCULATION SYSTEM WITH RELAP5/ MOD 3.2

Manas Ranjan Gartia, D. S. Pilkhwal, P.K. Vijayan(*) and D. Saha
Reactor Engineering Division
Bhabha Atomic Research Centre
Trombay, Mumbai- 400 085(India)
Phone: +91-22-25595157
email: vijayanp@apsara.barc.ernet.in

Keywords: metastable regime, parallel channel systems, flow reversal

ABSTRACT

The objective of the present study is to probe the capability of RELAP5/MOD 3.2 computer code to predict the metastable regime (multiple steady state) in a parallel channel system under natural circulation. To examine the basic behavior of such a system, a three parallel channel system with non-uniform heat inputs and a common downcomer, was investigated using RELAP5/ MOD 3.2. The results showed the existence of a metastable regime below a critical heat input ratio. A Non-Dimensional Heat Flux Ratio (N_H) has been proposed to predict the flow reversal. The heat flux level at which flow reversal occurs has been predicted for different rates of power rise and power reduction (with different input heat flux). It was found that the power level at which the flow reversal occurs depends upon the operating procedures (i.e. power rise and power reduction). The flow direction in different channels will depend on the available buoyancy difference among channels and downcomer. The flow direction in a channel, where power variation is taking place, will be decided by the channel with the maximum temperature difference between the top end and bottom end.

1. INTRODUCTION

Natural circulation flows in multiple-channel systems operating with various levels of heat inputs occur in diverse applications. One of these can be found in nuclear reactors where under certain normal operating or upset conditions, natural circulation flow cools the core. Unequally heated parallel channel systems can exhibit interesting flow behaviours during natural circulation. Flow instabilities are undesirable in two-phase flow processes for several reasons. Flow oscillations can affect the local heat transfer characteristics, possibly resulting in oscillatory wall temperature, or may induce boiling crisis (Critical Heat Flux, DNB, burnout, dry out). Hence it is of particular importance to predict the metastable regime and the threshold of flow instability, so that this can be taken care of in the design. Chato (1963) studied, analytically and experimentally, the metastable regime in a three channel system with one channel heated, one channel unheated, and the third channel either heated or cooled. For this arrangement he found that two different stable flow rates can occur for a given set of channel heating rates. He has predicted the flow reversal of a heated channel from down flow to up flow while increasing power of the down flowing channel, keeping the power of the heated upward flowing channel constant. But the range of power level at which metastable regime occurs has not been clearly shown. Takeda et al. (1987) numerically and experimentally studied a system of four vertical channels with different heat generation rate. They found that a one-dimensional modeling of the channels could predict the reversal of a heated channel from downflow to upflow, but not from upflow to downflow. Yahalom et al. (1979) has suggested a downflow preference number, which says that a heated channel with the highest value of non-dimensional preference number will flow downward. Todreas et al. (1990) defined an upflow preference number. This says that in a parallel channel system in which the heated channels are in downflow, the channel with the highest upflow preference number will reverse first from downflow to upflow. Preference numbers can only tell which channels are favorable to flow reversal, but the question still remain is exactly at what power or heat absorption ratio the flow in a heated channel will reverse from upflow to downflow and downflow to upflow. Does rate of increment or decrement of power affect the power level at which flow reverses? Therefore, an analysis has been carried out to predict the metastable regime in a natural circulation system with three parallel vertical channels connected between common inlet and outlet headers and a downcomer.

In the present work, the possibility of the existence of a metastable regime has been investigated with nonuniform heat inputs with RELAP5/ MOD 3.2 computer code.

2. DESCRIPTION OF THE LOOP

The loop considered for analysis consists of three vertical channels having equal diameters (Inside diameter = 25.5 mm, Thickness = 2.7 mm) and equal lengths (5 m) along with common downcomer of same dimensions as that of the channels. These channels are connected to an inlet header (plenum), (Inside diameter = 250 mm, Thickness = 2.7 mm, Length= 964 mm) at the bottom and same size of an outlet header at the top. The channels are heated with equal power input from the outside and the downcomer is kept unheated. Equal amount of heat is assumed to be removed through a tube-in-tube cooler (Inside diameter= 150 mm, Thickness= 2.7 mm) at the top header. The schematic of the loop is shown in Fig.1.

3. MODELING AND NODALISATION SCHEME

The different components of the three parallel channel systems are modeled as pipes (control volumes) interconnected by junctions. The pipes are modeled as pipe volumes with corresponding cross-sectional flow area and lengths. The downcomer, top and bottom header are also modeled as pipe volumes. Our system is natural circulation based, which is driven by the density difference. The plenum is modeled as pipe, since the density distribution among its volumes can be accounted. Usually, the plenna are modeled as branch components (which is a single volume) in the RELAP5/MOD3.2 nodalisation scheme. Use of branch component will not give the variation of pressure in the plenna. The three parallel channels are heated with the help of appropriate heat structures. A grid independence test was performed with 3 sets of grid size i.e. 1 m, 0.1 m and 0.01 m for the heated section. In all the three cases, it was found that the results are not significantly different. Hence grid size of 1 m was used for the present analysis. The time step employed was 0.01 s. The heat transfer from the primary (shell side) to secondary (tube side) of the cooler is modeled with an appropriate heat structure. The nodalization scheme is shown in Fig. 2.

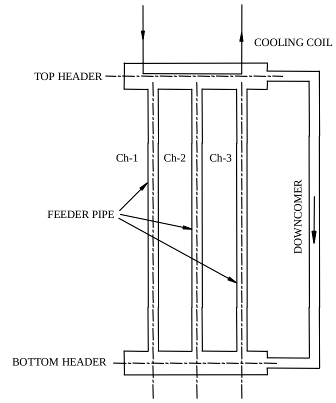


Fig.1: Schematic of the natural circulation loop

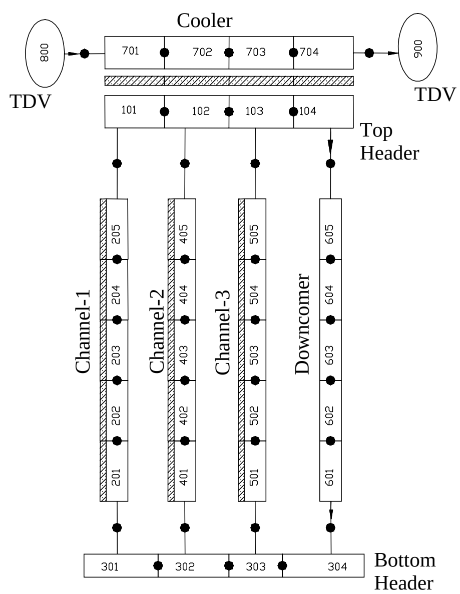


Fig.2: Nodalisation scheme for the natural circulation loop

4. INITIAL CONDITIONS

The initial conditions were corresponding to ambient pressure (1 bar) and temperature (300 ^{o}K) with zero mass flow rates. The validity of RELAP5/MOD3.2 computer code was checked for the single-phase natural circulation flow at atmospheric conditions by Kamble et al. (2002) in a rectangular loop. They found that the steady state flow rate predictions by the RELAP5/ MOD3.2 computer code are in good agreement with the experimental results.

4.1 CASES STUDIED

Four cases were studied in the present analysis. Out of these, in two cases all the three channels have initial heat fluxes of 10 kW/m^2 or 5 kW/m^2. In the third case, the initial heat fluxes in two of the channels were 10 kW/m^2 and the third channel was unheated. In the fourth case the initial heat fluxes in two of the channels were 5 kW/m^2 and the third channel was kept unheated. In all the cases the steady state was achieved.
The transient study was carried out both by decreasing the heat flux and by increasing the heat flux. The details of the different cases studied are tabulated in Table 1.

Table 1: Cases studied with initial heat fluxes (kW/m^2)

Case No.	Initial Heat Flux		
	Ch-1	Ch-2	Ch-3
1	10	10	10
2	5	5	5
3	10	0	10
4	5	0	5
Heat Flux during Transient Conditions			
Case No.	Ch-1	Ch-2	Ch-3
1	10	Decrease power till it reverses the flow	10
2	5	Decrease power till it reverses the flow	5
3	10	Increase power till it reverses the flow	10
4	5	Increase power till it reverses the flow	5

5. RESULTS AND DISCUSSIONS

In Case-1 the initial steady state has been achieved with equal heat flux of 10 kW/m^2 to each of the three channels. The transient was started long after steady state was achieved.

During transient in one of the channel the heat flux was reduced from 10 kW/m^2 with a particular rate. Figure 3 & 4 show the variation of temperatures and density differences in different channels.

It is seen from these figures that the channel in which the heat flux is reduced, the temperature of the channel also reduces. As a result of decrease in temperature the density in the channel rises. The temperatures in the other two heated channels decrease because of the rise in the mass flow rate in these channels. Hence the densities in those two channels also rise slightly. Figure 4 shows the density difference between the bottom and top end of different channels. Clearly, the flow reversal is taking place when the density difference is the minimum in channel-2. Also the flow direction in channel-2 will be decided by the channel with the maximum density difference. As a result, the local

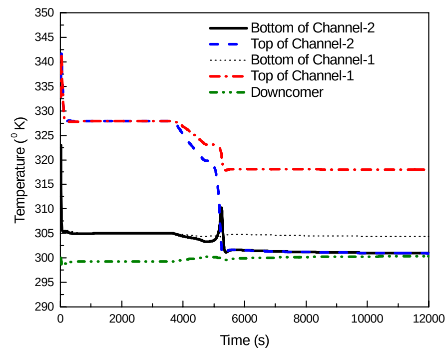


Fig. 3: Temperature variation at different Channels (Case-1)

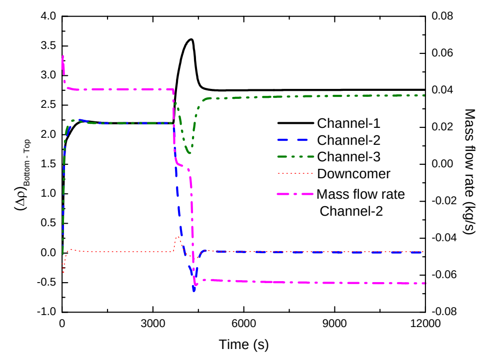


Fig. 4: Density variation at different Channels (Case-1)

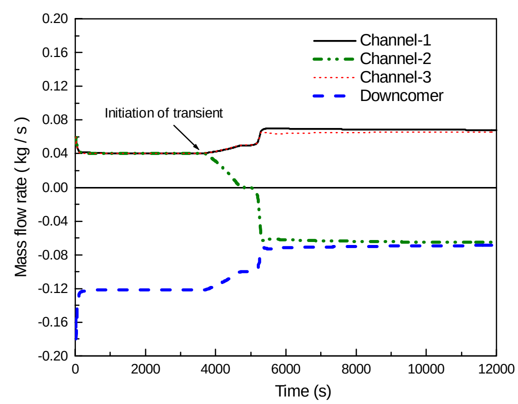


Fig. 5: Mass flow rate variations in different channels (Case-1)

loop will be set up between channel-1 and channel-2. Since the flow direction in channel-1 is upward, the flow direction for channel-2 must be downward. The mass flow rate in the channel in which heat flux was decreased, falls gradually and after some time the flow reversal takes place. Consequently the flow rate in the other two channels increases. Figure 5 shows the variation of mass flow rate in the different channels.

The corresponding variation of temperature, density and mass flow rate in Case-2 is for channel heat flux at 5 kW/m^2. The power in one of the channel was decreased from 5 kW/m^2 after steady state, where initial heat fluxes in all channels were kept same. The effect of decreasing the power on temperatures, densities and mass flow rates are shown in figure 6, 7, 8 and 9 respectively.

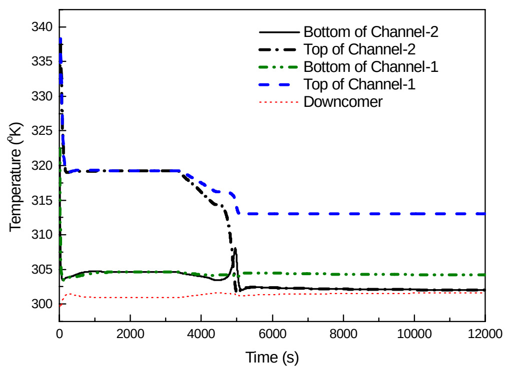


Fig. 6: Temperature variation at different Channels (Case-2)

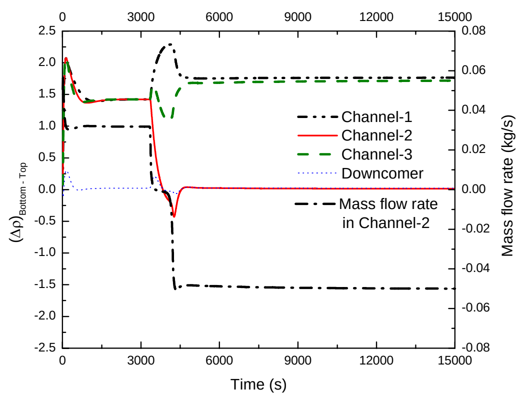


Fig. 7: Density difference between the bottom and top of different channels (Case-2)

To explain the flow reversal phenomena, the density difference between the bottom and top of the channels were taken for analysis. The result is shown in Fig. 7. This result corresponds to Case-2. It is seen from the figure, after the power was reduced in channel-2 the density difference gradually fell and became equal to that of downcomer. This caused the flow to get reversed. Another reason for the flow reversal is the local loop set up between channel-1 and channel-2. It is evident from the fact that the difference in densities between channel-1 and channel-2 is the maximum. Figure 8 shows the temperature difference between the top and bottom header at different channels. It clearly shows that the flow reversal occurs for the channel in which the temperature difference is the minimum.

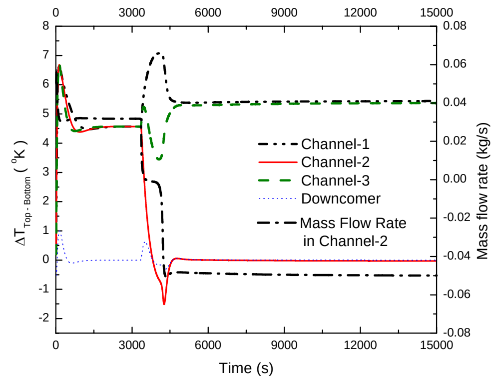


Fig. 8: Temperature difference between the top and bottom of different channels (Case-2)

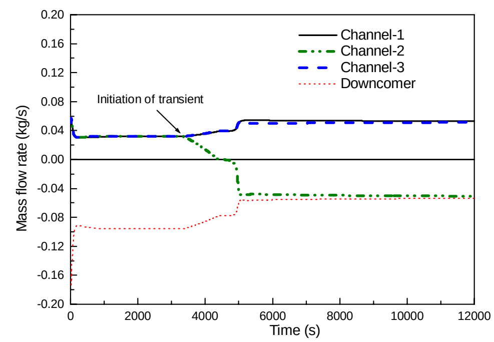


Fig. 9: Mass flow rate variations at different channels (Case-2)

In Case-3 the initial steady state has been achieved with heat flux of 10 kW/m^2 in two channels and the third channel remains unheated. The transient was initiated by heating the unheated channel. During transient the heat flux in the unheated channel was increased from 0 kW/m^2 with a particular rate upto a heat flux where the flow reversal takes place. The flow direction in the unheated channel and downcomer is same initially. The heating in this channel causes the coolant temperature to rise as shown in figure 10.

As the temperature in this channel increases, the density decreases. The change in density causes the flow to reduce in the downward direction and changes the direction slowly. The change in density difference in hot leg and cold leg causes the flow to reverse in this channel. The variation of density difference and mass flow rate is shown in figures 11 and 12 respectively.

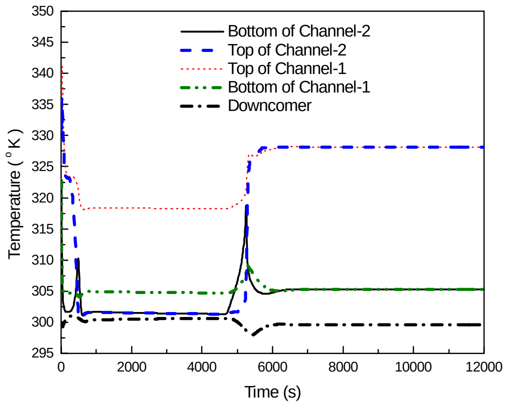


Fig.10: Temperature variation at different Channels (Case-3)

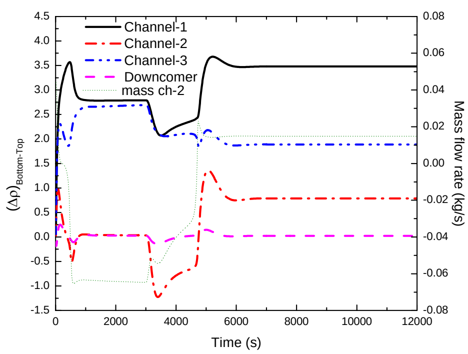


Fig. 11: Densities variation at different channels (Case-3)

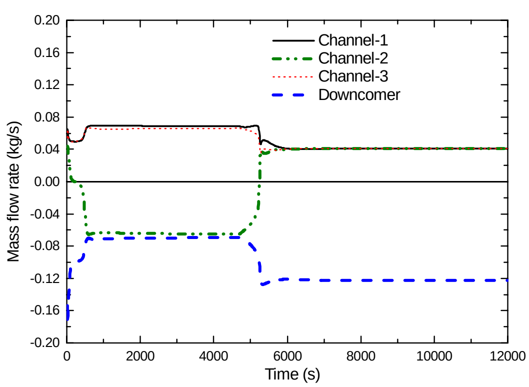


Fig. 12: Mass flow rate at different channels (Case-3)

Consequently the mass flow rate in the other two already heated channels decrease slightly. Due to the decrease in mass flow, the temperatures in the heated channels rise. Again because of the rise in temperature, the density in the channels decreases.

For the Case-4, two channels are at a heat flux of 5 kW/m^2 each and third channel was unheated. The flow direction in heated channels was upward before the transient was initiated while in the unheated channel and down comer, it was downward.

During transient the heat flux in the unheated channel was increased from 0 kW/m^2 with different rates upto a heat flux when flow reversal takes place. The effect of increasing the power in unheated channel on temperatures, densities and mass flow rates were found to be similar to that of Case-3 and are shown in figures 13, 14 and 15 respectively. These are shown for a particular heat flux increase rate of 0.1 W/m^2s.

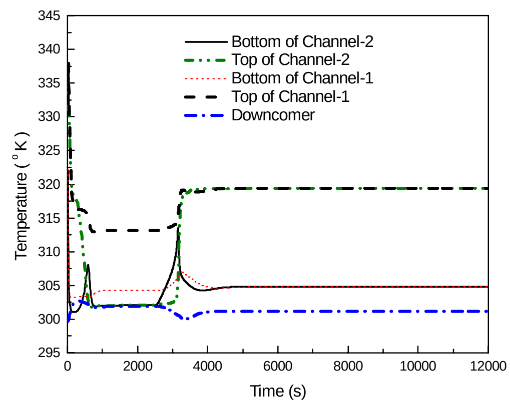


Fig.13: Temperature variation at different Channels (Case-4)

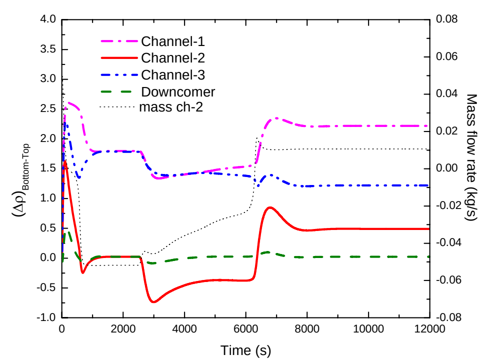


Fig. 14: Densities variation at different channels (Case-4)

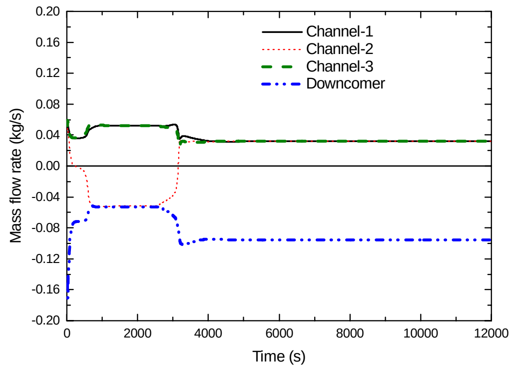


Fig. 15: Mass flow rate at different channels (Case-4)

Figure 16 shows the flow reversal power level for all the four cases. Form this figure it is seen that if the initial heat input rate is lower, the power level for flow reversal decreases in case of power increase. On the other hand for the lower value of initial power, the flow reversal power level increases for power increase. The metastable regime depends not only on the increment or decrement rate, but also on the actual power level of the other channel which was maintained constant. For example it can be stated that for all range of increment and decrement rate, the metastable regime falls between 62.5 W/m^2 to 2815 W/m^2 with an initial heat flux of 10 kW/m2 as shown in Fig. 16.

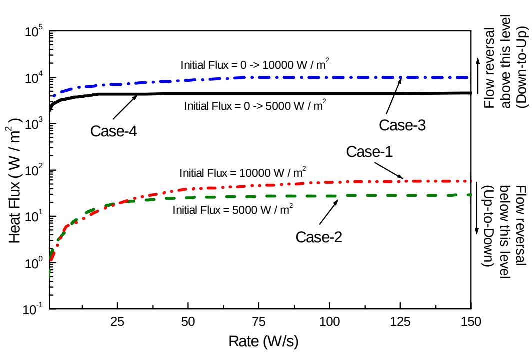


Fig.16: Flow reversal power level depe nding upon operation procedure at diffe rent power.

Figure 17 shows the variation of non-dimensional mass flow rate, N_m (= m_u / m_h), where m_u is the mass flow rate in the unheated channel and m_h is the mass flow rate in the heated channel, with non-dimensional heat flux ratio, N_H (=q_u / q_h), where q_u is the heat flux in the initially unheated channel and q_h is the heat flux in the heated channel. Initially the heat flux in the unheated channel is zero (i.e. q_u=0). The flow (m_u) in the unheated channel is downward while the flow in the heated channel (m_h) is upward (i.e. initially when N_H=0, N_m is a negative quantity).

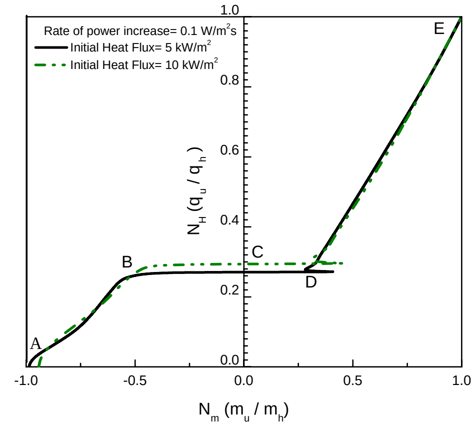


Fig. 17: Non-Dimensional Heat Flux Ratio (N_H) for initial heat fluxes of 5 kW/m^2 and 10 kW/m^2 (Case-3 & 4)

This state is shown at point A. As soon as we start heating in channel-2, the flow in this channel decreases in downward direction with N_H. There is a critical value of N_H at which the flow reverses. This value is corresponding to point B. There is a jump in curve from B to D, through point C where N_m is zero. With further increase in N_H, the value of N_m increases. It should be noted that the above plot has been taken for particular value of initial heat fluxes and for the case of power increase (=0.1 W/m^{2}s). The curve will be different for different initial value of heat flux and different operating procedure (viz. power rise and power set back).

Figure 18 shows both the power level at which flow reversal occurs, while decreasing and while increasing the heat flux. It can be seen that in the case of power rising, the level at which flow reversal takes place is higher than that of power level corresponding to power set back. Referring to Fig. 18 it is seen that corresponding to certain range of heat flux ratio there are two different steady state points differing in flow direction. This special phenomenon of static instability, characterized by multiple steady states in different flow direction is known as metastable regime. Welander (1967) and Creveling et al. (1975) analysed a single channel system where they observed oscillatory behavior of flow before the reversal. In the experiments of Bau et al. (1981), this phenomena was also observed. However, Yahalom et al. (1979) and Linzer et al. (2003) have not reported this type of oscillatory behavior before flow reversal in parallel channel system in conformity with the present findings.

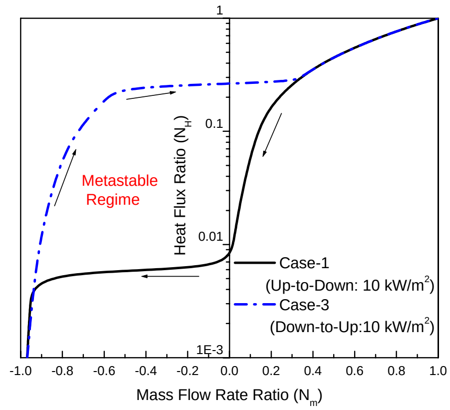


Fig. 18: Non-Dimensional Heat Flux Ratio (N_H) for initial heat flux of 10 kW/m^2 (Case-1 & 3)

Figure 19 shows the density difference ratio between channel-2 and channel-1 for Case-2 and Case-4. It is clear from the figure that the flow reversal occurs only when it reaches a definite value of density difference ratio for a particular initial heat flux level. In the present case, after reaching the value of 0.2 for both the operating procedure (Case-2 and Case-4) the flow reversal is taking place.

The values of the non-dimensional heat flux ratio (N_H) for different initial heat fluxes and operating procedures is shown in Table 2.

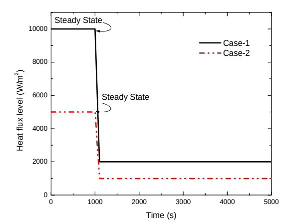
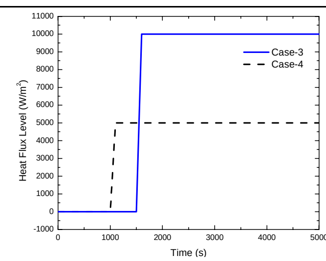
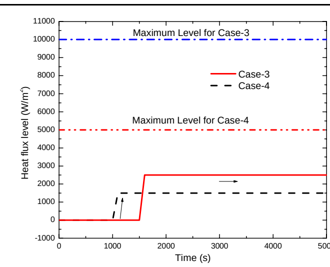
Case No.	Initial Heat flux in Ch-2	Final Heat Flux in Ch-2	Rate (W/s)	N_H at flow reversal	Ratio (q_h/q_u)	Operating Procedure
1	10000	62.5	765	0.00625	160	
	10000	38.5	50	0.00385	259.64	
	10000	6.0	6.66	0.0006	1666.67	
2	5000	28.5	163	0.0057	735.4	
	5000	19.5	25	0.0039	256.4	
	5000	2.5	2.5	0.0005	2000.0	
3	0.0	8614.5	50	0.8615	1.16	
	0.0	5900.0	10	0.59	1.7	
	0.0	2815.0	0.1	0.28	3.6	
4	0.0	4872.5	25	0.97	1.026	
	0.0	3240	5	0.65	1.54	
	0.0	1353.4	0.1	0.27	3.7	
3	0.0	2720.0	2.72	0.272	3.67	
4	0.0	1287.5	1.29	0.26	3.88	

Table 2: Non-dimensional heat flux ratio for different operating procedures and different initial heat fluxes

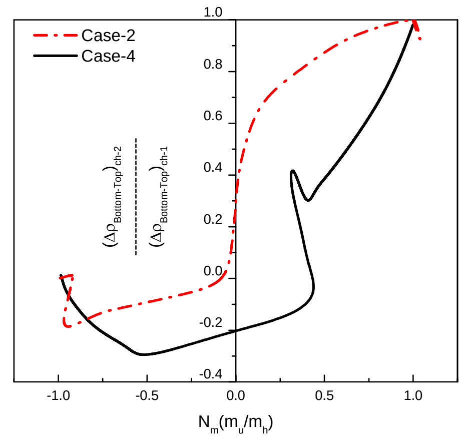


Fig. 19: Density difference ratio between Initially unheated and heated channel for initial heat flux of 5 kW/m^2 (Case-2 & 4)

6. CONCLUSIONS

The possibility of the existence of a metastable regime in multiple channel systems with non-uniform heat inputs has been studied. To examine the basic behavior of such a system, a three parallel channel set up with a downcomer, was investigated with RELAP5/MOD3.2 computer code. The results disclosed the existence of a metastable regime below a critical heat input ratio. A Non-Dimensional Heat Flux Ratio (N_H) has been proposed to predict the flow reversal. Further the heat flux level at which flow reversal occurs has been predicted for different rates of power rise and power set back. This has been done for different initial heat flux input. Finally it was found that the flow reversal power level for the same initial power input is different for power rise and power set back. That is, the flow reversal power level depends upon the operating procedures.

7. REFERENCES

1. Bau, Haim, H., Torrance, K. E., 1981, On the stability and flow reversal of an asymmetrically heated open convection loop, J. Fluid Mech., Vol. 106, pp 417-433.

2. Chato, J. C., 1963, Natural convection flows in parallel-channel systems, Journal of Heat Transfer,Vol. 85, pp 339-345.

3. Creveling, H. F., et al., 1975, Stability characteristics of a single-phase free convection loop, J. Fluid Mech., Vol. 67, pp 65-84.

4. Fletcher, C. D., Schultz, R. R., 1995, “RELAP5/MOD3 Code Manual Volume II: User’s Guide and Input Requirements”, Idaho National Engineering Laboratory, Idaho, USA.

5. Kamble M. T. et al., 2002, Simulation of Single Phase Natural Circulation in a Rectangular Loop Using RELAP5/MOD3.2, 1st National Conference on Nuclear Reactor Safety, November 25-27, Mumbai INDIA

6. Linzer W. and Walter H., 2003, Flow reversal in natural circulation systems, Applied Thermal Engineering, Vol. 23, pp 2363-2372.

7. Takeda T. et al., 1987, Natural circulation in parallel vertical channels with different heat inputs, Nuclear Engineering and Design, Vol. 104, pp 133-143.

8. Todreas N. E. and Kazimi M. S., 1990, “ Nuclear System II, Elements of Thermal Hydraulic Design”, Hemisphere Publishing Corporation, New York.

9. Welander, P., 1967, On the oscillatory instability of a differentially heated fluid loop, J. Fluid Mech., Vol. 29, part 1, pp 17-30.

10. Yahalom, R. and Bein M., 1979, Boiling thermal hydraulic analysis of multichannel low flow, Nuclear Engineering and Design, Vol. 53, pp 29-38.