NUMERICAL INVESTIGATION OF A MULTIPLE CHANNEL NATURAL CIRCULATION LOOP IN SINGLE-PHASE

Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

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By

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This is to certify that the thesis entitled "**Numerical Investigation of a Multiple Channel Natural Circulation Loop in Single-Phase**", which is being submitted by **Praneet Kumar Singh** in partial fulfilment of the requirements for the award of the degree of "**Master of Nuclear Engineering"** at the School of Nuclear Studies and Application, Jadavpur University, Kolkata700032, during the academic year 2018-2019, is the record of the student's own work carried out by him under our supervision.

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The foregoing thesis entitled "**Numerical Investigation of a Multiple Channel Natural Circulation Loop in Single-Phase**" is hereby approved as a creditable study of an engineering subject carried out and presented in a satisfactory manner to warrant its acceptance as a prerequisite for the degree of "**Master of Nuclear Engineering"** at the School of Nuclear Studies and Application, Jadavpur University, Kolkata700032, for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn there in but approve the thesis only for the purpose for which it is submitted.

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It is hereby declared that the thesis entitled "**Numerical Investigation of a Multiple Channel Natural Circulation Loop in Single-Phase**" contains literature survey and original research work by the undersigned candidate, as part of his degree of "**Master of Nuclear Engineering"** at the School of Nuclear Studies and Application, Jadavpur University, Kolkata700032.

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It is also declared that all materials and results, not original to this work have been fully cited and referred throughout this thesis, according to rules of ethical conduct.

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ABSTRACT

Reactor safety is a topic of utmost importance when it comes to generation of power in a nuclear thermal power plant. The incidents in recent years e.g. Three Mile Island (1979), Fukushima nuclear accident (2011) etc. have contributed in, increasing the gravity of reactor safety. Severe accident scenarios can arise due to several reasons. One of them is loss of coolant accident or LOCA. This is composed of failure in primary cooling system of the reactor, causing insufficient supply of coolant to the core as a result of which heat removal rate from the reactor core gets drastically reduced. As a counter measure, the reactor is shut down and emergency heat removal system is engaged to remove the residual heat form the reactor core. Since, almost all mechanisms and systems of a nuclear thermal power plant, are based on active devices, failure of which leads to accidents, in recent years a lot of work have been carried out both experimentally and numerically to develop passive emergency cooling systems for the removal of residual heat and to understand their behaviour in different operating conditions.

Passive systems are highly susceptible to flow instabilities due to their sole dependency on natural forces such as density differences or buoyancy forces. This attribute causes flow oscillations or reversals and exclusively for natural circulation loops with multiple parallel vertical channels, there is generation of an internal loop within the main loop, which in turn affect the heat transferring capacity of the loop, which causes failure of the loop and in practical cases can lead to severe accident scenario. Thus, it is important to observe and analyse thermal hydraulic behaviour of natural circulation loop under different operating parameters and geometrical configuration, for realisation of various flow regimes of a natural circulation loop.

The present work focusses on numerical study of a natural circulation loop with multiple parallel vertical channels using Relap5/module3.4 codes, transferring heat from a heat source to a heat sink. The loop is of square geometry, with cooler and heater situated at upper and lower horizontal limbs respectively, connected by multiple parallel vertical channels. To observe the variation of mass flow rate through the loop the heat input is varied and simulation is carried out on a loop of stainless steel using light water as a coolant at atmospheric pressure. In order to simplify the model, it has been considered that there is no energy exchange between the loop and ambient. At the settlement of initial transient, the mass flow pattern is analysed in order to observe the average mass flow rate and the flow reversal tendency.

KEYWORDS: *Natural Circulation Loop, Multiple Vertical Channel, Relap5, Passive Safety System*

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LIST OF ABBREVATIONS

NCL- NATURAL CIRCULATION LOOP

LOCA- LOSS OF COOLANT ACCIDENT

PWR- PRESSURIZED WATER REACTOR

PHWR- PRESSURIZED HEAVY WATER REACTOR

BWR- BOILING WATER REACTOR

ABWR- ADVANCED BOILING REACTOR

NCBWR- NATURAL CIRCULATION BOILING WATER REACTOR

DRDD- DOUBLE RISER DOUBLE DOWNCOMER NCL

DRSD- DOUBLE RISER SINGLE DOWNCOMER NCL

SRDD- SINGLE RISER DOUBLE DOWNCOMER NCL

LIST OF FIGURES

For Double Riser Double Down-Comer

For Single Riser Double Down-Comer

For Double Riser Single Down-Comer

Uniform Tube Diameter Case

Half the Tube Diameter for Riser Section Casse

For Double Riser Single Down-Comer with Header Type Configuration

For Comparative analysis

CHAPTER 1

INTRODUCTION

In recent years, passive safety systems are being considered as an important and pivotal topic of research, in the field of nuclear reactor safety. Due to their sole dependency on natural forces such as buoyancy and density difference, they present a high scope of application in reactor safety, by eliminating usage of active systems and devices which further eliminates the chances of manual fault, mechanical and technical failures, thus aids in avoiding disastrous scenarios. Natural circulation loops are a version of passive safety systems which are incorporated in nuclear thermal power plants for the purpose of removal of residual heat from the reactor core, in case reactor needed to be shut down due to failure of primary cooling system.

Natural circulation loop (NCL) or thermosyphon, serves the purpose of transferring heat from a high temperature source to a low temperature sink, and their passive nature enhances their reliability. Moreover, due to weak driving forces or small hydraulic driving head, natural circulation loops are more susceptible to flow instabilities and flow reversals as compared to forced circulation systems. Initially, in a natural circulation loop the fluid is at rest, as heat is supplied, density difference arises and motion is imparted to the fluid in a particular direction. With time as fluid absorb more and more heat its mass flow rate goes on increasing or in other words the time interval for which a particular fluid element remain inside the heater or cooler goes on decreasing. Thus, heat supplied to or absorbed from the fluid is not sufficient to maintain the direction of the flow. As a result, cold and hot pockets are created in the hot and cold leg of the loop, respectively, which leads to flow oscillations and flow reversal.

In today’s era natural circulation loops have many engineering applications in electronic chip cooling, refrigeration, nuclear power reactor, thermal power plants, solar heating system, geothermal heat extraction system, I.C. engine cooling and chemical industry. Due to this flow behaviour and dynamics of natural circulation loops, has received attention of many researchers and scientists in recent decades. The advantage of natural circulation loop over, traditional forced circulation removal systems is that, it does not require external power source, there is no moving mechanical part and it does not need any external signal of intelligence to operate. However, they show flow instabilities and reversals under some operating conditions.

Natural circulation loops are used as a residual heat removal system in nuclear power plants. The single-phase loops and the dynamics related to them are applied in pressurized water reactor (PWR) and in pressurized heavy water reactor (PHWR), whereas in boiling water reactor (BWR), natural circulation boiling water reactor (NCBWR) and advanced boiling water reactors (ABWR), concepts of dual phase natural circulation loop are applied. Many experimental and numerical work have been done by scientists and researchers in the past to observe and analyse the flow behaviour and other physical parameters of a natural circulation loops subject to different operating conditions.

Bodhka et al. [1] has done experiment and numerical analysis on a loop having 3 channels and single down-comer operating under steady and transient conditions. Under steady conditions, the numerical and the experimental data are in agreement with each other. Moreover, in transient conditions the flow reversal in a channel depend not only on the power level but also on the power history and path through which heat is added to the system.

Gartia et al. [2] has also carried experiment and numerical works in which they have found that, on increasing the heat supply to the down-flowing channel when the power input to other two channels were kept unchanged, then a flow reversal occur in it and upward motion of fluid occur in it at a threshold value of power, and same goes with the riser channel, which will flow in opp. direction, after power is reduced to a particular level. It is also observed that power level at which flow reversal occur is also dependent on the initial starting power.

Moreover, analysis was done by Mangal et al. [3] to check the applicability of RELAP5 codes on multiple channel loop operating with single and two phases. It has been found that results obtained through RELAP codes are highly sensitive to nodalisation scheme, the coarse and fine nodalisation scheme changes the results significantly. The code may be successful in predicting the characteristic of oscillations for one operating condition, but when a different parameter was incorporated the efficiency of the code was not as it was expected. The reason behind this shortcoming is the numerical model considered for relap5.

Jain et al. [4] has conducted various experiments on a multiple channel loop, operating with two phases, to study the flow instability behaviour. The value specified for loop was 1 and 9 bar, and under them experiments were carried out separately. It was observed that, a single-phase flow was achieved, then onset of boiling occurred which introduced oscillations, at low power input there was a rise in instabilities which gets reduced with further increase in power, and a steady state flow is observed at a moderate power level, when power level is further increased then the loop becomes more unstable. An important observation was made that there was unequal distribution of mass flow rate among the vertical channels, even after supply of equal heat input.

Venkatesh et al. [5] in their work, regarding 'analysis of natural circulation loop', pointed out that instabilities in single phase natural circulation loop, such as flow reversals etc., can be suppressed by application of localised losses or by use of nano-fluids such as $Al_2 O_3$. Further they demonstrated a series of experiments to observe the effects of Nano-fluids at different concentrations. As the result, they have found that hot fluid inlet temperature and the mass flow rate is directly proportional to heat transfer rate, and same goes with the cold fluid.

Goudrazi et. al. [6] has done a piece of work concerning heat removal ability for different cooler-heater orientations of single-phase natural circulation loops. The effect of various parameters such as loop diameter, heater/cooler length, heater/cooler diameter, on stability of loops of various orientations has been observed, like for HHHC and HHVC loops, decreasing the loop diameter make the two loops stable. Whereas, shortening of cooler makes the HHHC loops unstable, but enhances the stability of HHVC loops. Similar kind of inferences were made for heater diameter and length also.

Basu et al. [7] have carried out vital study to understand the effect of sudden change in the power supply on the stability of a single-phase natural circulation loop. It was observed that flow reversal was obtained earlier if there is an increase in power input in a single step, whereas, step signal improves the transient performance, and similar inferences were made for exponential, ramp etc. signal profiles. Moreover, Lakshmanan et al. [8] have carried numerical investigation of startup instabilities in parallel-channel natural circulation boiling systems, using RELAP5/MOD3.4 codes for parallel-channel pressure tube type natural circulation boiling water systems. Sarkar et al. [9] has conducted a work to identify the effect of loop parameters such as diameter, height, heater length etc. on the thermo-hydraulic properties of a supercritical CO_2

based NCL. It has been observed that reducing the loop diameter or increasing the horizontal length without affecting the heat exchanging sections increase the friction and reduces the mass flow rate.

A new approach in study of NCL was implemented by Cheng et al. [10] in which rather than using electricity to heat up the loop fluid, hot fluid was used and a theoretical analysis was carried and it was observed that the heat transfer rate increases with loop diameter, but there was also a drop in temperature difference between hot and cold liquid. Wu et al. [11] has carried out a study to analyze the roles of local and frictional resistance in natural circulation loop, and it was expected to obtain relations between mass flow rate, the heating power and flow resistance. Upon the experimental verification, it was confirmed that total flow resistance, rises with natural circulation mass flow rate, and similar other deductions were made.

Liu et al. [12] have considered a fluid in super critical zone and studied the effect of temperature on thermal and heat transfer properties. A model is developed to predict the threshold point for variation of heat transfer mode. It is observed that, in a natural circulation loop subjected to supercritical conditions, an increase in the system pressure and the local conductance in the hot leg, and a decrease in the local conductance in the cold leg, system stability can be increased. Yadav et al. [13] carried subcritical and supercritical experiments on a natural circulation loop having CO_2 as primary fluid. The transient behavior of the loop is observed by tilting it at various angles in different planes. The loop conditions are chosen in a way that the loop fluid remains in single phase in subcritical or supercritical region. It is observed that more is the loop pressure quickly the steady state is reached, moreover, as the conditions of the loop move towards criticality there is a delay in obtaining steady state.

Thalange et al. [14] has considered a natural circulation loop with a hemisphere facet as a receiver surface, and a steady state power input of 300 Kw is provided. Here, the eutectic mixture of 60% by wt. sodium nitrate ($NaNO_3$) and 40% by wt. potassium nitrate (KNO_3) was used as the primary fluid. The results of the analysis show that salt side heat transfer coefficient in the jacket side of hemispherical receiver (heater) and in the steam generator (cooler) surface are 103 w/m^2-k and 42 w/m^2-k respectively. Sarkar et al. [15] carried a comparative analysis of a natural circulation loop incorporating different primary fluids such as water, carbon dioxide and refrigerant R134a at similar working environment. In the analysis water is kept at single-phase liquid condition, for

R134a the conditions were established at the supercritical region. The state of carbon dioxide was in between of sub to super critical zone. The main focus of the analysis was to identify the best fluid in terms of heat transfer properties, to carry out this, velocity and temperature distribution profiles of mentioned primary fluids were compared.

Sadhu et al. [16] presents a numerical analysis of a natural circulation loop having carbon dioxide as a primary fluid at supercritical state, a steady state heat input and a heat sink. The heat exchange between risers/downcomers and the ambient was also taken into account, and phenomena of axial conduction through fluid and the pipe wall were also given weightage in the study. Thus, a detailed study of the alternations caused by these and other important factors on the performance of natural circulation loop was carried out. It has been noticed that with increase in diameter of the pipes present in the loop, increase in the cross-sectional area is much more than the increase of mass which reduces the velocity, and when heat supply is increased, the mass flow rate through the loop gradually increases, attains a maximum value and then starts decreasing.

Sadhu et al. [17] have designed and developed a natural circulation loop having water as coolant and carbon dioxide as primary fluid. The power input is provided by an electrical heater, heat sink is consisting of air-based heat exchanger, fins are provided to enhance heat exchange and riser and downcomer sections are provide proper insulation. The consequences of factors like power input, air velocity and inlet temperature are observed and further, a scenario of fan failure is created to observe its effect on loop performance. It was found that, there was a significant effect on the temperature with which air enters the heat exchanger, moreover, this observation was entirely from water based natural circulation loop, where more precise maintenance of secondary fluid temperature is possible, moreover it is also concluded that in case of high pressure the fan is prone to fail.

Ruiz et al. [18] have taken a natural circulation loop into consideration in which the primary fluid is subjected to single phase conditions, and the loop has the attribute of internal generation of heat. Then investigation of the stability of two loops having different heater cooler configuration i.e. Vertical Heater - Horizontal Cooler and Vertical Heater - Vertical Cooler was carried out. It was observed that instability in both of the loops increases when the heat generated by the fluid increases.

Ho et al. [19] carried an experimental work to understand the effect on a NCL due to presence of nano fluids on the heat transfer capability. To carry the analysis an alumina–water nano-fluid was chosen and mass fraction was in the range of 0.1–1 wt. %. It was noticed that the presence of Al_2O_3 water nano fluid improves the heat-transfer capacity of the NCL considered.

Liu et al. [20] have considered a natural circulation loop with carbon dioxide as primary fluid with supercritical conditions and studied the alternations caused by buoyancy forces and flow acceleration on heat transfer properties. The experiments were performed for pressure from 7.45 to 10.19 MPa, mass flux from 235 to 480 kg/m^2s, bulk fluid temperature from 21^0C to 205^0C, and heat flux from 10.5 to 96 kW/m. It has been observed that due to buoyancy forces and flow acceleration the heat transfer capability gest affected.

1.1 OBJECTIVE

A numerical model of natural circulation loop was developed with dimensions 1m x1m having pipe diameter of 30 mm and stainless steel as the structural material, with light water as coolant. A steady state power input was provided to the loop and simulation run was carried out of time interval 30,000 seconds and the generated output were recorded.

To push the scope of the analysis further numerical models of natural circulation loop having different geometrical orientations were created and their performance under similar operating conditions were recorded and analysed. Finally, a comparative study is done to understand the behaviour of natural circulation when subjected to varying geometrical conditions.

CHAPTER 2

NUMERICAL MODELLING

2.1 RELAP5/MOD 3.4

RELAP (Rector Excursion and Leak Analysis Program) is a series of codes developed by Idaho National laboratory, USA. It is a simulation tool that allow to model the coupled behaviour of the reactor coolant system and the core for various operational transients and potential accidents that might occur in a nuclear reactor.

It is a general-purpose commercial code which can be used to model the thermal and hydraulic behaviour which are observed in a nuclear reactor coolant system. RELAP5/MOD3.4 uses the concept of control volume or control mesh upon which the conservation equations of mass and energy are applied by equating the rate of accumulation to the sum of rate of inflow and source term minus the rate of outflow.

The RELAP5/MOD 3.4 code is creating a non-homogeneous numerical model for the analysis of two-phase system and solve it by a semi-implicit numerical scheme for calculation of transients. The main aim of RELAP5 is to produce a code that involve accurate prediction of system transients but that was sufficiently simple and effective so that steady and transient state studies are possible.

The system mathematical models are including a code structure. The code carries out intensive input checking, inherently, for catching input errors and inconsistencies. There are other helpful facilities such as free-format input, restart, nodalisation, and variable output edit features. These major advantage of this computer code over traditional methods is that they involves extensive engineering labour, working hours, and cost, while the computer cost associated with generation of the final result is usually small.

CHAPTER 3

RESULTS AND DISCUSSIONS

The simulations have been carried out for 30,000 seconds at steady power input, and the effect of ambient temperature on the loop performance has been ignored. The initial stage of simulation for every loop was highly transient and fluctuating, thus, the results published in this work are after the settlement of initial transients. The study of mass flow and temperature distribution pattern at various sections of an individual loop is carried out separately, then a comparative study is done to compare the performance of loops having different geometrical orientations.

The presence of more than two parallel vertical channels give rise to an internal loop within the main loop, and their behaviour is different for different loop geometries. This aspect of multiple channel natural circulation loop has been considered here, and individual and comparative analysis has been carried out.

The results published in this work are at steady power level of 300 watts, because at this power input the first substantial circulation of fluid has been observed, which was absent in the case of power levels of lower value. The power input of 300 watts is enough to create the minimum buoyancy difference, required to generated appreciable mass flow rate through the loop and thus provide a platform for comparative stability analysis.

3.1 NCL with Double Riser and Double Down-comer

Figure 1 shows the schematic diagram of the nodalisation scheme for the RELAP code, of a natural circulation loop containing two risers and two down-comers. The total loop geometry is divided in twenty-three sections, which includes 19 pipe and 4 branch sections. The heater section is represented by '120-Pipe' component, the components '240-Pipe' and '230-Pipe' represent the cooler section. The risers are established by the components '290-Pipe' and '300-pipe' and the down-comers are constructed by the help of '170-Pipe' and '180-Pipe'. The lower and upper horizontal arms of the loop are consisting of '110-Pipe', '130-Pipe' and '220-Pipe', '250-Pipe'.

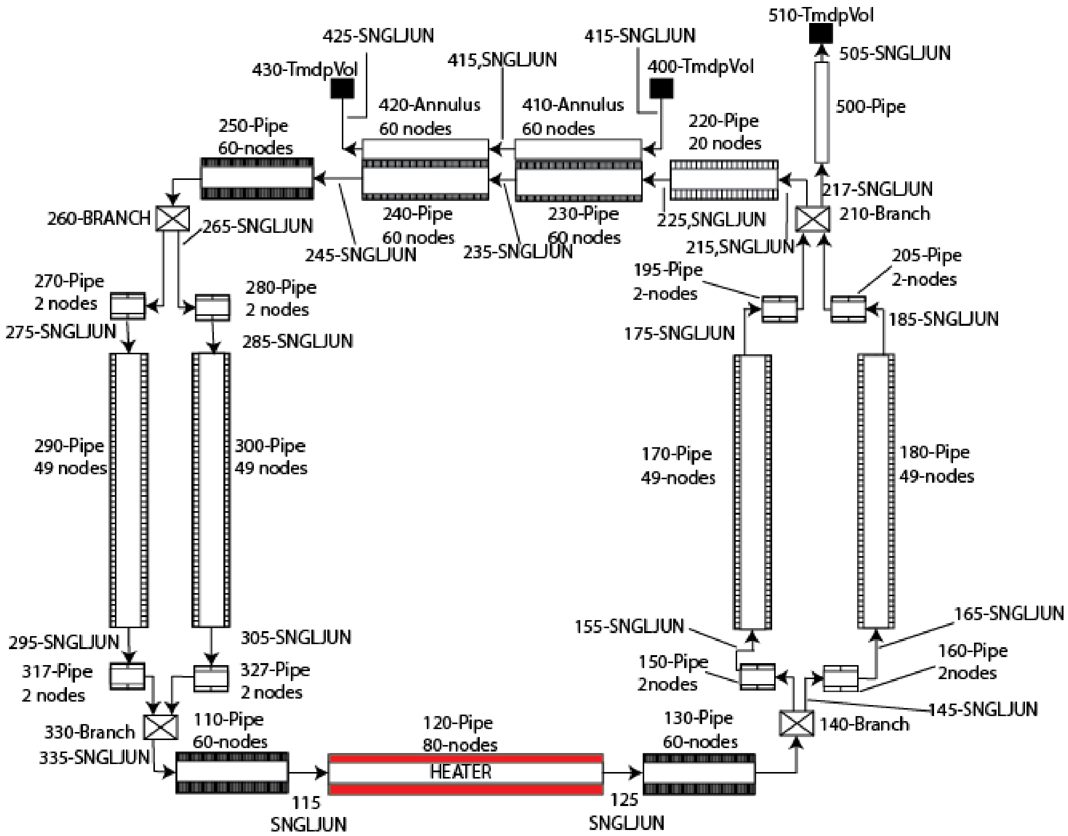

Figure 1: Schematic Diagram for RELAP Code.

Moreover, four branch components '140-Branch', '210-Branch', '260-Branch' and '330-Branch' are used at four corners of the loop where there was a requirement to create multiple connections. The expansion tank is represented by '500-Pipe'. The heat exchanger comprised of two annulus section i.e. '420-Annulus' and '410-Annulus', the time dependent volume '400-TmdpVol' serve as inlet to the heat exchanger and specifies the mass flow rate through the heat exchanger, and the time dependent volume '420-Annulus' is the outlet of the heat exchanger and specifies its pressure, which in this work is considered to be atmospheric. The pipe sections '150-Pipe', '160-Pipe, '195-Pipe', '205-Pipe', '270-Pipe', '280-Pipe', '317-Pipe and '327-Pipe' are the connecting links between the branches and the respective risers or downcomers.

Two components are joined with the help of 'Single Junction'. The heater section is consisting of 80 nodes and the two components of the cooler section is consist of 60 nodes each. The two risers and the downcomer are having 49 nodes each. The two other pipe sections of the lower horizontal arm have 60 nodes each and the additional pipe sections in the upper horizontal sections have 20 nodes and 60 nodes.

Figure 2 demonstrate the mass flow rate variation in the lower horizontal arm of the loop where the heater is situated. The mass flow rate is highly unsteady and unpredictable even after the settlement of initial transients. The flow is highly chaotic and undergo reversals frequently.

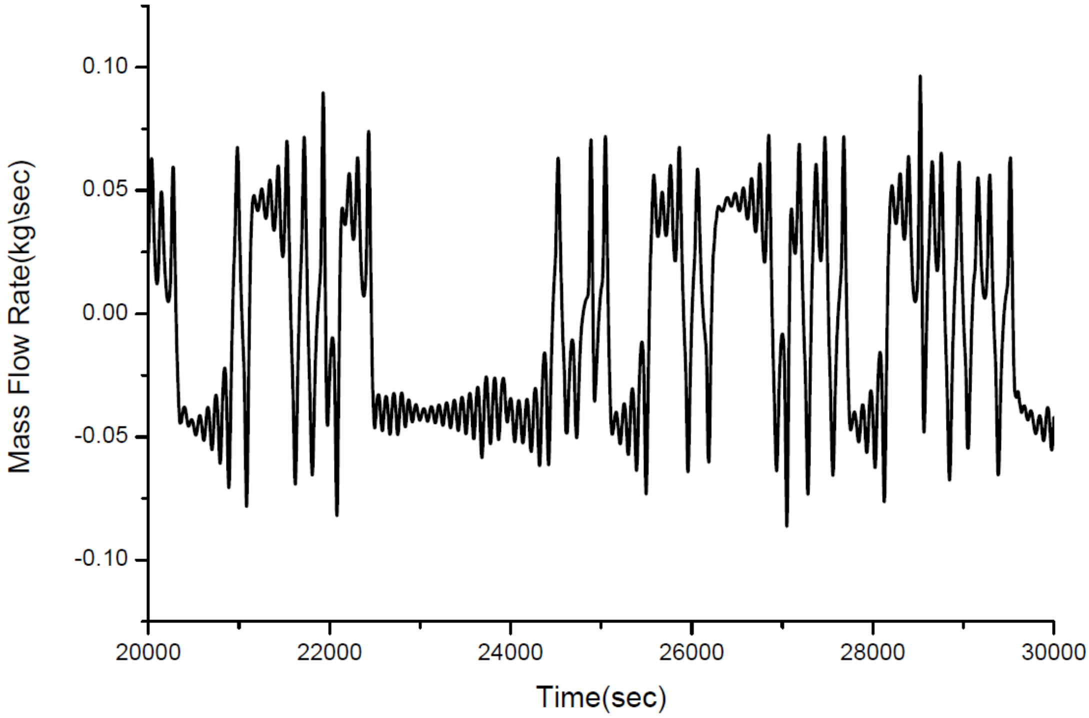

Figure 2: Mass Flow Rate Variation in Heater Channel.

Figure 3 and 4 displays the mass flow behaviour of the two downcomers and risers situated on the right-hand and left-hand side of heater, respectively. It can be observed that mass flow output of the either of the horizontal arms is not equally divided in the two downcomers/risers. The tendency of flow reversals is highly dominating in both of the channels. Moreover, at some instances the direction of flow the downcomers is exactly opposite to each other, thus an internal loop is generated within the main loop.

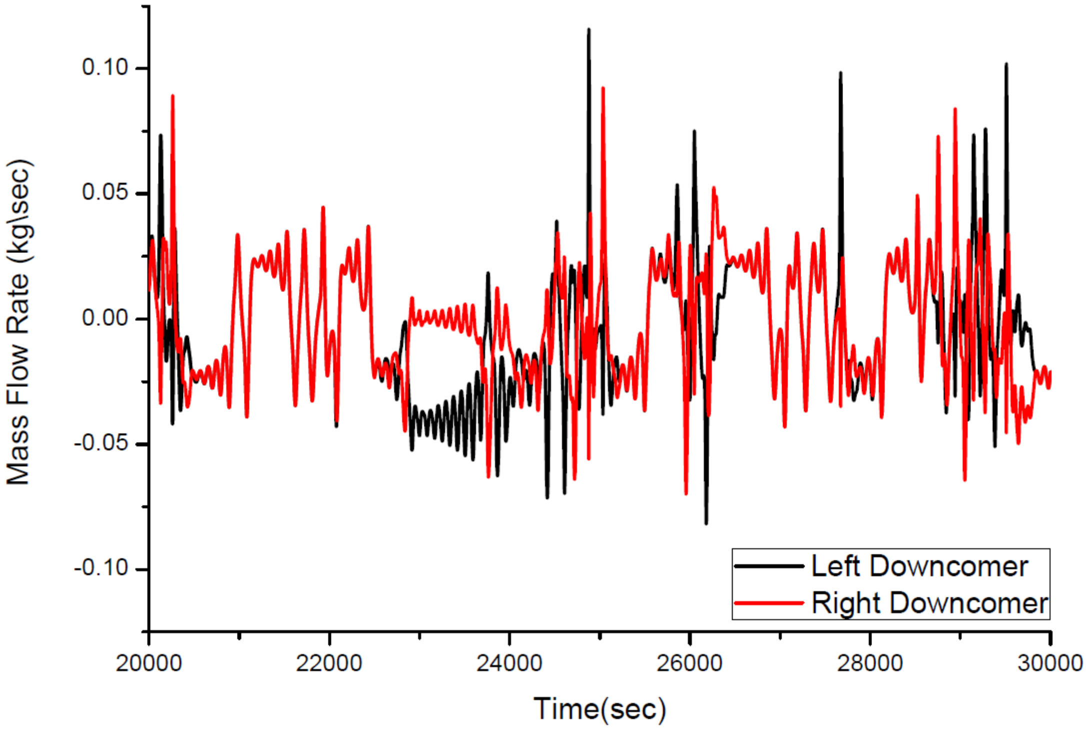

Figure 3: Mass Flow Rate Variation in Down-comer Channels.

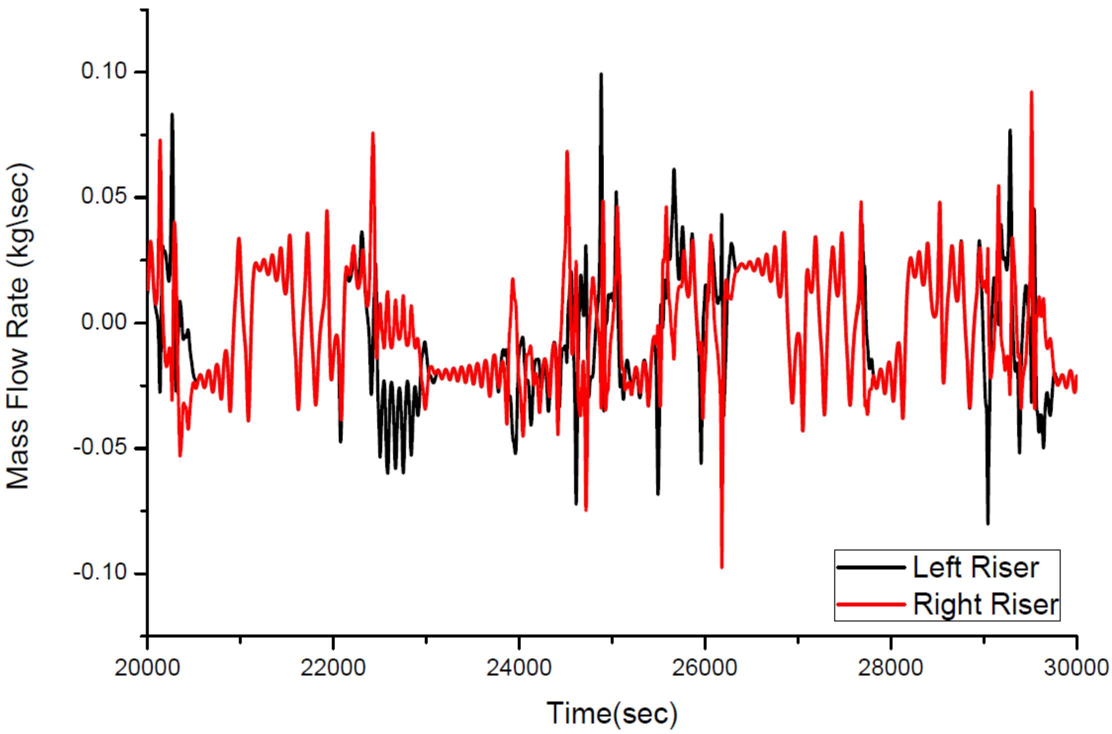

Figure 4: Mass Flow Rate Variation in Riser Channels

Considering the Fig. 4a, the positive values refers to the condition where the flow direction in both of the risers are same and on the other hand the negative values suggests that the flow in the risers are in opposite direction which in turn generate an internal loop. One thing must be noted that for a particular value (either positive or negative), the specific direction of flow in a riser can't be stated with surety. The spikes in the graph denotes, the number of times mass flow rate in the left riser is greater than that of the right one. This gives an important inference that, intermittently, almost whole of the mass flow input to the riser section is passing only through left riser, or in general terms, only through one riser.

Figure 4b is the magnified view of Fig. 4a, which provide a deeper insight to understand the pattern of mass flow variation in the risers. The observation of the graph below, suggests that the flow in the riser section is highly unpredictable. For a brief time period the ratio of mass flow pattern of the risers has a value of one which signifies that both the risers are carrying equal mass flow rate and in the same direction, but for the majority of time the value of ratio of mass flow in risers is highly oscillating, which suggests that the magnitude and direction of flow in the risers are changing frequently.

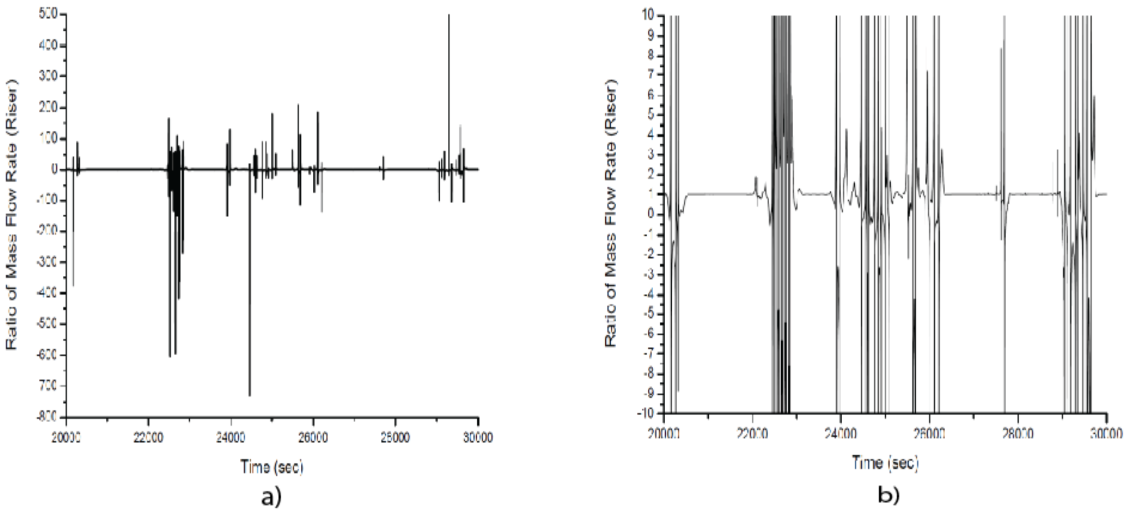

Figure 5: Ratio of Mass Flow Rate of Risers

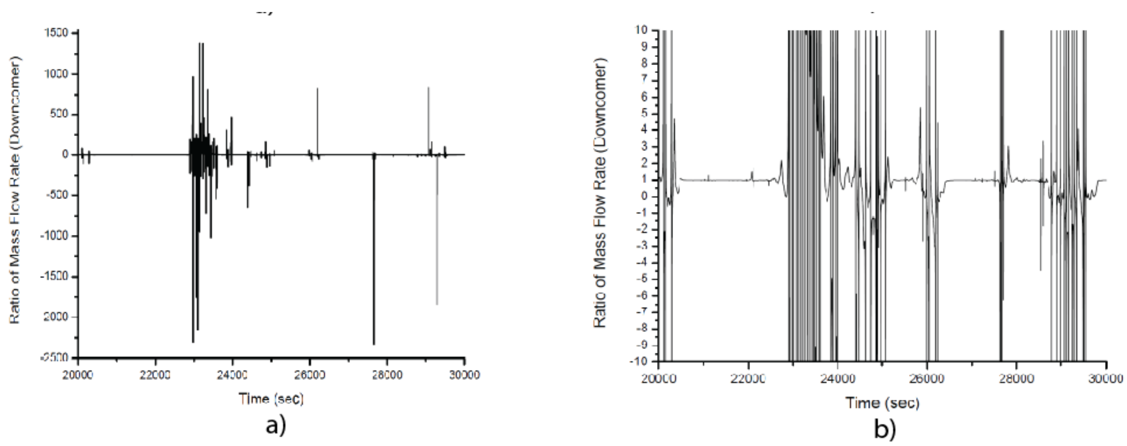

Figure 6: Ration of Mass Flow Rate of Downcomers

Figures 5a, 5b, 6a, 6b demonstrate the variation of ratio of mass flow rate of risers and down-comers. Figure 4a and 5a displays the data in normal view, whereas, Fig. 4b and 5b displays the same, but in a magnified form. The ratio is generated by dividing the mass flow rate of left-side riser/down-comer to that of right-side riser/down-comer. Then, the obtained ratio is plotted against a time series, keeping the direction of the flow under consideration.

Figures 5a and 5b contain the data regarding ratio of mass flow rate of downcomers. The comparison of Fig. 5a and 4a suggests that, the pattern of the variation of mass flow in terms of magnitude and direction is almost same for risers and down-comers.

3.2 NCL with Single Riser and Double Down-comer

The schematic diagram shows the scheme of nodalisation for the RELAP codes, of a natural circulation loop containing one riser and two down-comers. The total loop geometry is divided in eighteen sections, which includes 14 pipes and 4 branch sections. The heater section is represented by '120-Pipe' component, the components '240-Pipe' and '230-Pipe' represent the cooler section. The riser is established by the component '290-Pipe' and the down-comers are constructed by the help of '170-Pipe' and '180-Pipe'. The lower and upper horizontal arms of the loop are consisting of '110-Pipe', '130-Pipe' and '220-Pipe', '250-Pipe'.

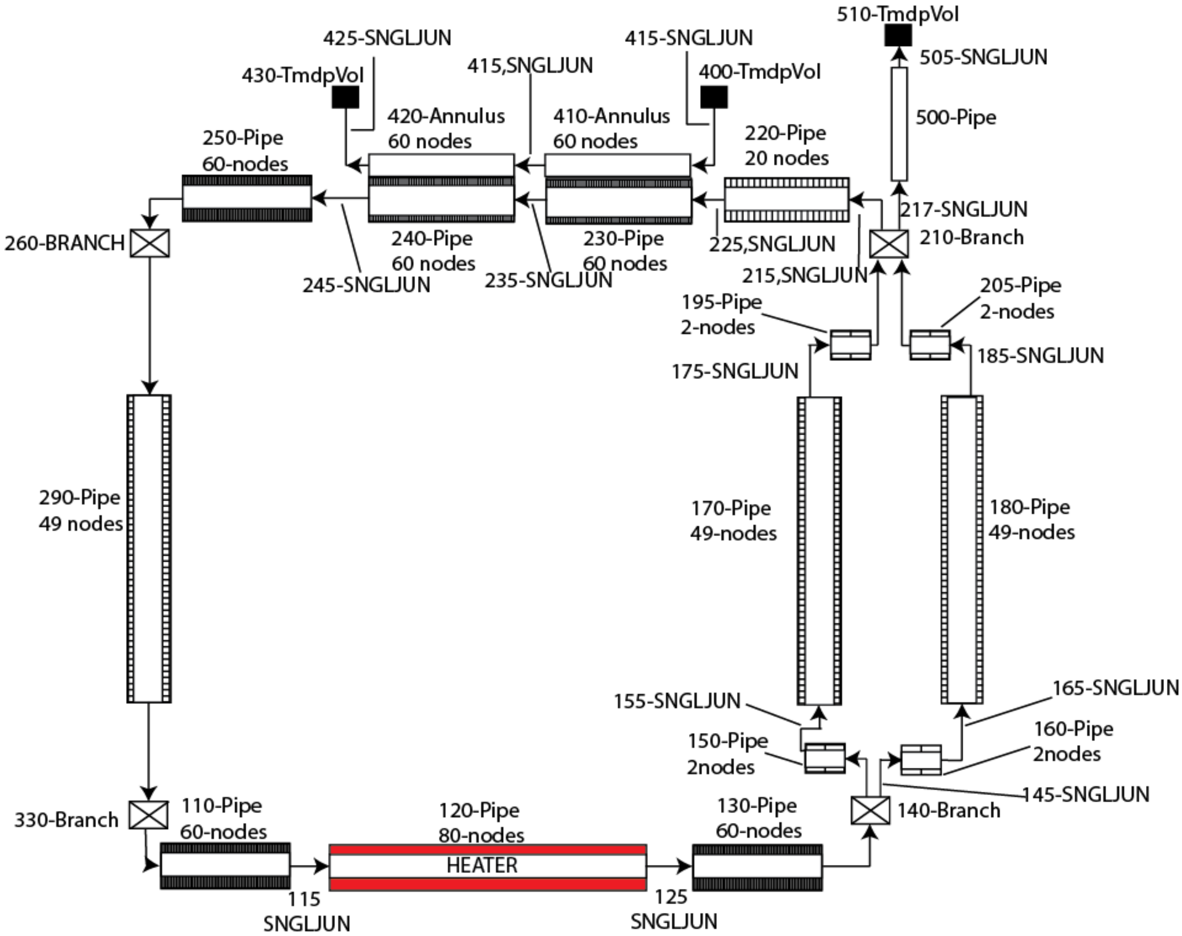

Figure 7: Schematic Diagram for RELAP Code.

Moreover, two branch components '140-Branch' and '210-Branch' are used at right bottom and upper corners of the loop where there was a requirement to create multiple connections. The expansion tank is represented by '500-Pipe'. The heat exchanger comprised of two annulus section i.e. '420-Annulus' and '410-Annulus', the time dependent volume '400-TmdpVol' serve as inlet to the heat exchanger and specifies the mass flow rate through the heat exchanger, and the time dependent volume '420-Annulus' is the outlet of the heat exchanger and specifies its pressure, which in this work is considered to be atmospheric. The pipe sections '150-Pipe', '160-Pipe, '195-Pipe' and '205-Pipe' are the connecting links between the branches and the respective downcomers. Two components are joined with the help of 'Single Junction'.

The heater section is consisting of 80 nodes and the two components of the cooler section is consist of 60 nodes each. The riser and the two downcomers are having 49 nodes each. The two other pipe sections of the lower horizontal arm have 60 nodes each and the additional pipe sections in the upper horizontal sections have 20 nodes and 60 nodes.

The figure 8 shows the mass flow rate variation in the lower horizontal arm of the loop containing the heater. It can be observed that after 22500 seconds the mass flow rate is about an average value of 0.04 kg\sec, undergoing unidirectional oscillations and intermittent flow reversals.

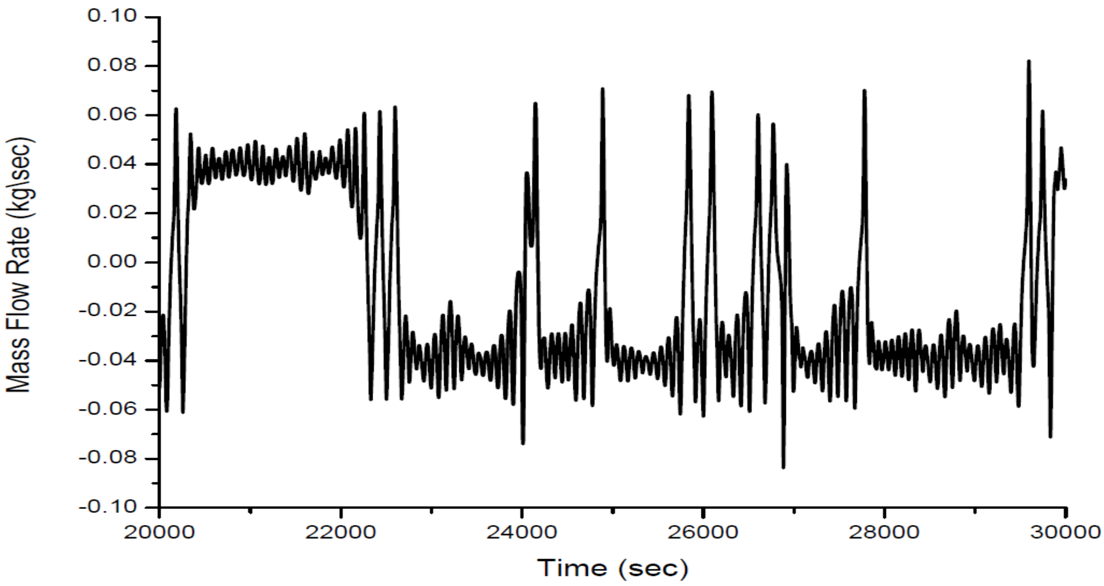

Figure 8: Mass Flow Variation in Heater Channel

Figure 9 displays the mass flow behaviour of the two downcomers, situated on left-hand side of heater. It can be observed that mass flow rates in both of the downcomers are not equal always. The tendency of flow reversals is highly dominating in both of the downcomers. Moreover, at some instances the direction of flow the downcomers is exactly opposite to each other, thus an internal loop is generated within the main loop.

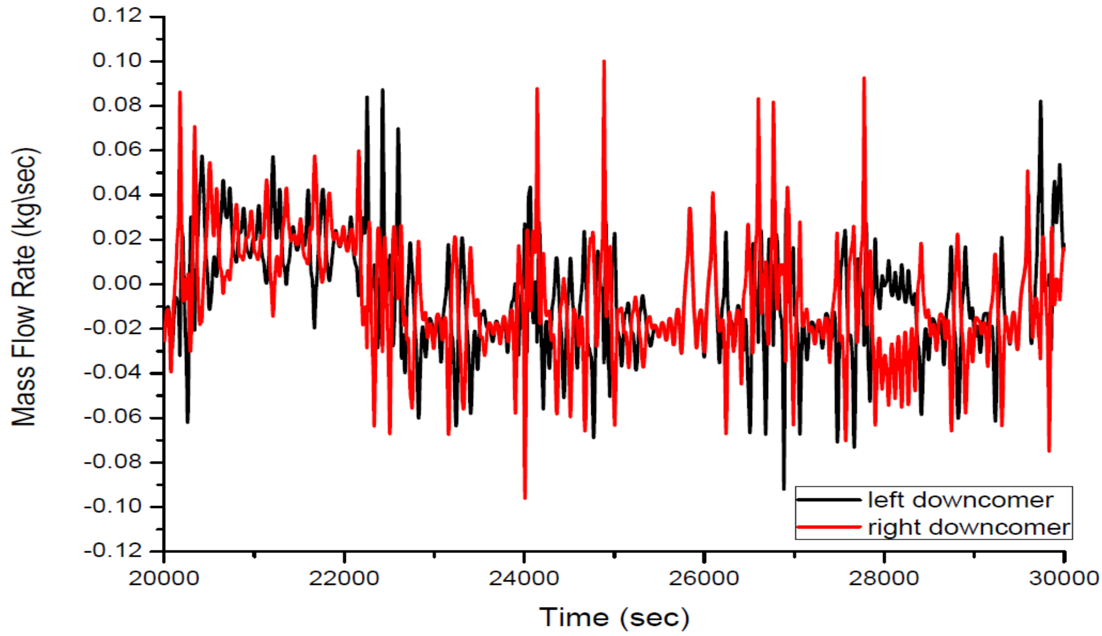

Figure 9: Mass Flow Variation in the Down-comer Channels

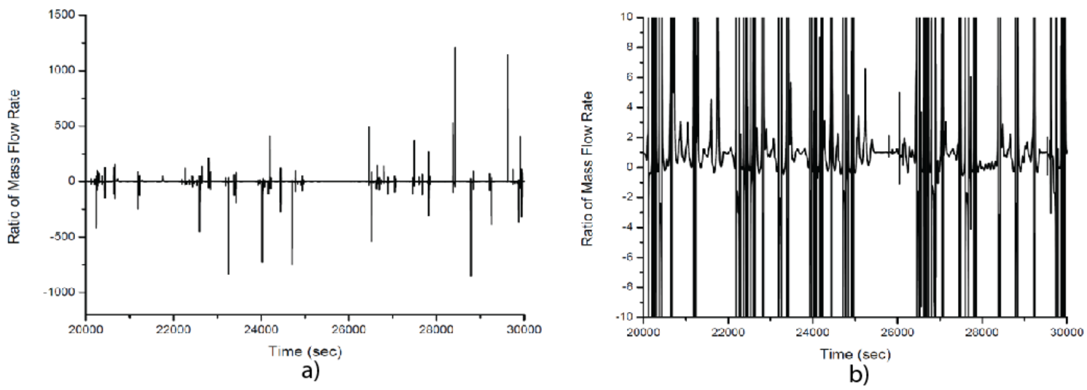

Figure 10: Ratio of Mass Flow Rate of Downcomers

Figure 10a show the variation of ratio of mass flow rates of the down-comers, as it is done in the case of ‘Double Riser Double Down-comer Loop. Figure 10b is a magnified view of Fig. 10a and it suggests that there are almost zero instances when both of downcomers carrying same amount of mass flow rate. The value of ratio of mass flow rate is changing rapidly with time, which explains the highly fluctuating nature of the flow. The presence negative values in the Fig. 9, proves the presence of internal loop but due highly oscillating behaviour of the flow, it is short lived.

3.3 NCL with Double Riser and Single Down-Comer

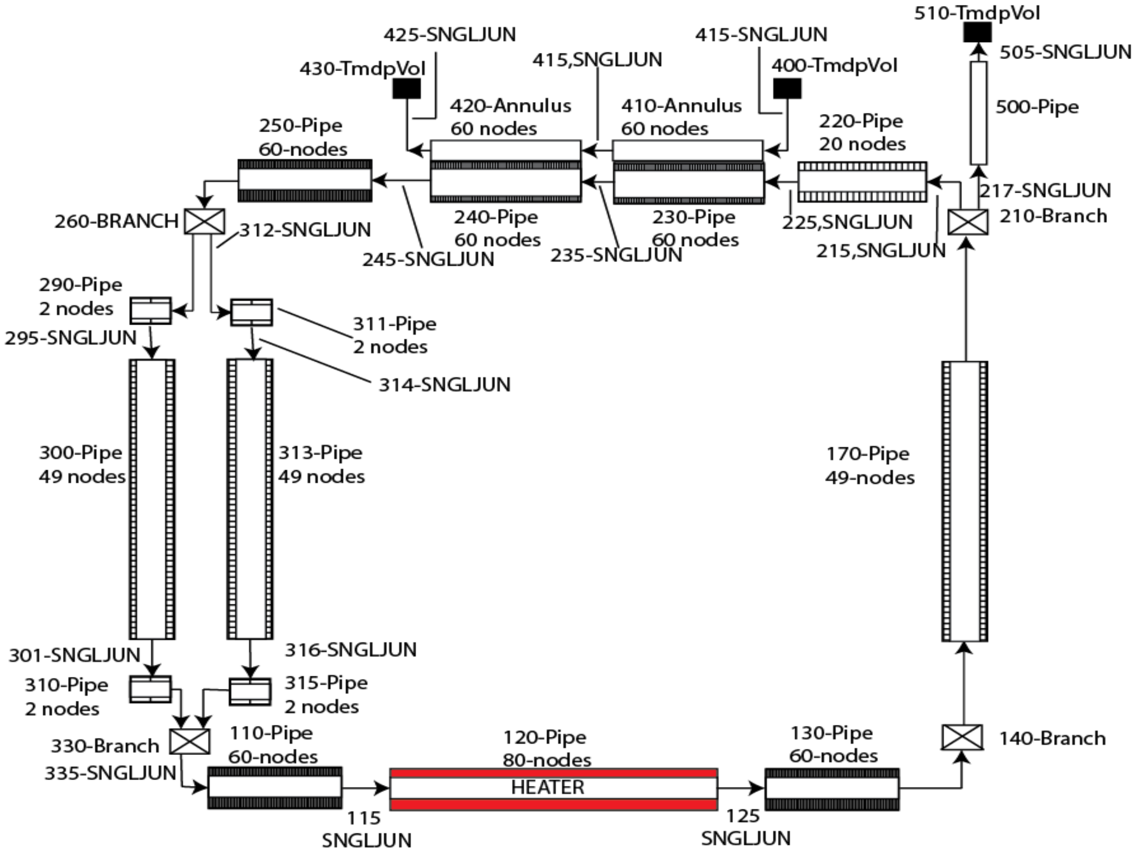

Figure 11: Schematic Diagram for RELAP Code.

The schematic diagram shows the scheme of nodalisation for the RELAP code, of a natural circulation loop containing two risers and one downcomer. The total loop geometry is divided in eighteen sections, which includes 14 pipes and 4 branch sections. The heater section is represented by '120-Pipe' component, the components '240-Pipe' and '230-Pipe' represent the cooler section. The risers are established by the components '300-Pipe'and '313-Pipe', and the downcomer is constructed by the help of '170-Pipe'. The lower and upper horizontal arms of the loop are consisting of '110-Pipe', '130-Pipe' and '220-Pipe', '250-Pipe'. Moreover, two branch components '260-Branch' and '330-Branch' are used at left lower and upper corners of the loop where there was a requirement to create multiple connections. The expansion tank is represented by '500-Pipe'.

The heat exchanger comprised of two annulus section i.e. '420-Annulus' and '410-Annulus', the time dependent volume '400-TmdpVol' serve as inlet to the heat exchanger and specifies the mass flow rate through the heat exchanger, and the time dependent volume '430-TmdpVol' is the outlet of the heat exchanger and specifies its pressure, which in this work is considered to be atmospheric. The pipe sections '290-Pipe', '311-Pipe, '310-Pipe' and '315-Pipe' are the connecting links between the branches and the respective downcomer risers. Two components are joined with the help of 'Single Junction'.

The heater section is consisting of 80 nodes and the two components of the cooler section is consist of 60 nodes each. The two risers and the downcomer are having 49 nodes each. The two other pipe sections of the lower horizontal arm have 60 nodes each and the additional pipe sections in the upper horizontal sections have 20 nodes and 60 nodes.

The double riser single downcomer loop is studied under two different geometrical arrangements. In the first configuration, the cross-sectional area of pipe components present in the risers is same as that of the rest of the loop, on the other hand in the second loop components of the risers have half cross-sectional area to that of the rest of the loop. Both of the configurations are discussed separately.

Uniform Tube Diameter through out the Loop

Figure 12 shows the mass flow rate in the lower horizontal arm where the heater is situated, the flow pattern suggests that in last 6,000 seconds of total simulation run time of 30,000 there is an unidirectional mass flow with an approximate average value of 0.04 kg/sec, as it is seen in the single riser double downcomer loop, with intermittent flow reversals.

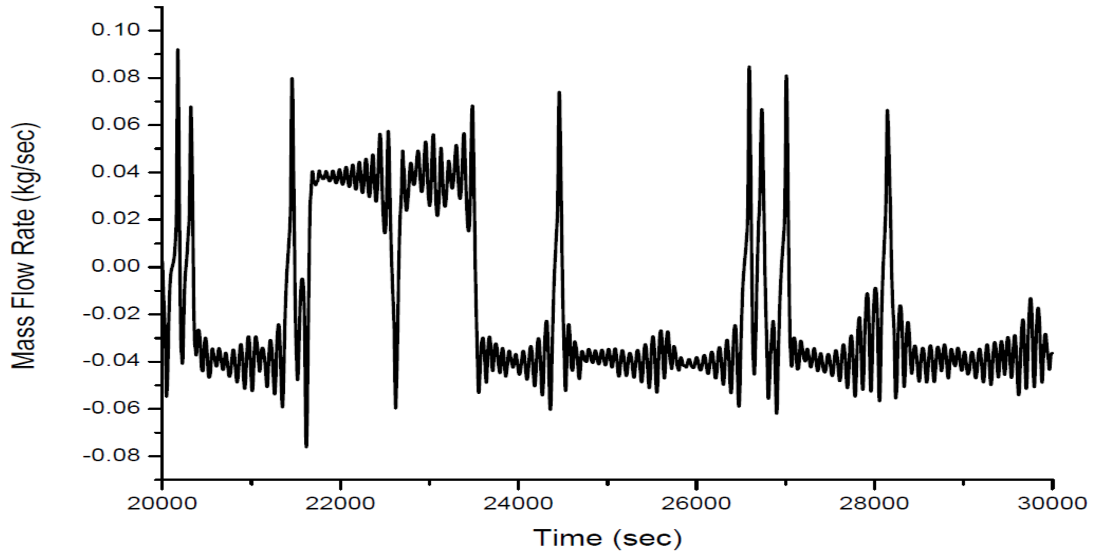

Figure 12: Mass Flow Pattern in Heater Channel

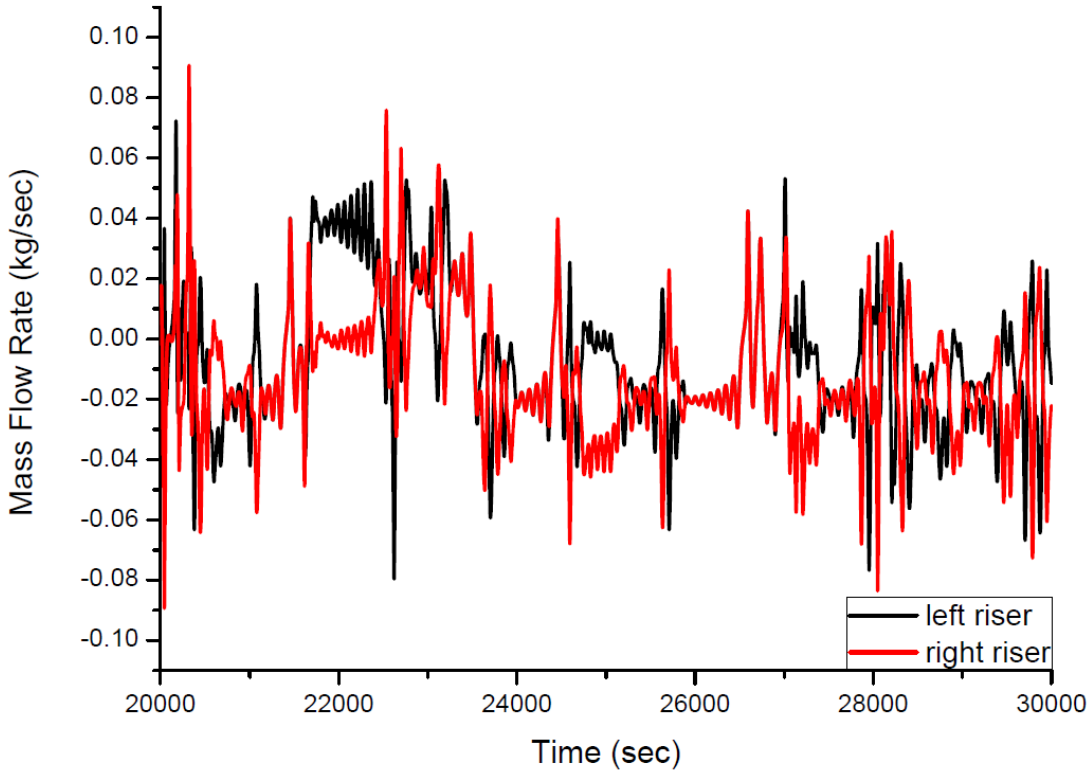

Figure 13: Mass Flow Variation in Riser Channels

Figure 13 displays the mass flow behaviour of the two risers, situated on right-hand side of heater. It can be observed that mass flow rates in both of the risers are not equal always. The tendency of flow reversals is highly dominating in both of the risers. Moreover, at some instances the direction of flow in the risers, is exactly opposite to each other, thus an internal loop is generated within the main loop.

Figure 14a show the variation of ratio of mass flow rates of the risers, as it is done in the previous cases. It displays the normal view of the data, and the very long spike towards the end of the simulation having value of about 65,000 suggests that, the value of mass flow rate in the left risers is very large as compared to the right one, this gives the inference that, almost all of the mass flow input to the riser section is flowing through the left riser only.

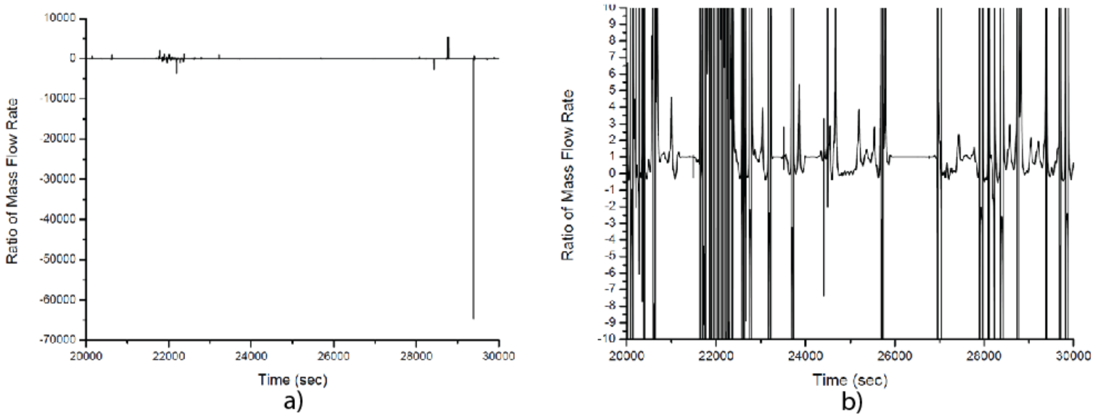

Figure 14: Ratio of Mass Flow Rate of Riser Channels

The magnified view of Fig. 14a is shown in Fig. 14b to drawn some deeper inferences. It can be stated that value of mass flow rate in the risers is changing rapidly in terms of both direction and magnitude as the value ratio of the same is changing rapidly with time. Moreover, there is a non-homogenous distribution of mass flow in the risers most of the time and the instances when there is an equal distribution of flow in risers are very less.

Half the Tube Diameter for the Riser section

Figure 15 shows the mass flow rate in the lower horizontal arm where the heater is situated, the mass flow pattern is highly chaotic undergoing frequent flow reversals. The region of unidirectional oscillating flow observed in uniform cross-sectional loop is absent in this case.

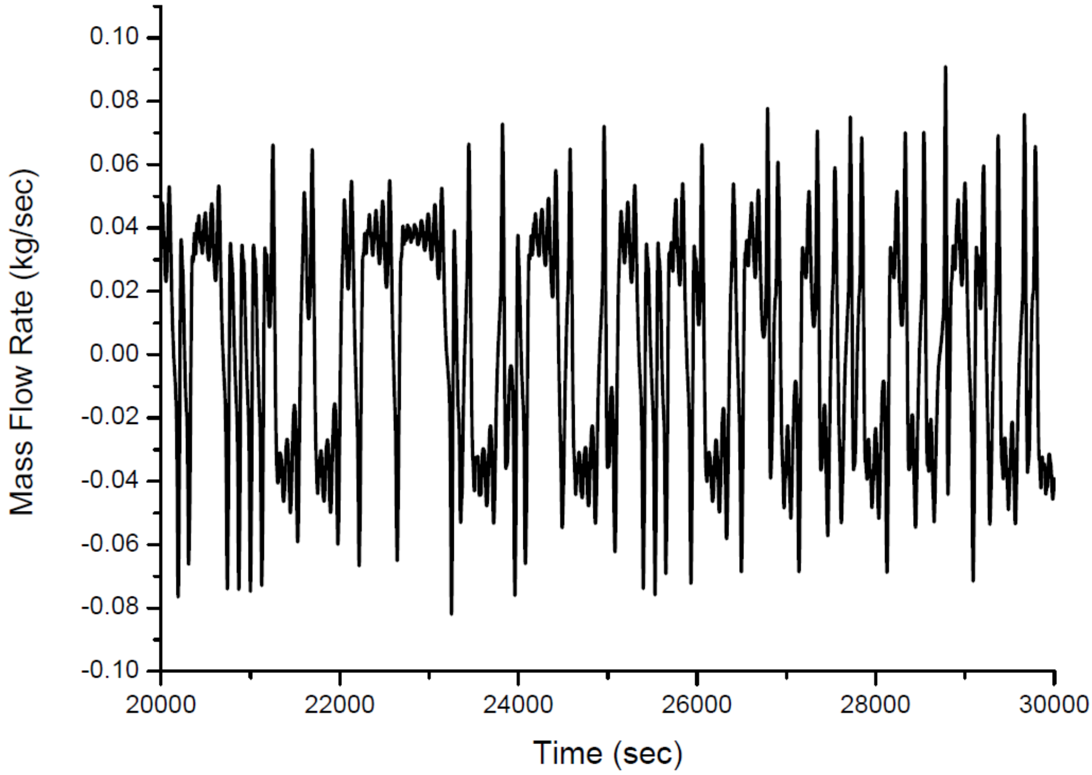

Figure 15: Mass Flow Rate Variation in Heater Channel

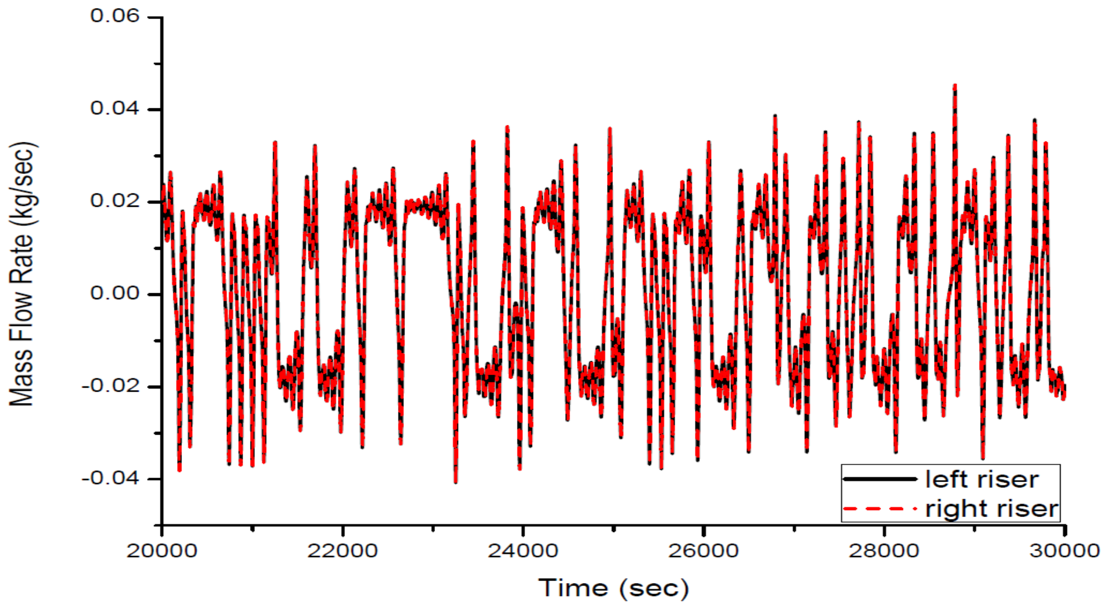

Figure 16: Mass Flow Variations in Riser Channel

Figure 16 shows the mass flow rate variation in the both of the risers, which is highly chaotic and undergoing frequent flow reversals. The point which should be noted here that, the mass flow input to the riser section is equally divided among the risers, which is an observation occurring only in this case only.

Figure 17 shows the variation of ratio of mass flow rate of the risers, from the graph it can be derived that the average value of the mass flow rate ratio of the risers is one, which again supports the fact that both the risers are carrying equal amount of flow rate. There are some positive and negative spikes but their value is very small, thus their effects can be ignored.

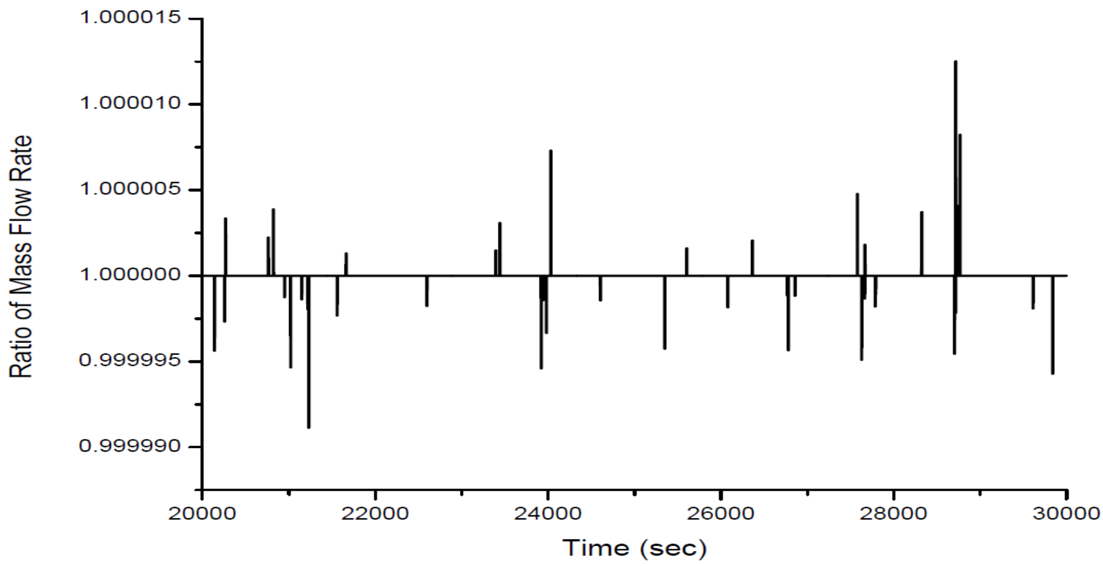

Figure 17: Variation of Ratio of Mass Flow Rate in Risers

3.4 NCL with Double Riser and Single Down-Comer for Header Type Configuration

The schematic diagram shows the scheme of nodalisation for the RELAP code, of a natural circulation loop containing two risers and one down-comer having an inlet and an outlet header. The total loop geometry is divided in sixteen sections, which includes 10 pipes and 6 branch sections. The heater section is represented by '120-Pipe' component, the components '240-Pipe' and '230-Pipe' represent the cooler section. The risers are established by the components '103-Pipe'and '107-Pipe', and the down-comer is constructed by the help of '170-Pipe'. The lower and upper horizontal arms of the loop are consisting of '101-Pipe', '110-Pipe', '130-Pipe' and '220-Pipe', '250-Pipe', '105-pipe' respectively.

Three branch components '102-Branch', '210-Branch, and '260-Branch' are used create multiple connections at a particular location. The expansion tank is represented by '500-Pipe'. The heat exchanger comprised of two annulus section i.e. '420-Annulus' and '410-Annulus', the time dependent volume '400-TmdpVol' serve as inlet to the heat exchanger and specifies the mass flow rate through the heat exchanger, and the time dependent volume '430-TmdpVol' is the outlet of the heat exchanger and specifies its pressure, which in this work is considered to be atmospheric. Two components are joined with the help of 'Single Junction'.

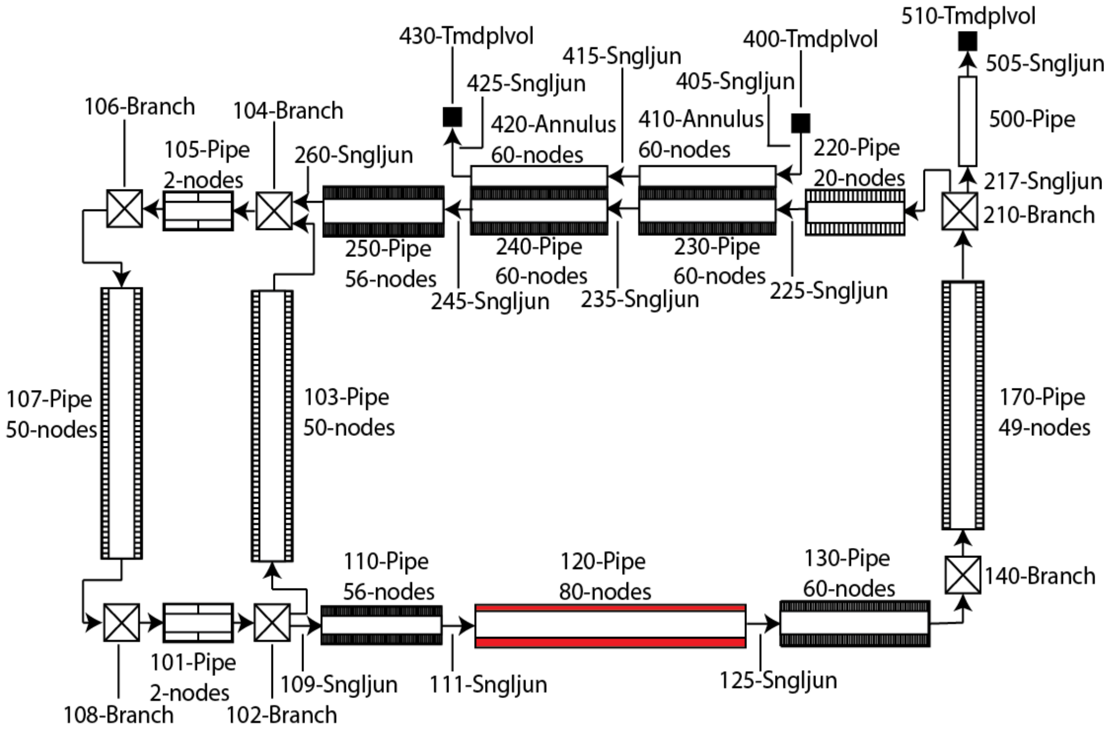

Figure 18: Schematic Diagram for RELAP Code.

The heater section is consisting of 80 nodes and the two components of the cooler section is consist of 60 nodes each. The two risers and the downcomer are having 49 nodes each. The three other pipe sections of the lower horizontal arm have 2, 56 and 60 nodes each and the additional pipe sections in the upper horizontal sections have 2, 56 and 20 nodes.

In the header type loop the cross-sectional area of the risers are half of that of rest of the loop. The figure 19 displays the mass flow rate variation in the lower horizontal arm containing the heater, as we can see that mass flow pattern is highly chaotic, unpredictable and undergo severe flow oscillations, throughout the considered time period.

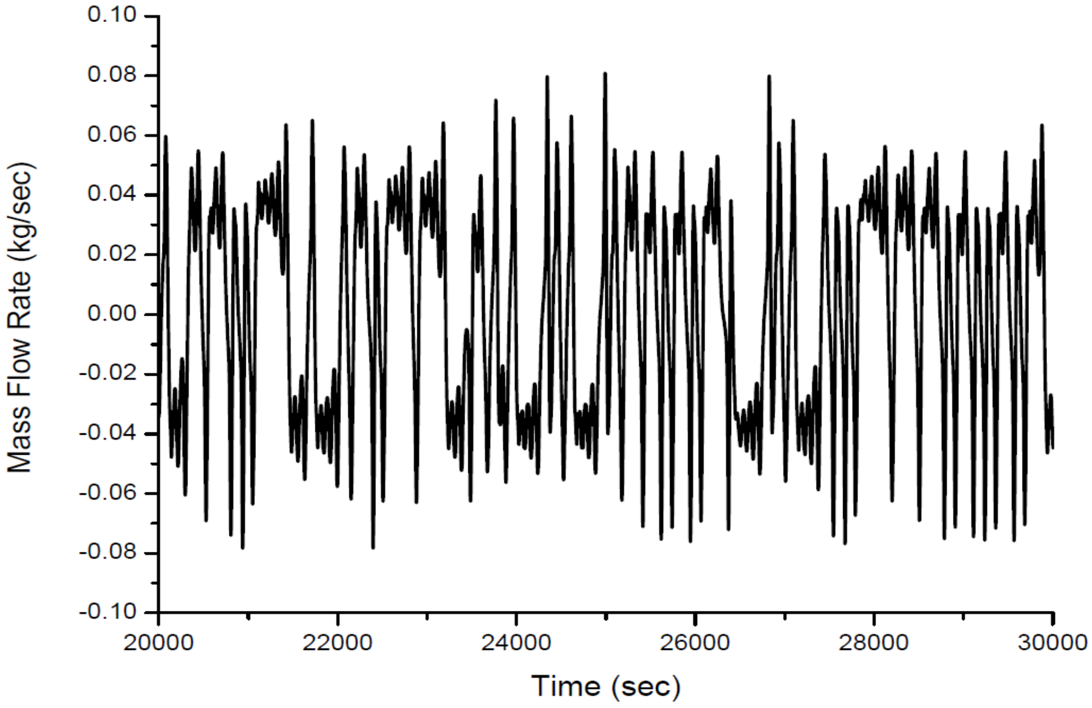

Figure 19: Mass Flow Rate Variation in Heater Channel

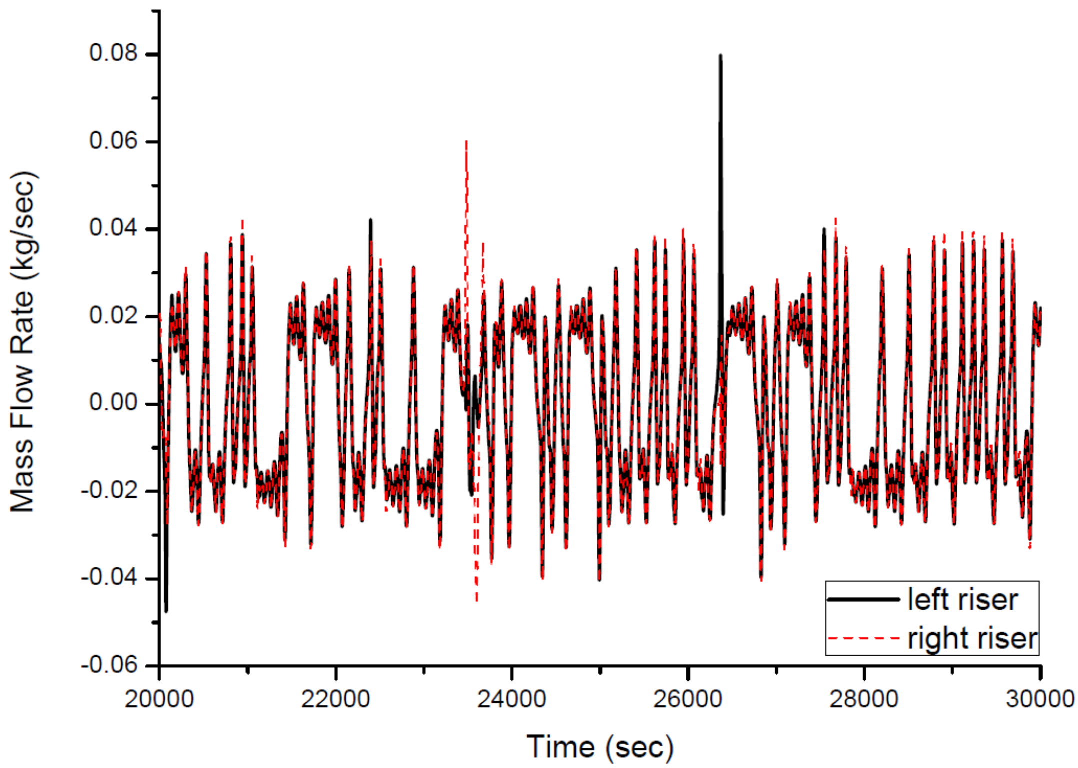

Figure 20: Mass Flow Variation in the Risers

Figure 20 shows the mass flow rate variation in individual risers, of the loop. The graph displays that mass flow rate flowing through the both risers, are having close value with respect to that in other loops. Although, there are instances where the flow rate in one of the risers is different than the other.

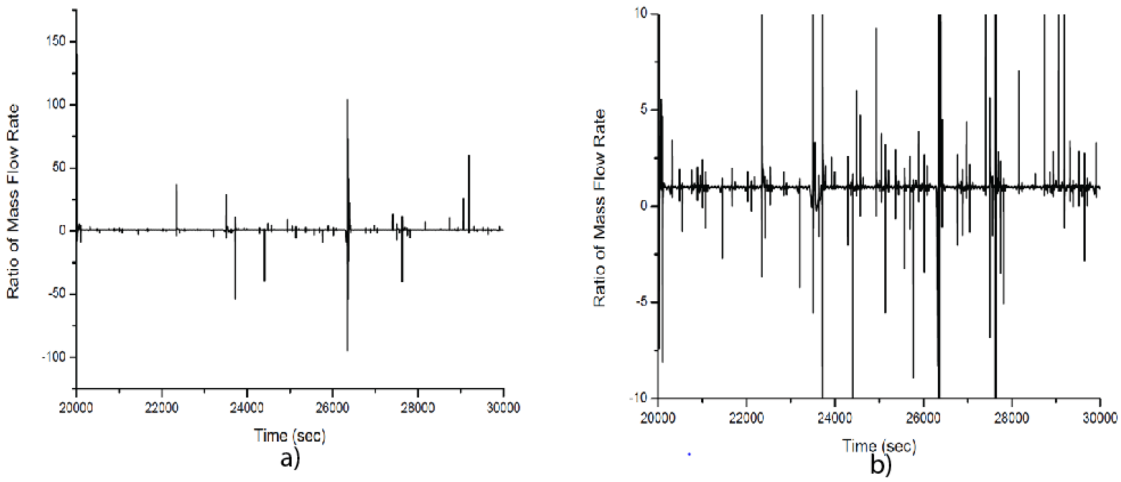

Figure 21: Variation of Ratio of Mass Flow Rate in Risers

Figure 21 show the variation of ratio of mass flow rate of the risers and Fig. 20 show the same in a magnified form. From both the graphs it can be concluded that, the mass flow rate fluctuations in the risers are not as severe as they were in previous loops. Moreover, there are some spikes in the positive and negative regions, but their corresponding values are very less compared to that of other loops, this suggests that difference between the mass-flow rates of the individual risers are not as much as they were in loops considered before.

The graph also shows that, there is an appreciable interval of time when the ratio of mass flow rates has value approximately equal to one, i.e. both of the risers are carrying almost same amount of mass flow.

The values of the mass flow rate ratio present in the negative side of the graph shows that, an internal loop is generated, but since the flow in the risers are fluctuating frequently, the internal loops exist for a very short amount of time.

3.5 Comparative Analysis of NCLs with Different Vertical Channels

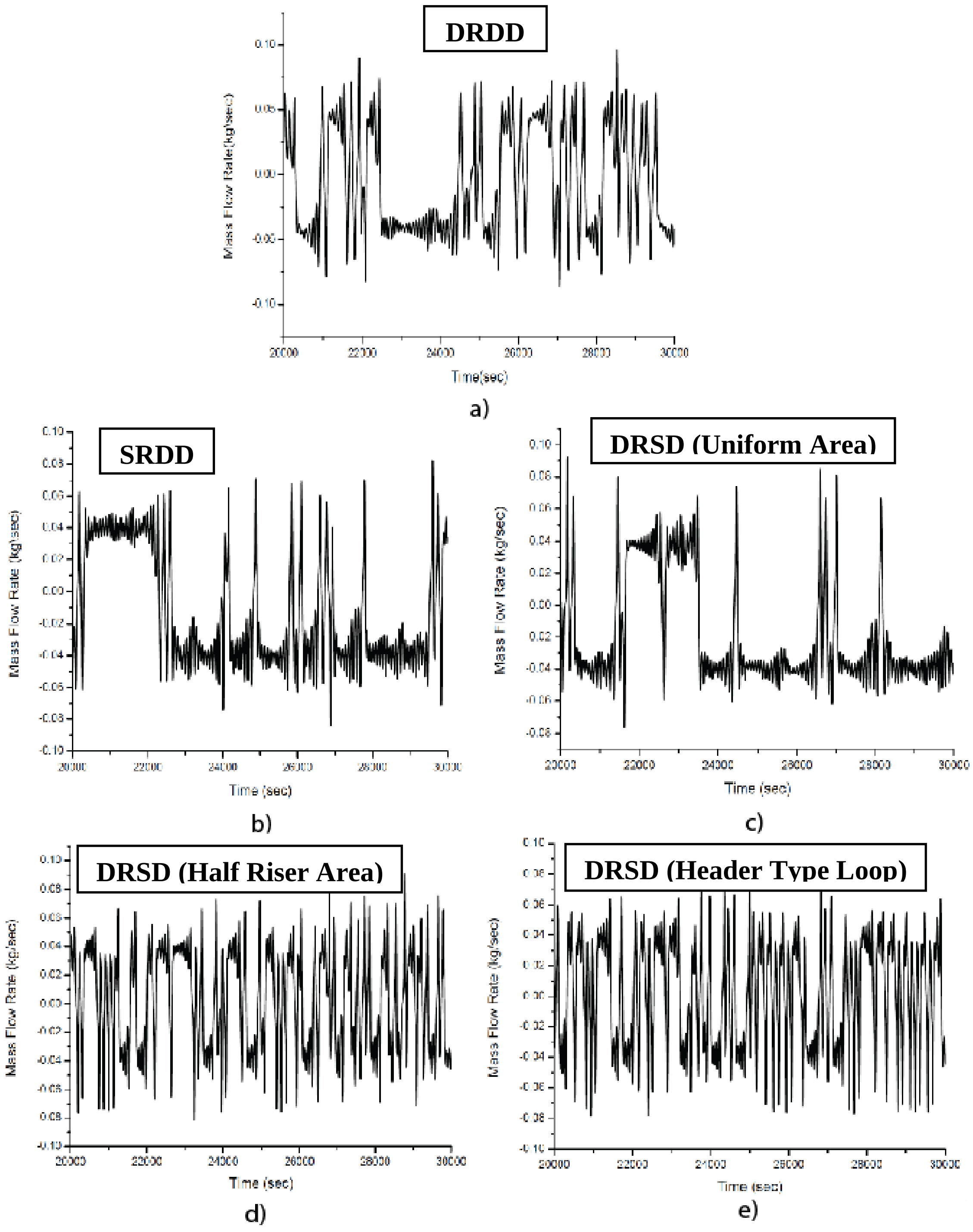

Figure 22: Mass Flow Rate Variation in NCLs with Different Vertical Channels

Figure 22 shows the mass flow rate variation in natural circulation loops with different vertical channels. It can be observed from Fig. 22(a) that in DRDD loop the mass flow is highly oscillating and chaotic in nature, moreover, the fluid motion in the loop is undergoing severe flow reversals.

In case of SRDD loop as it can be inferred from Fig. 22(b), almost after 22,000 seconds there is a unidirectional oscillating flow undergoing intermittent flow reversals. The same nature of mass flow rate variation is observed is observed in DRSD (uniform area) loop Fig 22(c), but the differences are the unidirectional oscillating mass flow is occurring about after 24,000 seconds instead of 22,000 seconds and the numbers of flow reversals incident are much more in SRDD loop than DRSD (uniform area) loop.

With reference to the data of DRSD (half riser area) Fig 22(d) and DRSD (header type loop) Fig 22(e), it can be concluded that the mass flow rate is highly chaotic, unpredictable and undergoing severe flow reversals and it is noticed that there is absence of unidirectional oscillating mas flow rate.

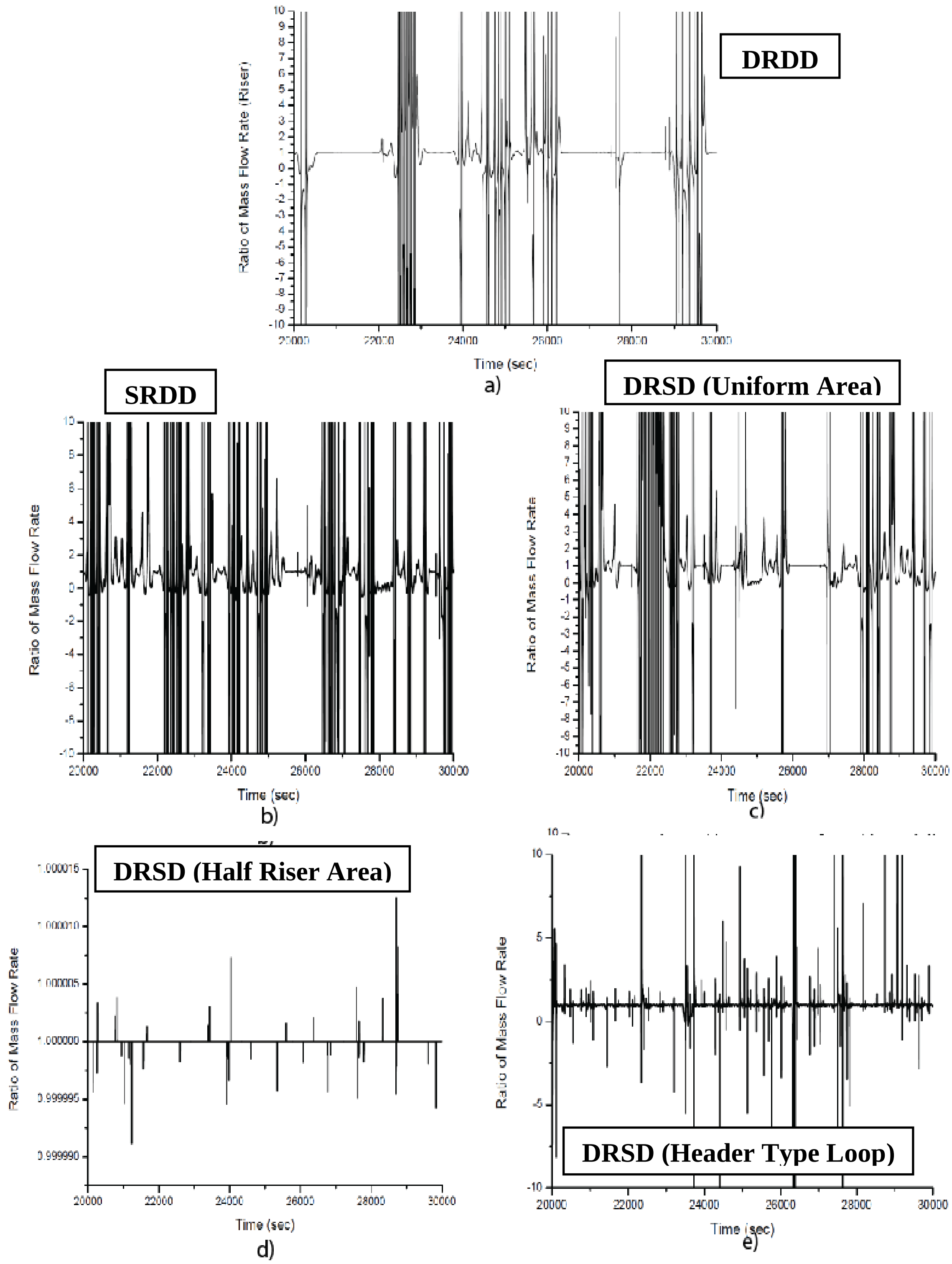

Figure 23: Variation of Ratio of Mass Flow Rate in Vertical Channels in NCLs with Different Vertical Channels

Figure 23, shows the variation of ratio of mass flow rate in the risers or downcomers (depending upon the loop), to predict the nature of mass flow in the vertical channels, to do so the ratio of mass flow rate of left riser or downcomer is divided by the right one, and the required ratio is generated, keeping the direction under consideration. The positive values infer that that the flow direction is in the same direction and vice-versa, from the pattern of negative values the intensity of internal loop generated in the main loop can be predicted.

In DRDD loop, Fig. 23(a), the mass flow rate variation ratio of risers predicts that there is an appreciable fluctuation in the relative magnitude and direction of mass flow in the risers, with regions, having equal distribution of mass flow in the risers with same directions, between the oscillating regions.

In SRDD loop, Fig. 23(b), the mass flow rate variation ratio of downcomers predicts that there is a severe fluctuation in the relative mass flow rate of the downcomers, accompanied with inconsistency of the direction. Similar observation is noticed in the case of DRSD (uniform area) loop, Fig. 23(c), where the relative fluctuation in the mass flow rate of the risers get a little bit less irregular towards the end of the simulation.

In DRSD (half riser area) loop Fig. 23(d), it can be observed that, the maximum variation of the graph from the mean value of one is negligible, this confirms that the relative mass flow rate of the risers in this case are in the same direction as only positive values are encountered and there is an equal distribution of mass flow rate.

In DRSD (header type loop) loop Fig. 23(e), it can be stated that the level of irregularities in the relative mass flow rate of the vertical channel in context of magnitude and direction is more than that of DRSD (half riser area) loop, Fig. 23(d), but less than that of other three geometries included in the study.

CHAPTER 4

CONCLUSIONS & FUTURE SCOPE

4.1 Conclusions of the Proposed Study

The present study based on multi-channel single phase natural circulation loop having horizontal heater and cooler has given a deep insight about the related phenomena, and the conclusions based on given work are listed below: -

I. The flow reversals and oscillations can't be eliminated from the various geometries of the natural circulation loops included in the study, however, their intensity and number of occurrences is different for different geometries. Concerning the mass flow behaviour in horizontal arms of the loops, the loop with four vertical channels is having highly chaotic and unpredictable flow with high number of flow reversals (figure 20(a)).Moreover, in case of loops with three vertical channels having same cross-sectional area for each of the pipe component, the flow is showing unidirectional oscillations about an average value, with comparatively a smaller number of flow reversals (figure 20(b), (c)) than the loop having four vertical channels. Through the analysis of natural circulation with loop three vertical channels having risers with half cross-sectional area as compared to the other pipe components of the loop, it has been noticed that, the flow is more chaotic, unpredictable and undergoing intense flow reversals in comparison of loops having four and three vertical channels (figure 20(d), (e))

II. To analyse the pattern of mass flow rate in the respective downcomers/risers of the concerning natural circulation loops, the respective ratio of mass flow rate is plotted against a time series, this also aided in predicting the generation of internal loop inside the main natural circulation loop. In general, it can be stated that there is no prominent existence of an internal loop, in any of the geometries considered in this study, although the required condition for their generation has aroused intermittently but it was for a minute interval of time.

III. The data regarding natural circulation loop with four vertical channels show that the relative direction and magnitude of mass flow rate of downcomer/risers is changing, but intermittently, there are time intervals when there is an equal distribution of mass flow rate in the risers/downcomers (figure 21(a)).

IV. In the case of loop with three vertical channels with uniform cross-sectional area, relative magnitude and direction of the risers/downcomers is changing, much more intensely than that of loop with four vertical channels and equal distribution of mass flow rate in risers/downcomers in not observed (figure 21(b), (c)). For the loops with three vertical channels and riser cross-sectional area of half value as compared to the rest of the loop, it can be stated that, they provide the most uniform distribution of mass flow rate in the risers in terms of magnitude and direction, among the geometries considered in the present study. Segregating further, it can be observed that the variation of ratio of mass flow rate of the branched loop (figure 21(d)) is much smoother than that in the case of header type loop (figure 21(e)).

V. Concerning the mass flow rate through heater of the loop it can be stated that performance of the three channel loops with uniform cross-sectional area is much better than that of loop with other geometrical configuration included in the study.

VI. If mass flow distribution in the risers/downcomers is considered then it is inferred from the study that loops with three vertical channels with risers having half cross-sectional area as compared to the rest of the loop perform better than the loops with four vertical channels. Moreover, the branched type loop, displays better results than the header type loops.

4.2 Future Scope

The present analysis can be extended in future by analysing the effect of different orientations of heater or cooler on performance of the loop. Also, studies can be carried out with different varieties of coolants such heavy water, carbon dioxide etc.

Moreover, the effect of geometrical dimensional such as variations of aspect ratio of the loop or pipe diameter can serve an interesting topic of research. Further, the effect of reactivity of a nuclear reactor on the performance of the loop can be analysed and the ability of natural circulation in removal of decay heat can also be studied.

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