CATHENA ANALYSIS OF CANDU ADVANCED PASSIVE MODERATOR CONCEPT IN NORMAL OPERATION CONDITION

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ABSTRACT

CATHENA ANALYSIS OF CANDU ADVANCED PASSIVE MODERATOR CONCEPT IN NORMAL OPERATION CONDITION. In the CANDU – advanced passive moderator (APM) concept, the positive void reactivity is eliminated by reducing the density of the moderator. The simple model for the CANDU APM concept consists of the calandria, heat exchanger, pump, and a stabilizing tank, along with connecting piping. The calandria is divided into two parts, one part simulates the down area, while the other simulates up flow area. To demonstrate the thermalhydraulic behavior of the APM concept, Canadian algorithm for thermalhydraulic network analysis (CATHENA) code is used. The simulation for a pressure boundary condition of 300, 330 and 360 kPa and for water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively have been studied. Preliminary results show that there is boiling in the core, with vapor condensing in the heat exchanger. It is important to note, that the solution had not reached steady state when the boiling occurred.

Keywords : CANDU - advanced passive moderator concept, thermalhydraulic, CATHENA.

ABSTRAK

ANALISIS KONSEP *CANDU ADVANCED PASSIVE MODERATOR* PADA OPERASI NORMAL MENGGUNAKAN CATHENA. *CANDU – advanced passive moderator (APM)* mempunyai konsep, bahwa reaktivitas positif fraksi hampa dihilangkan dengan jalan mengurangi densitas moderator. Secara sederhana model CANDU APM terdiri dari kalandria, penukar kalor, pompa, dan tangki stabilizer, yang seluruhnya dihubungkan dengan sistem pemipaan. Kalandria dibagi atas 2 bagian, dimana bagian pertama mensimulasikan daerah air yang turun, sedangkan bagian yang lain mensimulasikan daerah air yang naik. Untuk mendemonstrasikan perlakuan termohidraulika konsep CANDU APM, digunakan perangkat lunak *Canadian algorithm for thermalhydraulic network analysis* (CATHENA). Telah dibuat simulasi dengan kondisi batas tekanan 300, 330, 360 kPa dan kondisi batas laju aliran air pendingin 2000 dan 3000 kg/s. Hasil awal memperlihatkan bahwa terjadi pendidihan dalam teras reaktor, sedangkan di penukar kalor terjadi kondensasi. Perlu dicatat bahwa hasil tidak mencapai keadaan tunak bila terjadi pendidihan.

Kata kunci : konsep *CANDU – Advanced Passive Moderator*, termohidraulika, CATHENA.

I. INTRODUCTION

In the current CANDU 6 design, the heavy water moderator in the calandria is used to thermalize fast neutrons produced by fission. Heavy water is circulated through the calandria and moderator heat exchangers to remove the heat generated in the moderator during reactor operation.

In the first evolutionary step of the CANDU 6 moderator system, it was proposed the passive moderator system features two-phase natural circulation of the moderator during normal operation. In the CANDU-APM concept, the positive void reactivity is eliminated by reducing the density of the moderator.

Operation of moderator fluid through the calandria in single-phase, below saturation temperature with limited local boiling, any excess heat transferred to the moderator, locally or globally, will bring the moderator fluid to boiling locally or globally. The significant decrease in moderator two-phase density creates a rather strong feedback causing the core power to decrease, whereas an increase in moderator density will increase core power. If the excess heat originates from the fuel channel, such as an in-core failure of pressure - tubes, the negative reactivity feedback from the moderator will supplement the negative coolant void reactivity feedback of the coolant.

In the latest CATHENA analysis conducted, a parametric analysis of the moderator loop with pump assist was performed, based on full-power steady state of normal operating conditions. In this analysis, the shut down and the emergency loop were not modelled. The calandria was modelled as a set of circular pipe components, with D_2O as the fluid within the pipe with the heavy water inlet at the bottom of calandria.

In the present study, the improvement of the previous calandria system model has been done.

II. DESCRIPTION OF MODEL [1]

The objective of the current analysis was to demonstrate the thermalhydraulic behavior of the APM concept. This simple model for the APM concept consists of the calandria, heat exchanger, pump, and a stabilizing tank, along with connecting piping. The calandria is divided into two parts, one part simulates the down flow area, while the other simulates up flow area.

Moderation in the form of wet steam at saturation pressure flows from the vapor domes to a heat exchanger to condense the vapor. A wall model is attached to the tube side of the heat exchanger to transfer heat from the tube to the shell side. A flow boundary condition is imposed at the shell side of the heat exchanger.

The pressure in the moderator system is controlled passively through the use of a Constant pressure steam expansion tank (CPSET) in which a loaded piston with a constant weight is installed. Minor pressure fluctuations are compensated by expansion or compression of steam volume below the piston as it is moving up or down the CPSET. A simulation boundary condition at the top of the calandria establishes the temperatures and pressures.

The flow is driven by a pump which matches the specifications given in the Moderator system design manual for Wolsong[2] .

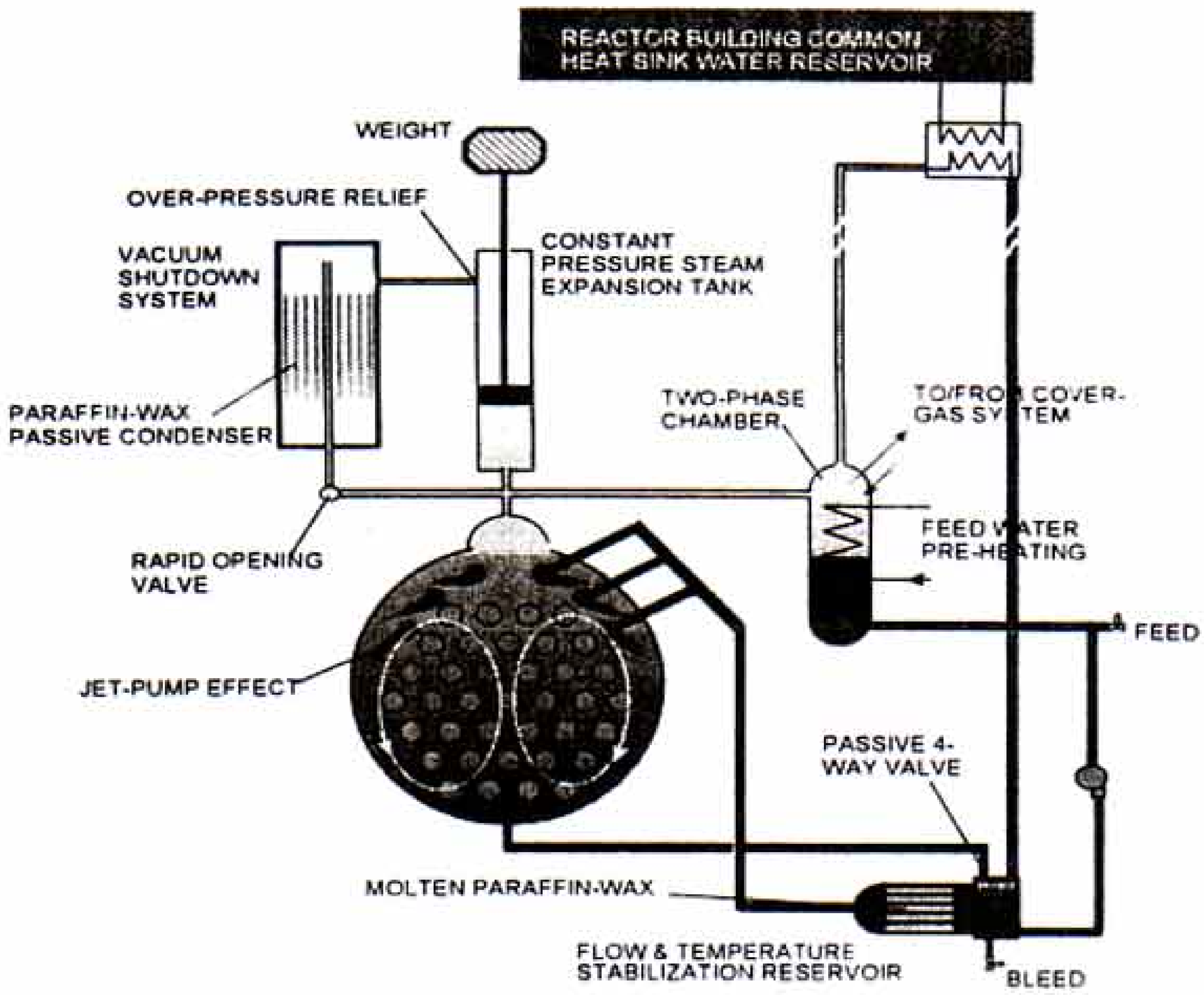

Figure 1. Schematic of CANDU-APM Moderator System

Canadian algorithm for thermalhydraulic network analysis (CATHENA) is a one-dimensional two-fluid thermalhydraulic code. The model consists of energy, mass, and momentum equations for both liquid and gas phases. The solid heat transfer model included in CATHENA is called Generalized heat transfer package (GENTHP). The CATHENA version used is MOD3.5c/Rev.0[3,4].

III. MODERATOR DESIGN PARAMETERS [2]

III.1. Control Parameters

Each simulation is completed for a total duration time of 5,000 seconds, with a minimum time step of 0.0001 s, and a maximum allowable time step of 0.5 s.

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III.2. Piping Components

The calandria is modelled as two sets of circular pipe components, with D_2O as the fluid within the pipe. The first set of circular pipe components, simulates the down flow area, which is divided into 29 sections, while the second set simulates the up flow area, which is divided into 32 sections. Length and height of pipe components in the calandria correspond to those of Figure 2. Cross-sectional area values are determined from specified volumes in Appendix. The total volume of the moderator calandria is 223 m^3 , with an overall height of 7.5 m. A low roughness value of 0.00001 m is used for the pipe walls.

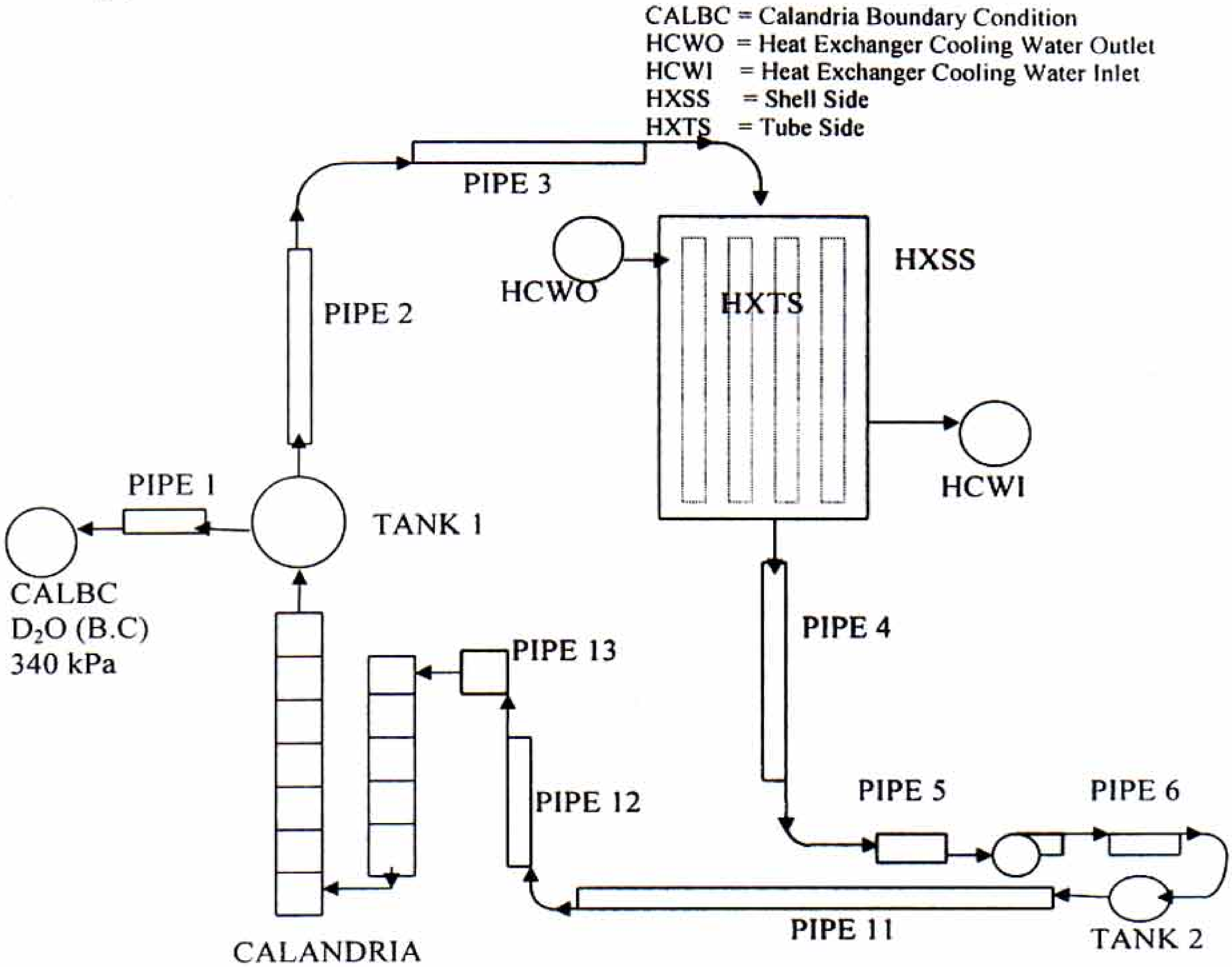

Figure 2 Diagram for CATHENA APM Simulation

The dome situated at the top of the calandria is modelled as a volume component of 4 m^3.

A vertical shell and tube heat exchanger for the moderator system is modelled as follows. The tube side of the heat exchanger is comprised of 1350 tubes, 0.0159 m in diameter and 6.0 m in length. The shell side is also 6.0 m in length. There is a wall model in the input file that transfers heat between the shell and tube sides.

The pump model utilized has the following characteristics, as found in the Wolsong Main Moderator System design Manual: rated head of 5.0 m; rated volumetric flow of 0.94 m^3/s; rated density of 1085 kg/m^3; rated and operating speed of 1180 RPM and stopped K factor of 3.572.

The paraffin wax tank is modelled as a volume component of 40 m^3.

III.3. Boundary Conditions

Boundary conditions are established using a reservoir component in CATHENA. The specific values used for the simulations are pressures of 360, 330 and 300 kPa.

The shell of the heat exchanger requires an inlet boundary condition, containing gas and liquid enthalpies for a temperature of 35°C, along with a flow boundary condition of 2000 and 3000 kg/s.

The total heat input to the calandria is 138MW. The heat input profile is found in Figure 3. Heat is removed via the wall model between the shell and the tube side of the heat exchanger.

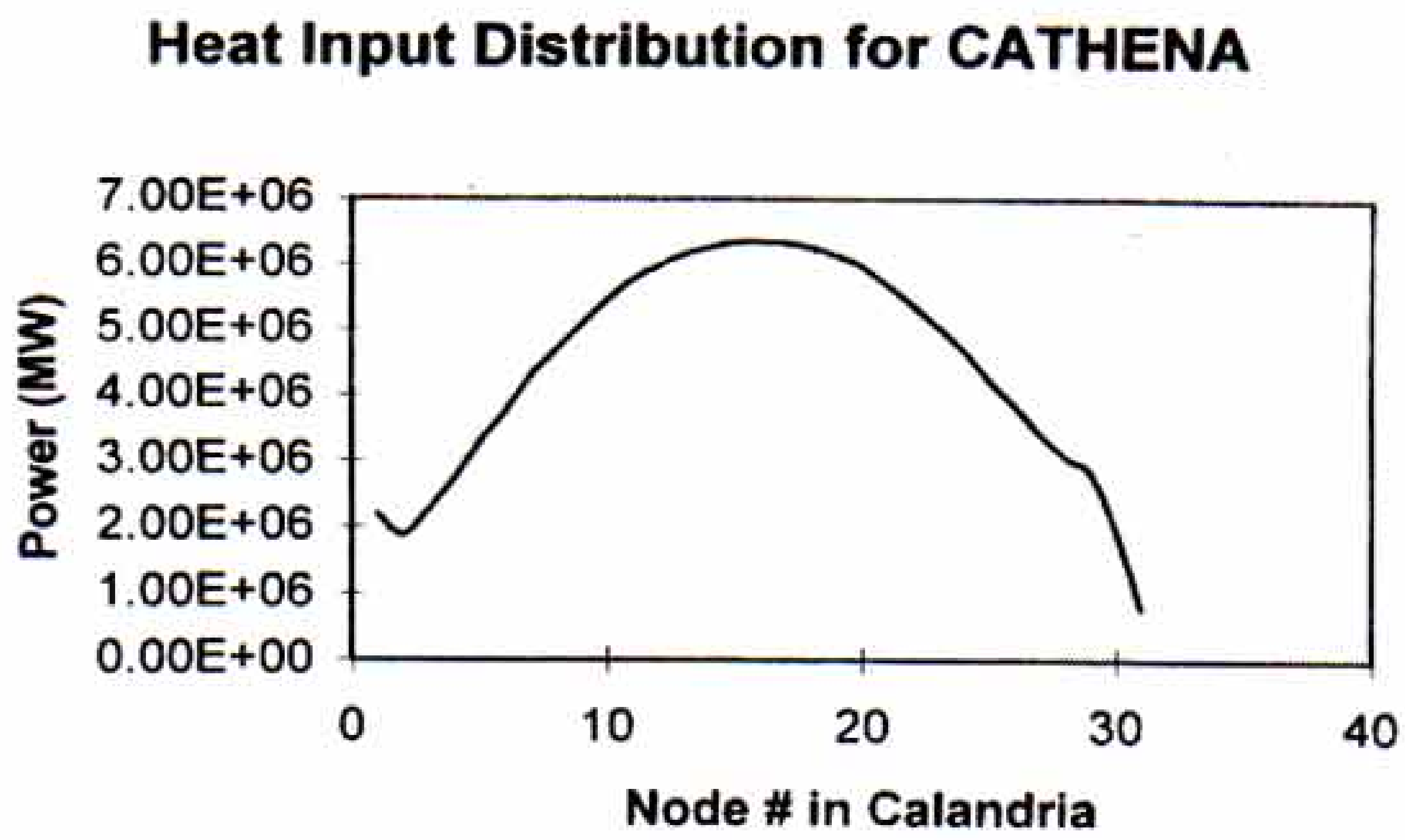

Figure 3. Heat Input Distribution for CATHENA

III.4. System Models

Pressure losses in CATHENA are automatically calculated across piping components.

The Pump Model is used to simulate a pump between two pipe components. An input table is utilized to specify the homologous pump head in single phase flow. By default, work done by the pump is not added to the energy equation.

III.5. Initial Conditions

All nodes with the exception of the secondary side of the heat exchanger are given the initial values of 300 kPa, and enthalpies corresponding to 92°C. Enthalpies for the secondary side of the heat exchanger are applied at 35°C. All node velocities are set to 0.0 m/s.

III.6. Heat Transfer Package Description

GENHTP in CATHENA models the heat transfer between solid components. This package is used in the simulation to calculate the heat transfer between the tube and shell side of the heat exchanger. Most of the heat transfer options used in the model are defaulted.

The wall model for the tubes in the heat exchanger are modelled in two radial regions, of thickness 0.00795 and 0.00908 m. The length of the tube side for the heat exchanger is 6.0 m, and is axially divided into 50 nodes of equal length.

The Hydraulic boundary conditions are used to attach GENHTP inner and outer surfaces to the fluid conditions in the CATHENA thermalhydraulic nodes. Parameters that determine heat transfer rates between the GENHTP model and CATHENA thermalhydraulic nodes are also included.

Inside boundary condition is applied at the tube side of the heat exchanger. The outside boundary condition is applied at the secondary side of the heat exchanger.

The Boiling indices entry defines the heat transfer correlations used to determine the heat flux belonging to the onset of nucleate boiling, critical heat flux and rewetting temperatures. The default values are used.

The HT-correlations entry is used to define the heat transfer correlations which calculate the heat transfer coefficient at the wall model surface. The default values are used. The heat flux integration scheme used is the Linear-inferred-temperature-3-point, which linearly interpolates the wall model temperatures between two neighbouring axial segments.

The Interface entry defines which heat transfer correlations are used to calculate heat transfer directly from the GENHTP wall models to the steam/liquid interface. The default setting selects the Saha-Zuber onset of significant void correlation to calculate wall vapor generation and wall condensation.

The material properties entry defines the thermal properties for each radial region specified in the model. The thermal properties of stainless steel are found in the GENHTP library.

The heat generation entry defines the heat generation rates in each radial region of the solid component model. No heat generation is assumed as the default entry. The initial condition for the temperature distribution in the solid is set to 35°C at all locations.

IV. RESULTS & DISCUSSIONS

In the present study, the analysis simulations have been conducted to examine the thermal hydraulic behavior of the proposed moderator system. Six cases for any combination of pressure boundary conditions and water coolant mass flow rate boundary conditions have been simulated.

The simulation for a pressure boundary condition of 300, 330 and 360 kPa and for water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively have been studied. Preliminary results show that there is boiling in the core, with vapor condensing in the heat exchanger. The following results correspond to a total heat load of 138 MW throughout the circuit, of 1350 tubes in the vertical heat exchanger, with a pump head of 5 m.

A mass flow rate simulation plot is shown in Figure 4. Single phase solutions are found for pressure boundary conditions of 360 kPa and water coolant mass flow rate boundary conditions of 3000 kg/s. A total mass flow rate of about 558 - 600 kg/s, single phase throughout and a stable solution has to be reached. For the pressure boundary conditions of 300, 330 and 360 kPa with water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively, the two phase solutions are found. It is important to note, that the solution had not reached steady state when the boiling occured.

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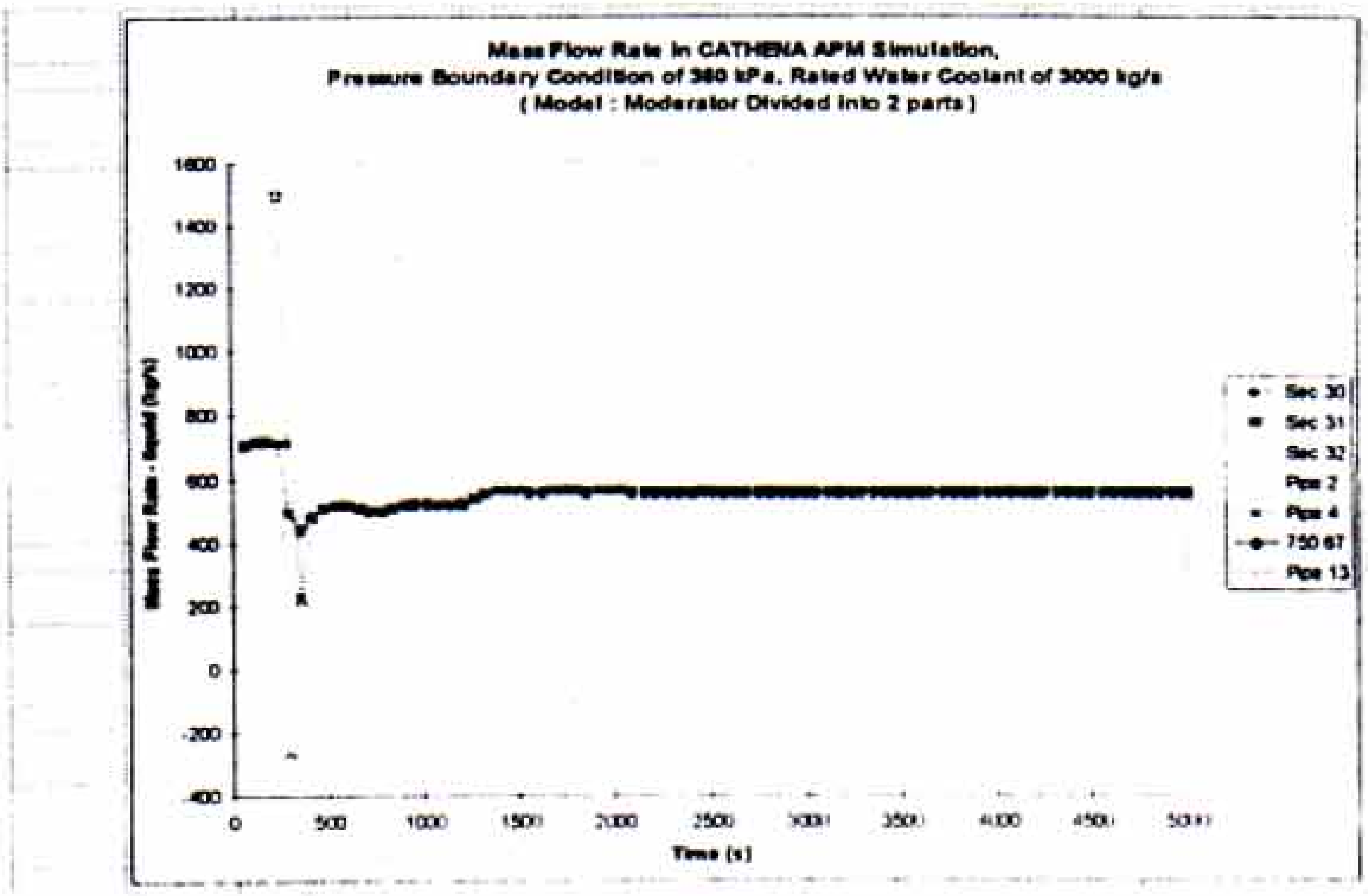

Figure 4. Mass Flow Rate in CATHENA APM Simulation,
Pressure Boundary Condition of 360 kPa, Rated Water Coolant of 3000 kg/s

A pressure simulation plot is shown in Figure 5. Similarly with a total mass flow rate, a stable solution has to be reached for pressure boundary conditions of 360 kPa and water coolant mass flow rate boundary conditions of 3000 kg/s.

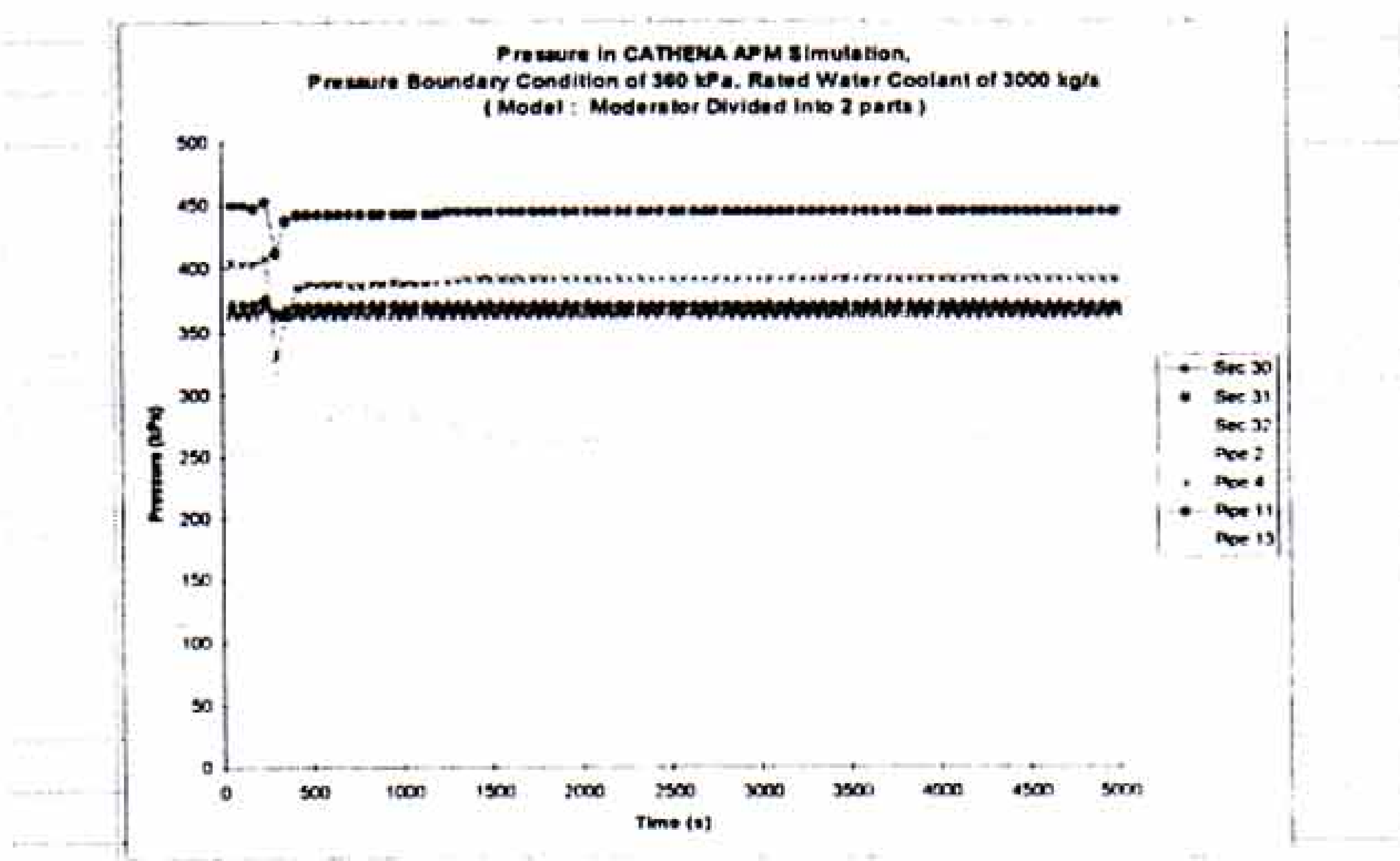

Figure 5. Pressure in CATHENA APM Simulation,
Pressure Boundary Condition of 360 kPa, Rated Water Coolant of 3000 kg/s

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The inlet temperature to the calandria for the pressure boundary conditions of 300, 330 and 360 kPa with water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively, are 75.7°C, 75.5°C, 73.4°C, 78.3°C, 81.2°C and 83.1°C while exit temperatures at the top of the calandria are 134.7°C, 137.9°C, 132.3°C, 134.7°C, 137.9 and 134.7°C. A temperature simulation plot for the pressure boundary condition of 300 kPa with water coolant mass flow rate boundary conditions of 2000 kg/s is shown in Figure 6.

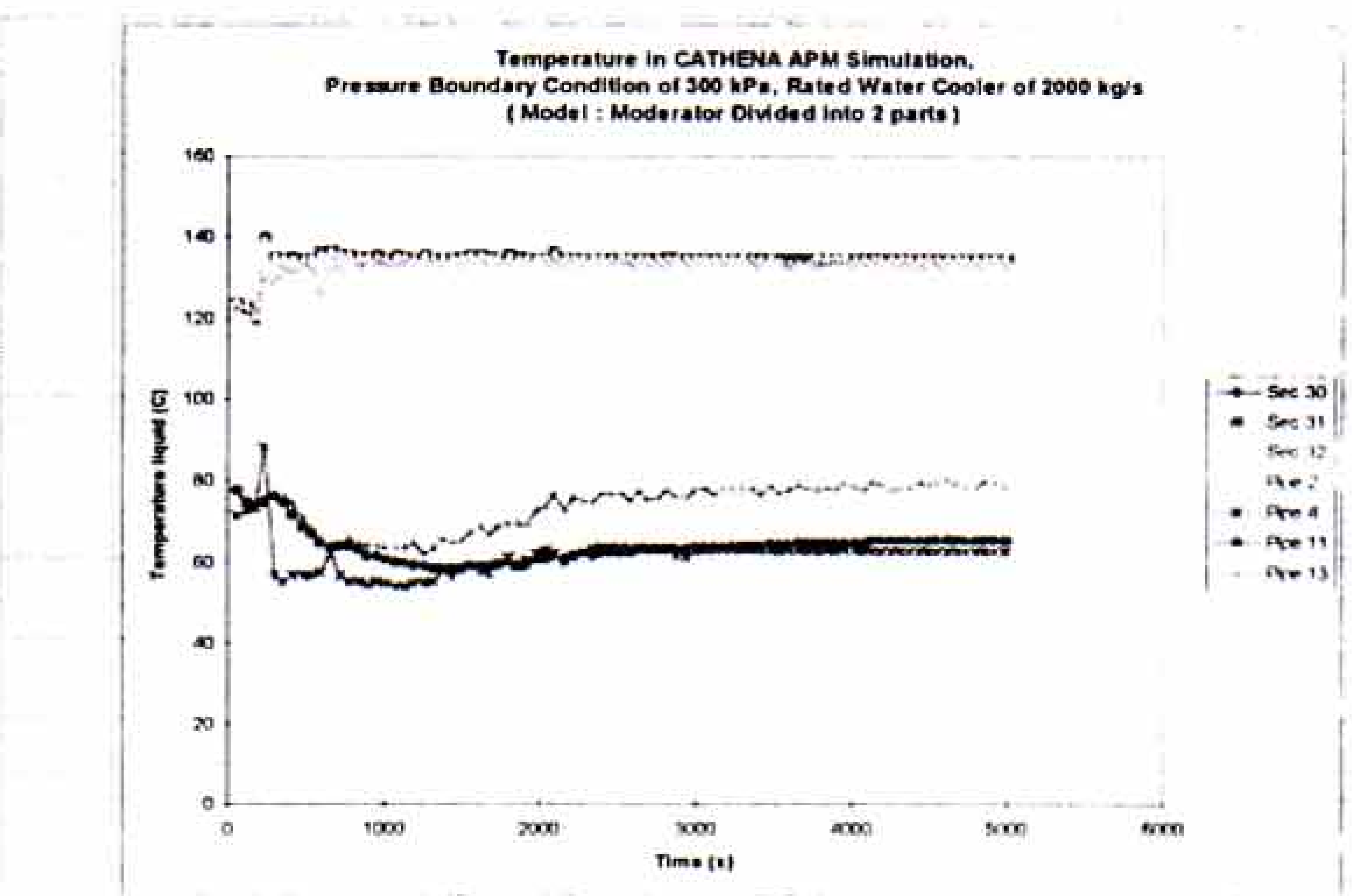

Figure 6. Temperature in CATHENA APM Simulation,
Pressure Boundary Condition of 300 kPa, Rated Water Cooler of 2000 kg/s

A void simulation plot is shown in Figure 7. The fluctuation in mass flow rate did not affect the void quality and the temperature distribution by any significant amount.

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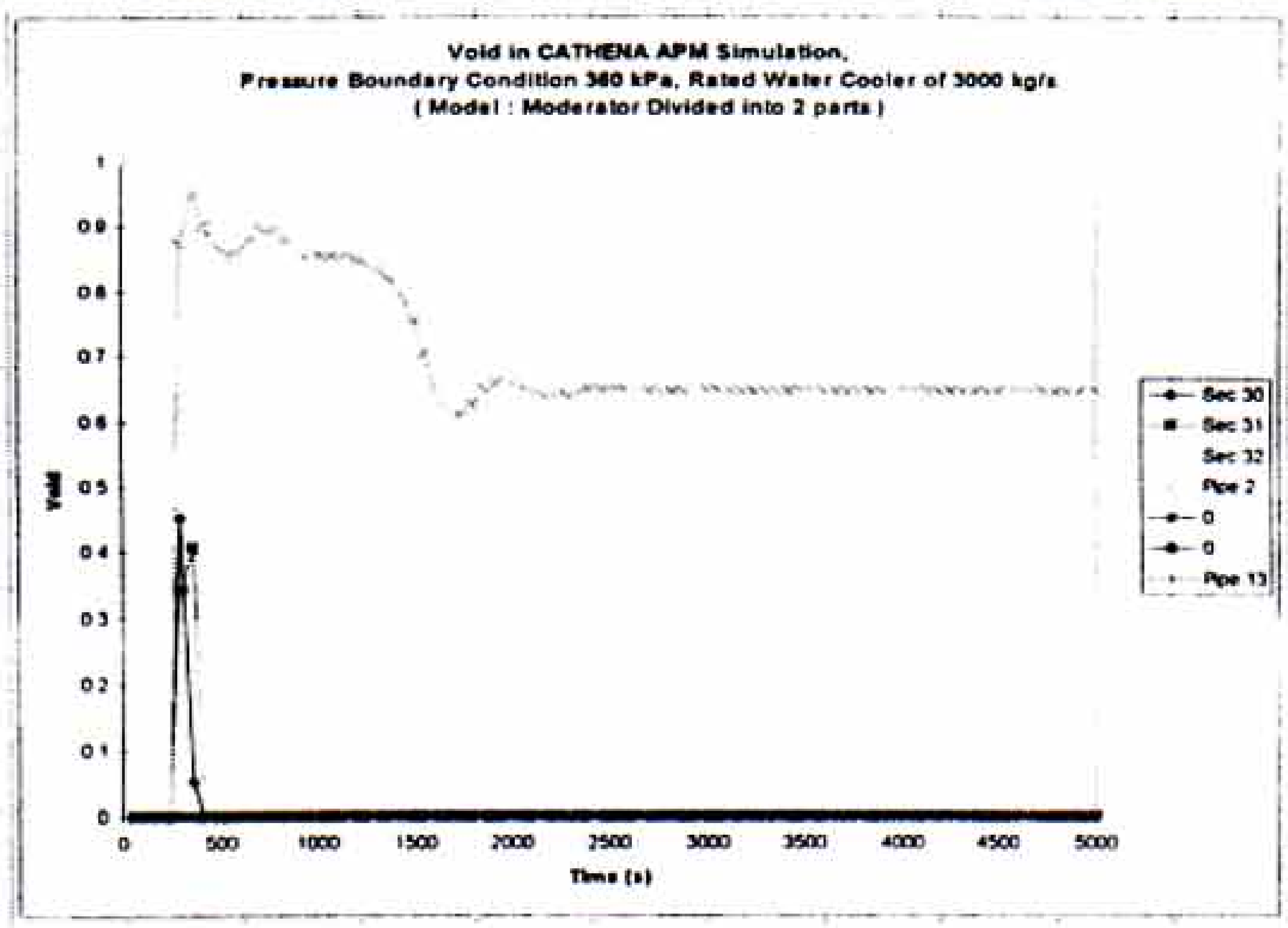

Figure 7. Void in CATHENA APM Simulation,
Pressure Boundary Condition 360 kPa, Rated Water Cooler of 3000 kg/s

A pressure distribution plot throughout the circuit for a pressure boundary condition of 360 kPa and water coolant mass flow rate boundary condition of 3000 kg/s is found in Figure 8. The lowest pressure point is found at the node prior to the heat exchanger inlet. The pressure starts to rise once the fluid enters the heat exchanger. That is expected since the density of the fluid also increases as it is cooled.

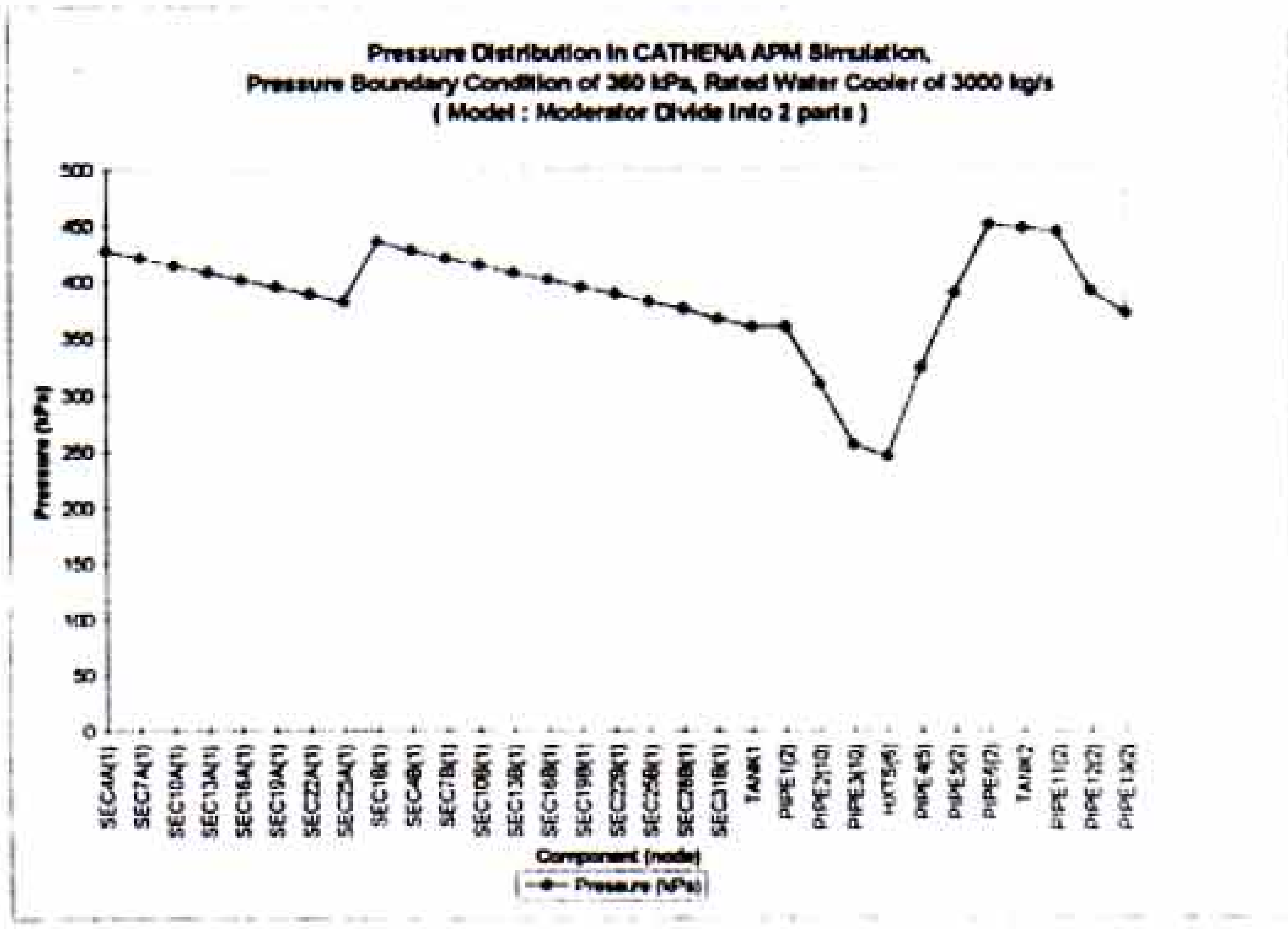

Figure 8. Pressure Distribution in CATHENA APM Simulation,
Pressure Boundary Condition of 360 kPa, Rated Water Cooler of 2000 kg/s

A temperature distribution plot throughout the circuit for pressure boundary condition of 360 kPa and water coolant mass flow rate boundary condition of 3000 kg/s is found in Figure 9. The inlet temperature to the calandria is 73.4°C and the exit temperature at the top of the calandria is 132.3°C.

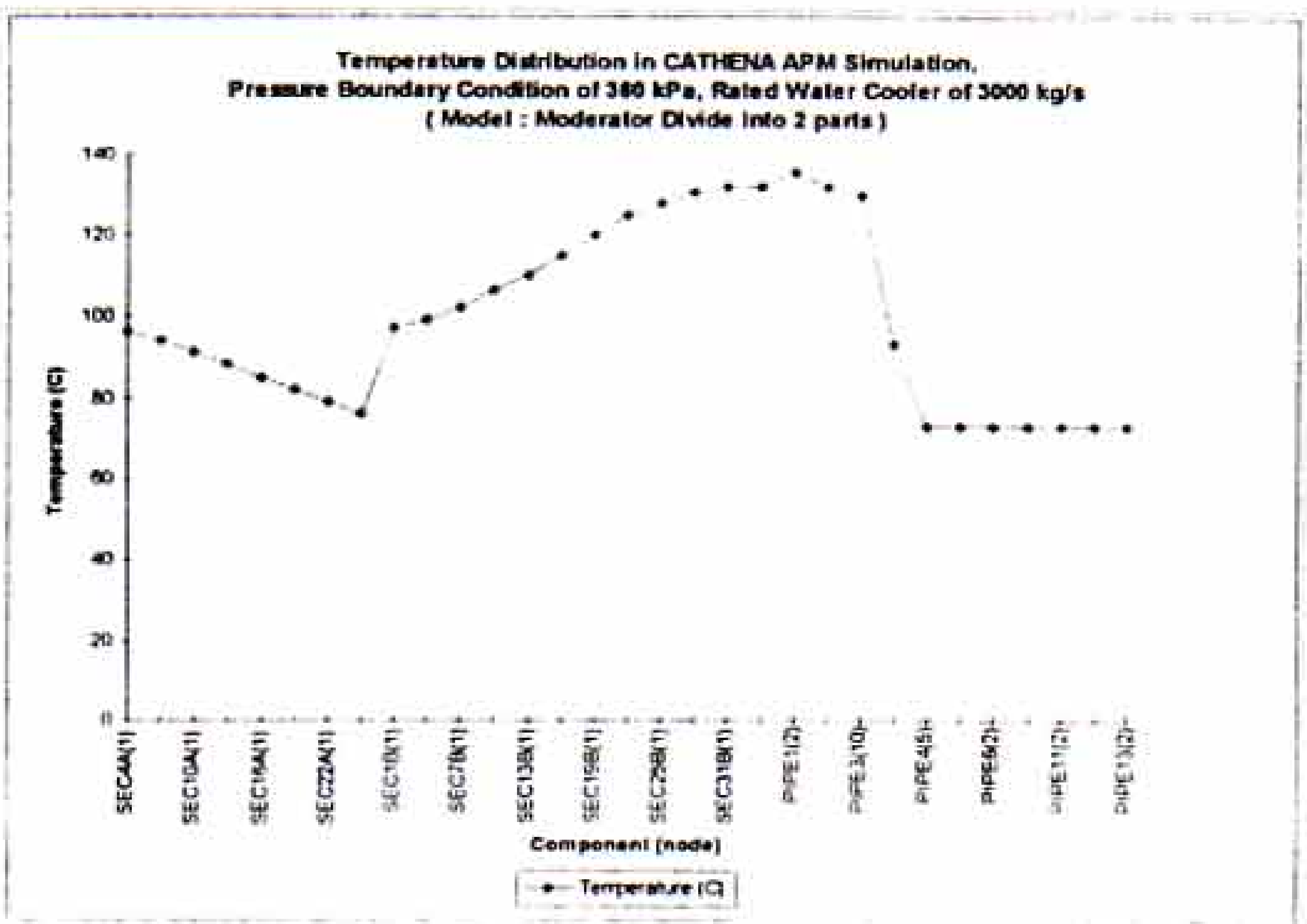

Figure 9. Temperature Distribution in CATHENA APM Simulation, Pressure Boundary Condition of 360 kPa, Rated Water Cooler of 3000 kg/s

Mass flow rate, pressure, temperature and void plots as a function of time for specific nodes in the circuit for pressure boundary conditions of 300, 330 and 360 kPa and for water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively have been simulated.

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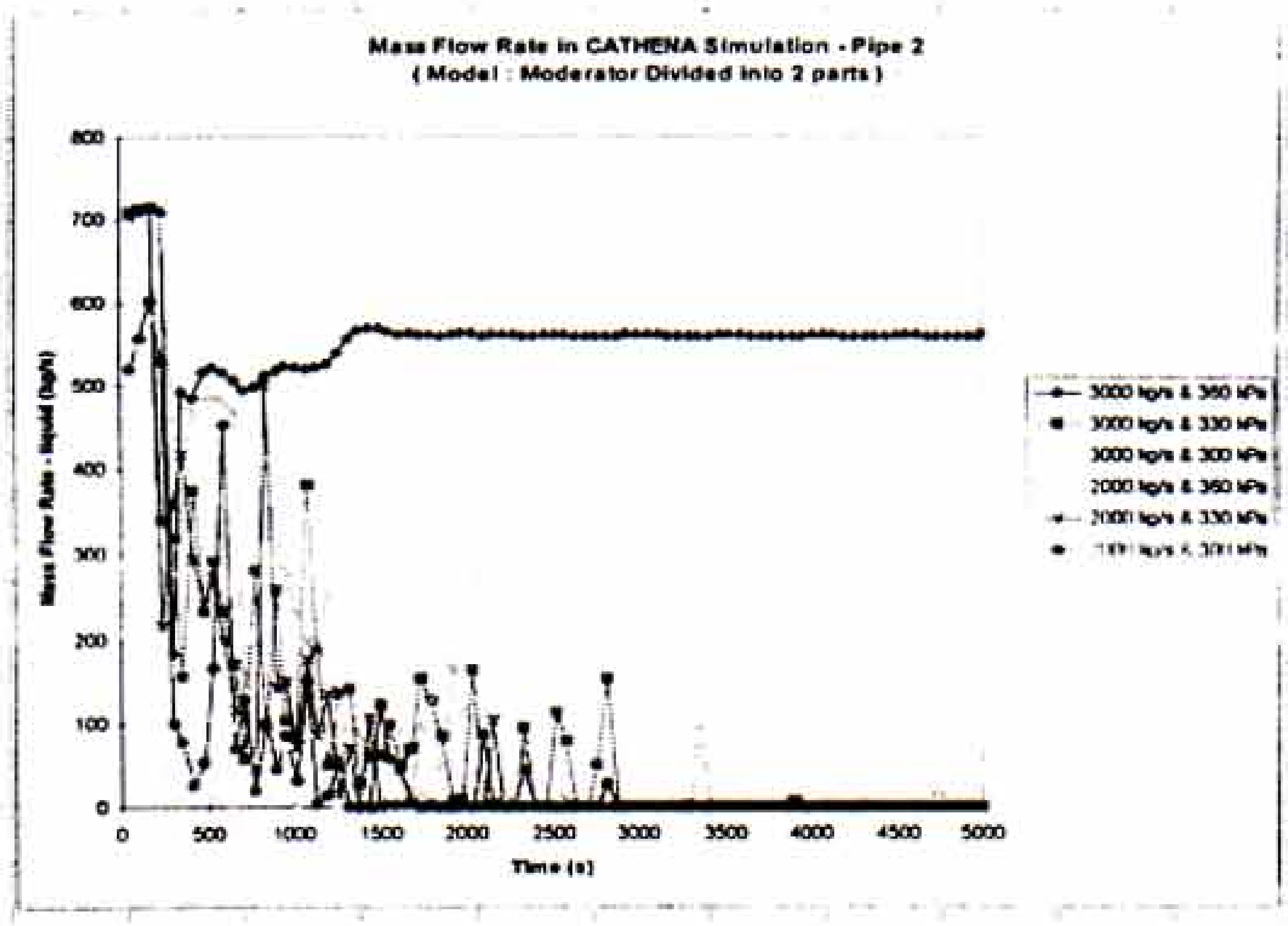

Figure 10. Mass Flow Rate in CATHENA Simulation - Pipe 2

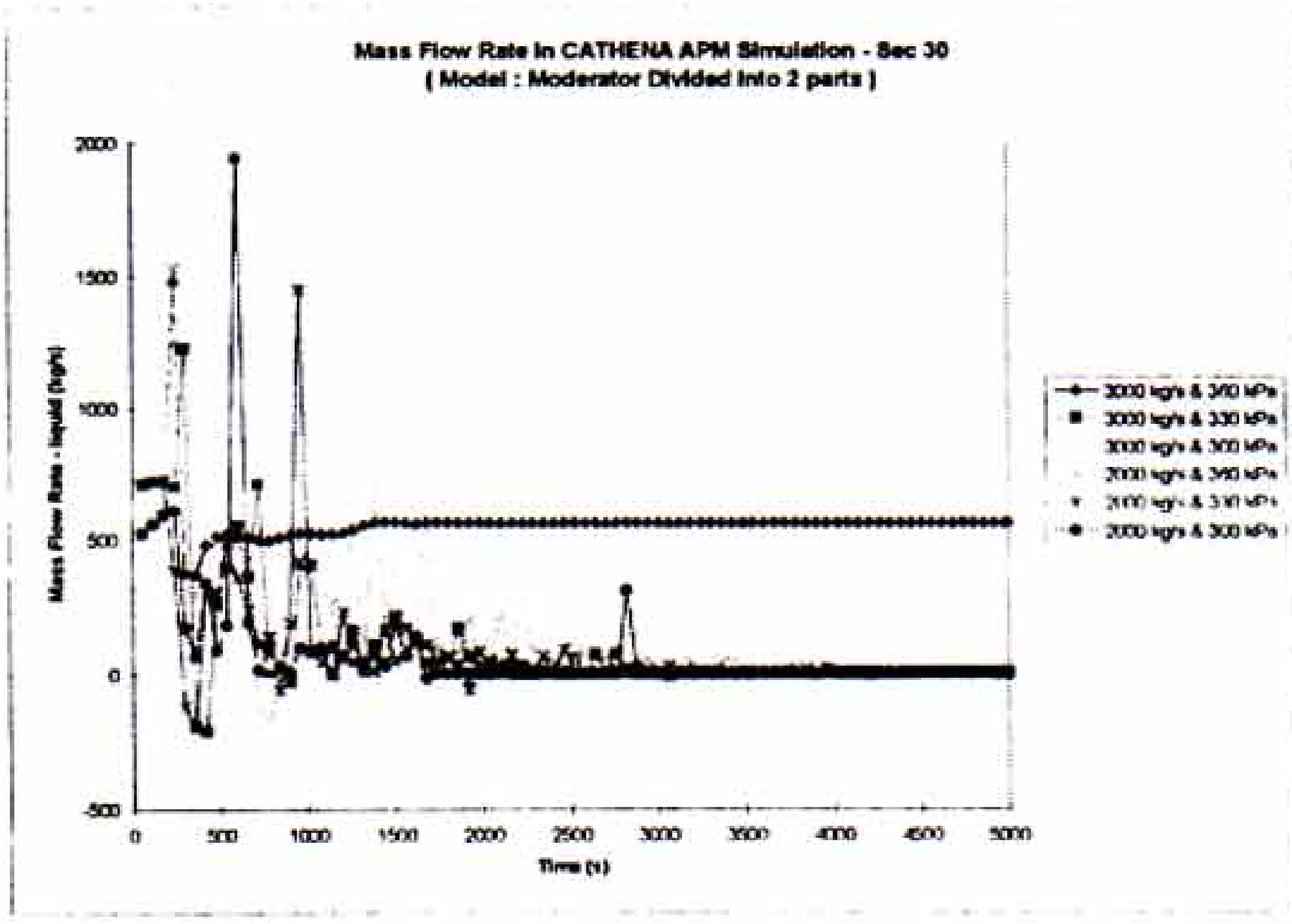

Figure 11. Mass Flow Rate in CATHENA Simulation – Sec 30

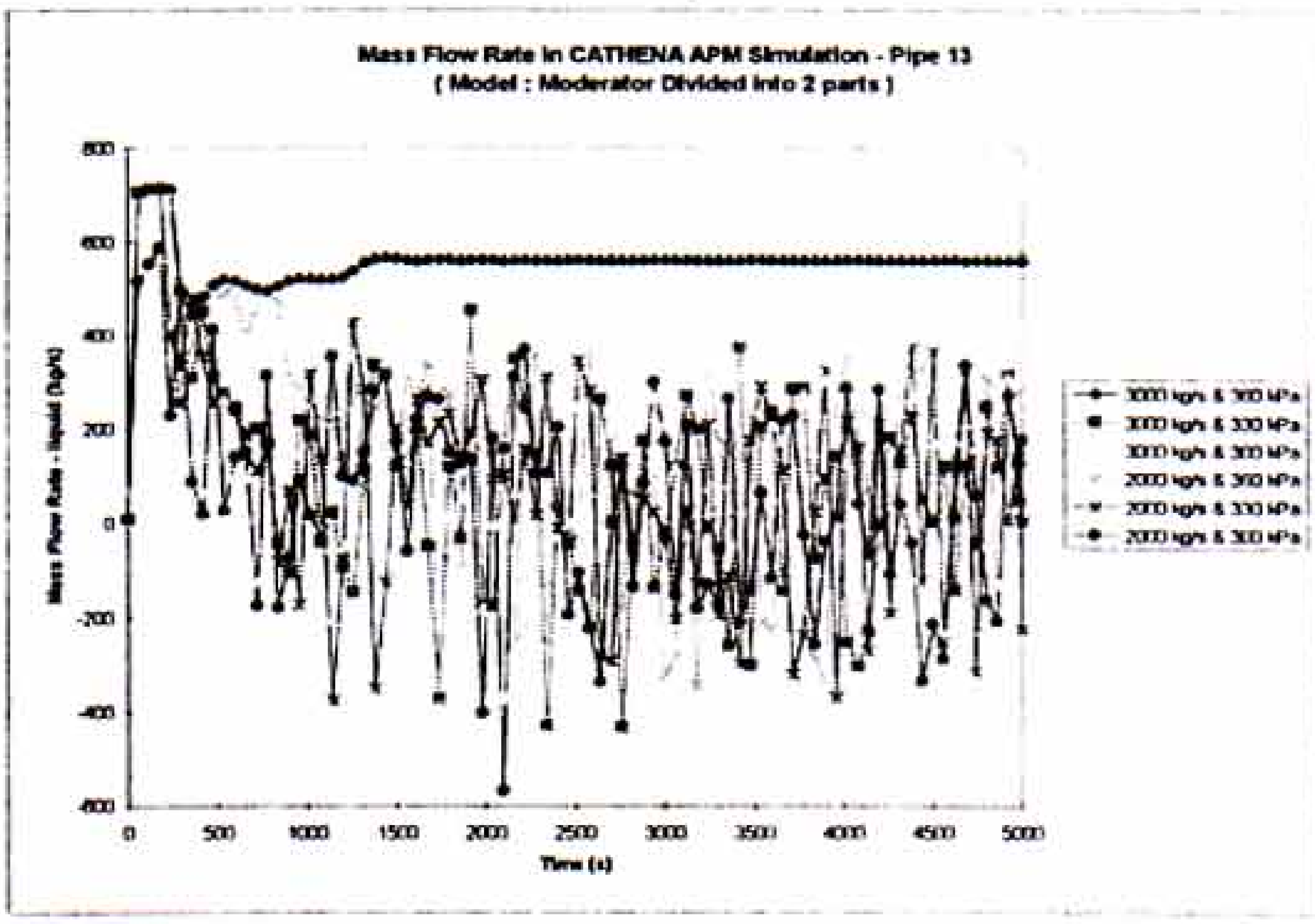

Figure 12. Mass Flow Rate in CATHENA Simulation – Pipe 13

As had been shown in Figures 10 - 12, a mass flow rate simulation for pressure boundary conditions of 360 kPa and water coolant mass flow rate boundary condition of 3000 kg/s is stable.

Void fraction plots as a function of time for specific nodes in the circuit for pressure boundary conditions of 300, 330 and 360 kPa and for water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively, are found in Figures 13 and 14.

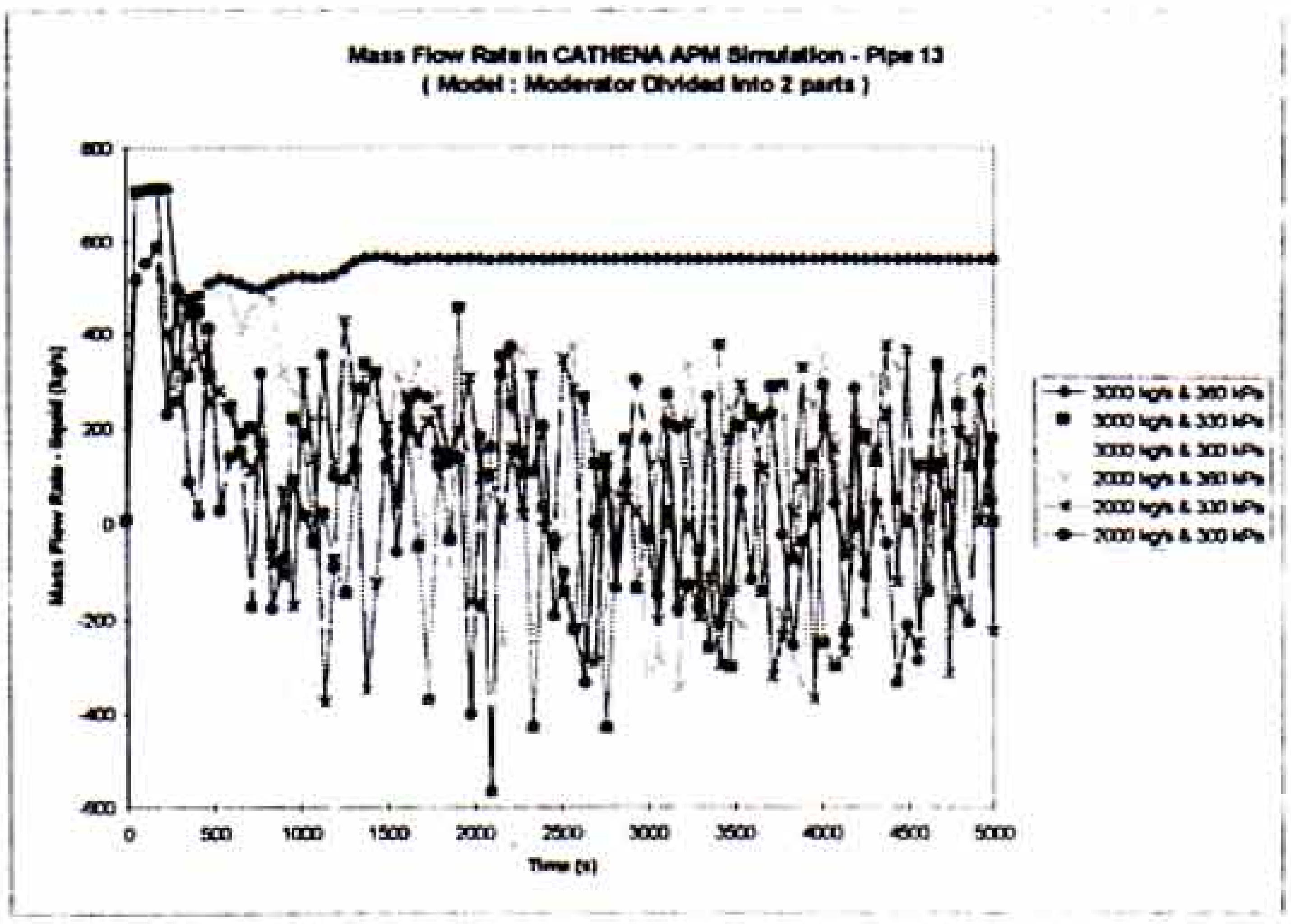

Figure 13. Void in CATHENA APM Simulation – Pipe 2

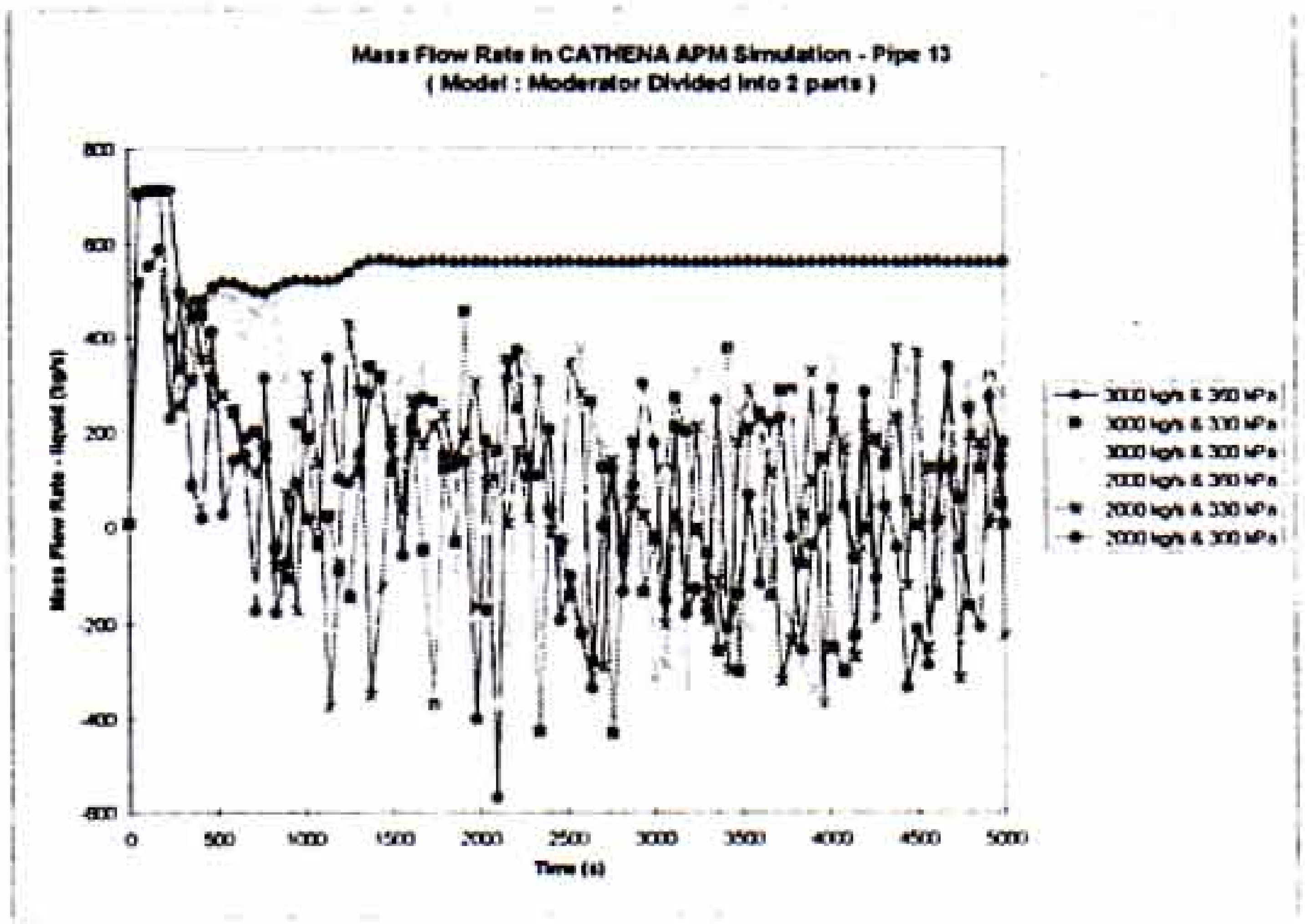

Figure 14. Void in CATHENA APM Simulation - Sec 30

By controlling the pressure and water coolant mass flow rate, the void fraction in the calandria can be controlled.

V. CONCLUSIONS.

The thermalhydraulic behavior of the Advanced Passive Moderator concept have been tested in CATHENA simulation. The pressure boundary condition of 300, 330 and 360 kPa and water coolant mass flow rate boundary conditions of 2000 and 3000 kg/s respectively is used. The results show that there is boiling in the core, with vapor condensing in the heat exchanger, and the solution had not reached steady state when the boiling occurred.

VI. ACKNOWLEDGMENTS

I wish to expresse my special gratitude to Dr. Nik Popov, Ross Tran and Dr Rayman Solichin for their help and guidance throughout my work. I also wish to offer my thank to Kris Mohan and Premila, for their help and contributions during the completion my work.

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Appendix 1. Summary of CALANDRIA CATHENA APM Input Deck (total heat load 138 MW)

L	HEAT(W)	0.4*P	0.6*P	V	0.4*V	0.6*V	A	0.4*A	0.6*A	D1	D2
0.41	2.19E+07	875600	1313400	5.557605	2.2230421	3.3345631	0.926268	0.3705072	0.5557608	0.686699	0.84103117
0.21	1.88E+07	750000	1125000	4.300975	1.7203902	2.5805853	0.716829	0.2867316	0.4300974	0.604095	0.73986340
0.21	2.25E+07	901200	1351800	4.673703	1.8694814	2.8042221	0.778951	0.3115804	0.4673706	0.629728	0.77125649
0.21	2.73E+07	1091200	1636800	5.092692	2.0370770	3.0556155	0.848782	0.3395128	0.5092692	0.657349	0.80508520
0.21	3.27E+07	1306400	1959600	5.568709	2.2274836	3.3412254	0.928118	0.3712472	0.5568708	0.687384	0.85915126
0.21	3.73E+07	1491600	2237400	5.799663	2.3198652	3.4797978	0.966611	0.3866444	0.5799666	0.701494	0.85915126
0.21	4.27E+07	1708400	2562600	6.128083	2.4512333	3.6768500	1.021347	0.4085388	0.6128082	0.721082	0.88314176
0.21	4.69E+07	1875200	2812800	6.400634	2.5602539	3.8403808	1.066772	0.4267088	0.6400632	0.736943	0.90256724
0.21	5.08E+07	2030400	3045600	6.624498	2.6497993	3.9746990	1.104083	0.4416332	0.6624498	0.749719	0.91821551
0.21	5.45E+07	2178400	3267600	6.804899	2.7219598	4.0829397	1.13415	0.45366	0.68049	0.759859	0.93063421
0.21	5.76E+07	2304400	3456600	7.027519	2.8110077	4.2165116	1.171253	0.4685012	0.7027518	0.772188	0.94573426
0.21	5.98E+07	2391200	3586800	7.213519	2.8854076	4.3281115	1.202253	0.4809012	0.7213518	0.782340	0.95816808
0.21	6.15E+07	2460000	3690000	7.283353	2.9133412	4.3700118	1.213892	0.4855568	0.7283352	0.786118	0.96279492
0.21	6.26E+07	2503600	3755400	7.402283	2.9609132	4.4413698	1.233714	0.4934856	0.7402284	0.792511	0.97062397
0.21	6.34E+07	2534000	3801000	7.489773	2.9959092	4.4938639	1.248296	0.4993184	0.7489776	0.797180	0.97634331
0.21	6.36E+07	2542800	3814200	7.546701	3.0186806	4.5280209	1.257784	0.5031136	0.7546704	0.800204	0.98004676
0.21	6.33E+07	2530800	3796200	7.573622	3.0294488	4.5441732	1.26227	0.504908	0.757362	0.801630	0.98179292
0.21	6.26E+07	2505600	3758400	7.570791	3.0283167	4.5424751	1.261799	0.5047196	0.7570794	0.801480	0.98160973
0.21	6.14E+07	2455600	3683400	7.619969	3.0479879	4.5719818	1.269995	0.507998	0.761997	0.804079	0.98479258
0.21	5.97E+07	2387600	3581400	7.557272	3.0229089	4.5343633	1.259545	0.503818	0.755727	0.800764	0.98073259
0.21	5.71E+07	2282000	3423000	7.463871	2.9855487	4.4783231	1.243979	0.4975916	0.7463874	0.795801	0.97465359
0.21	5.39E+07	2155600	3233400	7.420609	2.9682438	4.4523657	1.236768	0.4947072	0.7420608	0.793491	0.97182459
0.21	5.06E+07	2024000	3036000	7.344372	2.937749	4.4066235	1.224062	0.4896248	0.7344372	0.789404	0.96681966
0.21	4.71E+07	1882400	2823600	7.233374	2.8933498	4.3400248	1.205562	0.4822248	0.7233372	0.783416	0.95948577
0.21	4.24E+07	1694000	2541000	7.085256	2.8341024	4.2511536	1.180876	0.4723504	0.7085256	0.775354	0.94961138
0.21	3.85E+07	1541600	2312400	7.060482	2.8241928	4.2362892	1.176747	0.4706988	0.7060482	0.773997	0.94794974
0.21	3.41E+07	1364400	2046600	6.827796	2.7311186	4.0966779	1.137966	0.4551864	0.6827796	0.761136	0.93219852
0.21	3.06E+07	1222000	1833000	6.708802	2.683521	4.0252815	1.118134	0.4472536	0.6708804	0.754475	0.92403983
0.21	2.82E+07	1127600	1691400	6.695841	2.6783367	4.0175051	1.115974	0.4463896	0.6695844	0.753746	0.92314687
0.4	1.93E+07	772800	1159200	12.26261	4.9050464	7.3575697	2.043769	0.8175076	1.2262614	1.020032	1.24927966
0.4	7.72E+06	308800	463200	9.804635	3.9218540	5.8827810	1.634106	0.6536424	0.9804636	0.912091	1.11707897
0.41				5.563048	2.2252192	3.3378288	0.927175	0.37087	0.556305	0.687035	0.84144284

Appendix 2. Summary of CATHENA APM Input Deck (total heat load of 138 MW)

Component	Length (m)	Moderator Volume (m^3)	Nodes	Heat Input (WATT)
SEC1A	0.41	2.223042	1	875600
SEC2A	0.21	1.720390	1	750000
SEC3A	0.21	1.869481	1	901200
SEC4A	0.21	2.037077	1	1091200
SEC5A	0.21	2.227484	1	1306400
SEC6A	0.21	2.319865	1	1491600
SEC7A	0.21	2.451233	1	1708400
SEC8A	0.21	2.560254	1	1875200
SEC9A	0.21	2.649799	1	2030400
SEC10A	0.21	2.721960	1	2178400
SEC11A	0.21	2.811008	1	2304400
SEC12A	0.21	2.885408	1	2391200
SEC13A	0.21	2.913341	1	2460000
SEC14A	0.21	2.960913	1	2503600
SEC15A	0.21	2.995909	1	2534000
SEC16A	0.21	3.018681	1	2542800
SEC17A	0.21	3.029449	1	2530800
SEC18A	0.21	3.028317	1	2505600
SEC19A	0.21	3.047988	1	2455600
SEC20A	0.21	3.022909	1	2387600
SEC21A	0.21	2.985549	1	2282000
SEC22A	0.21	2.968244	1	2155600
SEC23A	0.21	2.937749	1	2024000
SEC24A	0.21	2.893350	1	1882400
SEC25A	0.21	2.834102	1	1694000
SEC26A	0.21	2.824193	1	1541600
SEC27A	0.21	2.731119	1	1364400
SEC28A	0.21	2.683521	1	1222000
SEC29A	0.21	2.678337	1	1127600
SEC1B	0.41	3.334563	1	1313400
SEC2B	0.21	2.580585	1	1125000
SEC3B	0.21	2.804222	1	1351800
SEC4B	0.21	3.055616	1	1636800
SEC5B	0.21	3.341225	1	1959600
SEC6B	0.21	3.479798	1	2237400
SEC7B	0.21	3.676850	1	2562600
SEC8B	0.21	3.840381	1	2812800

SEC9B	0.21	3.974699	1	3045600
SEC10B	0.21	4.082940	1	3267600
SEC11B	0.21	4.216512	1	3456600
SEC12B	0.21	4.328112	1	3586800
SEC13B	0.21	4.370012	1	3690000
SEC14B	0.21	4.441370	1	3755400
SEC15B	0.21	4.493864	1	3801000
SEC16B	0.21	4.528021	1	3814200
SEC17B	0.21	4.544173	1	3796200
SEC18B	0.21	4.542475	1	3758400
SEC19B	0.21	4.571982	1	3683400
SEC20B	0.21	4.534363	1	3581400
SEC21B	0.21	4.478323	1	3423000
SEC22B	0.21	4.452366	1	3233400
SEC23B	0.21	4.406624	1	3036000
SEC24B	0.21	4.340025	1	2823600
SEC25B	0.21	4.251154	1	2541000
SEC26B	0.21	4.236289	1	2312400
SEC27B	0.21	4.096678	1	2046600
SEC28B	0.21	4.025282	1	1833000
SEC29B	0.21	4.017505	1	1691400
SEC30B	0.40	12.26262	1	1159200
SEC31B	0.40	9.804635	2	463200
SEC32B	0.41	5.563048	2	
TANK1	-	4.0	1	
PIPE1	2	0.5837	4	
PIPE2	10	2.9188	20	
PIPE3	10	2.9188	20	
HXTS	6	1.6200	12	
HXSS	6	1.6200	12	
PIPE4	11.5	3.3566	10	
PIPE5	4.5	1.3135	4	
PIPE6	4.5	1.3135	4	
TANK2	-	40.0	1	
PIPE11	13.0	3.7944	2	
PIPE12	6.29	1.8359	2	
PIPE13	6.0	1.7513	2	