DEVELOPMENT AND VALIDATION OF THE SHUTDOWN COOLING SYSTEM CATHENA MODEL FOR GENTILLY-2

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ABSTRACT

A CATHENA representation of the Gentilly-2 Shutdown Cooling system has been developed for Hydro-Québec. The model includes the SDCS circuit piping, valves, pumps and heat exchangers. The model is integrated in the G2 CATHENA overall plant model and coupled with the plant control software simulator TROLG2 to allow the simulation of various plant operational modes using the SDCS. Results have been obtained for normal cooling of the primary heat transport system following a planned shut down (transition from full power to shutdown) and for two special SDCS configurations that were used on September 14 and 15, 2006 at Gentilly-2. The results show close match with values measured at Gentilly-2 during either steady or transient states.

1. INTRODUCTION

The Shutdown Cooling System (SDCS) is an essential feature of the CANDU®-6 nuclear plant designed for cooling the Primary Heat Transport System (PHTS) following a reactor shutdown. This system operates in normal conditions with the PHTS coolant around 160°C or in abnormal conditions with the PHTS coolant temperature up to 260°C according to the SDCS operating manual. With the SDCS online (isolating valves open), flow can be forced either by the four PHTS pumps or by the two SDCS pumps (3341-P1 and P2). Figure 1 shows a simple schematic of the Gentilly-2 (G2) PHTS with the two SDCS loops between each PHTS main loop. Each of the two SDCS loops has a set of piping, pump, heat exchanger and a proper number of valves for isolation from the PHTS.

The residual heat generated in the core after shutdown is transferred to the Recirculated Service Water (RSW) through the secondary side of the two SDCS heat exchangers (3341-HX1 and HX2). The SDCS is also designed as the main cooling source when the PHTS is drained at the header level for steam generators or main PHTS pumps maintenance. The SDCS operation can also be called by emergency procedure following some low probability events such as loss of class IV power, secondary side breaks or loss of coolant accidents (for cooling of the intact loop).

The study aims to document and validate the G2 SDCS CATHENA model. This model is a mathematical representation of the SDCS circuit translated to be used as an input model with the one-dimensional, two-fluid thermalhydraulic CATHENA [2] simulation code. CATHENA is designed to analyze two-phase flow and heat transfer in piping networks. The updated SDCS model provides all the essential information for an adequate idealization of the entire G2 SDCS in CATHENA. It includes the geometry and nodalization of each pipe component, heat exchangers and pumps models, valves representations and all the system control models needed. This model is designed to be used for the simulation of specific SDCS configurations during the shutdown state. These configurations are required for normal maintenance (e.g. maintenance on ECC valves), for accident analysis affecting the SDCS (e.g. loss of one SDCS pump) and for complete core defueling before the refurbishment project.

The SDCS model has also been merged to the overall G2 circuit CATHENA model. The integrated model allows the simulation of the transient of a normal plant shutdown from full power state, with all the normal required steps including those with the SDSC online. The main part of the required plant parameters control is allowed by coupling CATHENA with the G2 plant control software TROLG2.

2. SDCS CIRCUIT OVERVIEW

2.1. SDCS Components

The SDCS includes two symmetrical loops, one at each end of the reactor as shown in the simplified scheme of the PHTS in Figure 2. Five channels per pass are modeled to represent the 95 typical channels in CANDU-6 plants.

Both SDCS loops contain a centrifugal pump, a tube and shell heat exchanger, four main isolating valves, a pump by-pass line with restriction orifice and all the required piping, elbows and tees to connect with the PHTS.

SDCS loop #1 includes pump 3341-P1 with the pump suction connected to the outlet header (OH) #1 (throughout isolating valve 3341-MV9) and to OH #5 (throughout isolating valve 3341-MV1). The flow is first discharged and cooled through the heat exchanger 3341-HX1 and then returns to the PHTS via the inlet header (IH) #2 (throughout isolating valve 3341-MV5) and IH #6 (throughout isolating valve 3341-MV15). In some particular manoeuvres, the pump 3341-P1 can be by-passed by the opening of valve 3341-MV17 located on the line between the pump suction and the pump discharge.

SDCS loops are identical except that pump 3341-P2 suction is connected to OH #4 and OH #8 (throughout respectively isolating valve 3341-MV16 and 3341-MV6). After going through heat exchanger 3341-HX2, the cooled flow returns to the PHTS via IH #3 and IH #7 (throughout respectively isolating valve 3341-MV16 and 3341-MV6). The pump 3341-P2 by-pass line can be used by the opening of valve 3341-MV18.

2.2. SDCS Operating Modes

In the normal operating mode, the SDCS is designed to provide cooling of the PHTS from around 160°C to a temperature close to the RSW and maintain this temperature during the entire reactor shutdown period. Prior to the initiation of the SDCS cooling mode, the PHTS is cooled by the control software BPC (Boiler Pressure Control), with the controlled opening of the CSDV (Condenser Steam Discharge Valves) and the ASDV (Atmospheric Steam Discharge Valves).

The initiation of the SDCS in normal mode is obtained in two steps. The first step uses the PHTS main pumps to circulate the coolant through the core and through the SDCS heat exchangers until the PHTS is close to 80°C. In this configuration, the PHTS flow circulates in the reverse direction in both SDCS loops (from SDCS pumps discharge to SDCS pumps suction). The second step begins with the trip of the four main PHTS pumps and the start up of the two SDCS pumps. The flow in the SDCS loops is reversed and circulates in the normal direction (from SDCS pumps suction to pumps discharge). The PHTS is then cooldown to a temperature around 40°C.

3. METHODOLOGY

3.1. Development of the SDCS Model

The SDCS model has been developed in a systematic way so that the documentation verification and further reference are easy and straightforward.

The first step has been to break-up the actual G2 SDCS circuit into small sub sections named "segments". Figure 1 shows this segmentation and the assigned reference flow direction. Each SDCS segment is then characterized clearly in a table. The required physical entries (pipe length, elevation change, flow area, etc.) have been obtained from the G2 As-Built plans. In the third step, each segment is properly labelled and converted into a CATHENA input by filling its Segment Description Form (SDF). A representation of the CATHENA model is presented in Figure 3. The last step was to construct the CATHENA input file from the SDF.

The hydraulic resistances have been calculated according to reference [1]. Pressure drops in the piping elbows, tees, orifice restrictions and manual valves are included in the flow resistance of each corresponding pipe component segment. Multiple CATHENA "VOLUME" geometries have been used to properly represent a tee junction or when more then three pipe components are connected together.

The two cooling units of the SDCS are tube and shell heat exchangers with four passes through the tubes (two "U" tubes) and one pass through the shell side. These heat exchangers are modeled in CATHENA by a simple two passes in the primary side ("U" tubes) and one pass through the shell side with twice the tube length to preserve the same total heat exchange surface. The secondary side of the heat exchangers is modeled by a boundary condition representing the Recirculated Service Water (RSW) at the entrance of the heat exchangers; the RSW temperature and flow rate are imposed.

3.2. Validation Cases and Comparison Data

The results shown in this paper have been obtained with the G2 CATHENA overall plant model with the SDCS included. The CATHENA version used was 3.5d rev 2. The plant control is achieved by coupling CATHENA with TROLG2 version 02.04. Three different validation cases are assessed.

3.2.1. Case #1: Controlled Cooldown

The first case is for demonstration purpose and do not include comparison with measured data. This case reproduces the normal G2 plant shutdown. The reactor is shutdown at time zero and the power decay is imposed in CATHENA based on a calculated power transient by the thermahydraulic software code SOPHT-G2. The PHTS is cooled at a controlled rate of 2.8°C/min, with the opening of the CSDVs or the ASDVs. At time 2500 s, all the isolating valves of the SDCS are manually opened and the coolant circulation is induced by the PHTS main four pumps. From that point, the residual heat generated in the core is evacuated by the SDCS heat exchangers. At 3500 sec, the PHTS pumps are tripped, the pressurizer is isolated and the SDCS pumps are started up. The transient simulation runs until power reaches 0.52%FP at 50000 s.

3.2.2. Case #2: SDCS in cross-mode with 3341-P2 stopped

This particular configuration of the SDCS is illustrated in Figure 4. This configuration was used at G2 for a maintenance purpose on the ECC 3432-MV42 valve around 5 days after reactor shutdown during the 2006 plant outage. Two out of four isolating valves were closed on each SDCS loops in a symmetrical way (one at the suction and one at the discharge of each SDCS pumps). In this configuration, the PHTS flow is induced by only one SDCS pump (3341-P1) and the cooling is performed by the two SDCS heat exchangers. Initial conditions for this case are those generated at the end of case #1 with a reduction in the residual reactor power. Finally, the results produced by CATHENA/TROLG2 for the temperature transient at the headers and at the SDCS heat exchangers are compared with measured data

3.2.3. Case #3: Isolation of the SDCS loop 1

This third configuration of the SDCS is illustrated in Figure 5. This configuration was used around 12 hours after the one described in case #2. Isolating valves of the SDCS loop #1 were closed and the pump 3341-P1 was stopped. The pump 3341-P2 was started up so that circulation and cooling of the PHTS was made by only one loop of the SDCS (SDCS loop #2). As for case #2, the results produced by CATHENA/TROLG2 for the temperature transient at the headers and at heat exchanger 3341-HX2 are compared with plant measured data.

4. RESULTS

4.1. Case #1: Controlled Cooldown

The intent of this simulation is to show the ability of CATHENA/TROLG2 to reproduce the PHTS main behaviour following a reactor shutdown and controlled cooldown. The simulation was run for 60000 sec.

The reactor is tripped at time zero. The PHTS temperature drops quickly as shown in Figure 6 for the inlet headers (IH) and in Figure 7 for the outlet headers (OH). The temperatures then stabilise until the controlled cooling mode by BPC is activated by the operator; the cooling rate is fixed at 2.8 °C/min. BPC controls the PHTS cooldown through the boilers by acting on the CSDVs at first and then on the ASDVs. At 2500 sec the SDCS is connected to the PHTS by opening manually the SDCS isolation valves. The flow is still induced by the PHTS pumps and circulates in the reverse direction in both SDCS pumps (from pumps discharge to pumps suction, see Figure 8). The cooling is now achieved by the two SDCS heat exchangers. At time 3500 sec, the PHTS pumps are tripped and the SDCS pumps are started-up. After the PHTS circulation is switched from the PHTS pumps to the SDCS pumps, the temperature in the headers decreases rapidly as shown in Figure 6 and Figure 7 because the 16 MW of mechanical heat released in the PHTS by the four PHTS pumps is stopped. With the SDCS pumps in operation, the flow in the SDCS loops returns to normal direction, from pump suction to pump discharge as shown in Figure 8. After that, the PHTS temperature continues to slowly decrease until it reaches a temperature close to the RCW. Figure 9 illustrates the CATHENA/TROLG2 plant conditions, almost 14 hours (50000 sec) after the initial reactor trip.

4.2. Case #2: SDCS in cross-mode with 3341-P2 stopped

This case compares the results obtained by CATHENA/TROLG2 with G2 data collected while the plant was in a shutdown state with the two SDCS loops connected to the PHTS. Both SDCS pumps were in operation. Around five days after the reactor shutdown, during the 2006 plant outage, this configuration was modified by closing the SDCS valves 3341-MV6/ MV9/ MV10/ MV15 and by tripping the SDCS pump 3341-P2. In this particular configuration, the flow in the core from IH4 to OH1 and from IH6 to OH7 reverses. The residual power from the core was low and the boilers were cold. The flow is induced by one SDCS pump (3341-P1) and the cooling is provided by the two SDCS heat exchangers.

In CATHENA, the transient manoeuvres are initiated at time 9000 s (time before 9000 is used to stabilise the pre event conditions). Figure 10 to Figure 13 illustrate the temperature transient for each pair of headers of the same pass during and after the manoeuvres. The temperature transients at the inlet and outlet of both SDCS heat exchangers are showed in Figure 14 and Figure 15. The small discrepancy between CATHENA results and G2 data observed in Figure 14 is due to the behaviour of Boiler 3 which acts as a heat sink in the CATHENA simulation at the beginning of the transient. There is also an uncertainty about the value of the residual power in the core which dictates mostly the initial temperatures at the headers before the manoeuvres. For the CATENA simulations, the residual power was set at 0.22%FP to match initial header temperatures. This value is kept constant during the transient as the decay power decrease is very slow at these power levels. G2 data shows a thermal power during the transient of 0.72%FP. This value is not however reliable during a shutdown state. In comparison, *Origen* provides a value of 0.34%FP while the *Nuclear Engineering Handbook* provides a 0.37%FP value, both five days after a reactor shutdown. These two references do not take into account G2 fuel real burn-up and they are generally considered as conservative (overestimate the reactor power).

Figure 10 to Figure 13 show that the results generated by CATHENA/TROLG2 reproduce closely the measured data at G2. The overall behaviour is the same (trends are the same) except that CATHENA/TROLG2 predicts a 3°C higher value at the IH #4 (Figure 10) during the beginning of the transient (from 9000 to 10000 sec). A temperature peak is also predicted by CATHENA/TROLG2 at the inlet of SDCS heat exchanger 3341-HX2. This came from the differences between the exact manoeuvres done at G2 and those reproduced in CATHENA. The time took by the operator to do each manoeuvre and the sequences of all the manoeuvres, which took almost 20 minutes (1200 sec), are not taken into account in the CATHENA/TROLG2 simulation. The configuration is changed in less than a minute in the simulation and may produce different values then those measured. Also, because all the exact manoeuvres have not been reproduced in the simulation, the temperature increase observed from G2 data between 10000 and 11000 sec, due to the opening for a few seconds of SDCS valve 3341-MV9, is not observed in the CATHENA model results (Figure 10 to Figure 13).

CATHENA/TROLG2 is able to reproduce the overall transient behaviour and the measured data in steady conditions. The maximum difference observed after 5000 sec. is only 0.9°C at OH #7.

4.3. Case #3: Isolation of the SDCS loop #1

Twelve hours after the last configuration has been aligned, the operator switched to the configuration where only the SDCS loop #2 is connected to the PHTS. The other loop #1 is completely isolated after that.

Initial conditions for the CATHENA/TROLG2 simulation are obtained from case #2. The transient is pursued with a lower residual power (0.18%FP) until the measured inlet header temperatures are reached. As in the previous case, theoretical power values are slightly higher then the one used here (0.32%FP for *Origen* and 0.35%FP for the *Nuclear Engineering Handbook*, 5.5 days after reactor shutdown). Case #3 is simulated by changing the previous case #2 SDCS configuration: isolation of the SDCS loop #1 by closing 3341-MV1/ MV5/ MV9/ MV15 and tripping the SDCS pump 3341-P1. The isolating valves of SDCS loop #2 are opened and SDCS pump 3341-P2 is started up. In this particular configuration, the flow in the core from IH4 to OH1 and from IH6 to OH7 returns to the normal direction. The flow is induced by one SDCS pump (3341-P2) and the heat sink is provided by one SDCS heat exchanger (3341-HX2).

The transient manoeuvres in CATHENA are initiated at time 3000 seconds after the end of case #2 (this time is used to stabilise the initial conditions). Figure 17 to Figure 20 illustrate the temperature transient by pair of same pass headers. The temperature transient at the inlet and outlet of the 3341-HX2 is showed on Figure 21. Finally, Figure 22 compares steady state conditions between CATHENA and G2, around 4 hours after that the case #3 configuration has been aligned.

For this case, the difference between the values predicted by CATHENA and those measured at G2 during the transient do not exceed 1°C at the headers and 2°C at 3341-HX2. The same behaviour is observed during and after the transient. On the long term, the differences observed in Figure 22 do not exceed 1.3°C at the headers and at the heat exchanger 3341-P2 (~3.5 hours after the manoeuvres). With only one heat exchanger, the PHTS temperature begins to rise comparatively to the previous case #2 but it stabilises for the long term with the heat losses to the environment helping the only available heat exchanger. This behaviour is not simulated as none of the heat loss is accounted for during the transient.

5. CONCLUSION

This paper summarizes the development and the validation of a CATHENA model of the Gentilly-2 Shutdown Cooling System.

The model has been compared against measured plant data acquired during the 2006 G2 outage specifically for this validation exercise. Header temperature results, which are the key parameters, produced by CATHENA/TROLG2 have been compared to G2 data measured during two special SDCS operational modes used during this outage. In one case, the SDCS has been used while only one SDCS pump is operational with the two heat exchangers available (cross-mode configuration). In the other case, only one SDCS loop is connected to the PHTS (other loop isolated). In both cases, either during the transient (circuit alignment) or after (steady state conditions), the differences between the predicted and the measured values do not exceed 2°C, with an average of only 1°C difference.

REFERENCES

[1] Idelchik, I.E., « Handbook of hydraulic resistance », Hemisphere Publishing Corporation, Second Edition, 1986.

[2] B.N. Hanna, 1998, “CATHENA: A Thermalhydraulic Code for CANDU Analysis”, Nuclear Engineering and Design, Vol. 180 (2), pp. 113-131.

FIGURES

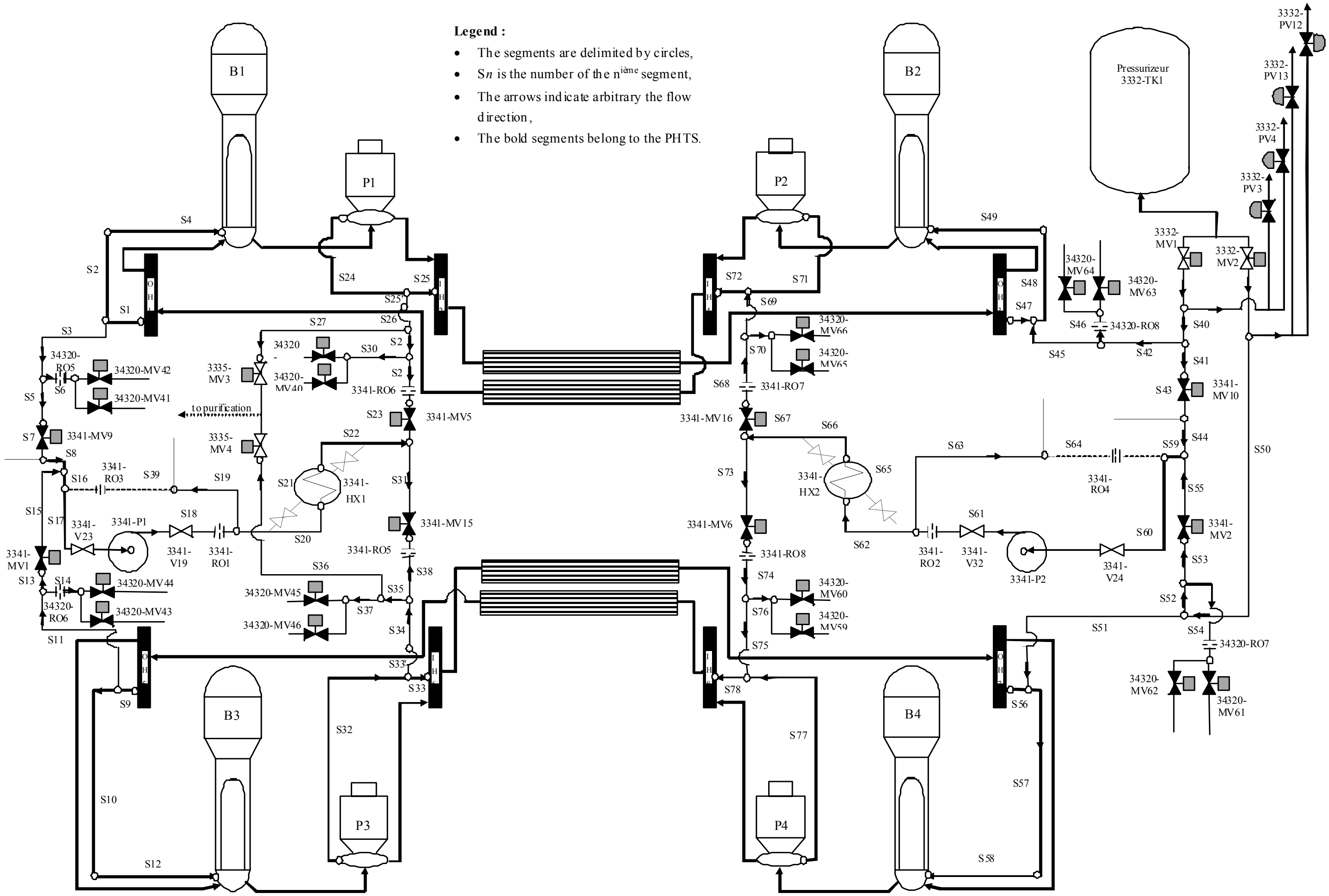

Figure 1 : PHTS and SDCS Circuits Segmentation

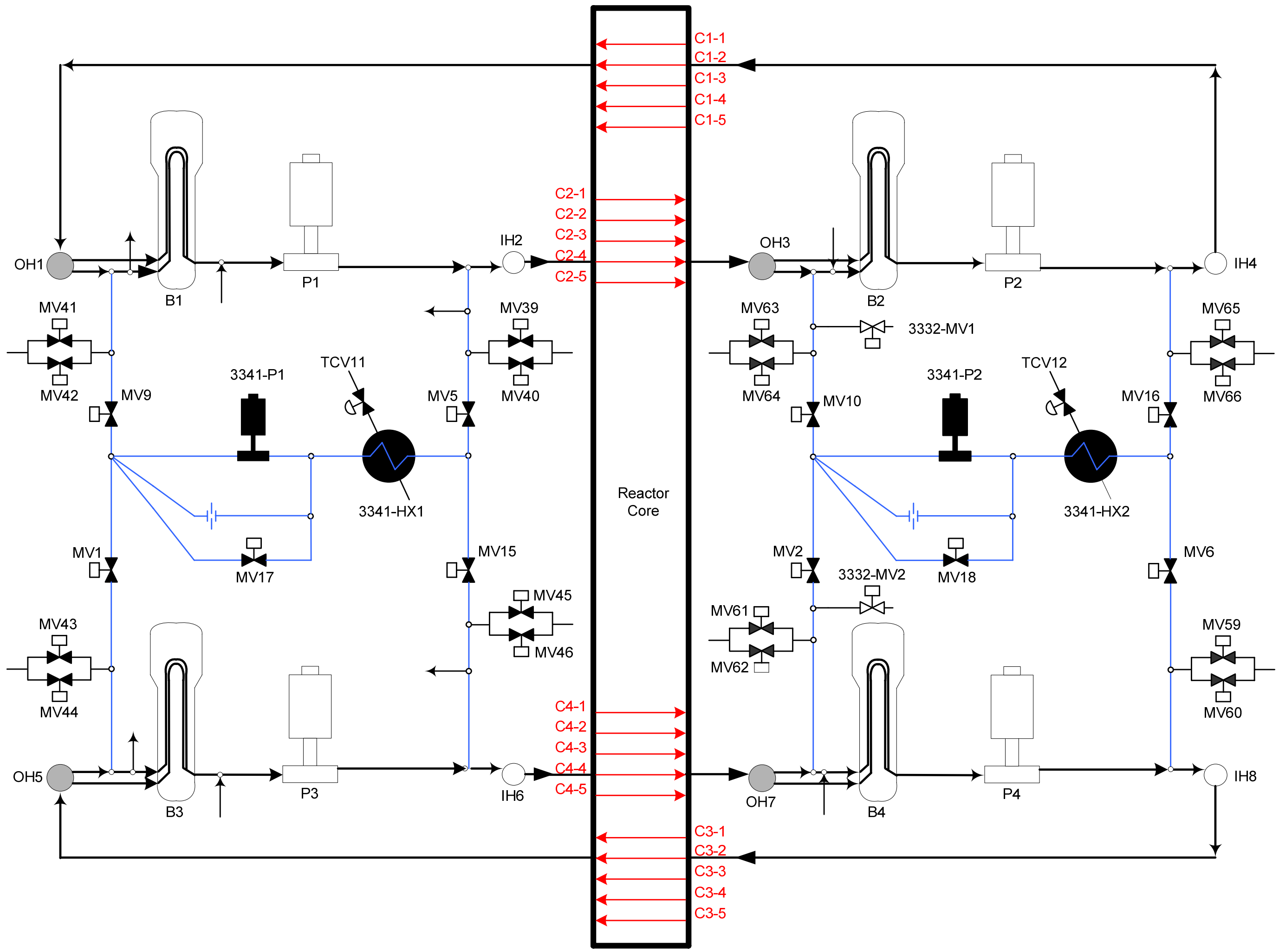

Figure 2: Representation of the PHTS and SDCS Circuits (case #1)

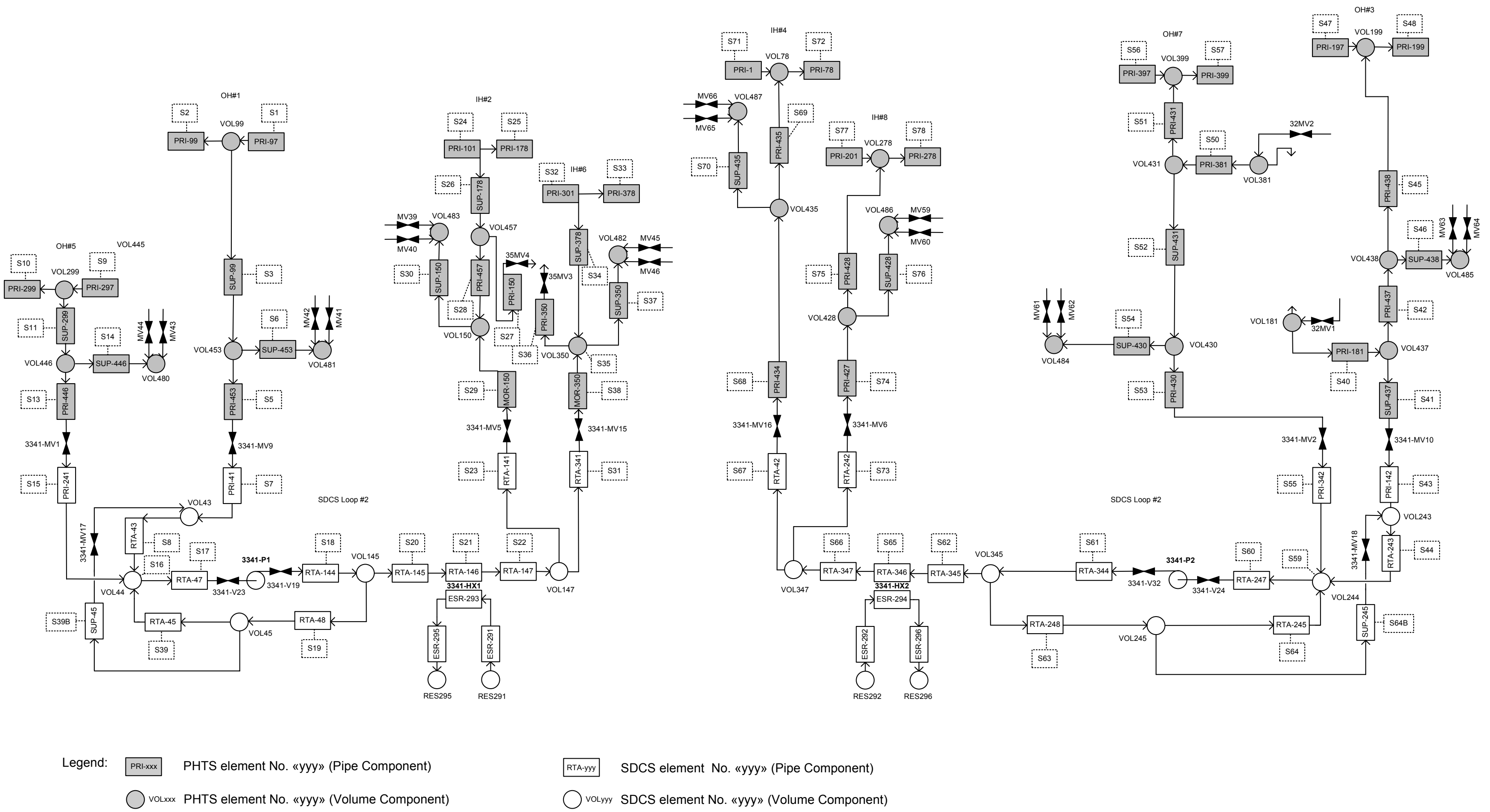

Figure 3 : CATHENA Model of the SDCS

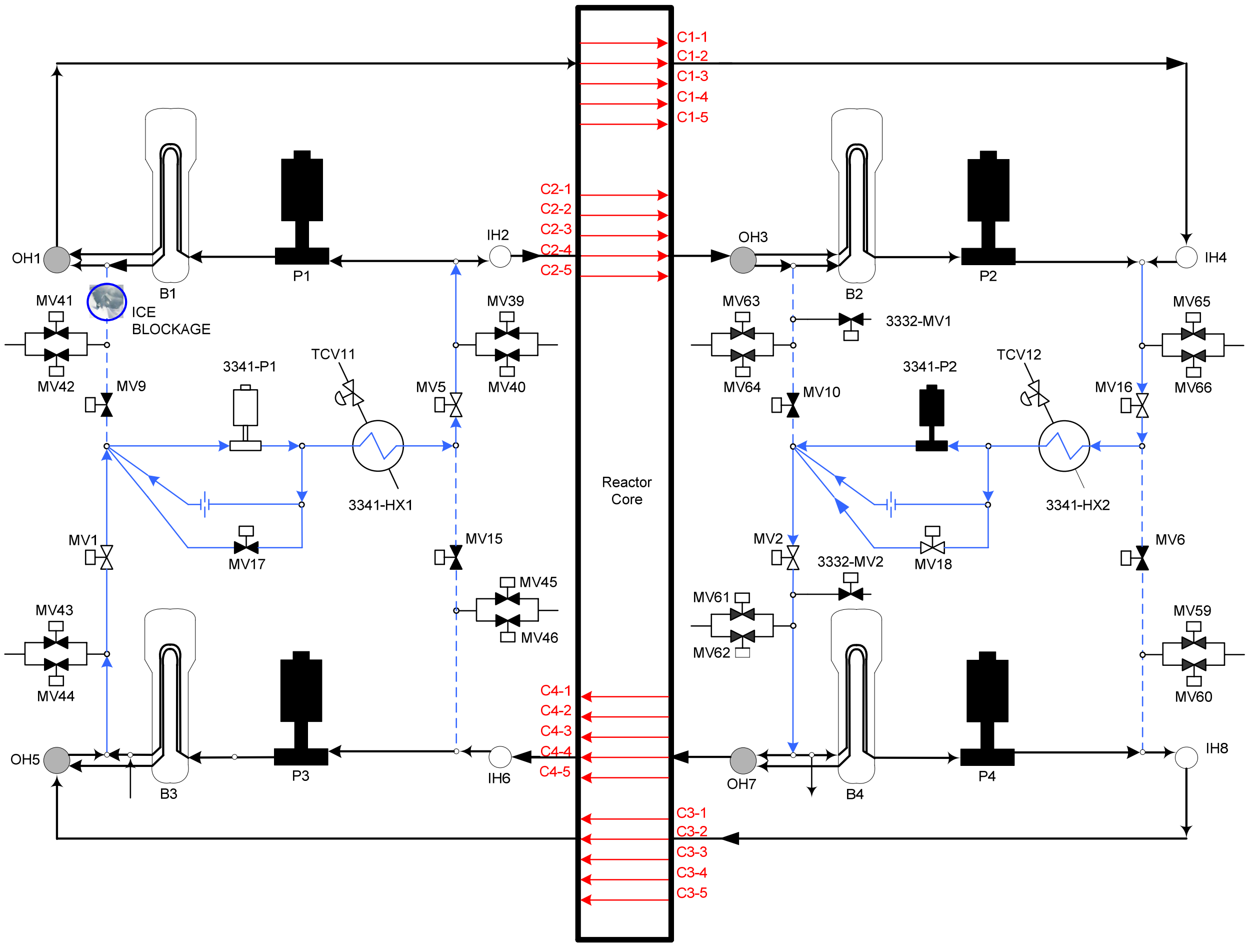

Figure 4: Flow Path of the PHTS and SDCS in Cross-mode with 3341-P2 Stopped (case #2)

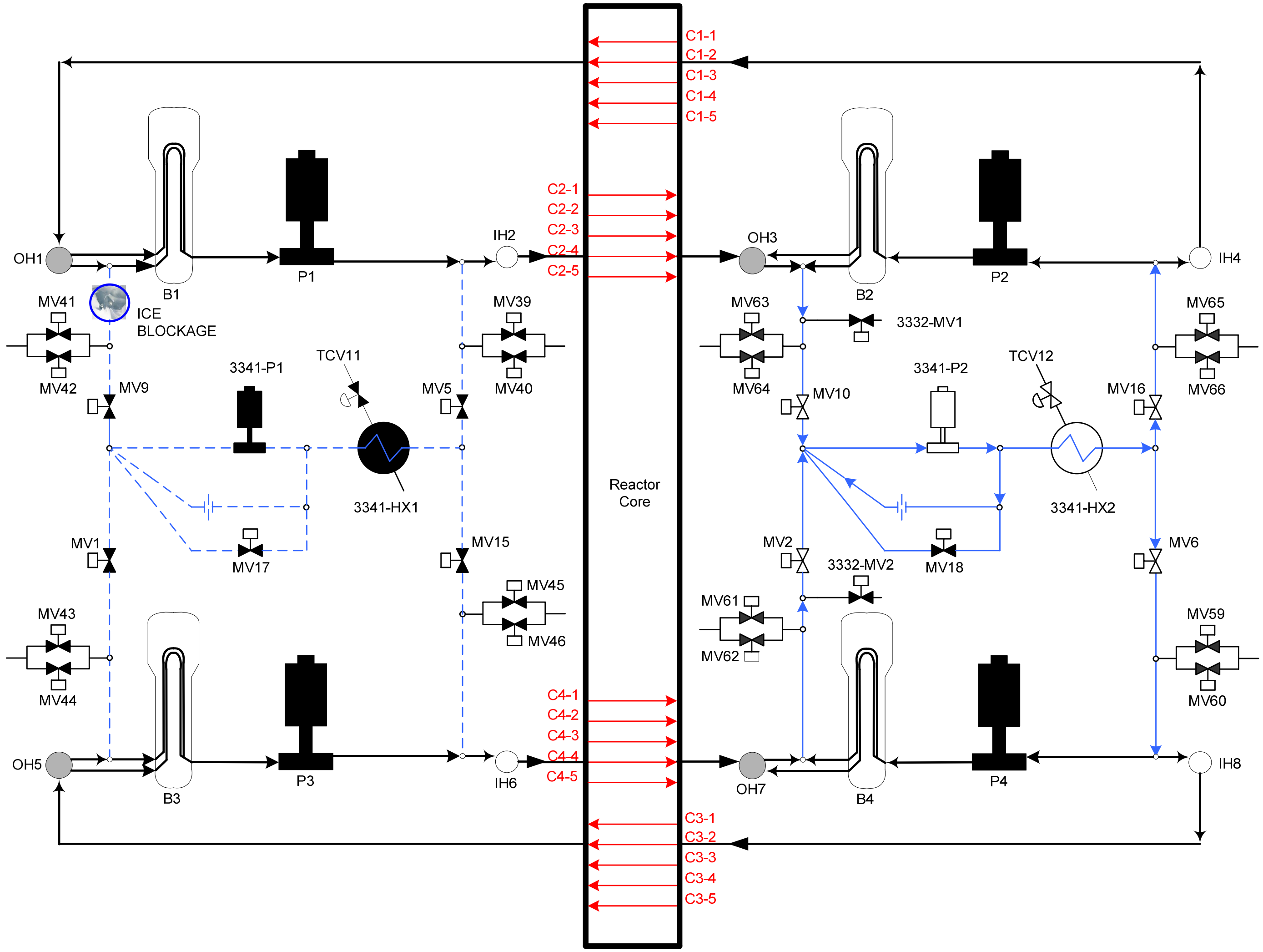

Figure 5 : Flow Path of the PHTS and SDCS in Cross-mode with SDCS Loop 1 Isolated (case #3)

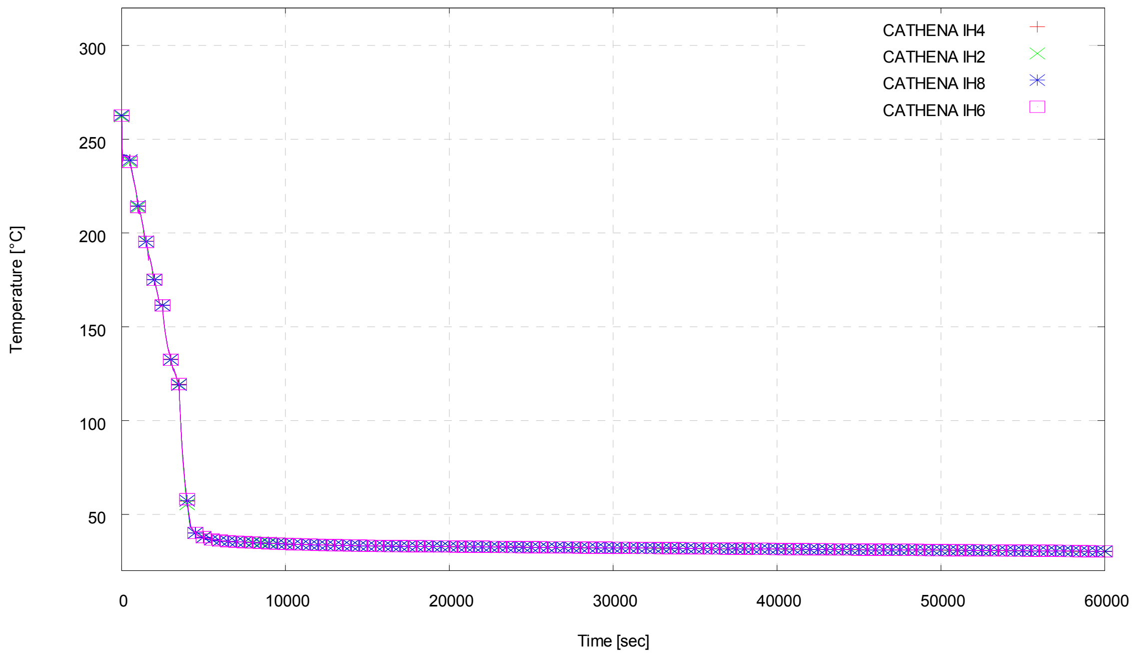

Figure 6 : Inlet Headers (IH) Temperature (case #1)

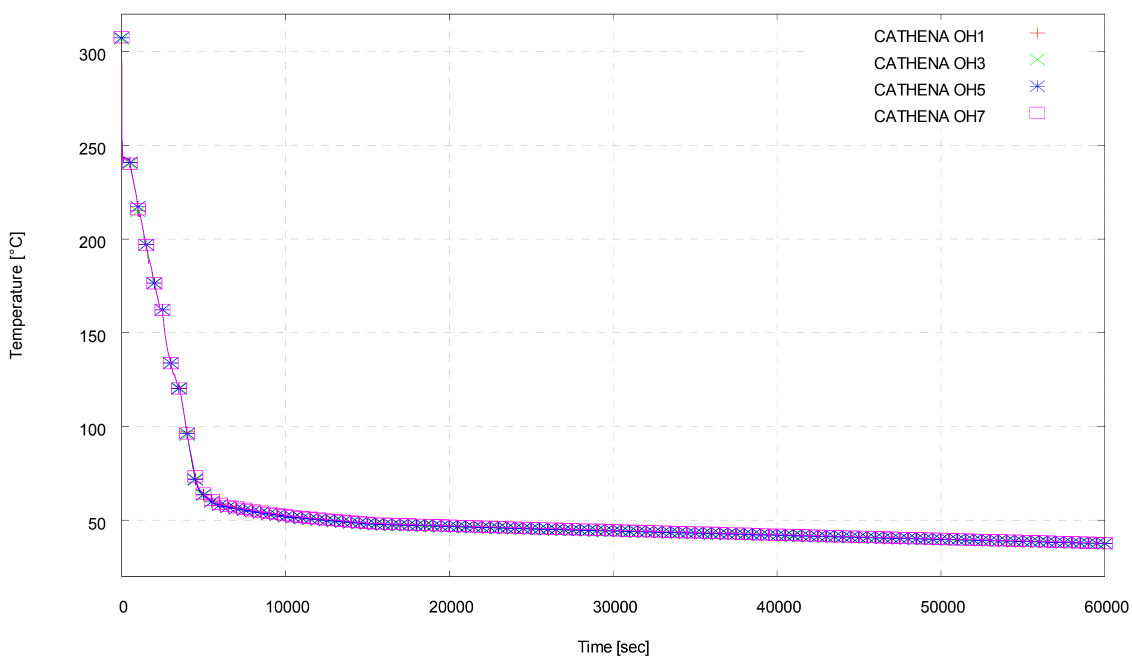

Figure 7 : Outlet Headers (OH) Temperature (case #1)

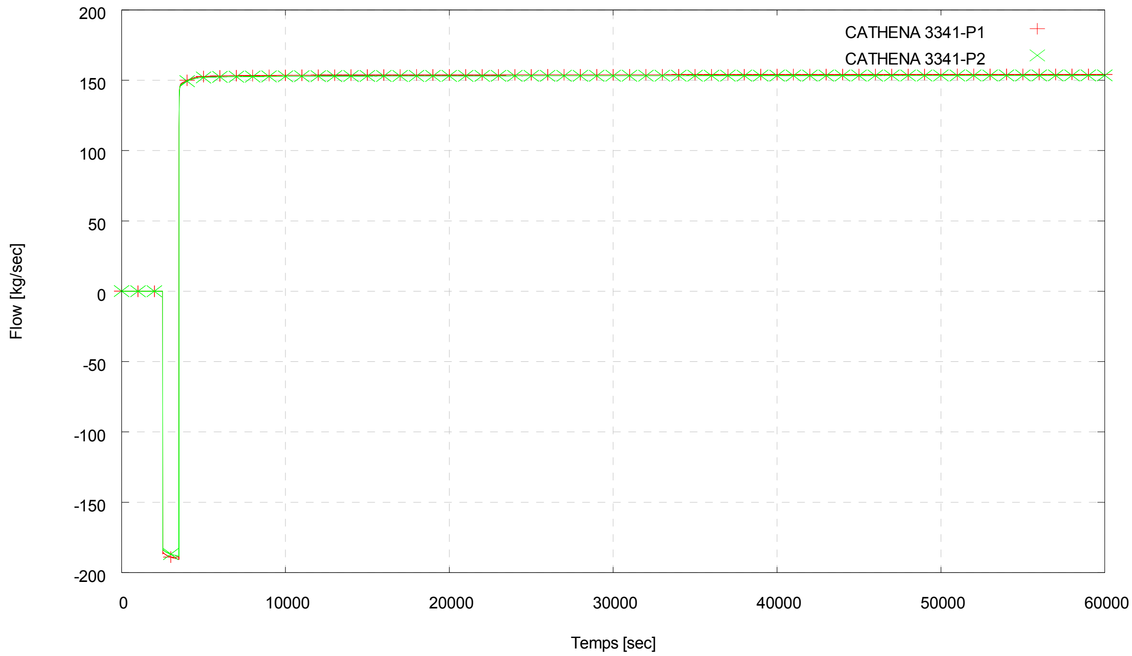

Figure 8 : Flow through SDCS Pumps (case #1)

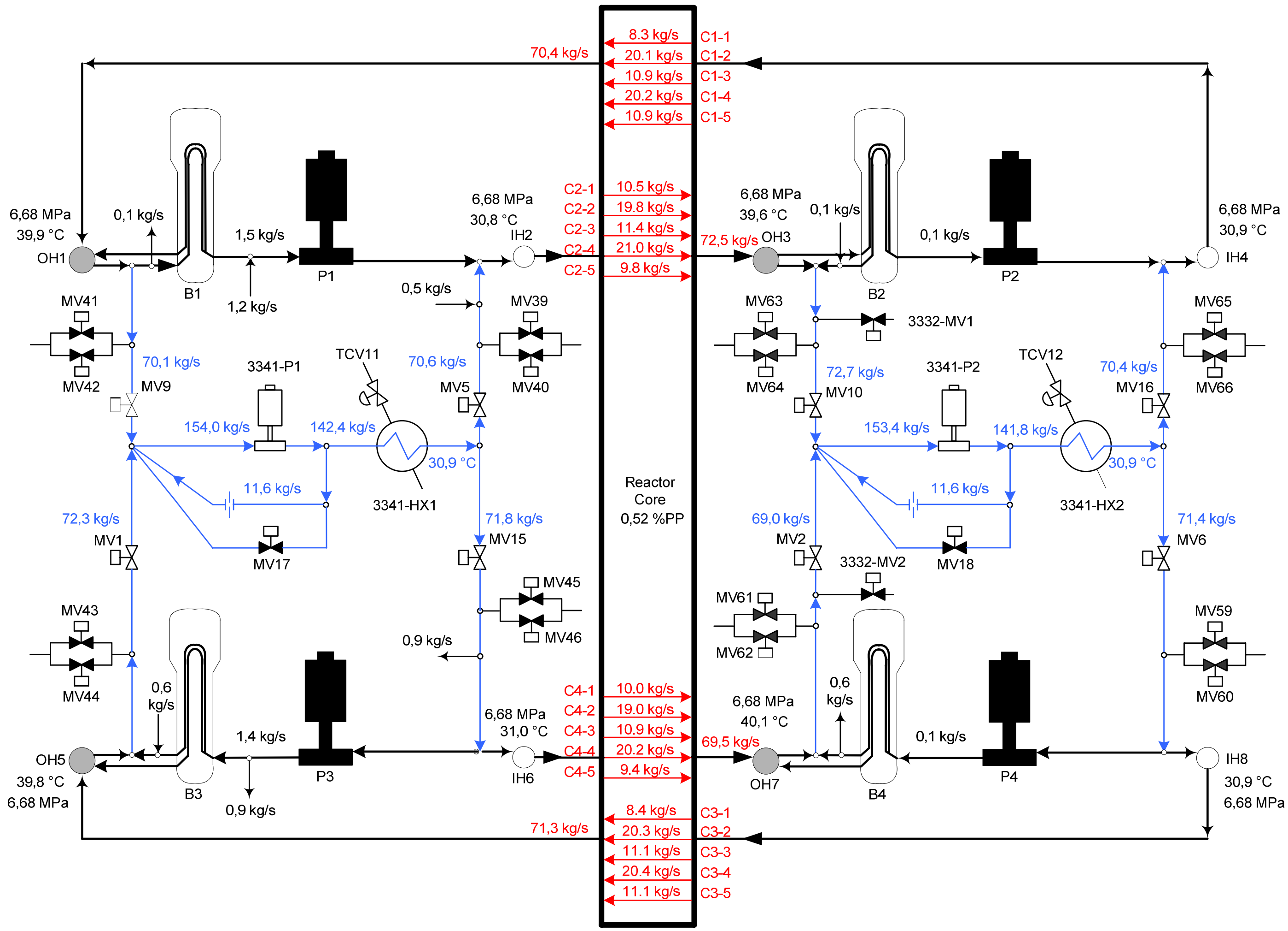

Figure 9: Plant Conditions after 50000 sec (case #1)

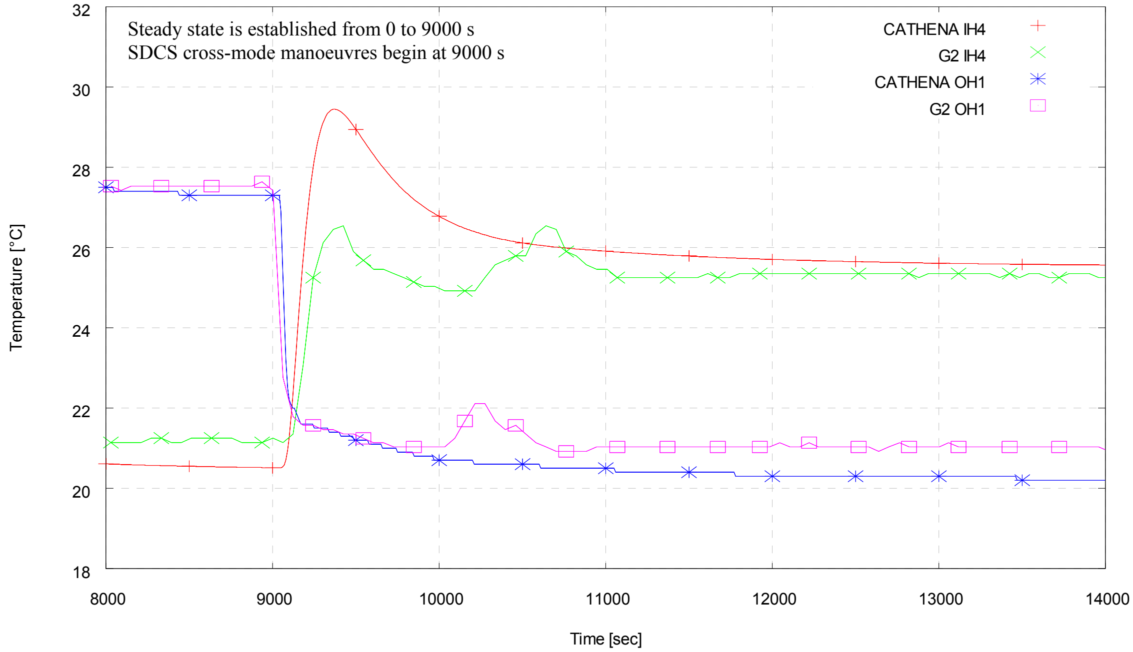

Figure 10 : Transient Temperature at Inlet Header 4 (IH4) and Outlet Header 1 (OH1) (case #2 : 0.22%PP)

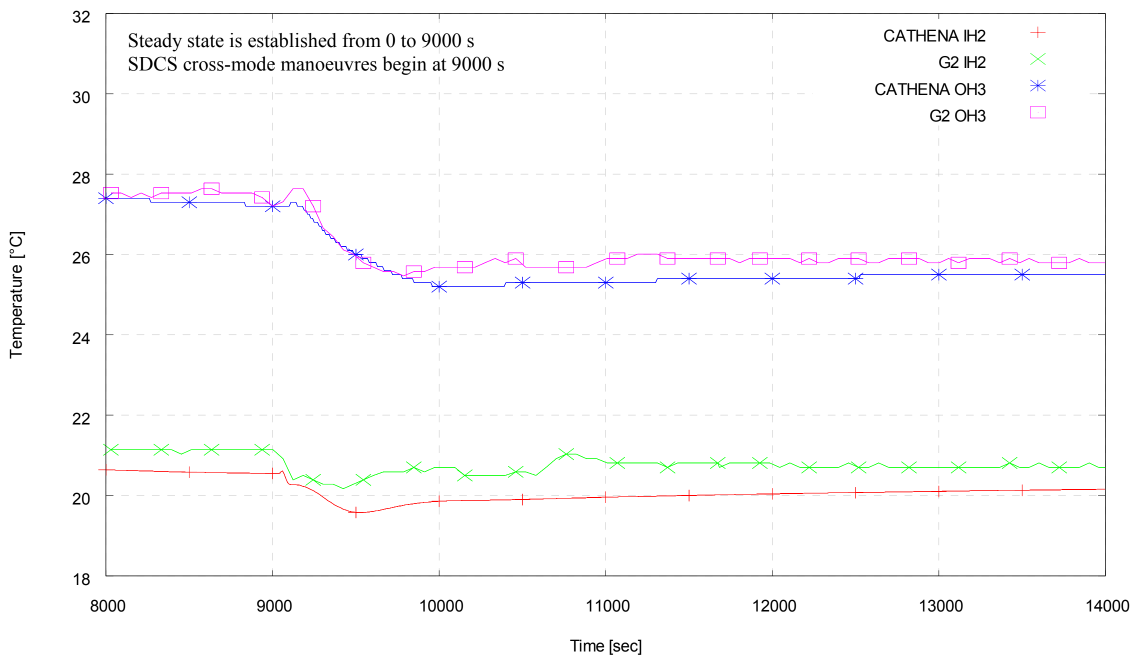

Figure 11 : Transient Temperature at Inlet Header 2 (IH2) and Outlet Header 3 (OH3) (case #2 : 0.22%PP)

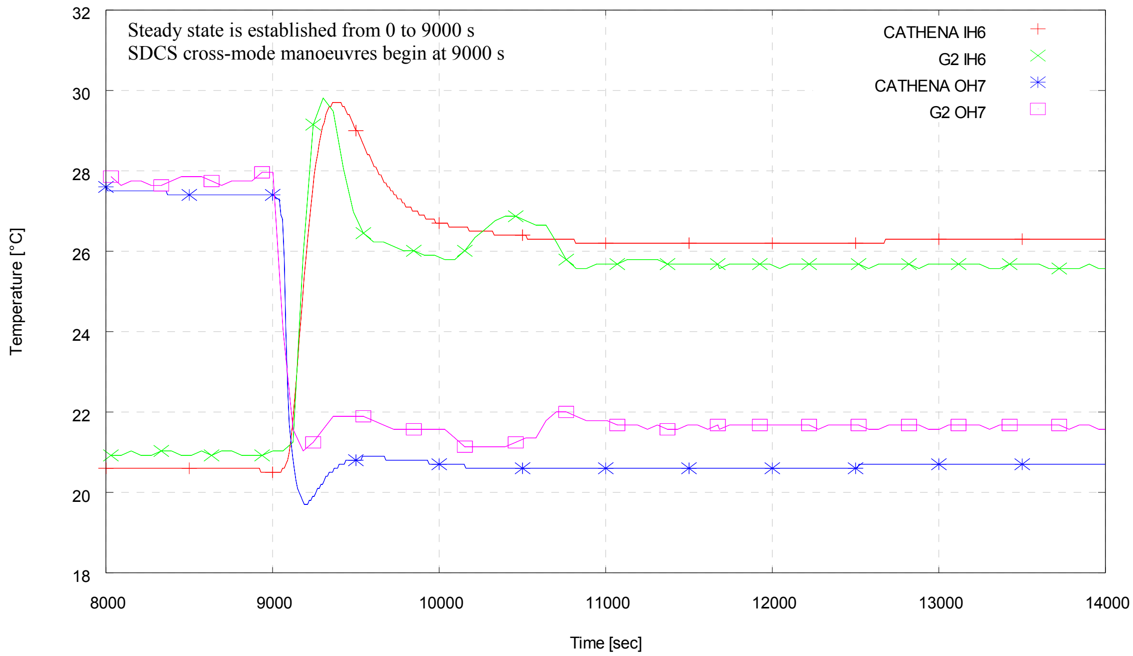

Figure 12 : Transient Temperature at Inlet Header 6 (IH6) and Outlet Header 7 (OH7) (case #2 : 0.22%PP)

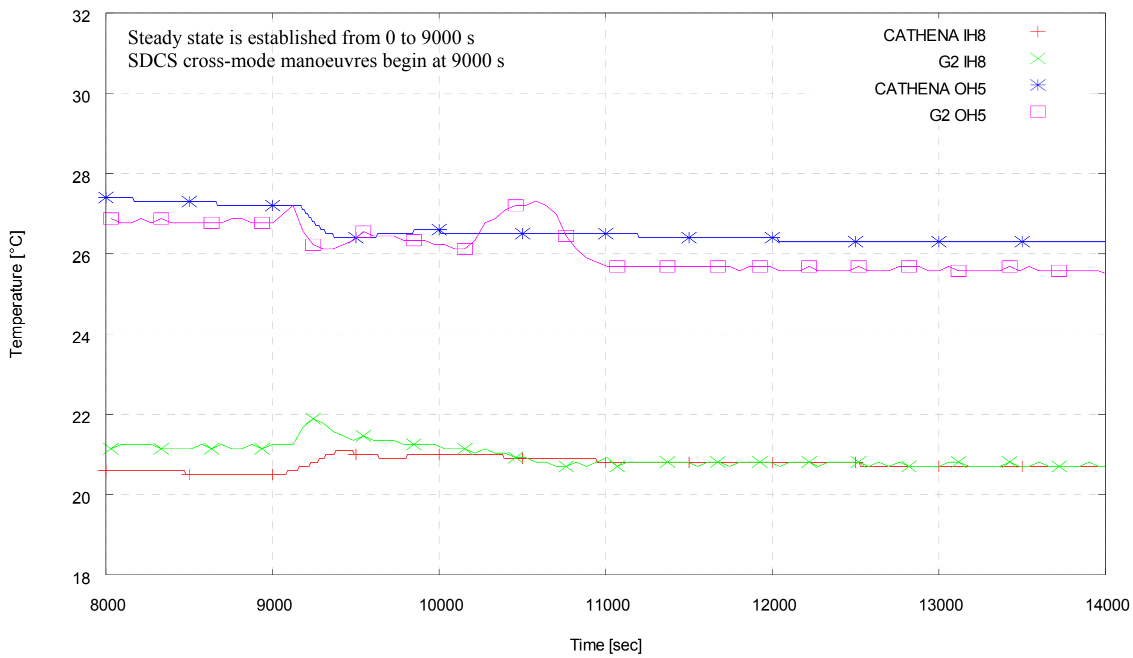

Figure 13 : Transient Temperature at Inlet Header 8 (IH8) and Outlet Header 5 (OH5) (case #2 : 0.22%PP)

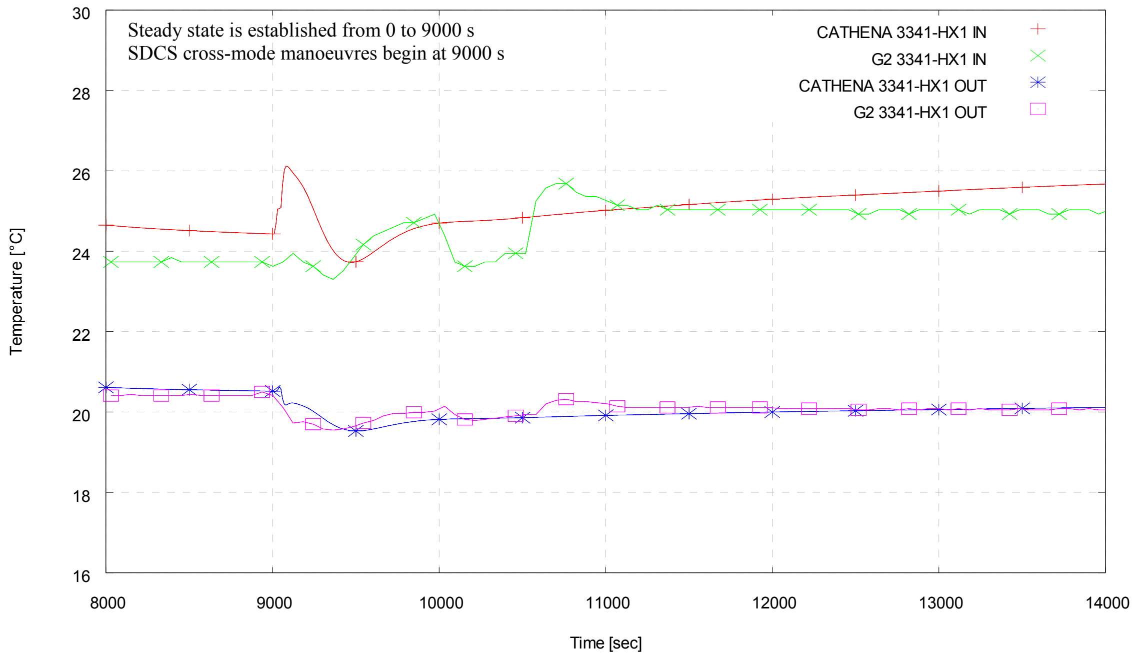

Figure 14 : Transient Temperature at SDCS Heat Exchanger 3341-HX1 (case #2 : 0.22%PP)

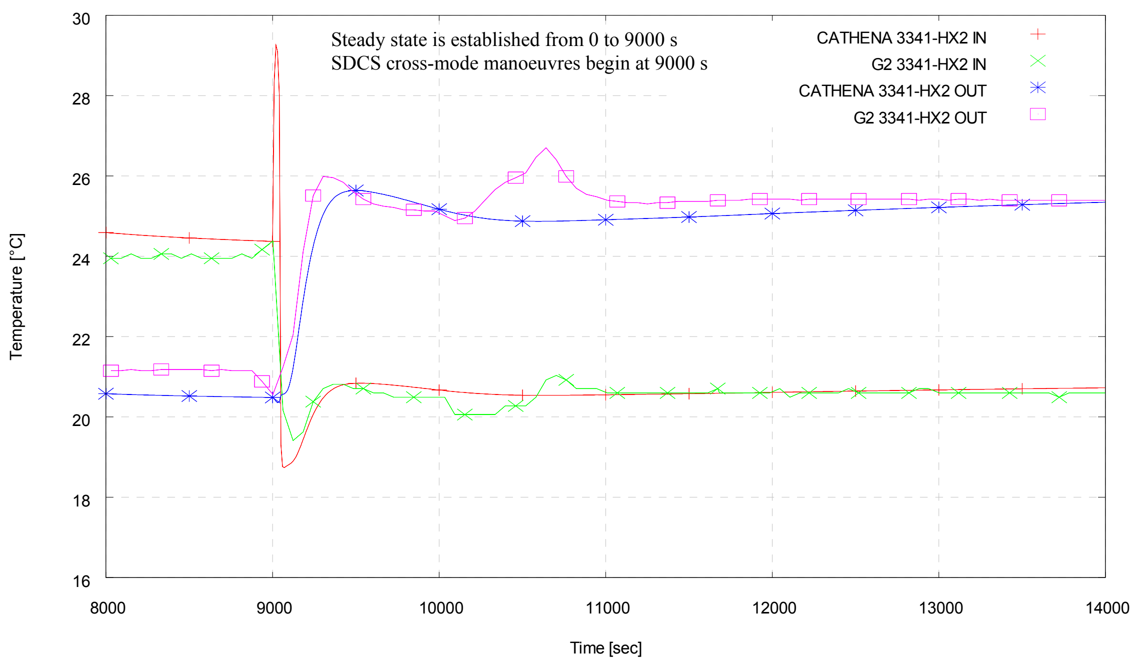

Figure 15 : Transient Temperature at SDCS Heat Exchanger 3341-HX2 (case #2 : 0.22%PP)

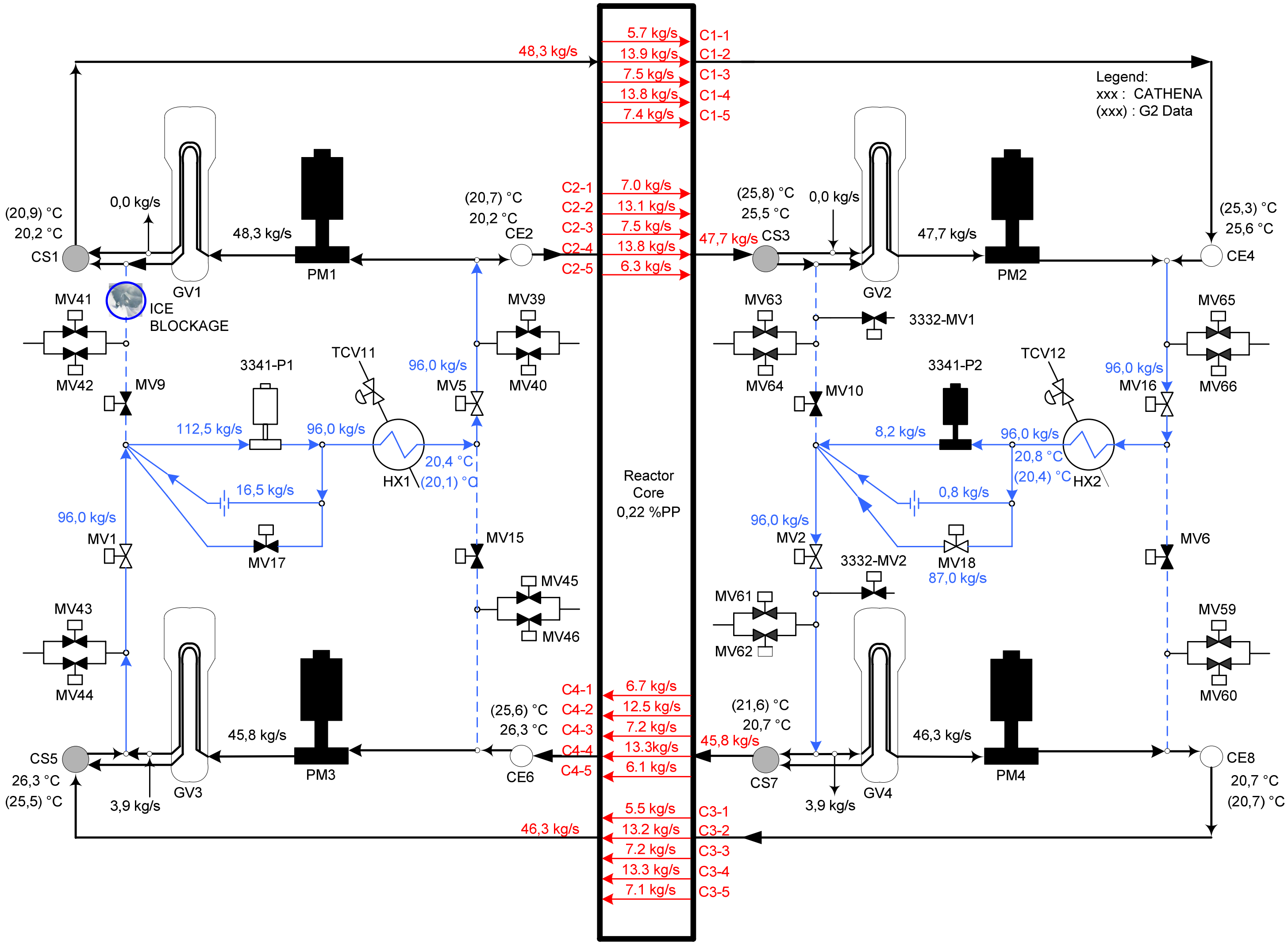

Figure 16 : Steady Plant Conditions after 14000 sec (case #2)

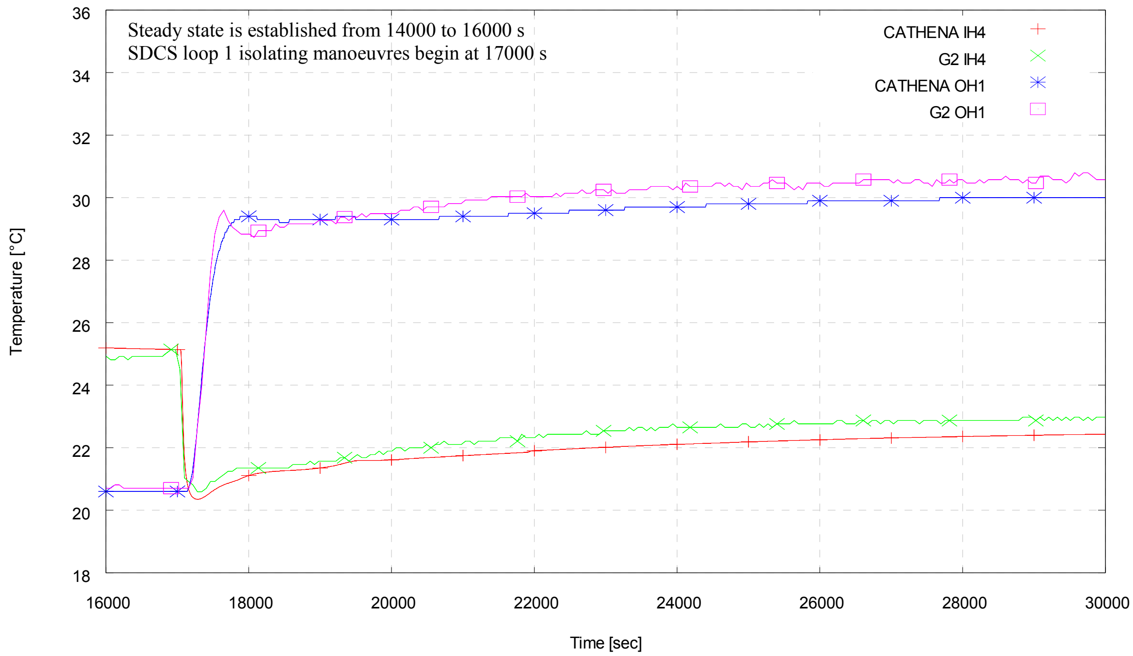

Figure 17 : Transient Temperature at Inlet Header 4 (IH4) and Outlet Header 1 (OH1) (case #3: 0.18%PP)

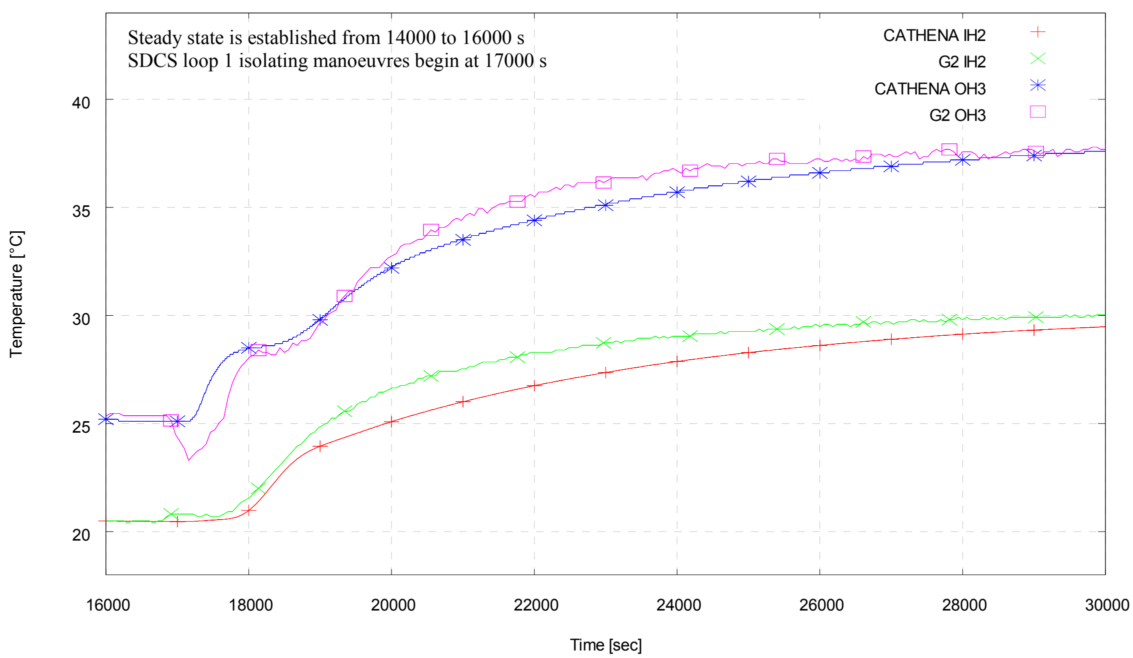

Figure 18 : Transient Temperature at Inlet Header 2 (IH2) and Outlet Header 3 (OH3) (case #3: 0.18%PP)

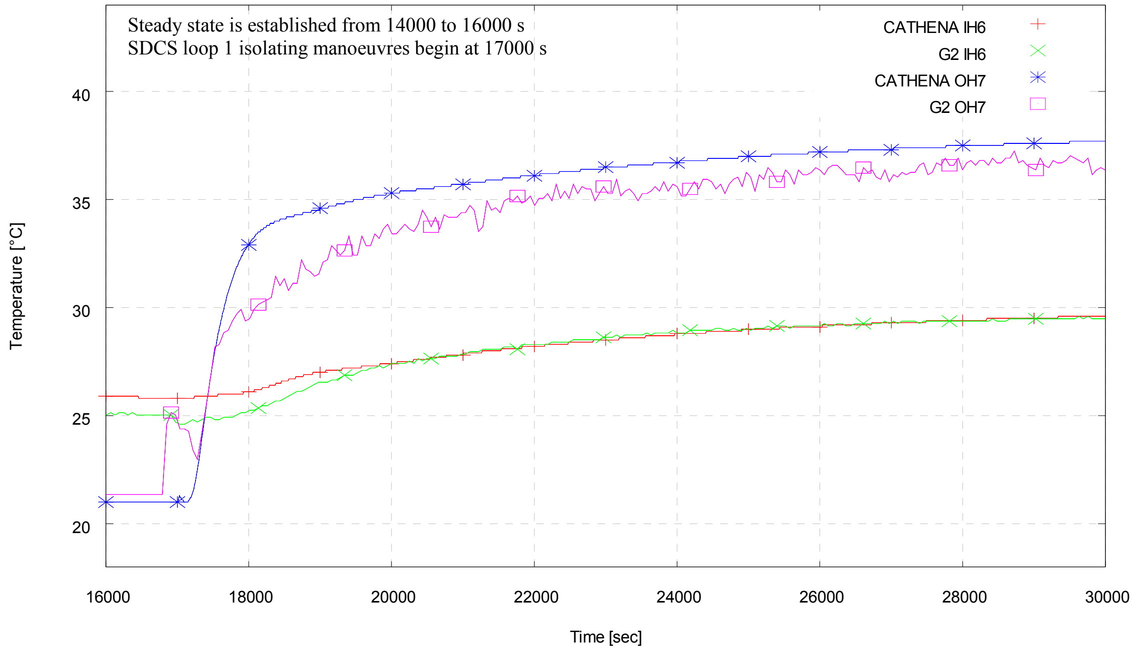

Figure 19 : Transient Temperature at Inlet Header 6 (IH6) and Outlet Header 7 (OH7) (case #3: 0.18%PP)

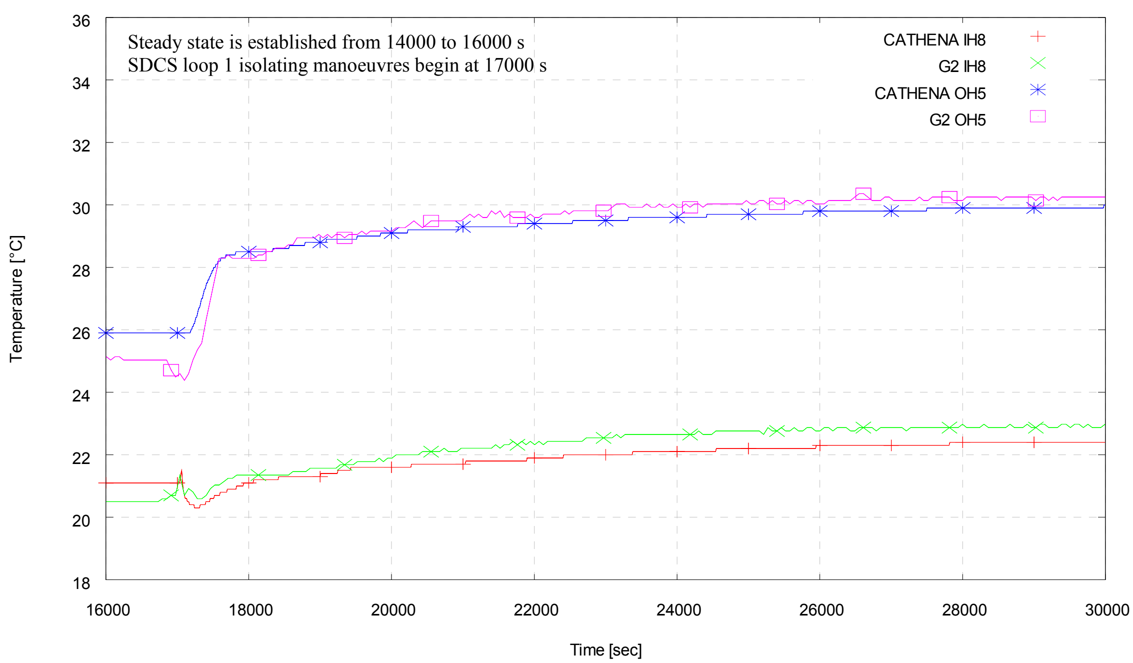

Figure 20 : Transient Temperature at Inlet Header 8 (IH8) and Outlet Header 5 (OH5) (case #3: 0.18%PP)

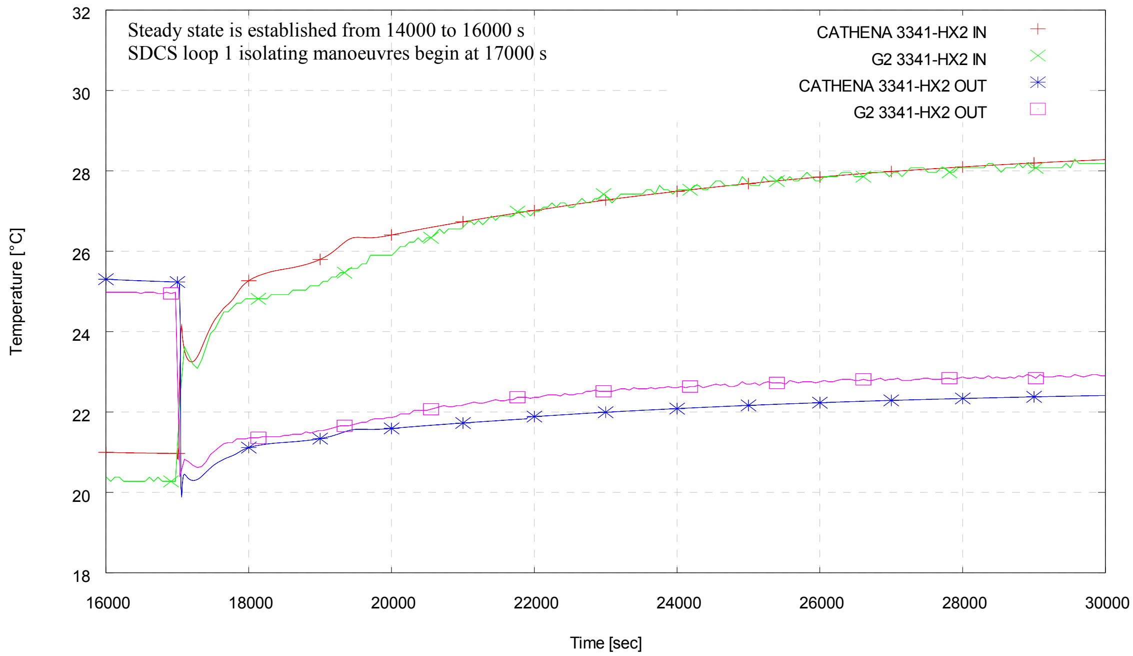

Figure 21: Transient Temperature at SDCS Heat Exchanger 3341-HX2 (case #3 : 0.18%PP)

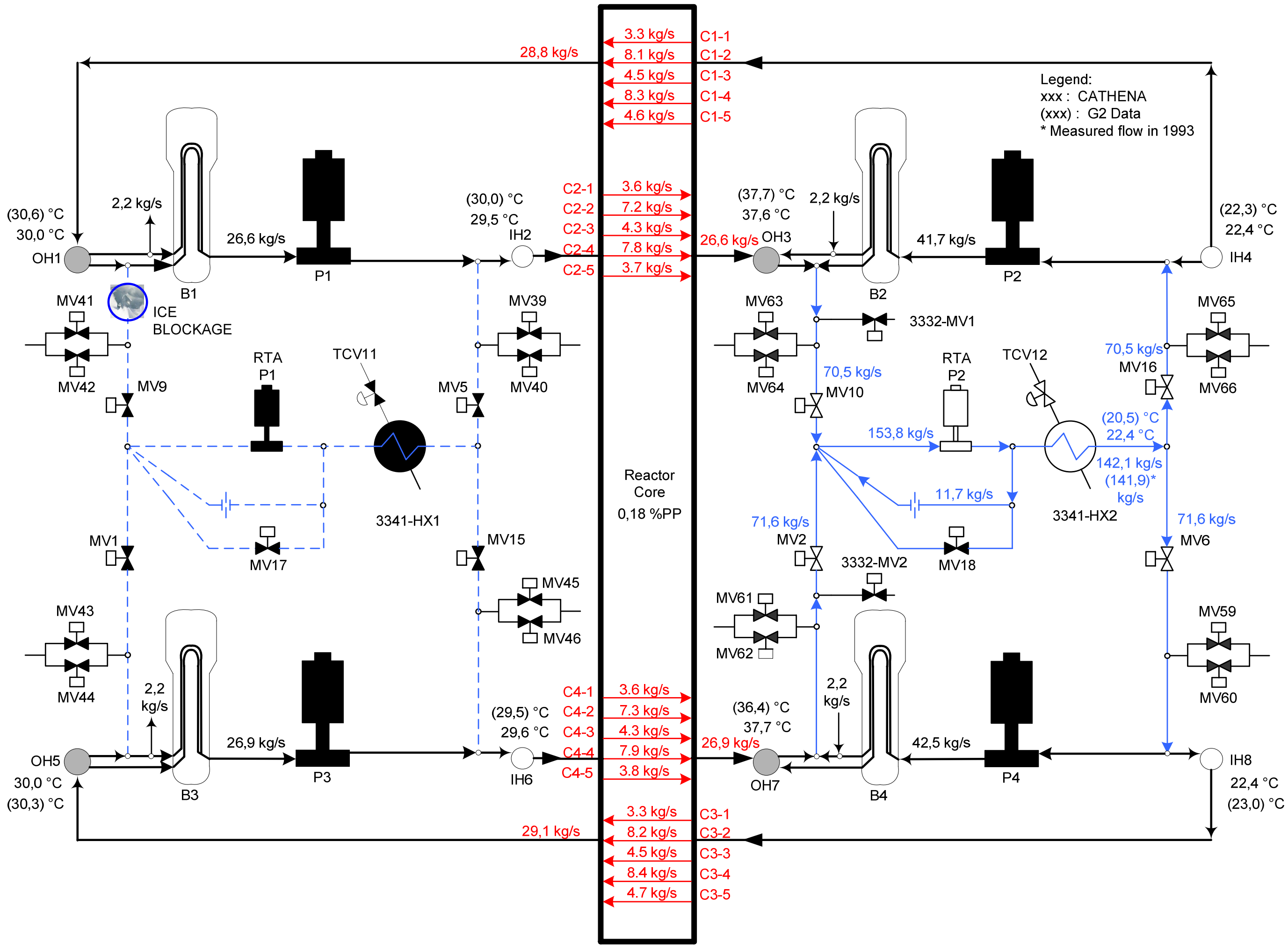

Figure 22: Steady Plant Conditions after 30000 sec (case #3)