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Abstract – Gas coolant at low pressure exhibits poor heat transfer characteristics. This is an area of concern for the passive response targeted by the Generation IV GCFR design. For the first 24 hour period, the decay heat removal for the GCFR design is dependent on an actively powered blower, which also would reduce the temperature in the fuel during transients, before depending on the passive operation. Natural circulation cooling initiates when the blower is stopped for the final phase of the decay heat removal, as under forced convection the core decay heat is adequately cooled by the running blower. The ability of the coolant to flow in the reverse direction or having recirculation, when the blowers are off, necessitates more understanding of the flow behavior characteristics in the upper plenum. The work done here focuses primarily on the period after the blower has been turned off, as the core is adequately cooled when the blowers are running, thus there was no need to carry out the analysis for the first 24 hours. In order to understand the plume behavior for the GCFR upper plenum several cases were run, with air, helium and helium-air mixture. For each case, the FLUENT was used to characterize the steady state velocity vectors and corresponding temperature in the upper plenum under passive decay heat removal conditions. This study will provide better insight into the plume interaction in the upper plenum at low flow and low pressure conditions.

I. INTRODUCTION

The Gas Cooled Fast Reactor (GCFR) employs He as the primary coolant. It can be operated at high temperatures, has a high thermal efficiency because of the high temperature of the coolant, and being chemically inert by nature, it does not react with the structural materials in the core. Gas coolant at low pressure exhibits poor heat transfer characteristics. This is an area of concern for the passive response targeted by the Generation IV GCFR design. For the first 24 hour period, the decay heat removal for the GCFR design is dependent on an actively powered blower, before reliance on the passive safety system; natural circulation cooling initiates when the blower is stopped for the final phase of decay heat removal.

Since the natural circulation mass flow rate and the corresponding heat removal rate both increase with system pressure, a guard containment structure surrounding the primary system is designed to support an elevated back pressure condition in a depressurization accident. In the GCFR the heat is removed by a combination of active and passive systems, and the maximum fuel and core outlet temperatures are maintained within acceptable limits. For the first 24 hours after shutdown when natural circulation alone is not sufficient to cool the core, the ECS (Emergency core cooling system) equipped with battery powered blowers will operate. Since the active system provides a relatively large mass flow rate, recirculation phenomena is unlikely and plume behavior is not considered.

The ability of the coolant to flow in the reverse direction or having recirculation, when the blowers are off necessitates a better understanding of the flow behavior characteristics in the upper plenum. The natural circulation mass flow rate is two orders of magnitude smaller than forced circulation allowing significant plume interaction during passive cooling. In order to understand the interactions between hot plumes in the upper plenum in the core during low flow/low pressure transients, a GCFR upper plenum model is generated in GAMBIT and the CFD analysis is carried out in FLUENT (6.3.21). The dimensions are provided by the Brookhaven National Laboratory RELAP5 (2.4.1.1A) input deck. The 2400MWt GCFR is designed for a system pressure of 7.0 MPa and a core pressure drop of 5.2 x 10^4 Pa. The primary coolant flow rate is 1249kg/sec and the core inlet and outlet temperatures are 480^o C and 850^o C, respectively. In order to understand the plume behavior for the GCFR upper plenum several cases were run. For each case, FLUENT was used to characterize the steady state velocity vectors and corresponding temperature in the upper plenum under passive decay heat removal conditions.

II. ANALYSIS AND MODELING PROCEDURE

At reduced power and reduced pressure, the mass flow rate of the coolant under natural circulation is much lower than forced circulation (blower flow). This gives rise to the dilemma of decay heat removal of GCFR based only on the passive safety system, and makes the understanding of the plume behavior interaction important. In order to understand the interactions between hot plumes in the upper plenum above the core during low flow/low pressure transients, a GCFR upper plenum model was generated in GAMBIT and the CFD analysis was carried out in FLUENT (version 6.3.21). The dimensions were provided by the BNL RELAP5 (version 2.4.1.1A) input deck.

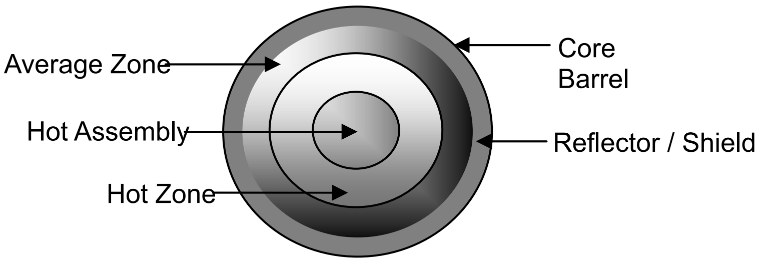


Figure 1: Horizontal cross-section of GCFR core (not to scale).

The RELAP5 model of the fuel in the core is grouped into three radial zones by power (refer Table 1). These radial zones are the hot assembly, the hot zone, and the average zone, as can be seen in the Figure 1. 1.7 % of the power is produced by the hot assembly, 14.1% of the power is produced by the hot zone and the remaining 84.2% is produced by the average zone, here the percentage corresponds to the number of fuel assemblies in that respective radial zone. The 2400MWt GCFR is designed for a system pressure of 7.0 MPa and a core pressure drop of 5.2 x 10^4 Pa. The primary coolant flow rate is 1249 kg/sec and the core inlet and outlet temperatures are 480^o C and 850^o C, respectively [1].

Table 1. Power Distribution in Fuel Zones[1]

	Hot Assembly	Hot Zone	Average Zone
Regular Assembly	6	48	303
Control Assembly	0	7	54
Power Fraction (%)	1.7	14.1	84.2
Relative Radial Power Shape	1.31	1.21	0.967

The upper plenum, consisting of a hot assembly, hot zone and average zone, was modeled with GAMBIT. These radial zones acted as the inlet channels to the upper plenum. The gap between the core barrel and the shield along with the gap between the reflector and the shield acted as outlets from the upper plenum. Also included in the model were the PCU (power conversion unit) inlet, which acted as an outlet from the upper plenum and also the lumped PCU (combining the remaining three PCUs together, as we require four PCUs for the 2400 MWt GCFR). Piping to the ECS also acted as an outlet vent from the upper plenum. The inlet mass flow rate and the respective temperature were specified for their corresponding radial zone as inlet boundary conditions, whereas for the outlets, temperatures and pressures were used as the boundary conditions. These values were obtained with the BNL-RELAP5 deck. Figure 2 shows the dimensions of the GCFR upper plenum, and a 3-D rendering is shown in Figure 3. In GAMBIT, the symmetry condition was used in order to reduce the number of meshing nodes and the run time in FLUENT.

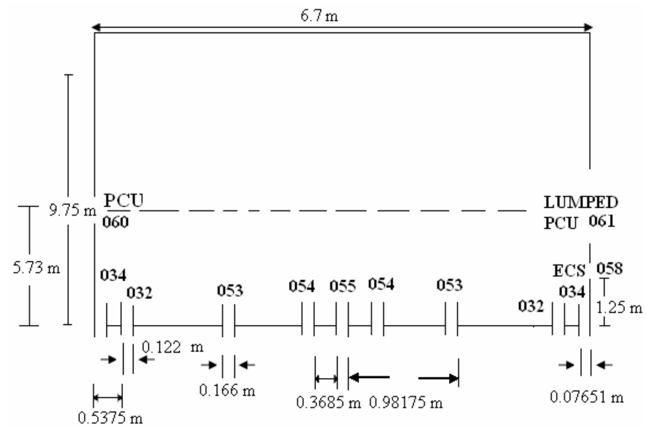


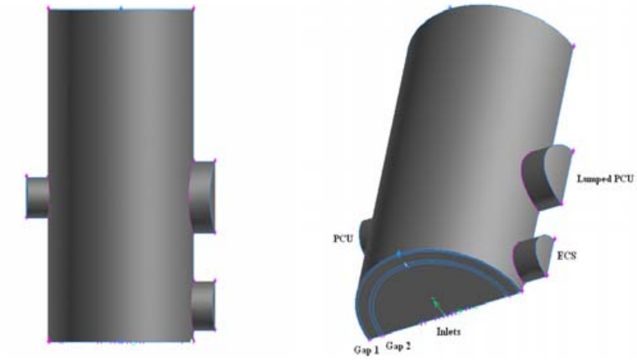
Figure 2. GCFR upper plenum geometry

Label numbers given in Figure 2 are described in greater detail in Table 2.

Table 2. Upper Plenum Parameters

Volume Number	Component Name	Flow Area (m2)	Radius (m)	Temperature (K)	Pressure (Pa)	Inlet/Outlet
O32	Gap II	0.0154	0.061	762.394	8.00522E+05	Outlet
O34	Gap I	0.0103	0.038255	579.794	8.00520E+05	Outlet
O53	Average Channel	6.2487	0.083	994.957	8.00524E+05	Inlet
O54	Hot Zone	0.9626	0.083	1035.916	8.00524E+05	Inlet
O55	Hot Assembly	0.105	0.083	1092.152	8.00524E+05	Inlet
O58	ECS	2.262	0.84834	374.456	8.00473E+05	Outlet
O60	PCU	1.606	0.7144	380.697	8.00473E+05	Outlet
O61	Lumped PCU	4.818	1.236	376.934	8.00475E+05	Outlet

The different views of the upper plenum as shown in Figure 3 were made in GAMBIT, which is an integrated preprocessor for CFD analysis, and then the meshed file was exported to FLUENT for further analyses. In order to understand the plume behavior for the GCFR upper plenum, several cases were run, which will be described in detail in the next section. For each case, FLUENT was used to characterize the steady state velocity vectors and corresponding temperature in the upper plenum under passive decay heat removal conditions.



a) Front View b) Isometric View

Figure 3. Different views of the upper plenum

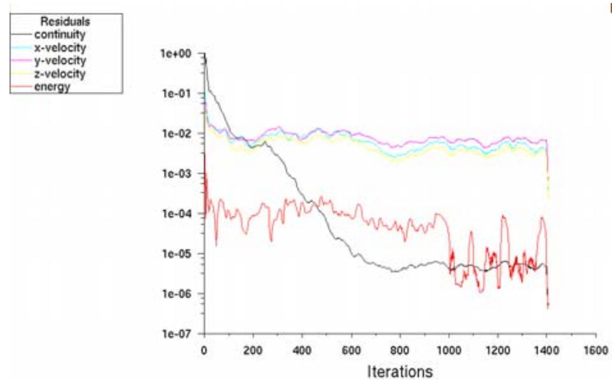
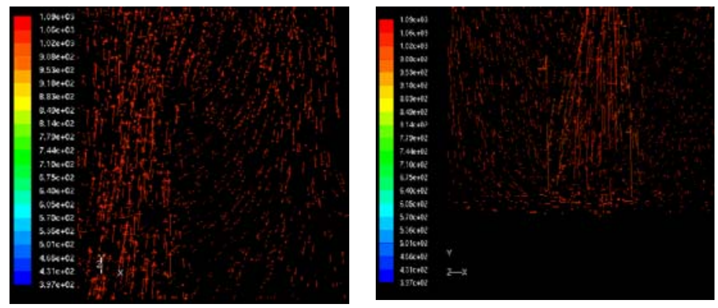


Figure 4. Residual plot for convergence (Case 1)



Flow out of Lumped_PCU Flow out of ECS

Figure 5. Velocity vector colored by static temperature (K)

III. MODELING RESULTS

As described above, several cases were run until the convergence criterion was met. In this case, convergence on energy was the most important parameter, and thus was set at 1E-06. In our analyses, the boundary conditions for the inlet and outlet were held constant, as these numbers were obtained from the BNL RELAP5 deck. These conditions correspond to values of mass flow rate, temperature and pressure 24 hours after the shutdown.

Table 3. Different Cases for the analyses†

Case	PCU	PCU_Lumped	ECS	Gap I	Gap II	AZ I	HZ I	HA	AZ II	HZ II
1	X	X	X	0	0	X	X	X	X	X
2	X	X	X	X	X	X	0	X	X	0
3	X	X	X	X	X	0	X	X	0	X
4	X	X	X	X	X	X	X	0	X	X

In Table 3, the X corresponds to "on" (coolant is flowing) and 0 corresponds to "off" (no flow). For all the cases, convergence criteria were met, both for steady and unsteady state. Conservation of mass was verified for all cases, as can be seen in Table 4.

III.A. Case 1

In case 1, the gap between the core barrel and the shield along with the gap between the shield and the reflector were closed. The convergence criteria were met as can be seen from Figure 4. The largest flow rate was through the lumped PCU opening, as expected.

Figure 5 shows the velocity vector colored by temperature, and the maximum amount of flow is through the lumped PCU. As can be seen from Figure 5 that all the velocity vectors are at nearly the same temperature, because no flow is allowed to go through the gaps which makes all the plumes to rise and thus colder plumes come in contact with the hotter plumes and attain the same temperature before leaving through other outlets.

III.B. Case 2

In this case, two inlets (hot zones) were closed. Gaps close to the average zone inlet had a net positive mass flow rate because the flow rate of the average zone was so high that it entrained the plumes entering the gaps with it and thus made the gaps behave like an inlet. In this case the maximum flow was out the lumped PCU, as expected.

† Refer the Nomenclature

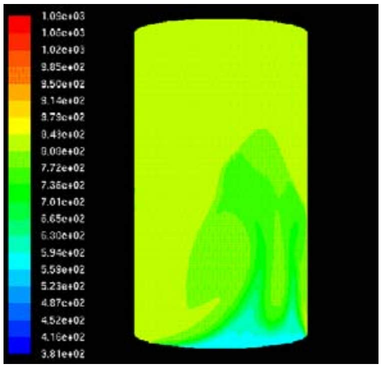
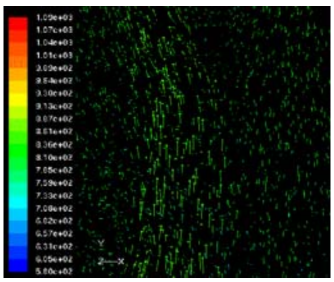
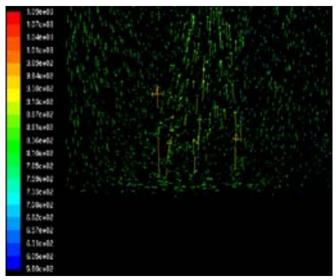


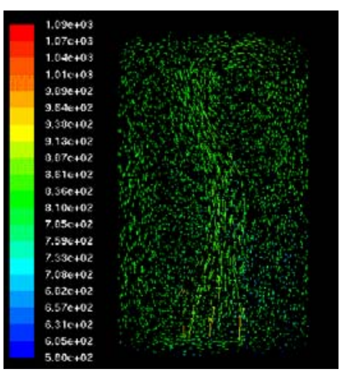
Figure 6. Contour Plot of temperature (K) in the upper plenum.



Flow out of Lumped_PCU



Flow out of



Entire Plenum

Figure 7. Velocity vector colored by static temperature (K)

Figure 6 shows the temperature contour plot for the upper plenum and since the hot zone inlets are closed, the plume near that region is at a colder temperature. In Figure 7, these plumes are represented by blue arrows.

III.C. Case 3

In this case the average zone inlets are closed and the gaps are acting as an outlet unlike in case 2, thus proving the

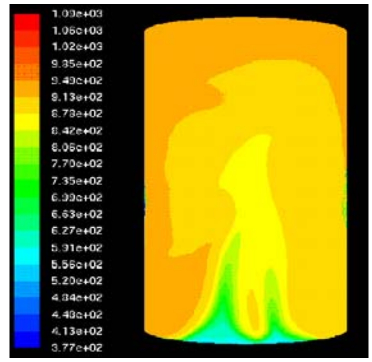
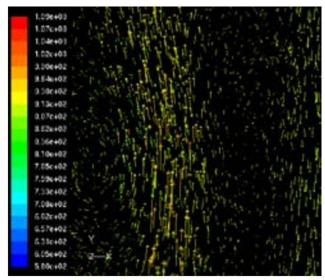
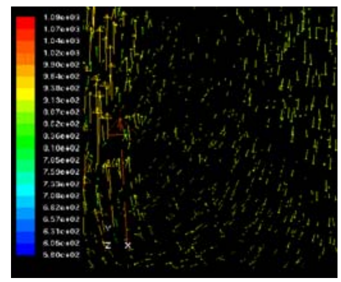


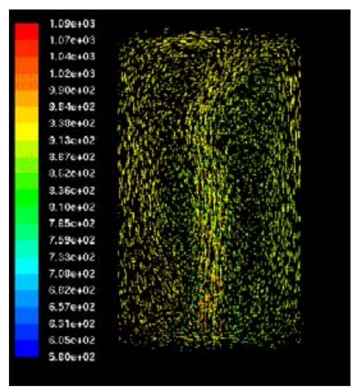
Figure 8. Contour Plot of temperature (K) in the upper plenum.



Flow out of Lumped_PCU



Fow out of ECS



Entire Plenum

Figure 9. Velocity vector colored by static temperature (K)

validity of the reasoning for case 2. The maximum amount of flow in this case is into the ECS.

As can be seen from Figures 8 and 9, most of the flow goes out of ECS because the average zone inlet channels are closed. Thus plumes near that location are comparatively cold, and thus do not have enough momentum to carry themselves upwards towards the lumped PCU.

III.D. Case 4

In this case the hot assembly inlet is closed. Since we have the average zone inlet open, it is forcing the gaps to act as an inlet, similar to case 2. In this case both the ECS and Lumped PCU have almost the same amount of flow leaving from the upper plenum.

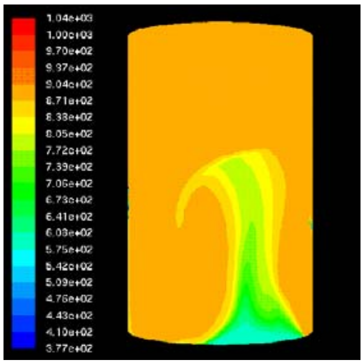
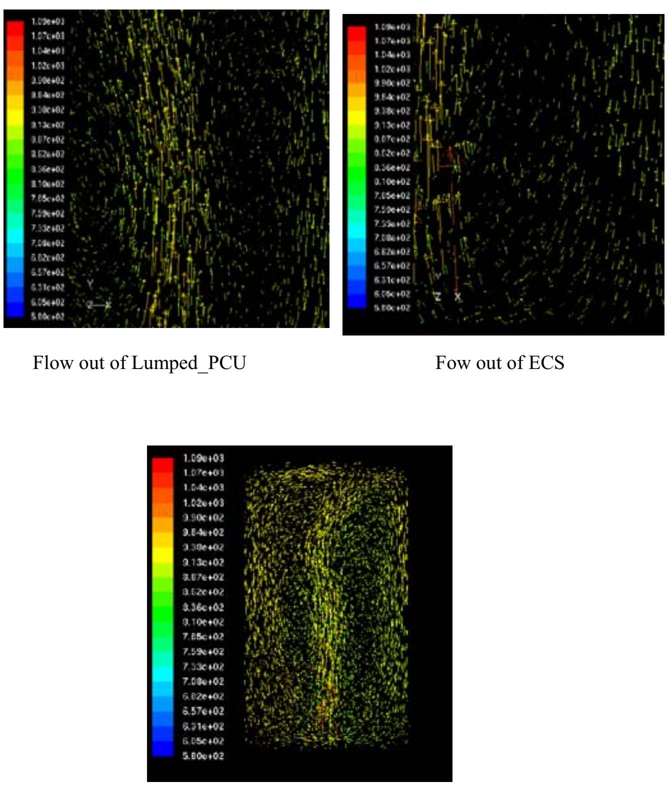


Figure 10. Contour Plot of temperature (K) in the upper plenum



Flow out of Lumped_PCU

Fow out of ECS

Entire Plenum

Figure 11. Velocity vector colored by static temperature (K)

As can be seen from Figures 10 and 11, the plumes near the hot assembly exhibit colder temperature and thus move towards the ECS, whereas the plumes near the hot zone and average zone make there way towards the lumped pcu.

IV. DISCUSSION

In all the cases investigated, as can be seen from Table 4, the net mass flow in the upper plenum is not equal to zero, because in an unsteady problem some amount of mass gets accumulated in the plenum, but the magnitude of the net mass flow was small enough to let us believe that mass was being conserved (or the problem was in steady state). The positive magnitude of the mass flow rate refers to the incoming flow whereas the negative magnitude of the mass flow rate refers to the outgoing flow. In all the cases the recirculation patterns of plumes were observed in the top of the upper plenum.

Table 4. Mass flow rate (kg/sec) for all the cases[‡]

Case	PCU	PCU_Lumped	ECS	Gap I	Gap II	AZ I	HZ I	HA	AZ II	HZ II	δm_{in}-δm_{out}
1	-0.754	-4.5733089	-2.18	0	0	1.526	1.5	1.47	1.53	1.5	0.00935891
2	-0.411	-6.8843565	-1.93	1.975	2.7216	1.526	0	1.47	1.53	0	-0.00492257
3	-0.138	-0.60658735	-3.26	-0.33	-0.054	0	1.5	1.47	0	1.5	0.082669511
4	-0.026	-3.120975	-3.02	0.019	0.1907	1.526	1.5	0	1.53	1.5	0.092100486

If the mesh is made more refined, then the net mass flow rate through the upper plenum could be further reduced and thus more precise values for the outlet mass flow rate could be obtained. The analysis done here indicates that the recirculation pattern and the outlet flow is dependent on which inlet channels are open, such as in case 2 when the average channel was off. Both the gaps were behaving as outlets and were aiding in the decay heat removal, whereas in the other cases there was no flow in those gaps, which in an actual system is similar to having a flow stagnation, leading to cracking, and also leading to generation of hot spots in the core. In order to fully understand the plume interaction behavior, this analysis should be performed with a finer mesh and with other coolants and mixtures. This may be important if blower power is lost. The analyses should also be carried out with CO_2 for comparison with He. CO_2 is denser than He and is thus a better natural convection coolant.

In an accident scenario, if air ingresses inside the vessel, there is mixing of air and He which has a critical effect on the He plume rising in the upper plenum. The initial vertical velocity of the plume is soon greatly reduced, upon encountering the air and if at the same time forced flow is not available, flow reversal in some of the inlet channels could result.

[‡] Positive values indicate flow into the plenum, whereas negative values indicate flow out of the plenum.

V. COMPARATIVE STUDY

In order to understand the plume behavior for the GCFR upper plenum a few different cases were run, with air, helium (Table 5) and He-air mixture (Table 6). For each case, FLUENT was used to characterize the steady state velocity vectors and corresponding temperature in the upper plenum under passive decay heat removal conditions. In the previous sections explanations have been provided for air as the coolant. In this section we will compare air to other coolants. In the case of He-air mixture, maximum flow was through the lumped PCU, similar to that of the air, but with He, maximum flow was through the ECS, for case 1. For case 2 the maximum flow was through the gap I for the He-air mixture, whereas maximum flow was observed through the lumped PCU for air and He. For case 3 maximum flow was observed through the lumped PCU for both He-air mixture and He, whereas for air, the maximum flow was through ECS. For case 4, maximum flow was observed through the lumped PCU for air and He, whereas in the case of the mixture of He and air, maximum flow was observed through gap1. The analysis done here indicates that the recirculation pattern and the outlet flow is dependent on which inlet channels are open and also indicate dependence of the mass flow on the type of the coolant, i.e for same conditions the behavior of plumes was observed to be different, which should be significant for the study of flow characteristics in the upper plenum during low flow/low pressure transients.

Table 5. Mass flow rate (kg/sec) for all the cases (He)

Case	PCU	PCU_Lumped	ECS	Gap I	Gap II	AZ I	HZ I	HA	AZ II	HZ II	$\delta m_{in}-\delta m_{out}$
1	38.88	-5.6760817	-46.7	0	0	1.526	1.5	1.47	1.5256	1.5	-5.961591
2	0.045	-5.8001235	-4.64	2.0268	2.888	1.526	0	1.47	1.5256	0	-0.958656
3	-0.46	-5.8489499	-4.05	2.1871	3.693	0	1.5	1.47	0	1.5	-0.006198
4	-0.9	-5.9815878	-1.49	0.7292	1.586	1.526	1.5	0	1.5256	1.5	-0.006638

Table 6. Mass flow rate (kg/sec) for all the cases (He+Air)

Case	PCU	PCU_Lumped	ECS	Gap I	Gap II	AZ I	HZ I	HA	AZ II	HZ II	$\delta m_{in}-\delta m_{out}$
1	-0.754	-4.5733089	-2.1847	0	0	1.526	1.5	1.5	1.526	1.5	0.009359
2	-0.254	-1.1788735	0.0624	-1.859	-1.517	1.526	0	1.5	1.526	0	-0.22535
3	-0.113	-2.203158	-0.0775	-1.254	-0.515	0	1.5	1.5	0	1.5	0.307385
4	-0.122	-0.63000469	-0.2092	-2.811	-2.583	1.526	1.5	0	1.526	1.5	-0.30352

VI. CONCLUSIONS

Flow within the upper plenum was characterized during natural circulation 24 hours after a LOCA. In future work, the same analyses should be carried out for mixtures of different gases such as helium (He) and carbon dioxide (CO_2), and also CO_2 and air. In all the cases, investigated here, the net mass flow in the upper plenum is not equal to zero, because in an unsteady problem some amount of mass is accumulated, but the magnitude of the net mass flow was small enough to assume that problem was in steady state. The positive magnitude of the mass flow rate refers to the incoming flow whereas the negative magnitude of the mass flow rate refers to the outgoing flow. In all the cases a recirculation pattern of plumes was observed at the top of the upper plenum. Performing the analyses with different coolants and using a finer mesh will lead to a better understanding of the plume behavior in the upper plenum at low flow and low pressure conditions.

VII. NOMENCLATURE

Inlets

AZ I – First inlet channel in the average zone
AZ II – Second inlet channel in the average zone
HZ I – First inlet channel in the hot zone
HZ II – Second inlet channel in the hot zone
HA – Inlet channel in the hot assembly

Outlets

ECS – Emergency core cooling system
Gap I – Gap between the core barrel and the shield
Gap II – Gap between the reflector and the shield
PCU – Power Conversion Unit

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