NATURAL CONVECTION HEAT TRANSFER IN A STRATIFIED MELT POOL WITH VOLUMETRIC HEAT GENERATION

Bal Raj Sehgal
Division of Nuclear Power Safety (NPS)
Royal Institute of Technology (KTH)
33A, Drottning Kristinas väg
SE-100 44 Stockholm, Sweden
e-mail: sehgal@ne.kth.se, fax: +46-8-790-9197

Abstract

This paper describes the results obtained from several sets of experiments, performed over several years in the SIMECO facility a the NPS Division, KTH on natural convection in multi-layered liquid pools with volumetric heat generation in one or more layers. The safety issue, to which these experiments are directed, is that of the thermal loading on the reactor pressure vessel (RPV) wall due to corium melt pool convection in the lower head. Multi layer pools are considered due to the observations made in the RASPLAV (Asmolov et al., 1998) and the MASCA (Asmolov et al.,2003) experimental programs on convection of prototypic material (UO_2+ZrO_2+ZR+Fe) melt pools. The SIMECO is a slice facility of 1/8th scale various liquids and cerrobend were employed respectively as simulants for corium and the melt layer are discussed.

1. INTRODUCTION AND BACKGROUND

This paper reviews the subject of the natural convection of a melt pool that may be formed in the vessel lower head in the last phase of the in-vessel progression of a severe accident in a pressurized water reactor (PWR). The safety issue is that of the thermal load imposed by the heat generating melt pool on the lower head wall, which will lead to the failure of the lower head, unless, as an accident management (AM) strategy, the outside of the vessel wall is cooled by flooding the containment. This is exactly the strategy, designed for the Westinghouse's AP-600 and AP-1000 reactors and for the Framatome's BWR-1000 and the KEPCO's Advance PWR-1400 reactors.. This, so called, in-vessel melt retention (IVMR) strategy aims to cool the core melt within the lower head as the stabilization, and ultimately, the termination point of the severe accident. In this strategy, the melt loading on the containment is avoided, thereby reducing the probability of failure of the containment by several orders of magnitude. Consequently, the probability of a large release of fission products to the environment is also reduced by several orders of magnitude.

The success criterion for the in-vessel retention is that the thermal loading imposed by the naturally-convecting melt on the lower head wall should be less than the critical heat flux for the water cooling it on its outside surface. Fortunately, the thermal loading on the lower head, exerted by the melt pool natural convection, varies along the polar angle in the same fashion as the critical heat flux. The licensing criterion for IVMR is that there should be sufficient margin between the critical heat flux (CHF) and the thermal loading at all locations of the lower head. This was the guiding principle for the evaluation made by Prof. Theofanous (Theofanous et al., 1996) for the AP-600.

The prototypic melt is a mixture of the many different materials resident in the reactor, e.g. UO_2, ZrO_2, Zr, Fe, Ni, Cr, control rod materials and perhaps burnable poisons. The melt pool may separate into stable layers performing natural convection, which affects the thermal loading on the vessel wall. Indeed, the melt pool configuration assumed by Prof. Theofanous, besides being the bounding configuration, also contained a metal layer on top of the oxidic melt pool. It was assumed that the oxidic melt pool contained the heat generating material, i.e. UO_2 and the fission products (FPs) and the metal layer contained the non-heat generating metal materials, i.e. stainless steel and Zirconium. It was found that the metal layer receiving heat from the oxidic melt pool focussed the heat onto the lower head wall facing it; and that was the most vulnerable region of the lower head wall. The focussing effect was found to be a function of the thickness of the metal layer, since the area of the wall in contact is a function of the thickness of the metal layer. Only for the metal layer thickness of less than ~30 cm, the focussed heat flux was found to be more than the CHF. The metal layer thickness for the AP-600 on the outside was found to be >30 cm, thus, a sufficient margin to the CHF was found, so that the in-vessel melt retention strategy was found to be feasible for the AP-600. The AP-600 findings were backed by the experiments conducted in the ACOPO, half scale facility (Theofanous et al., 1997) with a uniform pool of water; and by other experimenters, e.g. Asfiah and Dhir 1994, 1996 and other, 1997. An IVMR accident management strategy was also initiated for the Loviisa VVER-440 PWR in Finland, later approved by the Finnish regulatory authority STUK(Kymalainen et al., 1997), which was supported by the experiments performed in the COPO facility (Kymalainen et al., 1998), which is a half scale slice facility employing salt water with electrical resistance (volumetric) heating.

The COPO half- scale slice vessel experiments were followed by the experiments conducted on the full scale slice facility BALI in France (Bonnet et al. 1994), again employing resistance heating of salt water. A full-scale separate effect experiment performed by Bonnet et al., also employing water, simulated the metal layer and obtained data for the focussing effect. The BALI experiments obtained slightly different correlations for the upward and downward heat transfer, Nu_{up} Nu_{dn}, respectively, than those derived from ACOPO tests, however, their ratio was found to be similar to that employed for the AP-600 study. The classical correlations of Churchill and Chu,1975 and of Globe and Dropkin 1959, among others, were found to be quite valid for determining the heat flux at the wall surface adjacent to the pool.

It should be mentioned here that before the AP-600 study conducted by Prof. Theofanous, a substantial body of data and analysis existed on liquid pool natural circulation in rectangular and hemispherical vessels and correlations existed for the thermal loading. Indeed most of the experimental and analysis (CFD) studies conducted in the late

1980s and early 1990s confirmed the correlations derived earlier by Steinberner and Reincke, 1978, Mayinger et al., 1997, and others. It should also be mentioned that the upward and downward heat fluxes from a volumetric heat generating pool scale only with the Rayleigh number, which is quite remarkable. This has enabled the use of simulant materials like water and a relatively easy extrapolation to the prototypical reactor vessel.

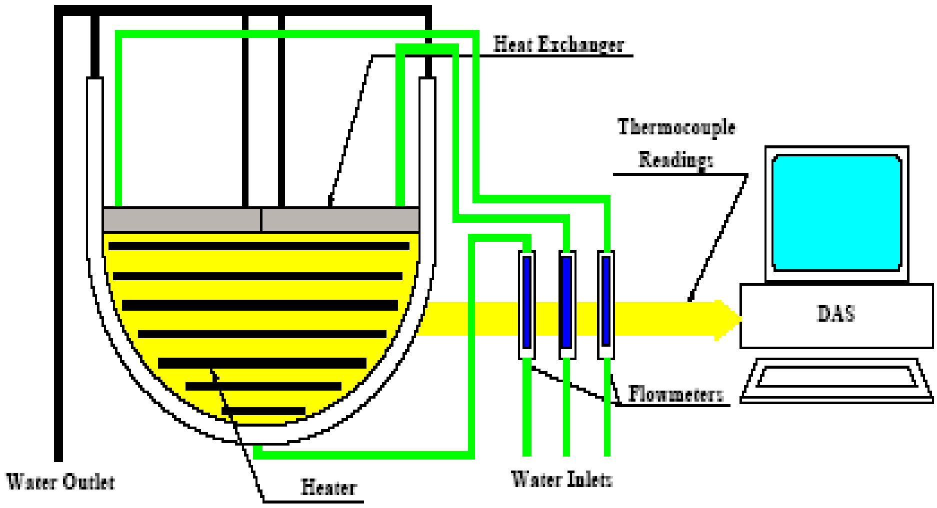
The next stage in the research concerned with the IVMR accident management scheme was the experiments conducted in the RASPLAV facility, (Asmolov et al., 1998) employing prototypical materials, i.e. UO_2+ZrO_2+Zr in their molten form at temperatures of ≥2500ºC. The RASPLAV experiments employed a 1/10th scale (40 cm diameter) slice vessel of tungsten containing the electrically heated melt, which was cooled externally with water. The melt was created by heating pellets of compacted powder material. The RASPLAV experiments confirmed that the prototypical melt performed natural convection similar to that performed by the simulant materials. The downward heat fluxes were measured. The more important finding from the RASPLAV experiments number 1 and 2 was that the oxidic melt, containing Zr, could separate into two stable layers when there was ≥ 0.3^{w}% carbon present in the melt. Such small amounts of carbon could be present in the melt in a prototypic BWR or a PWR if it contains control rods containing B_4C. The light and heavy layers of melt found in the RASPLAV 1 and 2 experiments contained, respectively, more ZrO_2 and more UO_2 from those contained in the originally uniform composition loaded in the facility.

Prototypic melts contain a large amount of stainless steel, most of which mixes into the melt from the core plate or the structures contained in the lower head. The MASCA (MAterial SCAling) Project, currently in its second phase, also conducted at the Kurchatov Institute, Russia, have employed melt mixture containing UO_2, ZrO_2, Zr and stainless steel in a relatively large scale experiment (~120 Kg of melt) and in much smaller scale experiments. The objective of the MASCA project is to determine the effect of the high temperature chemical interactions between the various components of the melt on the melt pool physical configuration which, in turn, affects the melt pool convection and the resulting thermal loading on the vessel wall. The MASCA tests found that in the presence of Zr in the melt, some Uranium (from the UO_2), and some stainless steel in the melt combine to form a metallic alloy, which is heavier than the main UO_2+ZrO_2 oxidic melt. Thus, it is conceivable that the melt pool could separate into 3 layers of different density. The top layer would be stainless steel and Zr, the middle would be UO_2+ZrO_2 and the bottom layer would be Uranium + steel. It is not clear what the multi layer pool configuration would be if there was some carbon present as well, since there is no data on such a chemical system. The MASCA program is continuing into Phase II and, perhaps, such compositions of the melt will be considered for experiments in future.

2. THE SIMECO EXPERIMENTAL PROGRAM

The SIMECO experimental program was started to investigate the effect of multi-layers on melt pool convection after the results from the RASPLAV 1 and 2 tests became known. The SIMECO experimental facility consists of a $^{1}/_{8}{}^{th}$ scale slice-type vessel, which includes a semicircular section and a vertical section (Figure 1). The diameter and height of the test section are 620 and 530 mm, respectively (Figure 2). The width of the slice, perpendicular to the page is 90 mm. The slice walls are made of brass, except for the front wall, which is made of a special high temperature glass allowing visualization of the flow and interface behaviour.

Figure 1. SIMECO experiment facility – Overview



The vessel's side wall, made from a 23 mm thick brass plate, is cooled by a regulated water loop. On the top of the pool a heat exchanger with regulated water loops is employed to provide the top boundary condition. The regulation is provided by a temperature controlled thermostat (JULABO), which controls the inlet temperature of the cooling water to within ±0.1ºC. Thin cable-type heaters, with a sheath diameter of 3 mm and 4 m in length, provide internal heating in the pool. Uniformly distributed in the semicircular section; they can supply a maximum of 4 kW power to the pool. The uniformity of heat generation is ascertained by the fact that the shape of the heat flux profile on the curved side wall and the value of Q_{up}/Q_{dn}, for a uniform pool (or that after complete mixing of the layers) agree well with those found in the literature.

The water loop temperatures are used to obtain the average heat flux on the side wall and on the top of the pool. A total of 36 K-type thermocouples are fixed inside the brass vessel wall at different angular locations in order to obtain local heat fluxes (Figure 3). The local heat fluxes are integrated to obtain the global downward heat flux and this is compared to the average heat flux obtained from the rise in the cooling water temperature. Inside the pool, 34 K-type thermocouples are installed to measure the pool temperature variation, with emphasis on the near-wall region (Figure 3). Video recording of the test section is done and post-processing of the video images is used to track the interface behaviour.

The SIMECO facility was employed to perform several types of experiments for investigation of the natural circulation phenomena. In most cases, the Rayleigh number varied from ~$4x10^{12}$ to ~10^{14}, which is not as high as needed to approximate that for the prototypic geometry and conditions (Ra=10^{16} to 10^{17}). However, it is in the range where the natural convection flow field in the SIMECO vessel is turbulent. In the following paragraphs, we will briefly describe these experiments with an emphasis on those employing the two and three layers.

Figure 2. SIMECO experimental facility – Main dimensions

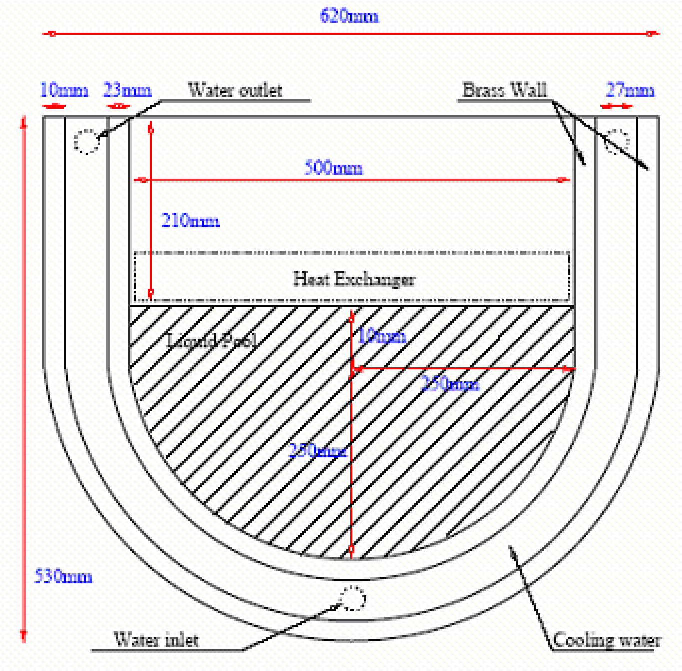


Figure 3. SIMECO experimental facility – Thermocouples location

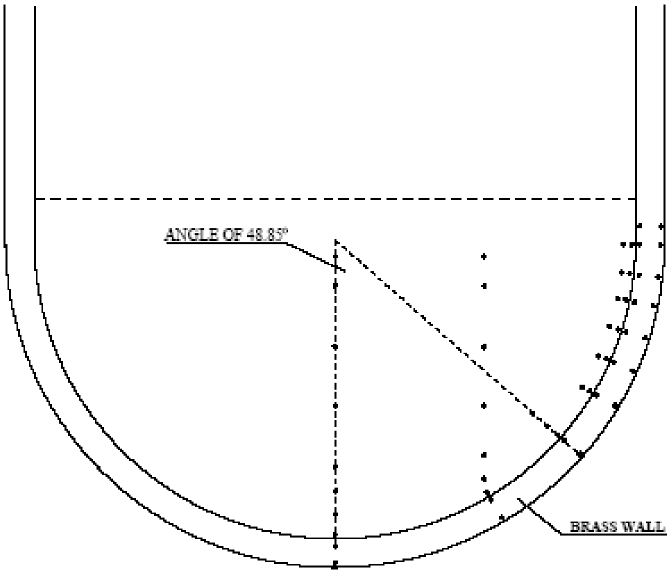
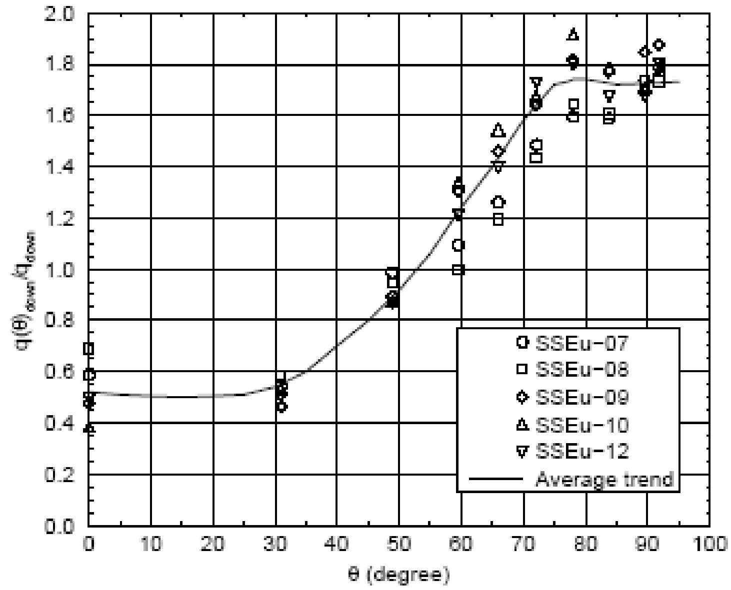


Figure 4. Heat flux profile along the vessel wall for different eutectic salt mixtures experiments.



2.1 Uniform Molten Salt Pool Experiments(Kolb et al. 2000)

These experiments were performed to ascertain whether the crust formed on the boundaries of a prototypic corium pool would invalidate the application of the data and correlations derived from the uniform water pool experiments. In this context, it was also important to determine whether the heat transfer characteristics of the crust formed for a eutectic binary melt would differ from those formed by a non-eutectic binary melt.

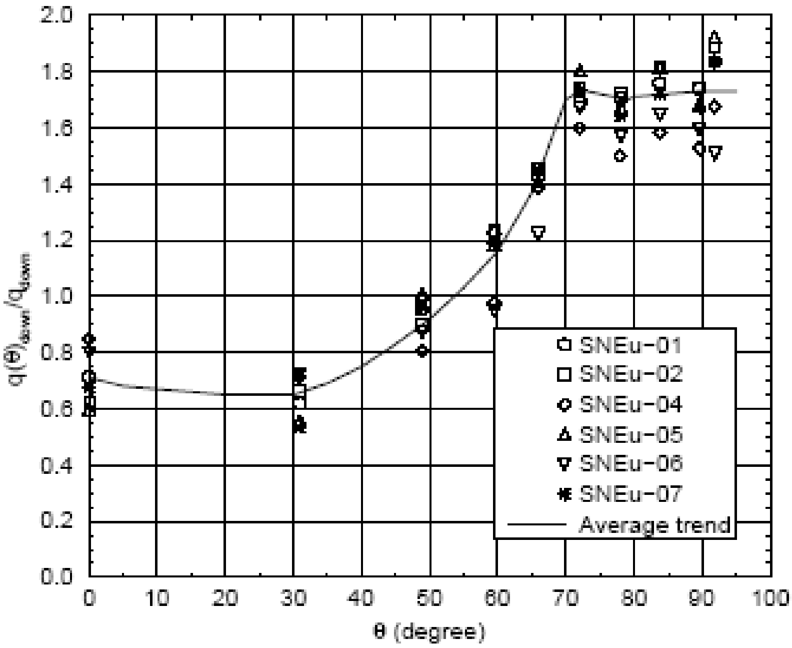
The experiments were performed with a eutectic (50-50) mixture of $NaNO_3$ and KNO_3 and a non-eutectic (20:80) mixture. The liquidus temperature for the eutectic salt mixture is 229ºC and it is 282ºC for non-eutectic salt mixture. The solidus temperature is 220ºC for both mixtures. The physical properties (Cp, k, ρ, μ, heat of fusion) for these mixtures were measured as a function of temperature. For the analysis of the experiments, the physical properties of the pool were calculated at the film temperature between the maximum temperature and the solid boundary temperature. In the experiments the eutectic and the non-eutectic salts were loaded as powders in the SIMECO vessel and heated in situ. The melting of the salts and the crusts formed were observed and photographed through the glass front side wall of the SIMECO vessel (see pictures in Kolb et al. 2000).

The data obtained from the eutectic and non-eutectic salt tests is shown in figures 4, 5, 6 and 7. The main conclusions are:

- since the crust interface is characterised by $T_{liquidus}$ (Froment and Seiler, 1999), the crust thickness is similar for both the eutectic (solid crust) and the non-eutectic (solid + mushy crust),
- local heat flux along the wall follows a similar average trend for both eutectic and non-eutectic cases (Figures 4 and 5),

- the lowest value of the heat flux occurs at the bottom of the vessel, whereas its constant maximum value occurs at θ>72°C (Figures 4 and 5),
- for low heat input, the non-eutectic melt experiment showed lower values of Nu_{up}/Nu_{down} due to build-up of mushy zone, however, the ratio of Nu_{up}/Nu_{down} remains the same as for other values of heat input,
- the non-eutectic and eutectic binary salt melt pool convection heat fluxes are, similar to those for water pool experiments,
- the downward Nusselt numbers showed good agreement with the correlation proposed by Theofanous et al. 1996 and the upwards Nusselt numbers lie in between the Mayinger et al. 1996, and Steinberner-Reineke 1978, correlations (Figures 6 and 7).

Figure 5. Heat flux profile along the vessel wall for different non-eutectic salt mixtures experiments



The SIMECO experiments, thus, established that the thermal loadings imposed by the natural convection of both prototypic eutectic and non-eutectic melt pools, with their crusted boundaries, would be similar to those imposed by liquid pools, having $T_{liquidus}$ as the boundary temperature. Again Ra number is the scaling parameter and the correlations derived from liquid pools would be valid for pools with crusts if the Ra number is calculated with the dimensions of the liquid part of the crusted pool (i.e. without the crust).

2.2 Two Layer Stratified Pool Experiments

The SIMECO facility was next employed to determine the character of the natural circulation for a melt pool containing two layers, like in the RASPLAV experiments No. 1 and 2. The experiments employed water and salt water with different salt concentrations to represent two miscible layers, and paraffin and water to represent two immiscible layers of different density melts. In some of these experiments, heating was directed to only the bottom layer (the main pool) to represent the condition in which all of the UO_2 and FPs remain in the main pool and in the other experiments both layers were heated. Experimental results were obtained for the upwards and downwards heat fluxes and for the split of the heat generation in upwards and downward directions. The Rayleigh number in these tests varied from ~9.6x10^{12} to 9.5x10^{13}.

Figure 6. Average upward heat transfer.

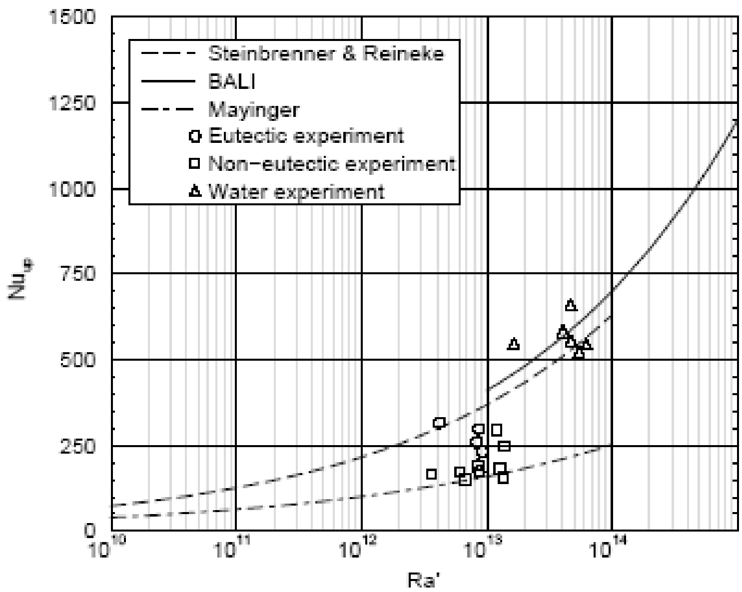
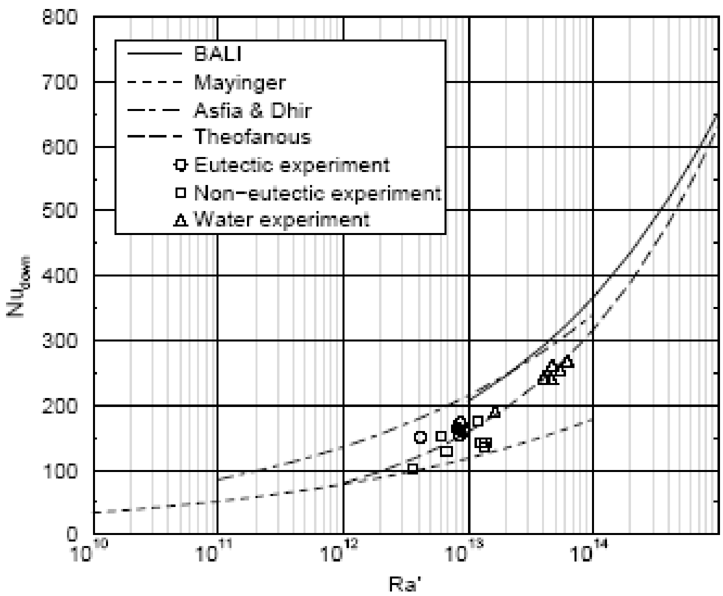


Figure 7. Average downward heat transfer.

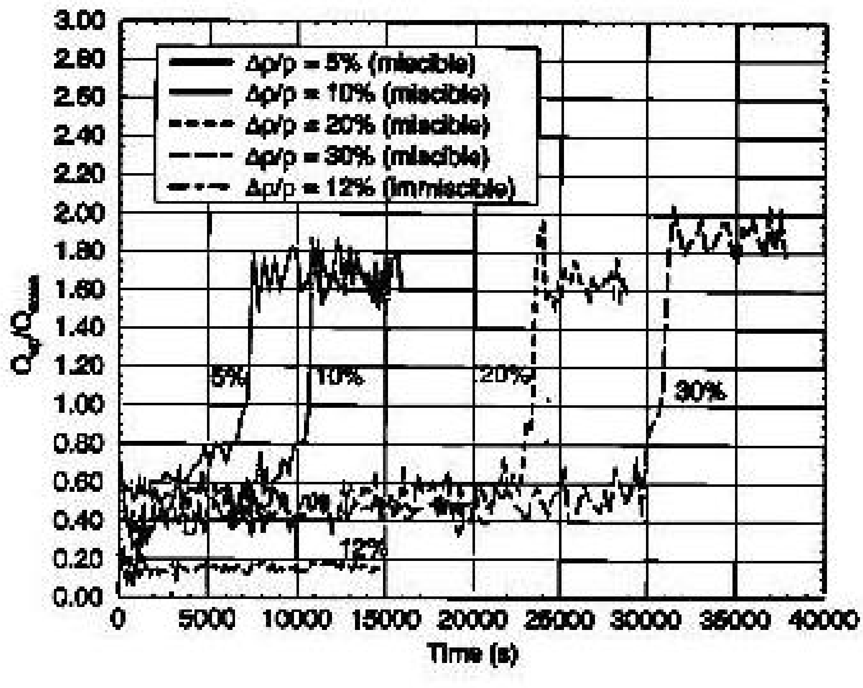


2.2.1 One Layer Heated Miscible and immiscible Layers (Theerthan at al. 2001)

The upper layer was water and the lower layer (or main pool) contained salt water with different concentrations of salt to have density differences ranging from 5% to 30%. The top layer thickness was varied from 4 to 12 cm, while keeping the total pool depth of 26 cm. The volumetric heat input was 1200 W, i.e. 0.15 MW/m^3. Each experiment was started with two separated layers and after initiating the heating, the experiment was continued until a steady state was reached in which a global heat balance of greater than 90% was achieved with temperature changes of less than 1°C/hour.

The results of the experiment are shown as the value of ratio of heat directed upwards to the heat directed downwards in Figure 8. The layers of water and salt water mix together after certain time, which is a function of the density difference. What is remarkable, however is that the ratio Q_{up}/Q_{down} fluctuates around the value of 0.50, when the layers are separated but it fluctuates around 1.8 or 1.9 when the layers mix together. This large difference in the split of the heat generated in the lower layer from the separated case to that of the uniform pool, indicates the large resistance to the heat transport at the interface between the lower pool and the upper layer due to boundary layers on either side. Similar results were obtained by Davaille 1999 in convection experiments in a Rayleigh-Bénard configuration, with a miscible two viscous layer stratification.'

Figure 8. Heat split transients for miscible and immiscible fluids.



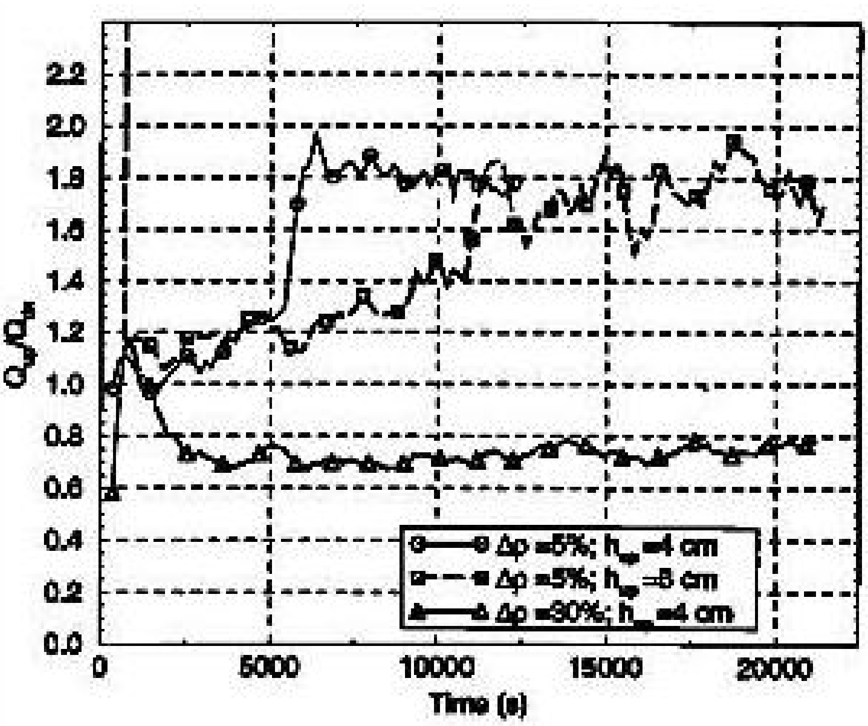
One layer heated immiscible layers experiments were performed with the top layer of paraffin and the bottom pool of water, which was heated. The density difference in this case is 12%. There was no mixing of the layers and the ratio Q_{up}/Q_{down} fluctuated around 0.18 also as shown in Figure 8. This implies that ~85% of the heat generated in the lower pool flows downwards. The absence of any mixing at the interface, the higher viscosity and lower conductivity of the upper layer (paraffin) with respect to those for the lower layer (water), contributed to this increased heat flow downwards.

Pool temperatures were measured along central axis through the interface and into the upper layer. They increase from the bottom of the pool to their highest value just below the interface. The temperatures in the upper layer also increase near the interface. Thus, there are large temperature gradients near the interface. These temperature profiles are very different from those for a uniform pool in which there is a very large upper region with an almost uniform temperature.

2.2.2 Two Layer Heated Experiments (Theerthan et al. 2001)

These experiments are a representation of the prototypical situation of having a reasonable amount of UO_2 and the metallic fission products in the upper layer so that there is substantial heat generation in it. The experiments assumed that the upper layer power density is the same as that in the lower layer. The miscible layer experiments again employed water as the top layer and salted water as the bottom layer. It was found in these experiments that mixing occurred only for the layers with $\Delta\rho/\rho \leq 5\%$. It did not occur for the $\Delta\rho/\rho \sim 30\%$. The values observed for the Q_{up}/Q_{down} are showed in Figure 9. The value of Q_{up}/Q_{down} ~0.75, instead of ~0.5 for the one layer heated experiments. This shows that in spite of uniform heat generation rate through the 2 layers of the pool, the presence of the interface is sufficient to inhibit the free transfer of heat and flow across it.

Figure 9. Heat split for miscible fluid cases when both the layers are heated internally.



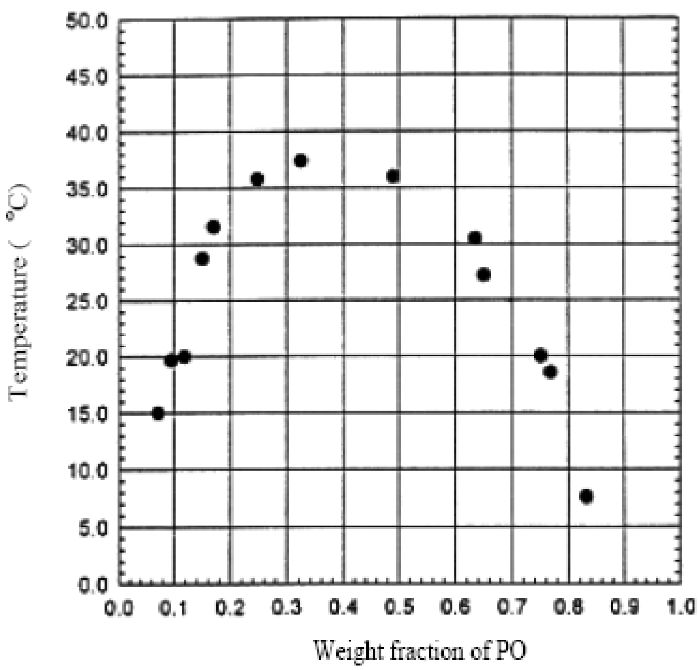
The center line temperatures behave quite similar to those for the one layer heated case, i.e. maximum near the interface and sharp drop off on both sides into the layers.

It is clear from the data obtained from these SIMECO experiments that as long as there is stratification, and a stable interface, much greater fraction of the heat generated in the pool is directed downwards. The top layer acts like a 'blanket' preventing heat flow to the upper surface of the pool.

2.2.3 Experiments on Natural Convection of fluids with a Miscibility Gap caused Phase Separation (PS), (Theerthan et al. 2001)

These experiments were directed towards investigation of the natural circulation of corium with compositions, which have a miscibility gap, as was found in the RASPLAV experiments with compositions having small weight percentage of carbon or those having steel. The miscibility gap can also occur below or above a certain temperature for some compositions.

Figure 10. The miscibility gap region of the mixture



The system chosen is a mixture of paraffin oil (PO) and Benzyl benzoate (BBO). Figure 10 shows the temperature curve as a function of the weight fraction of PO, below which the PO and BBO exist as two liquids and above which they mix into one liquid. Separated layers of PO and BBO, with a density difference of ~0.24 gm/cm^3, are established in the SIMECO vessel at a certain weight fraction of PO vs. BBO. These layers are then heated and they start natural circulation with the Ra number ~10^{12}. The split in the heat generation: Q_{up}/Q_{down} is measured as the two layers are in the miscibility gap region. Table 1 compares the value of Q_{up}/Q_{down} for the various levels of power added to the two fluid layers against the value of Q_{up}/Q_{down} for the one layer formed above the miscibility gap temperature. For reference the value of Q_{up}/Q_{down} for the 2 miscible and immiscible layers are also shown in Table 2. It is seen that for the miscibility gap fluid the mixing is not completely uniform. There are non-uniformities due to temperature gradients near the wall, near the interface, etc. The Q_{up}/Q_{down} for the BBO-PO system lies in-between those for the two miscible and two immiscible layers.

2.2.4 Experiments on Focussing Caused by the Top Metal Layer (Gubaidullin and Sehgal, 2002)

A series of experiments were conducted to investigate the focussing effect exerted on the vessel wall due to the presence of a metal layer on top of a corium melt. The SIMECO tests simulated the prototypic configuration by employing as bottom layer (a) a molten eutectic salt ($NaNO_3$-KNO_3, 50:50) pool at temperature of ~250°C having a crusted boundary all around and (b) a pool of glycerol at the maximum temperature of ~190°C. The upper layer was cerrobend maintained in a housing of thin copper plate suspended in the SIMECO vessel. The bottom of the housing was touching either the crust on top of the salt pool or the top of the glycerol pool. These two test configurations were employed in order to distinguish between the prototypic situations in which a crust exists between the corium pool and the metal layer or that in which the upper layer liquidus temperature is high enough that no crust exists between the higher conductivity upper layer and the lower conductivity lower layer. In all of these experiments the heat was delivered only to the bottom layer. The boundary conditions on the top layer were varied from isothermal to adiabatic. These experiments, unlike the separate effect experiment performed by Bonnet and Villermaux 2001and by Theofanous et al. 1996, are integral experiments, so that the interrelationship of the two layers with respect to heat transfer is determined.

Table 1. Heat flux values obtained from the Phase Separation (PS) and the two layer SIMECO experiments (h_{up} = 4cm).

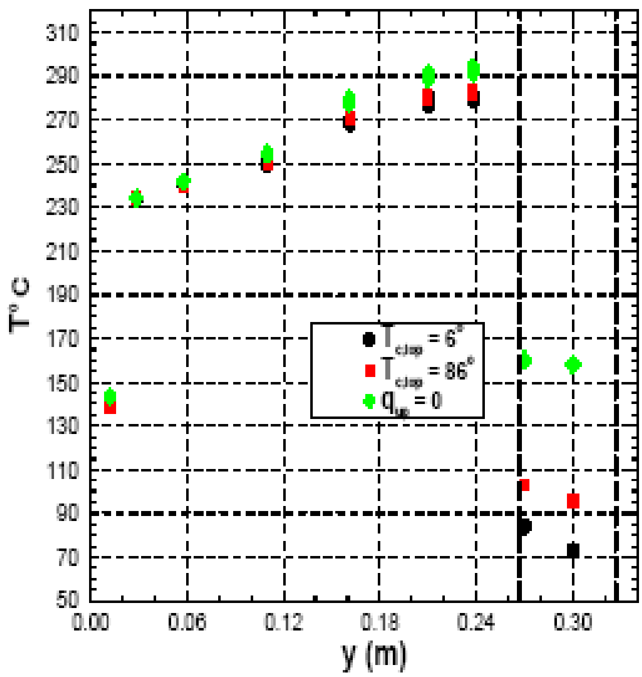
CASES	Q_{up}/Q_{dn}	q_{max}
1 layers (PS) (600W)	1.2	5200
1 layers (PS) (120000W)	1.2	8800
2 layers (PS) (600W)	0.27	9400
2 layers (PS) (1200W)	0.37	17214
2 layers (PS) (2000W)	0.38	26144
2 layers (immiscible) (1200W)	0.16	24500
2 layers (miscible) (1200W)	0.5	~20000 (during mixing)

It was established that employing the thin copper housing to separate the layers provided results for Q_{up}/Q_{down} similar to those obtained when the two immiscible layers were touching each other. This was done by repeating the earlier experiments of immiscible layers (Kolb et al. 2000) but having the paraffin oil contained in the housing.This result is corroborated by that obtained in similar experiments performed by Haberstroh and Reinders 1974.

The experiments with the lower pool of eutectic salt melt at ~250°C and the cerrobend layer in the copper housing employed two different thicknesses of the cerrobend layer, two different power inputs to the lower pool, providing Ra=$4x10^{12}$ and $6x10^{12}$, three different isothermal top boundary conditions with T=6°C, 40°C and 86°C, providing a thick crust, a thin crust and no crust at the top of cerrobend layer and finally an adiabatic boundary condition at the top of the cerrobend layer. The test matrix is shown in Table 2. The Prandtl numbers for the salt and the cerrobend are ~13 and ~$4x10^{-3}$, respectively, and the ratio of conductivities of cerrobend to salt is ~36.

Typical results obtained in the salt-cerrobend system are shown in Figure 11 for the center line temperatures with three top boundary conditions on the cerrobend layer, and in Figure 12 for the variation of heat flux as a function of polar angle in the SIMECO vessel with four top boundary conditions for the cerrobend layer.

Figure 11. Centerline temperature distributions for Q_{in} =3kW, L_{12} = 3 : 27.



The glycerol-cerrobend tests served as complementary to the salt-cerrobend tests and, specifically, obtained data for the cases of no crust in the lower pool and no solidification in the metal layer. The top boundary conditions employed for the cerrobend layer were either 77°C isothermal or adiabatic. The typical results are shown in Figures 13 and 14, respectively, for the center line temperatures and for the variation of heat flux versus the polar angle.

Figure 12. Local dimensionless heat flux distributions for Q_{in} =2kW, L_{12} = 6 : 27.

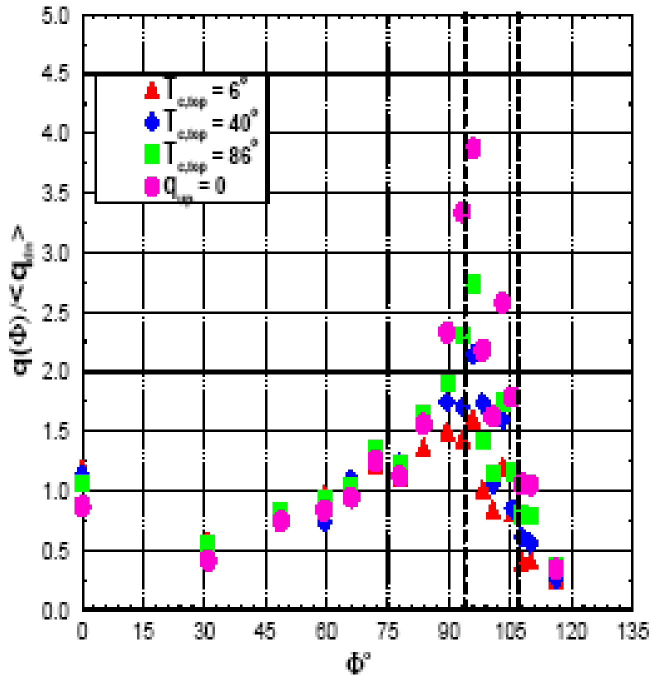
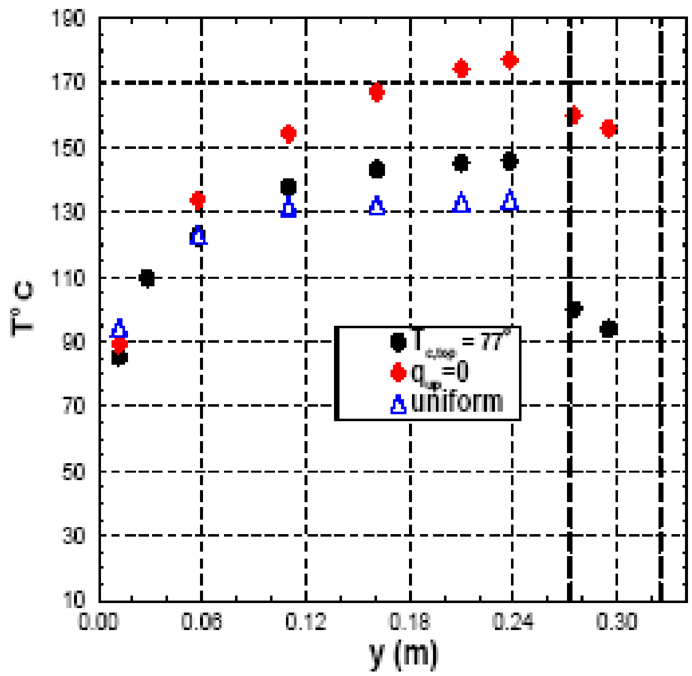


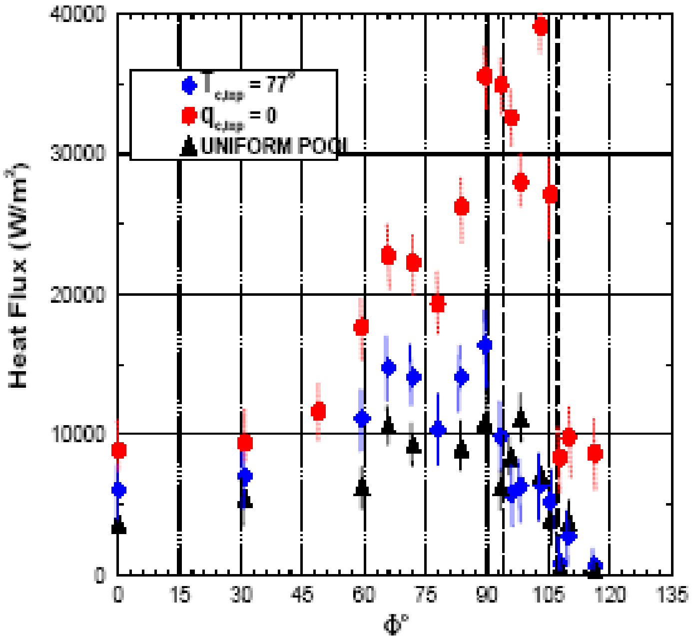
Figure 13. Centerline temperature distributions for Q_{in} = 1.5 kW, L_{12} = 6 : 27.



Following conclusions are derived from the experiments employing the cerrobend metal layer:

- Q_{up}/Q_{down} is affected by the stratification.
- The highest heat fluxes along the vessel wall and the highest temperatures inside the pool are located just below the interface.
- The salt-cerrobend tests showed that the presence of a crust between the lower pool and the upper layer uncouples the heat transfer processes in the two layers.
- Conversely, the glycerol-cerrobend tests showed that the pools are coupled through the interface if no crust is present. The top boundary condition for the cerrobend layer affected the temperatures in the lower pool.
- The focussing effect is strongest when the top boundary condition for the cerrobend layer is adiabatic. The focussing effect has a value of 3 to 4 for the salt pool and a value of ~2 for the glycerol pool.
- The focussing effect vanishes when the top surface of the cerrobend layer is cooled.

Figure 14. Local heat flux distributions for L_{12} = 6 : 27



2.2.5 Three-Layer Experiments

The recent observations from the MASCA Project (Asmolov 2003) indicate the potential of forming a 3-layer melt pool in the lower head. The chemical reactions in the prototypic melt mixture of UO_2 - ZrO_2 - Zr - stainless steel may result in an alloy formed from U and stainless steel as long as Zr is present. This alloy is heavier than the UO_2 - ZrO_2, mixture, thus, the melt pool may stratify into three layers of different density: the main layer of oxide melt containing most of the fission products in the middle, the bottom layer containing U – stainless steel alloy along with some metallic fission products and the top layer of stainless steel and Zr, with the Zr originally present in the melt and the stainless steel remaining from the original present after subtracting the fraction that combined into the Uranium from UO_2. It is not clear what the thickness of the top and bottom layers would be.

Considering the natural convection heat transfer, knowledge has to be gained about the angular distribution of thermal loading on the vessel wall for the 3-layer system. Towards this purpose, we have recently initiated a systematic program of experiments with 3-layer pools in the SIMECO facility. Preliminary results are reported here and some comparisons of the angular distributions of the heat flux have been made against those obtained in the 2-layer system.

Table 2. $NaNO_3$ – KNO_3/Cerrobend test matrix ($T_{c,\ side}$ ~ 6°C).

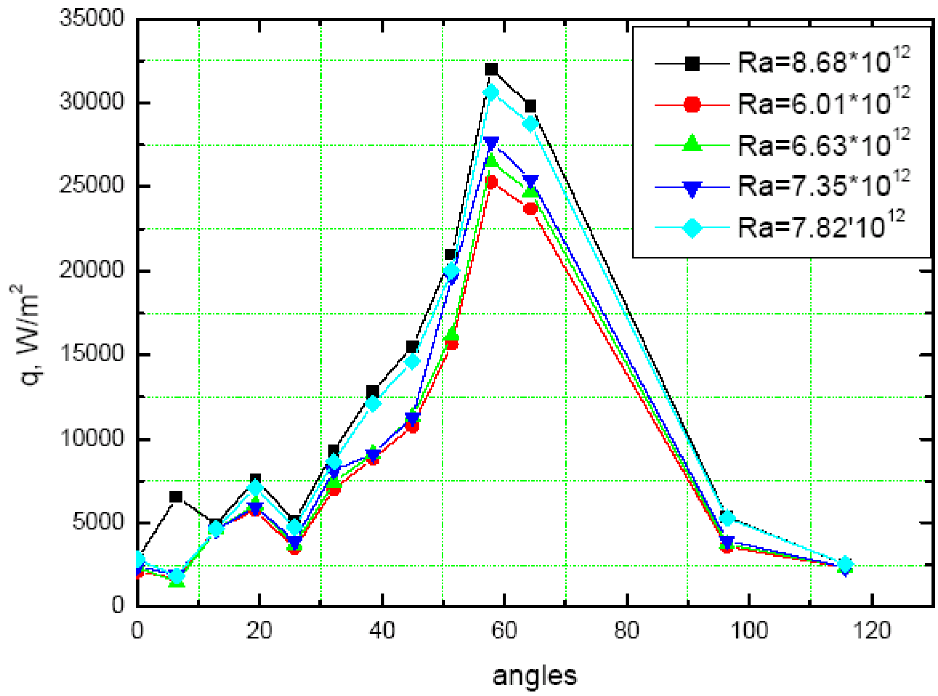
N	Q_{in} (kW)	$T_{c\ top}$	Upper Layer Thickness (cm)	q_{up}/q_{dn}
1	2	T=6°C	3	0.6
2	2	T=40°C	3	0.9
3	2	T=86°C	3	0.7
4	2	q=0 W/m^2	3	0
5	3	T=6°C	3	0.5
6	3	T=75°C	3	0.5
7	3	q=0 W/m^2	3	0.6
8	2	T=6°C	6	0.7
9	2	T=40°C	6	0.9
10	2	T=86°C	6	0.5
11	3	q=0 W/m^2	6	0
12	3	T=6°C	6	0.8
13	3	T=86°C	6	0.6
14	3	q=0 W/m^2	6	0

Paraffin oil, water and cholorobenzene were employed as simulants for stratification of the three immiscible fluids. The choice of these simulants is determined by different factors such as specific heat coefficient, miscibility, toxicity, as well as density. The density ratio between paraffin oil (880 kg/m^3) and water (999.1 kg/ m^3) is about 12% and between water and cholorobenzene (1160 kg/ m^3) is about 11%. Paraffin oil and water have been employed in the earlier 2-layer SIMECO experiments (see section 2.2.1). The height of the lower layer (cholorobenzene) was kept constant at 4 cm, the thickness of the middle layer (water) is 18 cm, and the thickness of the upper layer (paraffin oil) was 5 cm. Since, the heater is located on the 4 cm elevation, and has height of 20 cm, the heat was supplied to the whole middle layer, as well as partly to the upper layer (2 cm). The bottom layer of cholorobenzene is kept unheated. Cooling water mass flow through the sidewall was kept equal to 8.5 l/min and mass flow in the upper heat exchanger was kept at 3.0 l/min. The Raleigh number (Ra) ranges from $6.01*10^{12}$ to $8.7*10^{12}$, so, there is turbulent convection in set of experiments. Each experiment was started with three separated layers as the initial condition. Then the experiment is continued until the steady state was reached, which is defined as global heat balance greater than 90% and a thermal evolution less than one degree per hour.

To compare the heat flux distribution in the 3-layer system to the 2-layer system, corresponding 2-layer experiments were performed. Those employed paraffin oil and water as simulants of the upper layer and lower pool. The height of the lower pool was kept constant at 22 cm and thickness of the upper layer (paraffin) was kept 5 cm. The heater was located at the 4 cm level and it has the height of 20 cm. Thus heat was supplied partly (18 cm) to the water layer and partly (2 cm) to the paraffin layer, as it is in the 3-layer experiments described above. The coolant water flow rates to the side wall and the upper heat exchanger were the same as in the 3-layer experiments. The Raleigh number was also varied the same as for 3-layer system.

Angular heat flux distributions measured in the 2-layer and the 3-layer systems are shown in Figures 15 and 16. Those were measured with the ΔT measured from the thermocouples embedded in the SIMECO brass vessel side walls.

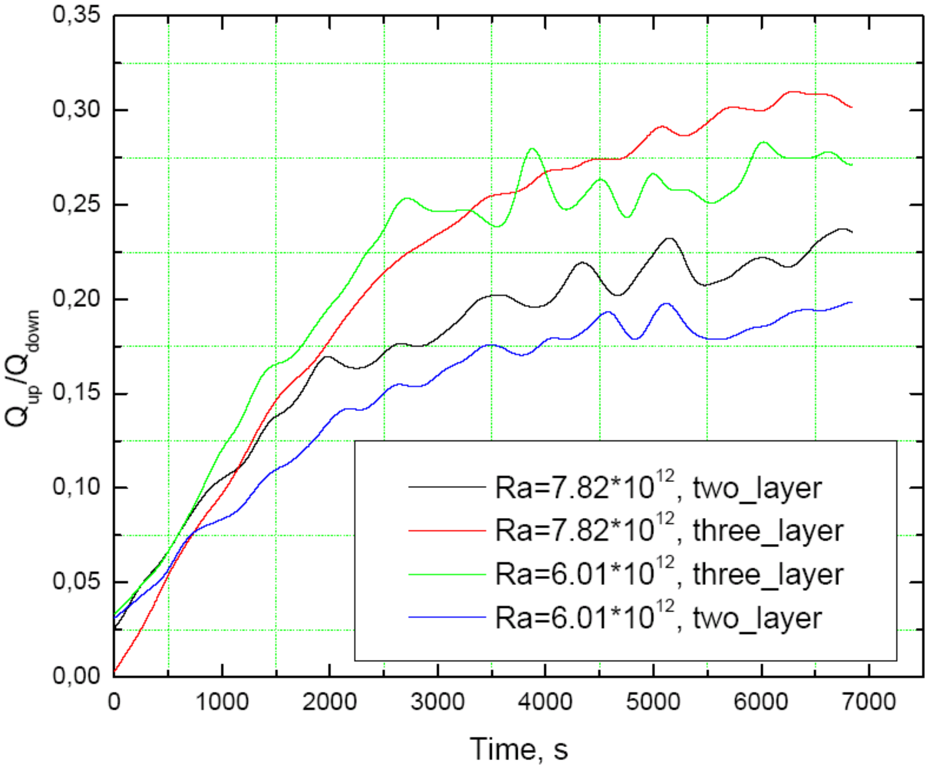
Figure 15. Heat flux distribution in the side wall for two-layer experiments.



It is observed that the maximum heat flux occurs in the vicinity of 57 degrees for the 2-layer system and in vicinity of 64 degrees for the 3-layer system. The peek heat flux in both systems are very similar, however it appears that less heat is directed to the vessel wall for the 3-layer system than that for the 2 layer system. The differences however are not large.

The measured values of Q_{up}/Q_{down} for the 2-layer and the 3-layer systems chosen here are compared in Figure 17, for two identical values of Ra number. It appears that the 3-layer system transfers greater amount of heat to the upper surface than the 2-layer.

Figure 16. ratio for both two- and three-layer experiment



The results described above are very preliminary. In those experiments no heat was provided to the bottom layer. Many more experiments are planned with variations of heat input, layer thickness etc. We hope to arrive at the pertinent conclusions after further experiments are performed. We will attempt to provide general conclusions about the character of natural circulation heat transfer in 3-layer systems.

3. ANALYSIS ACTIVITIES

Two pronged analysis activities were pursued at the NPS Division in connection with the melt-pool convection (a) the development of the MVITA code for the description of the melt-pool heat-up and convection in the lower head and its use for the analysis of the experiments and (b) CFD analysis with the code CFX of the melt pool convection process. Most of the publications that resulted from these analysis activities are either referred in Sehgal et al. 1998 or in the Ph.D. thesis of Nourgaliev, 1998, Bui, 1998 and Gubaidullin 2003. Specific analysis of the convection process in the stratified pool and the analysis of some of the two layer experiments are also reported in Gubaidullin et al. 1999, Gubaidullin and Sehgal, April 2000, Gubaidullin and Sehgal, August 2000, Gubaidullin and Sehgal, April 2001 and Gubaidullin and Sehgal, 2004.

The MVITA Code solves the energy conservation equations in the layers in general curvilinear coordinates in two dimensions. The method employed in the code describes the buoyancy-induced turbulent convective heat transport by means of an effective conductivity-convectivity model (Sehgal et al. 1998, Bui 1998). The MVITA code also models phase change, e.g. melting of a debris bed into a melt pool and the formation of crust layers in a convecting pool. The code has been applied to the case of a prototypic oxidic material (UO_2 +ZrO_2) melt pool with crusts all around performing natural convection with a metal layer on top, performing Rayleigh-Benard convection. The code predicted the focussing effect and compared well with the data and other evaluations.

The major conclusions of these analyses activities are that:

- the MVITA code can provide satisfactory analysis of the SIMECO experimental data for stratified pool convection and, thereby, can be considered as a predictive tool for prototypic accidents scenarios, e.g., for the focussing effect
- the CFD analysis, although difficult, can provide satisfactory predictions of the Q_{up}/Q_{down} and the flow fields for stratified melt pool convection with Rá numbers less than 10^{12}, where the laminar flow equations apply. Turbulent natural convection predictions were not attempted since there is no satisfactory turbulence model for the buoyancy-induced turbulence, which is highly anisotropic, (Dinh and Nourgaliev 1997, and Nourgaliev and Dinh 1997).

- Thus, CFD predictions of the SIMECO experiments were not performed, however, it was seen that the predictions made with the CFX code for the stratified SIMECO melt pools for the Rá numbers less than 10^{12}, fell on the same curve as the SIMECO data for Nu vs. Rá. The calculated pool temperature variation with the polar angle was also quite similar to that obtained from the experiments.

4. THEORETICAL MODEL OF SEILER ET Al.

Seiler et al. 2003 recently proposed a model describing the corium pool convective behaviour with a composition having a miscibility gap. The model employs the information from the phase diagram, and the heat transfer correlations obtained from convection experiments for a homogenous pool performed by several investigators. The upper layer's Rayleigh-Benard convection is also represented through correlations.

This model was applied to the analysis of experiments performed by Theerthan et al. 2001, described in Section II.B.iii above, in which the fluid used is a mixture of benzyl benzoate and paraffin oil, which undergoes separation in the liquid phase according to a known phase diagram.

Seiler et al. 2002 employed the correlations of Mayinger et al. 1976 and of Kelkar and Patankar 1992 for the upward heat transfer from the pool to the upper layer and the Churchill-Chu correlation for the heat transfer from the upper layer to the vertical wall. They calculated the power ratio W_{up}/W_{down}, which varied from ~0.12 to 0.20, respectively with the use of Kelkar and Patankar and of Mayinger correlations. The measured value in the SIMECO experiment was 0.38, which was in between the values for this ratio for one layer heated and two layer heated configurations. Seiler at al's model depends very much on the correlations employed and since each one of them has considerable uncertainty, the predicted ratio W_{up}/W_{down} can vary substantially from the use of one correlation to another or to the combination of correlations employed.

We believe that for the case of the prototypic melt with several oxide and metal components and having a very complex phase diagram, accurate predictions for W_{up}/W_{down}

are not possible with the simple model developed by Seiler et al. 2003 The MVITA Code provides quite accurate predictions, however, there is currently no models in the MVITA Code like those in the GEMINI Code, which calculate the phase diagram needed for determining the compositions of the layers and the corresponding liquidus temperatures.

5. SUMMARY AND DISCUSSION

We have described the results of the experiments performed on two layer stratified pool natural convection over the last few years in the SIMECO facility at the Royal Institute of Technology. In these experiments, the layers were either miscible or immiscible and the volumetric heat generation was in one layer or both layers. A special case was that of the top layer of a metallic melt, which was suspended on top of a liquid pool in a housing. The fluids employed were simulants representing the prototypical oxidic melts of UO_2 +ZrO_2 and the metallic melts of Zr and stainless steel mixtures.

The results obtained and the conclusions reached from the various experimental campaigns have been described in Section 2. It is abundantly clear that a two layer pool differs radically from a single layer pool, since most of the volumetric heat produced in the pool is directed downwards, instead of upwards as in a single layer pool. The blobs of fluid, which carry the heat up from the pool interior, encounter the tremendous resistance of the two boundary layers at the interface between the lower pool and the upper layer. This occurs for both miscible (as long as the layers do not mix) and the immiscible layers. Thus, any time a melt pool stratifies, the thermal loading downwards will increase radically.

Considering the in-vessel melt progression scenario of a severe accident and the results obtained from the RASPLAV and MASCA experiments, it becomes clear that the prototypic situations have greater uncertainties with respect to the pool configuration (multi layer) and, consequently, the vessel thermal loading due to the high temperature chemical reactions occurring in the lower head melt pool. It is stated that equilibrium chemical thermodynamics embodied in the GEMINI Code, a proprietry code, could establish the composition in each of the various layers. The present author is not so hopeful about the accuracy of such estimates, considering that <0.3% carbon was responsible in the RASPLAV test No.1, for the formation of a melt layer containing oxide and carbide materials, which had a lower density but a higher liquidus temperature than the original composition. This separation could not be explained, since there is no accurate phase diagram of the U-Zr-C-O system and similarly the identity of the miscibility-gap region in the diagram.

Experimental results obtained from the SIMECO tests and the MVITA code analyses validated against them could be employed for predictions of vessel thermal loadings for a 2 layer pool, whose configuration would have to be determined from a chemical equilibrium or non-equilibrium analysis, for which the GEMINI Code may be suitable. The three layer pools are another departure for which the experimental data base for partitioning of the volumetric heat generated is only now starting to be accumulated.

We have also described the recently-obtained very preliminary result of experiments on a 3-layer pool. We at NPS Division of KTH will employ the SIMECO facility for further experiments in the natural convection in the volumetrically heated three layer system. The intention is to determine the partitioning of the heat generated and the angular variation of the heat flux for a variation of parameters, e.g. heat generated in 1,2 or 3 layers, thickness of layers, heat generation rate or Rayleigh number, boundary conditions at the top, etc. These data could serve as the base for further development and validation of the MVITA code. Hopefully, more experimental information will be generated by the MASCA Program about the stratification and the partitioning of prototypic material melt pools, which could be used for the validation of the GEMINI Code. We believe that a coupled heat transfer and chemistry treatment, perhaps based on the MVITA and GEMINI codes, may be required for prediction of the vessel thermal loadings exerted by prototypical melts in different accident scenarios.

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