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Thermal loads on the RPV lower head in case of severe accident with core melt relocation

Caroli C.(1), **Magnaud J.P.**(2)
(1) ENEA Casaccia, Italy
(2) CEA, France

ABSTRACT

A systematic numerical study of the natural convection in a liquid hemispherical corium molten pool with a residual heat source is presented. The analyses have been carried out using the TRIO E.F. and CASTEM2000 numerical codes for a wide range of the Rayleigh numbers both for homogenous and stratified pools. The heat flux distribution at the pool boundary has been computed and the influence of the pool stratification has been pointed out. The work here presented is part of the RPVSA project partially sponsored by the CEC of the EU.

INTRODUCTION

In a severe accident with core melt relocation in the Lower Head (LH) of a Reactor Pressure Vessel (RPV) the risk of localised melting of the vessel wall can not be completely excluded. Uncertainties also exist on the effect of the corium stratification with an upper high conductive metallic layer that can strongly influence the heat transfer mechanism from the corium molten pool to the surrounding vessel wall. To asses the capability of the LH to withstand the molten corium attack we need to identify the heat fluxes (thermal load) from the molten pool to the vessel wall because the residual thickness of the LH, its temperature history and its mechanical behaviour are directly related to the heat fluxes. Even if the thermal load on the LH depends on several and correlated phenomena (corium convection, corium physical properties, corium crust, amount of relocated corium, corium stratification, external vessel cooling), a first estimation of the thermal load can be based on simplified analyses of the pure natural convection of the molten corium. In case of homogenous corium, the natural convection develops in a molten pool bounded by the corium crust at a fixed temperature corresponding to the corium melting point [1]. When stratification occurs, the upper high conductive metallic layer strongly influences the pool natural convection and the heat transfer to the vessel. Some experimental tests have been carried out in the last years on molten pools to determine the heat flux distribution [2],[3] but normally they refer to homogenous pools. Difficulties are also encountered during an experiment to reach high Rayleigh numbers as those encountered in a severe accident. Numerical analyses of the pool configuration have been recently carried out and some of them [4] point out the importance of the corium stratification on the global heat transfer mechanism. Uncertainties related to the knowledge of the corium physical properties are also shown. The work here presented is a systematic numerical study of the natural convection in a liquid hemispherical pool in presence of a heat source. To point out the influence of the corium stratification on the heat transfer mechanism the same conditions are simulated both for homogeneous and stratified pools. A wide range of Rayleigh number is considered to account for variation of the physical properties and of the heat source level.

THE PROBLEM ANALYSED

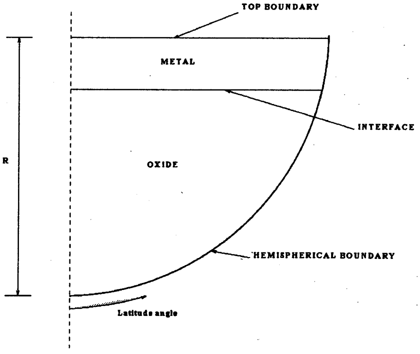

Fig. 1 - Geometrical configuration

The pure natural convection in a liquid hemispherical pool in presence of a heat source uniformly distributed in the volume and with a fixed boundary temperature has been considered (see fig. 1). Assuming an initial condition with fluid at rest and at uniform temperature (the same imposed as boundary condition) the natural convection has been simulated in transient condition till the global thermal equilibrium has been reached (thermal power produced by the heat source ≈ thermal power evacuated by the boundaries). Both homogeneous and stratified configurations have been considered. In homogeneous pools the physical properties have been assumed uniform in the whole fluid. In stratified pools, two non-miscible layers have been considered with the upper 10 % of the total pool volume and the physical properties have been assumed the same for the two layers except the thermal conductivity. The heat source has been considered uniform in the two layers. The internal Rayleigh number ($Ra=g\beta qR^5/\lambda\alpha\nu$) and the Prandtl number ($Pr=\nu/\alpha$) have been identified as the significant non-dimensional parameters and the analyses have been repeated for $10^8 \leq Ra \leq 10^{12}$ and $Pr = 1$; $Pr = 0.1$. In tab. 1 are summarised the cases analysed.

Pool configuration	**Turbulence model**	**Pr_{up}**	**Pr_{low}**	**$Log_{10}(Ra)$**							
Homogenous	Laminar	1.0	1.0	8	9	10	11	12	13		
“	K-ε	1.0	1.0			10	11	12	13	14	15
Stratified	Laminar	0.1	1.0	8	9	10	11	12	13		
“	K-ε	0.1	1.0			10	11	12	13	14	15

Tab. 1: Synthesis of cases analysed

NUMERICAL PROCEDURE

The mass, momentum and energy conservation equations have been discretised in axial-symmetric approximation on a grid mesh consisting of 3416 plane bilinear 4-node elements. The numerical method is based on a semi-implicit algorithm, implicit for pressure and explicit for the other unknowns. The spatial discretisation is based on a Galerkin weighted residual method with linear shape functions for velocity, temperature (and K, ε for turbulent simulation) and constant (within each element) pressure. The time discretisation is based on a first order scheme. In turbulent analyses a classical K-ε model [5] is used in conjunction with wall functions. The non-slip condition at the wall is imposed as boundary condition for the velocity. Constant temperature has been imposed at the wall. The computations have been carried out using the TRIO E.F. and CASTEM2000 numerical codes developed by CEA Saclay [6].

RESULTS AND DISCUSSION

The global thermal equilibrium (thermal power produced by the heat source = mean thermal power exchanged at the pool boundaries) has been reached in each case. The steady state regime has not always been reached, even in steady boundary conditions. Especially in laminar and high Rayleigh analyses the final state is characterised by fluctuations of the temperature and velocity fields around constant mean values. This effect is lower in stratified cases and nearly absent in turbulent simulations.

Temperature fields

In homogeneous pool a thermal stratification is showed in the lower part of the pool with a quasi-isothermal upper region. Very high temperature gradients are encountered near the external boundaries (pool top and external spherical surface). This situation is observed both in laminar and turbulent analyses and does not change substantially with Ra. In stratified pools and laminar analyses very high temperature gradients are encountered at the interface between the two layers with the upper quasi-isotherm. In turbulent analyses the temperature gradients are lower, sensibly vertical and extends through the upper layer.

Velocity fields

In homogeneous pool a large recirculation is observed. The corium flows downward near the external spherical boundary and several eddies develop in the central region of the pool. The eddies are not steady and change with time their dimension and position. In stratified pools approximately cylindrical eddies develop in the upper layer. Their number and intensity increases with Ra. The lower layer exhibit the same behaviour as in homogenous pool. For turbulent analyses the eddies are still present but their number and dimension increases compared with laminar analyses.

Heat flux distribution

The distribution of the heat flux along the hemispherical boundary is showed in figs. 2-5 in terms of the normalised Nusselt number Nu_n. Here $Nu_n = \Phi/\Phi_{mean}$ represents the ratio between the local heat flux and its mean value and is given as function of the latitude angle α. In homogenous pools and laminar analyses ($10^8 \leq Ra \leq 10^{11}$) Nu_n increases with α (fig. 2) reaching its peak for $\alpha \cong 85^\circ$. The Nu_n peak increases with Ra varying from $Nu_{n\,peak} \cong 1.5$ for $Ra = 10^8$ to $Nu_{n\,peak} \cong 2.0$ for $Ra = 10^{11}$. In the range $10^{10} \leq Ra \leq 10^{11}$ where both laminar and turbulent analyses have been carried out similar behaviour are showed for Nu_n but higher peak are predicted by laminar computations (figs. 2,4). In the range $10^{13} \leq Ra \leq 10^{15}$ $Nu_{n\,peak}$ does not exceed $Nu_{n\,peak} \cong 1.6$ being localised at $\alpha \cong 65^\circ$ (fig. 4). In stratified pool (figs. 3,5) lower Nu_n are predicted at the hemispherical boundary compared with the homogeneous cases. A step in the Nu_n distribution is observed in correspondence of the layers interface. The Nu_n peak is always localised in correspondence of the lower layer. The heat fluxes distribution predicted by turbulent analyses are always smoothed with lower peaks when compared with the laminar distribution. This effect is probably directly related to the turbulence model that seems to overestimate the diffusive effects of the turbulence. The mean Nusselt number $\overline{Nu}$ for the top and hemispherical boundaries is given in figs. 6-7 versus the Rayleigh number Ra. The computed $\overline{Nu}$ is compared with the correlation of Maynger [7] based on the experimental results of Jahn and Reineke for a homogeneous pool showing a good agreement. An increase of $\overline{Nu}$ with Ra is observed in each condition.

CONCLUSIONS

The natural convection in a hemispherical pool with a volumetric heat source has been investigated for a wide range of the Rayleigh number both for homogenous and stratified pools. The flow pattern shows instabilities and in some condition the steady state has not been reached. The use of a K-ε turbulence model at high Ra number stabilises the flow field, reduces the number of eddies and homogenises the temperature fields The analyses show that the heat flux distribution along the hemispherical boundary, for a given Ra, varies sensibly with the latitude angle α both for homogeneous and stratified pools. In homogeneous pools the heat flux minimum is always localised near the bottom of the pool whereas the maximum, localised near the upper corner for $Ra \leq 10^{11}$ moves downward increasing Ra and reaches the position $\alpha = 65^\circ$ for $Ra = 10^{15}$. Peak values of the local heat flux 2 times the mean heat flux are encountered. The effect of the stratification, compared with a homogeneous configuration at a fixed Ra, is to increase the heat fraction evacuated by the top boundary. Consequently lower heat fluxes at the hemispherical boundaries are computed and the local heat flux peak values do not exceed 1.5 the mean heat flux. In stratified pools the maximum of the local heat flux at the hemispherical boundary is always reached at the layers interface. A good agreement has be found between numerical data and experimental results in terms of mean Nusselt number.

REFERENCES

1. T.G.Theofanous, C.Liu, S.Angelini, O.Kymalainen, H.Tuomisto, S.Additon : Experience from the first two integrated approaches to in-vessel retention through external cooling. *Proc. "Workshop on Large Molten Pool Heat Transfer"*, Grenoble 9-11 March 1992
2. M.Jahn, H.H.Reineke : Free convection heat transfer with internal heat source, calculation and measurements. *Proc. "5th In. Heat Trans. Confer."*, Tokyo September 1994
3. O.Kymalainen, H.Tuomisto, O.Hongisto. T.G.Theofanous : Heat flux distribution from a volumetric heated pool with high rayleigh number. *Proc. "NURET6"*, Grenoble 5-8 October 1993
4. J.Artnik, C.Caroli, G.Cenerino, F.Parozzi, A.Pini, R.Sairanen, B.D.Turland : Molten pool behaviour calculations for reactor cases. *Proc. "FISA95"*, Luxembourg 20-22 November 1995
5. B.E.Launder, D.B.Spalding : The numerical computations of turbulent flows. "*Computer Methods in Applied Mechanics and Engineering*", 3, 269-289, 1974
6. J.P.Magnaud, C.Caroli : TRIO E.F. : A general computer program for thermal and fluid dynamics analysis. Part 1 : Basis and validation. "*Conf. Num. Analysis in Automotive Engineering*", Wuerzburg, 2-3 October 1990
7. F.Maynger, M.Jahn, H.H.Reineke, Steinbrenner : Examination of thermal-hydraulic process and heat transfer in a core melt . *BMFT R8 48/1*, 1976 Institut fuer Verfahrenstechnik der T.U. Hannover

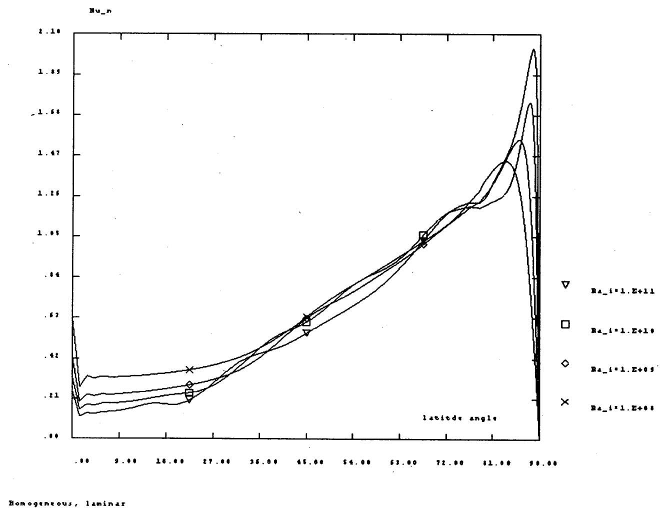

Fig. 2 - Nu_n versus the latitude angle α at the external pool boundary. Homogenous pools, laminar analyses, $10^8 \leq Ra \leq 10^{11}$

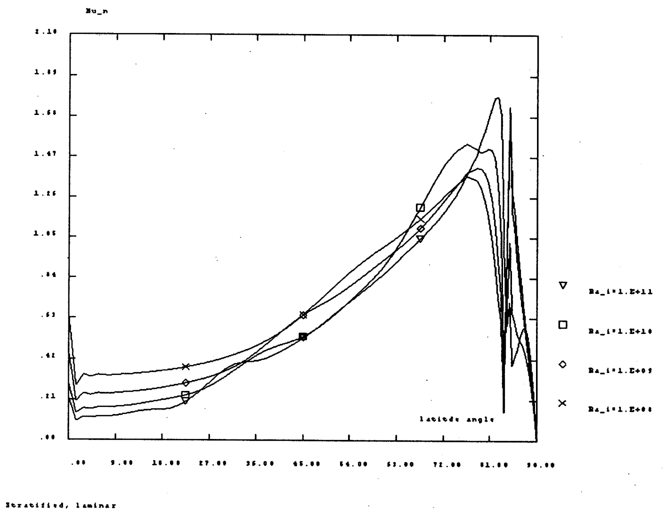

Fig. 3 - Nu_n versus the latitude angle α at the external pool boundary. Stratified pools, laminar analyses, $10^8 \leq Ra \leq 10^{11}$

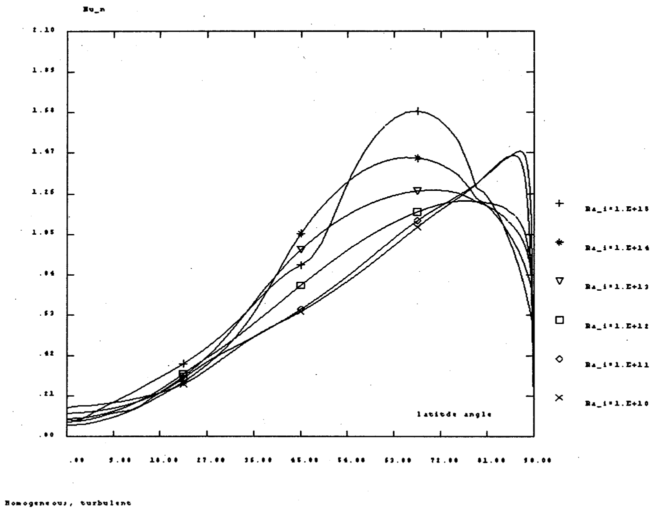

Fig. 4 - Nu_n versus the latitude angle α at the external pool boundary. Homogenous pools, turbulent analyses, $10^{10} \leq Ra \leq 10^{15}$

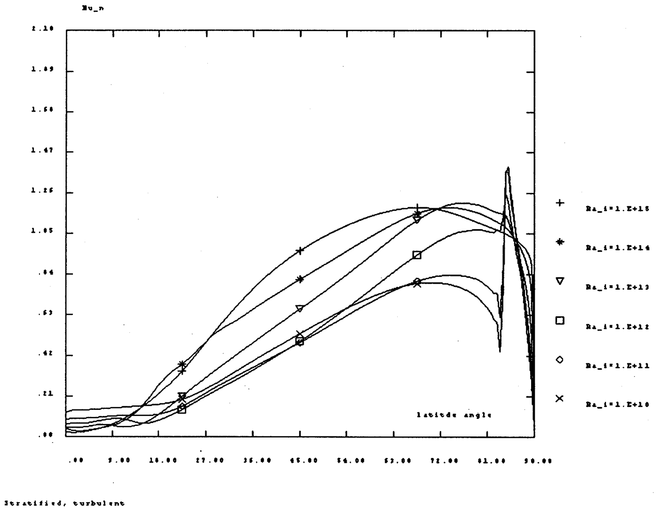

Fig. 5 - Nu_n versus the latitude angle α at the external pool boundary. Stratified pools, turbulent analyses, $10^{10} \leq Ra \leq 10^{15}$

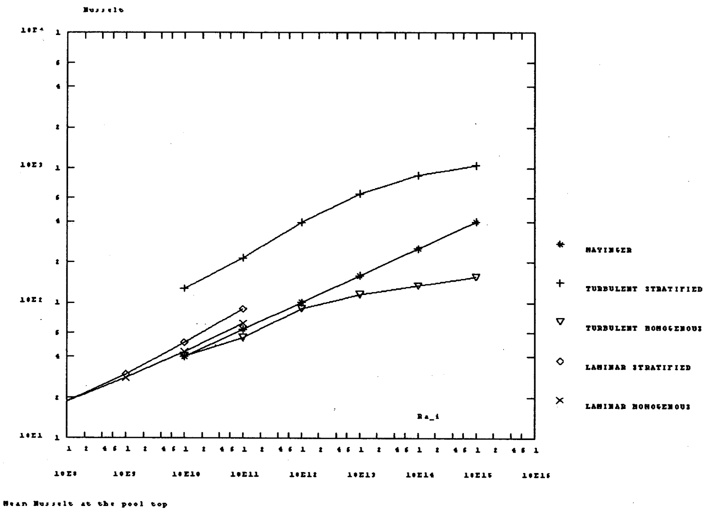

Fig. 6 - Mean Nusselt number at the pool top versus Ra

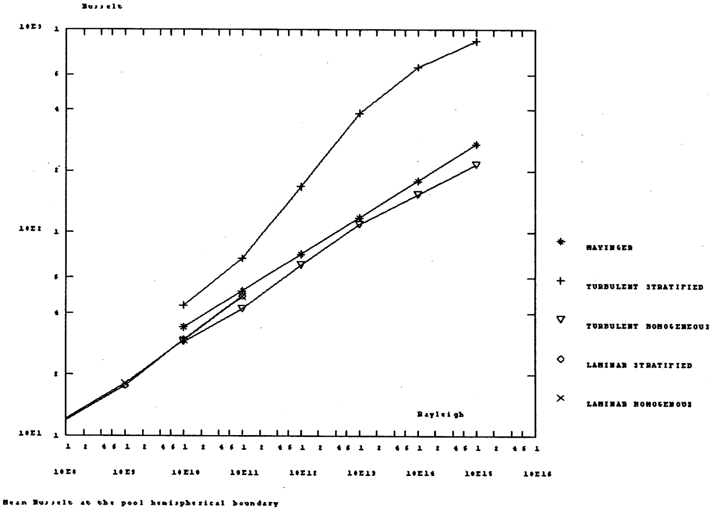

Fig. 7 - Mean Nusselt number at the pool hemispherical boundary versus Ra