Numerical estimation of reactor core melt cooling, *A. Horvat[+], I. Kljenak[+], J. Marn[*] ([+] "Jožef Stefan" Institute, [*] Univ. of Maribor)*

INTRODUCTION

During a hypothetical severe accident, a melt pool may form in the lower plenum of the reactor vessel as a consequence of reactor core overheating and melting. High temperatures and further heat generation due to fission products decay may jeopardise the integrity of the reactor vessel. To prevent this the plenum walls would have to be externally cooled. At present, external vessel flooding is one of the possible emergency procedures[1].

To determine the cooling characteristics of the melt pool, the heat transfer through the lower plenum wall must be known. The natural convection behaviour of the melt pool was studied for this purpose. Although some experimental studies have been carried out in the past[2] it is not feasible to perform large-scale experiments at realistic reactor conditions. Extensive numerical studies were also carried out regarding the lower plenum cooling problem[2] using one of k-ε models to model turbulent motion.

Because of extensive computational requirements of the k-ε models, we propose a modified Smagorinsky Large-Eddy Simulation model[3] which is mainly used in forced convection turbulence calculations.

PHYSICAL MODEL

In the present work, the melt in the lower plenum is modelled as an incompressible fluid with internal volumetric heat generation in a rectangular cavity. Using Boussinesq's approximation of buoyancy forces and applying a top-hat spatial filter, the equations of fluid motion are written as :

$$\nabla \cdot \bar{\vec{v}} = 0 \tag{1}$$

$$\frac{\partial \bar{\vec{v}}}{\partial t} + \nabla \cdot (\bar{\vec{v}} \otimes \bar{\vec{v}}) = -\nabla \bar{p} + \mathrm{Pr}\left(\nabla^2 \bar{\vec{v}}\right) - \mathrm{Ra}\,\mathrm{Pr}\,\bar{T}\frac{\vec{g}}{|\vec{g}|} + \nabla \cdot \left(\nu_{sgd}\, 2\underline{S}\right) \tag{2}$$

$$\frac{\partial \bar{T}}{\partial t} + \nabla \cdot \left(\bar{\vec{v}}\,\bar{T}\right) = \nabla^2 \bar{T} + 1 + \nabla \cdot \left(\upsilon_{sgd} \nabla \bar{T}\right) \tag{3}$$

where $^{-}$ denotes locally averaged values, *Ra* the Rayleigh number and *Pr* the Prandtl number. The last terms in eqs. (2) and (3) arise due to modelling of subgrid scale terms after the filtering process. *S* is the deformation velocity tensor, ν_{sgd} is the subgrid viscosity and υ_{sgd} is the subgrid thermal diffusivity[1] :

$$\nu_{sgd} = \left(C_s \Delta x\right)^2 \left(2\underline{S} : \underline{S} + \frac{\mathrm{Ra}\,\mathrm{Pr}}{\mathrm{Pr}_{sgd}}\left(\nabla \bar{T} \cdot \frac{\vec{g}}{|\vec{g}|}\right)\right)^{1/2} \quad \text{and} \quad \upsilon_{sgd} = \frac{\nu_{sgd}}{\mathrm{Pr}_{sgd}} \quad . \tag{4}$$

The presented modified Smagorinsky approach requires only two empirical constants C_s and Pr_{sgd}. In this work we prescribed the values of 0.143 and 0.35 [4], respectively.

To model solidification and melting processes on the boundaries, no-slip boundary conditions were used for the momentum equation and isothermal boundary conditions for the energy equation.

RESULTS

Numerical simulations were performed for Rayleigh numbers 10^{10} and 10^{13}. The results were plotted on Rayleigh vs. Nusselt number diagram in logarithmic scale together with other experimental and numerical data[2]. Because the data (fig. 1) revealed logarithmic linear relation between Rayleigh and Nusselt number, the values were further extrapolated to $Ra = 10^{15}$ which corresponds to realistic reactor conditions. In all cases the Prandtl number was 1.2. The obtained results show satisfactory agreement with experimental and numerically calculated data[2] .

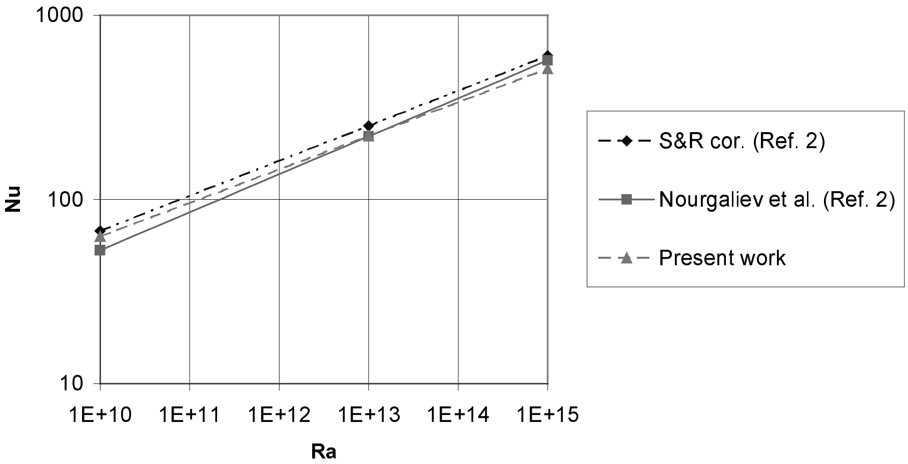

Figure 1. Rayleigh number vs. Nusselt number.

As expected from literature data[2], the maximum thermal load occurs on the side walls. The average Nusselt number reaches the value Nu = 511 in the case of realistic reactor conditions ($Ra = 10^{15}$). During our simulations we observed that the general circulation pattern is stable in the lower part and strongly influenced by Rayleigh-Taylor instabilities at the top boundary of the simulation domain (fig. 2).

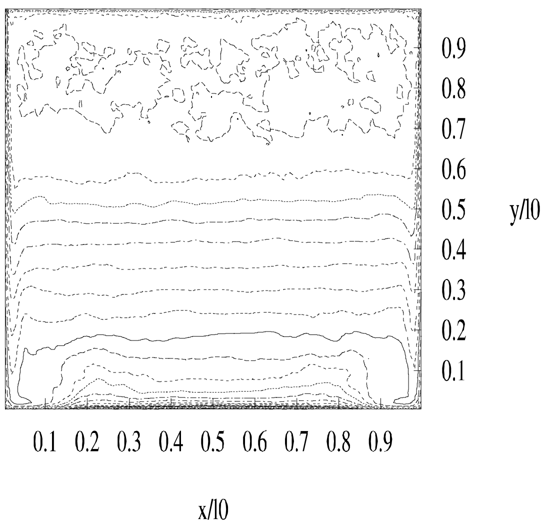

Figure 2. Temperature field.

CONCLUSIONS

The presented calculations demonstrate the suitability of the Large-Eddy Simulation model for calculations of turbulent natural convection flows in a fluid with internal heat generation. This method could become more popular in the field of severe accident thermal hydraulics in the future.

The calculated Nusselt numbers revealed the highest thermal loads on the side walls where the cooling would have to be modified when compared to the bottom to ensure the integrity of the lower plenum.

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