CFD ANALYSES OF NATURAL CIRCULATION IN THE RPV, THE TRANSFER ANI
THE COOLING PONDS OF VVER-440 TYPE REACTORS IN INCIDENTAL CONDITION

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ABSTRACT

During the annual maintenance of the VVER-440 type reactors, the RPV, the cooling pond and the transfer pond form a connected flow domain. The reactor cooled by the natural circulation, which develops in one or two main loops. The cooling pond has its own cooling loops. The CFX-4.3 code has been applied to investigate whether the natural circulation is sufficiently strong to make the cooling system of the cooling pond capable for cooling the whole system in case the main loops are lost and other emergency systems are not available. The calculations have shown that the cooling system of the cooling pond with the standard connection is not capable of removing the heat produced in the reactor core. Therefore modifications of the cooling system were investigated. The results has shown, that by moving the outlet of the cooling loop to the level of the water surface, or by using the discharge pipe of the transfer pond as outlet, the system cools down rapidly.

INTRODUCTION

During the annual maintenance of the VVER-440 type reactors, the filling up of the transfer pond (Fig. 1) (4) with borated water is followed by opening of the RPV (5). About four days after shut down, the transfer channel (3) is opened and the refuelling process starts. Meanwhile, the reactor core (6) is cooled by natural circulation, which develops in two or one main loop (8) of the reactor. The cooling pond (1) has its own cooling loops (7), one of which is also in operation. During the maintenance, losing the main loops and the emergency cooling systems in the same time has a low but a real possibility. Previous safety analyses have shown that in such situations the coolant in the reactor core comes to boil within a few hours.

On the other hand, the cooling pond and its cooling loops were not taken into account in these earlier calculations. Intensive circulation could even be caused by very small temperature differences in large water tanks [1, 2]. The CFX-4.3, a three-dimensional, high-capacity, computational fluid dynamics (CFD) code has been applied for investigating whether this natural
circulation is sufficiently strong to make the cooling system of the cooling pond capable for cooling the whole system including the reactor core.

THE CFX MODEL

The geometry elements and other settings were considered in the three-dimensional CFX model are listed below using the numbers of Fig. 2. The coolant enters into the cooling pond (1) at the bottom through four pipes and leaves via five pipes at 6.7 m under the water level. The Inlet I and Outlet I boundary conditions were defined as a 30 cm wide stripe at the corresponding height. The mass flow and the inlet temperature were set to 77.78 kg/s and 303 K, respectively [3].

The inflow and the outflow of the coolant of the RPV (5) during normal maintenance operation was considered as Inlet I1 and Outlet I1 boundary condition at the bottom plate, and one of the hot legs respectively. The mass flow and the inlet temperature were set to 70.4 kg/s and 313 K, respectively [3]. The lower plate of the cooling pond (2) and the reactor core (6) were defined as a homogeneous porous region of \( p = 0.4855 \) porosity. The decay heat power of the reactor core and the lower plate of the cooling pond was determined using the SCALE code system [4]. The calculations show that 10 days after shut down the total power of the cooling pond is 414 kW and the power of the core is 3.548 MW. The long transients described in this paper were investigated with a mesh of 100 000 control volumes.

Although the fluid flow in the system is slightly turbulent, the laminar flow model was used in the present calculations, because the low Reynolds-number turbulence models need such dense mesh that can not be used in this large fluid domain [6].

RESULTS OF THE CALCULATIONS

First, the normal maintenance conditions were investigated. These results provide good initial conditions for the calculations of incidental transients. By the investigation of the anticipated incident, the Inlet II and Outlet II boundary conditions (Fig. 2) were closed by wall type boundary conditions and transient calculations were performed.

Transient calculations on the incidental conditions

The results of the transient calculations (Figs. 3-6) have shown clearly that the cooling loop of the cooling pond by itself is not suitable for preventing nor significantly slowing down the heating up of the coolant in the reactor.
There is strong flow through the transfer channel. It means close interaction between upper part of the cooling pond and the transfer pond during the whole transient (F. Meanwhile, a very stable cold block (cold water trap) develops in the lower part of the pond, which is not influenced by the processes in the other parts of the system (Fig. 3). core, the velocity field depends on the space and time very heavily. In some segments core, the flow direction also alternates. There is a thin, very stable, nearly non-influence temperature stratification layer in the cooling pond at the bottom level of the transfer pond. Since the outlet in the cooling pond is below this level, only a few hundred kW of heat generated in the reactor core is removed from the system via the cooling loop of the cooling pond 5/A).

After t=2000 s, the temperature values at different points increase with the same gradient as can be seen in Fig. 6. Extrapolating with a point model, the calculations show that the temperature reaches the saturation temperature (125°C) at the top of the core in approximately 13.4 hours.

**Incidental transient calculations with modified cooling loop**

In order to improve the safety of the system, the heating-up should be slowed down and boiling should be avoided. Therefore, the effects of some geometrical modifications were investigated. In the first calculation, the cooling pond outlet was moved to the level of the core surface. The position and the mass flow of the cooling pond inlet were not changed. The results have shown that the remanent heat generated in the reactor core can be removed using a modified cooling system of the cooling pond. The cold water trap at the bottom of the cooling pond is overfilled by the modified cooling loop. Therefore, cold water flows in the transfer pond and falls on the core (Figs. 7 and 8). The system becomes cool rapidly. Beginning of the transient, the cooling loop of the cooling pond removes approximately twice more heat than that generated in the whole system (Fig. 5/B). The velocity and temperature dependence on position and time is greater (Fig. 9) than it was experienced in the previous calculation. On the other hand, it is important to state that the feasibility of this modified system on the real power plant was not investigated.

**Incidental transient calculations with using the discharge pipe**

Since building new pipe systems in operating nuclear power plant units is difficult, using an existing discharge pipe as outlet was investigated. This discharge pipe is an annular pipe at the bottom of the transfer pond and connected to the transfer pond at three points [5] (see Fig. 1.).

The results have shown that the remanent heat generated in the reactor core can be removed using the discharge pipe as outlet. The cold water trap in the bottom of the cooling pond can be overfilled (Figs. 10 and 11). Therefore, the system also cools down, but less rapidly than it was described in section 3.2. The heat removal is much greater than the heat generation, but still less than it was experienced previously (Fig. 5/C). Strong temperature stratification can...
experienced in the upper region. Presumably due to the stabilisation effect of this temperature stratification, the velocity and temperature fluctuation (Fig. 12) is lower than it was experienced previously. In the core, the cold coolant falls down in the same segment with uniform velocity, and in the other segments approximately uniform up-flow can be experienced, so this solution means a more uniform cooling of the reactor core.

SUMMARY

Three-dimensional CFD investigations were performed on the incidental maintenance conditions of the cooling pond, the transfer pond and the RPV of VVER-440 type reactors with the code CFX-4.3. The calculations have shown that the cooling system of the cooling pond with the present connection is not capable for removing the heat produced in the reactor core (Fig. 13.). Therefore, modifications of the cooling system were investigated. By moving the outlet of the cooling loop to the level of the water surface, the system cools down rapidly. By using the discharge pipe of the transfer pond as outlet, the heat removal of the core can also be ensured. This modification means a better solution both considering feasibility and the uniformity of the cooling of the reactor. This CFD analysis is of great importance since during refueling the safety of the VVER-440 units can be improved by these results.

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REFERENCES


Figure 1. The system connection

Figure 2. The CFX geometry model
Figure 3. Temperature field in the incidental transient, $t=10128\ s$, $331\ K < T < 346\ K$

Figure 4. Velocity field in the incidental transient, $t=10128\ s$
Figure 5. Thermal power removed by the cooling loop of the cooling pond

Figure 6. Temperature values in the monitored points
Figure 7. Temperature field, outlet at the water surface, $t=12 \, 500 \, s$, $303 \, K < T < 318 \, K$

Figure 8. Velocity field, outlet at the water surface, $t=12 \, 500 \, s$
Figure 9. Temperature values in the monitored points, outlet at the surface

Figure 10. Temperature field, outflow through the discharge pipe, t=10 000 s, 303 K< 325 K
Figure 11. Velocity field, outflow through the discharge pipe, $t=10,000 \text{s}$

Figure 12. Temperature values in the monitored points, outflow via discharge pipe
Figure 13. Temperature values in the monitored points for the whole transient calculation.