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Investigation of natural convection in large pools ☆

E. Krepper [a,*], E.-F. Hicken [b], H. Jaegers [b]

[a] *Forschungszentrum Rossendorf e.V., Institute of Safety Research, P.O. Box 510119, D-01314 Dresden, Germany*
[b] *Forschungszentrum-Jülich, Institute for Safety Research and Reactor Technology, D-52425, Germany*

Abstract

Natural convection is a basic principle for a lot of industrial processes. As an example for the investigation of natural convection phenomena, the paper describes investigations of a passive heat removal system in advanced designs of nuclear power plants. Modern Boiling Water Reactor concepts includes emergency condensers. In the Research Centre Jülich at the NOKO-test facility experiments were performed, to investigate the heat transfer capability of an emergency condenser under different operation modes. Recently the heating up phenomena on the secondary side of the condenser were investigated in detail. The paper describes simulations performed in the Forschungszentrum Rossendorf using the CFD code CFX-4, developed by AEA-Technology, and comparisons to the experiments. Applying the Boussinesq approximation the simulation of the heating up process is possible, at least qualitatively. Using the laminar approach, temperature oscillations caused by plumes could be simulated. Performing additional calculations, measures to avoid undesired temperature stratification were investigated. © 2002 Elsevier Science Inc. All rights reserved.

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1. Introduction

Problems in CFD modelling of natural convection phenomena may occur, because in many cases the validity of commonly used turbulence models is exceeded. Common applications assume the transport of turbulent energy to be proportional to the transport of turbulent momentum. In the case of a temperature stratification the assumption of an isotropic turbulent viscosity might be violated. With strong heating up, the phase transition has to be considered and the turbulence for two phase flow has to be modelled. The numerical simulation has to be validated against experiments.

The emergency condenser, which can be found in newer nuclear Boiling Water Reactor concepts is an example for the industrial application of natural convection processes. In the framework of BWR Physics and Thermohydraulic Complementary Action (BWR-CA) to the EU BWR R&D Cluster emergency condenser tests were performed by Forschungszentrum Jülich at the NOKO-test facility (Hicken and Verfondern, 2000; Jaegers, 1997). The main subject of the tests was to determine the heat transfer capability of the condenser under different operation modes. They were aimed at the investigation of the condensation phenomena in the primary tubes. Results are published e.g. by Schaffrath (1996), Schaffrath et al. (1997) and Krepper et al. (2000). Recently experiments were performed, to investigate the heating up processes on the secondary side (Hicken et al., 2000). These data were used, to validate CFD simulations of the natural convection in large pools. Comparing the measured data with CFD calculations, deficiencies in the models are revealed.

2. Basic principle of the emergency condenser

Newer concepts of nuclear power reactors are characterized in particular by passive safety systems (e.g. emergency condensers, building condensers, passive pressure pulse transmitters). The emergency condensers include heat exchangers, which consist of horizontal U-tubes arranged in a parallel manner between two

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* Corresponding author. Tel.: +49-351-260-2067; fax: +49-351-260-2383.

E-mail address: e.krepper@fz-rossendorf.de (E. Krepper).

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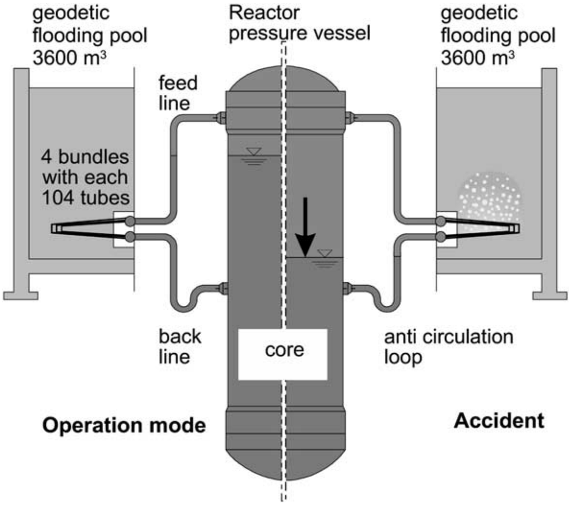


Fig. 1. Basic principle of the emergency condenser.

common headers (see Fig. 1). The top header is connected by pipes to the steam plenum of the reactor pressure vessel, while the lower header is connected to the reactor vessel below the reactor water level. The heat exchangers are located in the geodetic core flooding pool, which is filled with cold water. In this way the emergency condensers and the reactor vessel form a system of communicating pipes.

In normal conditions of reactor operation, the U-tubes of the emergency condenser are filled with water (see Fig. 1, left side) while almost no heat is transferred. In case of an accident, the main problem consist in the removal of the decay heat under loss of coolant conditions. With a decreasing water level in the reactor core, the water in the U-tubes of the emergency condenser is replaced by steam. The steam in the tubes is condensed and the heat is transferred to the secondary side of the condenser (see Fig. 1, right side). Under these conditions the condenser acts as considerable passive heat sink.

To investigate the heat removal capacity of an emergency condenser, comprehensive experiments were performed in the test facility NOKO at the Forschungszentrum Jülich (see Hicken and Verfondern, 2000; Jaegers, 1997). In 1998, tests were performed to investigate the heating up process in the secondary pool (see Hicken et al., 2000).

A schema of the NOKO-test facility is shown in Fig. 2. Main components of the facility are the pressure vessel (height 12.6 m, diameter 0.448 m) simulating the reactor vessel and the laterally connected emergency condenser bundle. The bundle of condensation tubes consists of eight tubes having a length of 8.5–10 m and an inner diameter of 44.5 mm. The bundle is arranged in a pool, which is a horizontal cylindrical tank with an inner diameter of 2 m and a length of 6 m. In the NOKO-test facility, the steam is produced by an electrical heater with a maximum power of 4 MW. The maximum steam mass flow is 2.5 kg/s.

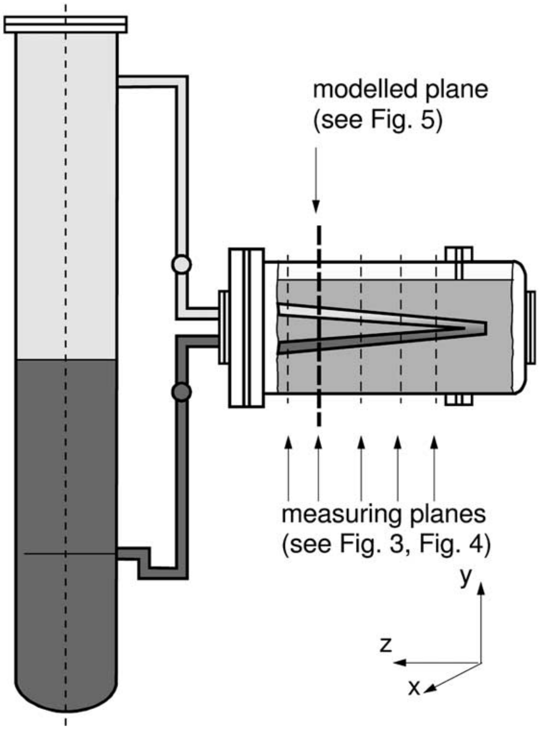


Fig. 2. Schema of the NOKO-test facility.

3. Experiments for the investigation of the heat-up process on the secondary side

During the operation of the emergency condenser both on the primary and on the secondary side, natural circulation is observed. In the present paper the processes on the secondary side are of particular interest. First single phase and later two phase natural circulation is established. In the tests the equipment with thermocouples on the secondary side of NOKO was realized in detail. 175 thermocouples were arranged in five cross-section planes A–E (see Fig. 3). Various tests with different primary and secondary pressure and different start-up temperatures were performed. In the present paper, a test with atmospheric pressure and a start-up temperature of 293 K on the secondary side is considered. During the referred test only the upper legs of three condensation tubes were active and were filled with steam, which might correspond to an early stage of the accident (see Fig. 2). The water level in the primary reactor vessel was adjusted to ensure that the boundary between steam and condensed water in these condensation tubes is fixed at the bent of the tubes (see Fig. 3 on the right side). The primary pressure amounts to 1 MPa. An overall power of 0.6 MW was transferred to

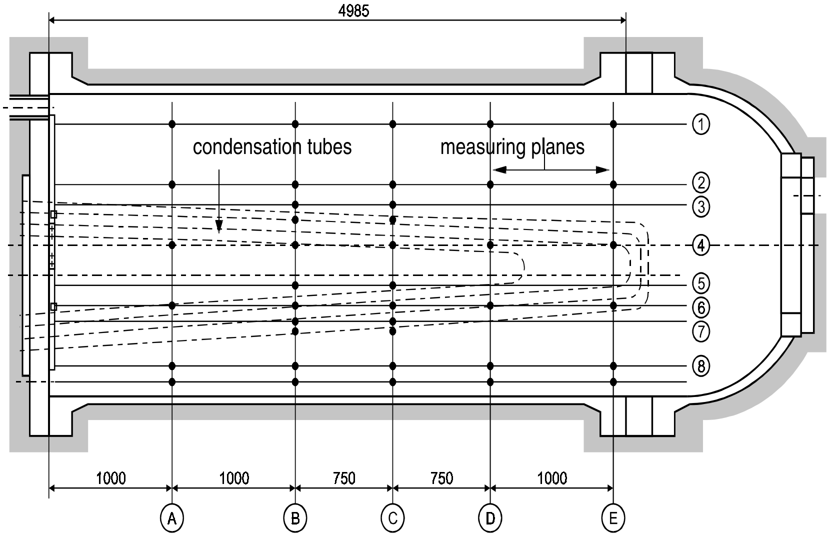


Fig. 3. Instrumentation of the NOKO secondary side during the heating up tests.

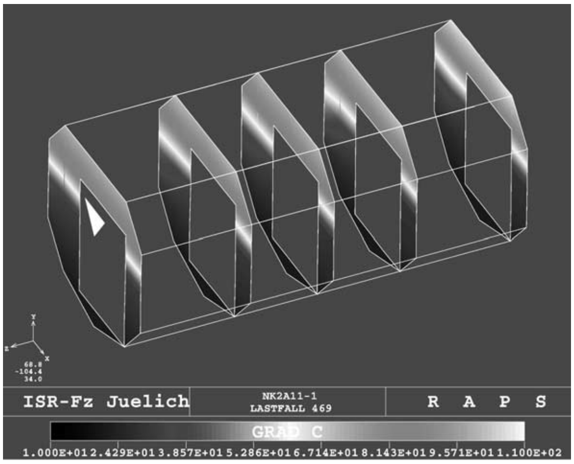


Fig. 4. Shaded contours of the temperatures in the five measuring planes. (Experiment A11 after 2000 s, see Hicken et al., 2000.)

the secondary side by condensation of steam from the upper legs of the three tubes. Heat transfer, equally distributed along the whole length of the tube, may be assumed. The heating up test was continued until the onset of boiling in the secondary tank. The five shaded contour planes shown in Fig. 4 represent the measured and interpolated temperature distributions in the measuring planes A to E after a heating up time of 2000 s (see Hicken et al., 2000). A strong vertical temperature stratification is observed. Since only the upper legs of three condensation tubes are active (the location of the heated tubes in plane A is marked by the white triangle), only the upper region of the secondary side is heated up. An essential portion of the fluid in the lower region is not involved in the heating up process. Moreover, the figure reveals, that the temperature field in the tank has almost no axial profile. Each measuring plane shows almost the same temperature distribution.

4. CFD calculations and comparison with the experimental results

To investigate the heating up processes in detail, CFD calculations using the finite volume code CFX-4 developed by AEA Technology were performed. For simplification, the condenser was modelled only in two dimensions. A vertical cross-section through the NOKO tank was considered (see modelled plane in Figs. 2 and 5). The experimental results shown in Fig. 4 indicate, that this approach is justified, because no horizontal temperature profile along the axial length of the tank was found. The computational grid consisted of about 60 000 cells. Especially in the region of the tubes, the spatial resolution was about 5 mm. A non-slip and a free-slip boundary condition was set at the tank wall and the water surface, respectively. In the CFX calculations an incompressible flow was assumed. Buoyancy was considered using the Boussinesq approximation. A central differencing scheme for Peclet numbers less than 2 and an upwind scheme otherwise was applied. For the time discretisation a fully implicit backward time stepping procedure was used. Only the single phase period of the transient was taken into account. The Rayleigh number of the problem was estimated to be in the order of 10^9. For the calculation of temperature stratification phenomena in the whole tank volume, a laminar flow my be assumed. The heat flux known from the experiments was given as a boundary condition at the heated tubes. The heat losses from the outer tank wall into the environment were estimated to be in the order of 6–8

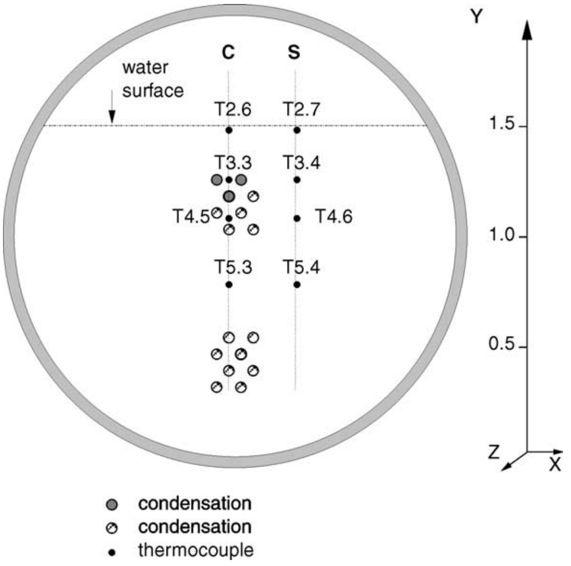


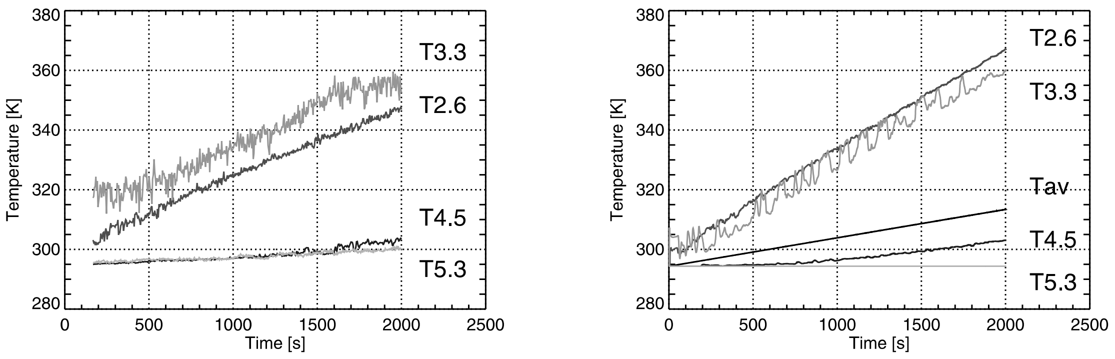
Fig. 5. Localisation of the considered thermocouples.

kW. As they are small compared to heating power of 0.6 MW, they were neglected.

To investigate the temperature stratification in the tank, from the about 40 data of the measuring planes those points were selected, which refer to vertical lines in the centre of the bundle (line C, $x = 0$ m) respective in the side area of the tank (line S, $x = 0.28$ m). The localisations of the considered thermocouples are shown in Fig. 5. In Fig. 6 measured and calculated temperature courses for selected points are compared.

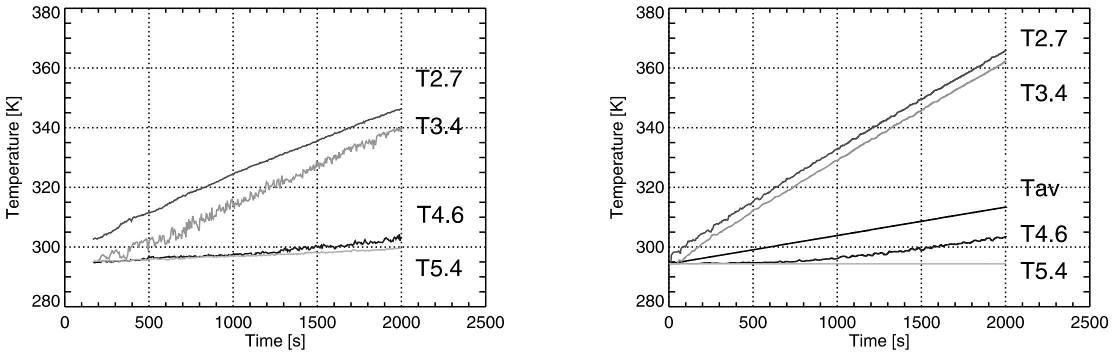
The strong temperature stratification is also reflected in the calculations. Fig. 7(a) and (b) show the temperature profile in the line C respective S and Fig. 8 the contours of the temperature field in the tank after 2000 s. The absolute temperature values in Fig. 8 might be estimated from the temperatures given in Fig. 7. In the lower part of the vessel almost no heat-up is found, neither in the experiment nor in the calculations.

The tendencies of temperature growth are qualitatively reproduced by the calculation. Whereas the upper temperatures are overestimated, the boundary between the heated water region and the region remaining almost at the initial temperature is calculated something too sharp (see Fig. 7(a) and (b)). In the experiment the temperature T3.3 ($y = 1.175$ m) is found to be larger than the temperature T2.6 ($y = 1.4$ m). The calculations depict T3.3 to be always smaller than T2.6 (see Fig. 6). Figs. 5 and 9 show that the thermocouple T3.3 is located in the centre between the three heated tubes. In the



a) Experiment, centre line C

b) Calculation, centre line C



c) Experiment, side line S

d) Calculation, side line S

Fig. 6. Measured and calculated temperature courses. T_{av}, mean pool temperature. Experiment: (a) centre line C and (c) side line S; calculation: (b) centre line C and (d) side line S.

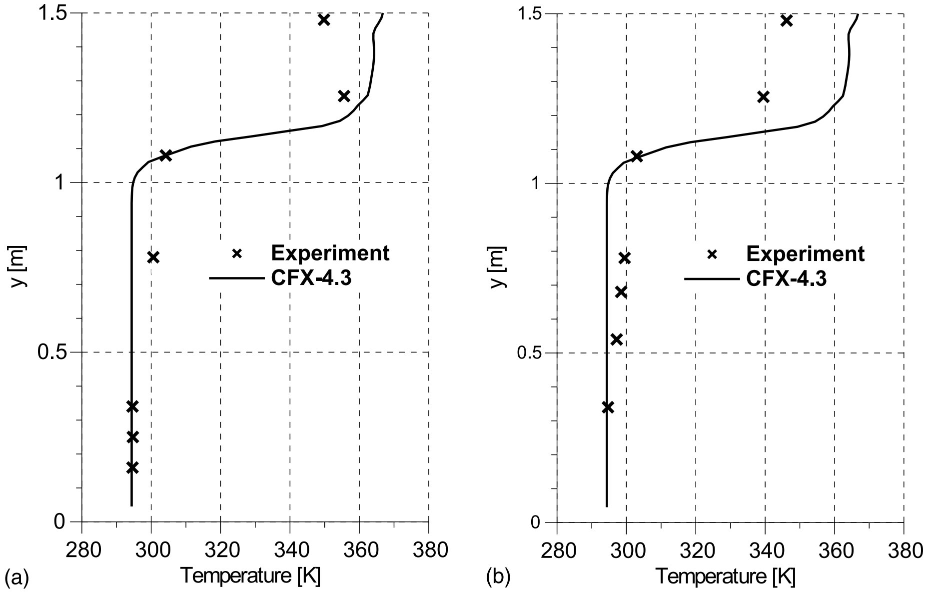


Fig. 7. Vertical temperature profile after 2000 s heat-up time: (a) line C and (b) line S.

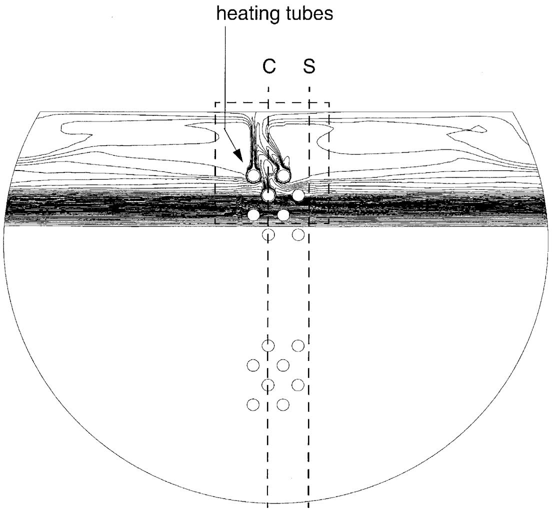


Fig. 8. Temperature field after 2000 s without internal constructions (only the upper three tubes are heated) (contour interval 1 K, temperature values see Fig. 7).

calculations the location of T3.3 is exposed only to the heat of the tube below the thermocouple. In the test T3.3 is influenced also by the other active tubes at the side of the thermocouple. The underestimation of T3.3 might be explained by this influence. Another source of discrepancy might be measuring errors caused by the near water surface to T2.6. Nevertheless the temperature oscillations of T3.3 found in the measurements were reproduced also in the calculations. They are probably caused by plumes above the heated tubes, which are also seen in Fig. 9. These highly transient plumes are only found in the calculations with the laminar approach.

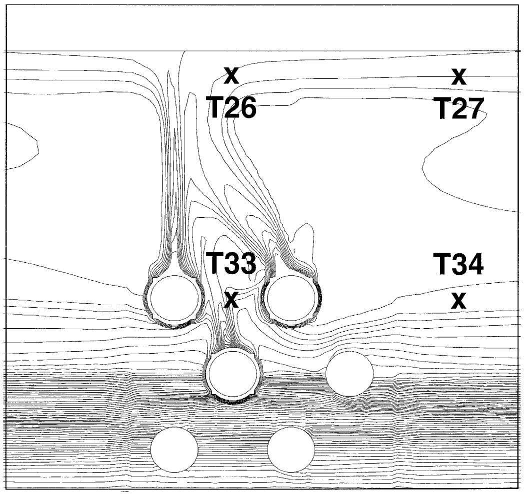


Fig. 9. Temperature field and location of thermocouples around the heated tubes (detail of Fig. 8) (contour interval 1 K).

Applying a standard K-Epsilon turbulence model, the plumes are not calculated and the oscillations of the temperature T3.3 are not found (see Fig. 10).

Assuming an ideal temperature mixing of the fluid, the heating from 294 K up to the boiling temperature of 373 K has to be expected as a result of the power that would be transferred after about 8000 s (compare the mean pool temperature T_{av} shown in Fig. 6(b) and (d), which reaches only 315 K after 2000 s). However, the boiling temperature is observed at the surface already after some 2000 s, because of the strong temperature stratification (see Fig. 6). If the secondary pressure is assumed to be 0.1 MPa, then boiling at the water surface occurs even after fourth of the time that would be

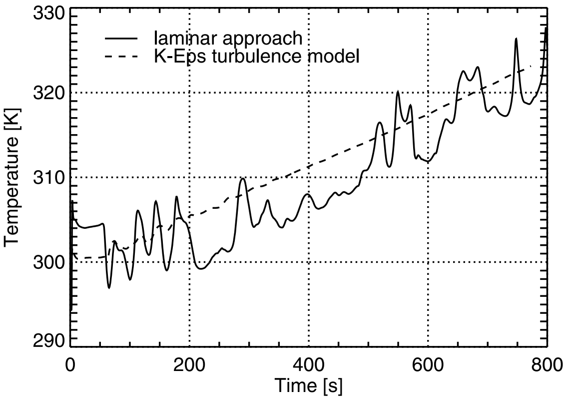


Fig. 10. Course of the temperature T3.3: applying a turbulence model, the temperature oscillations disappear.

necessary to heat-up the whole inventory to the boiling temperature.

5. Investigation of measures to avoid early onset of boiling

The early onset of boiling has to be avoided because the heat transfer capability is decreased and in the real facility the produced steam entering the containment is unwanted. The reason for the early boiling is, that only the fluid above the heated tubes is heated up. A large portion of the fluid in the pool is not involved in the heating-up process. The search for measures to avoid this phenomenon has to take into account, that the emergency condenser is designed to be a passive safety system, i.e. any equipment using active components is unacceptable. A possible solution could be the use of the chimney effect of two guide plates for a better mixing of the fluid volume during the heating up process. The arrangement of guide plates was investigated, which could improve natural circulation in the tank. Two straight vertical plates at a distance of 0.25 m are expected to act as a chimney and should transport the lower cold fluid to the upper heated tubes (see Fig. 11). Indeed after the first hundreds of seconds an enhancement of the natural circulation was observed. Fig. 13 shows the increased vertical velocity up to 0.2 m/s in a height of about $y = 0.5$ m at 200 s. However after about 1000 s the circulation has slowed down (see Fig. 13). The reason is the large amount of water sucked from the upper part into the area between the guide plates (see detailed velocity field, Fig. 12). The velocity scale might be estimated from Fig. 13. An even stronger heat-up at the surface and only a weak extension of the heated fluid area to the lower regions is the consequence (see Fig. 14). Applying the proposed construction of guide plates, the fluid is heated up to boiling temperature at the upper part of the tank even earlier than without plates. The results demonstrate, that the aim of reaching stable natural circulation has been missed and further investigations are necessary.

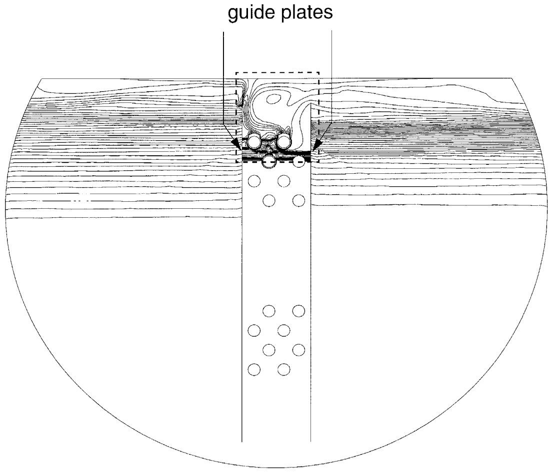


Fig. 11. Temperature field after 1000 s with two straight guide plates (contour interval 1 K, temperature values see Fig. 14).

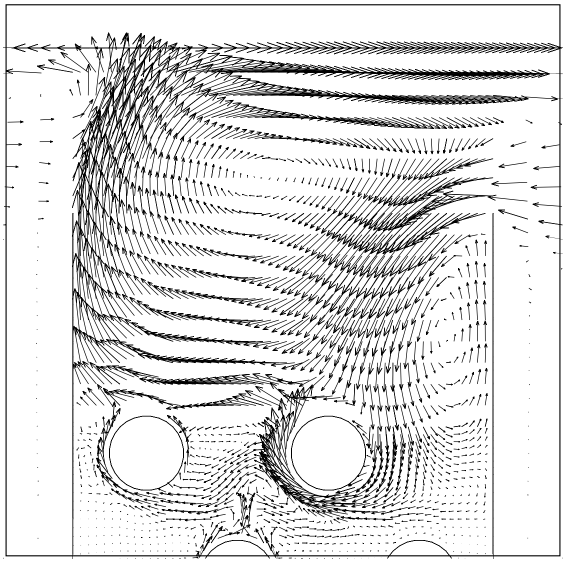


Fig. 12. Detailed view of the velocity field after 1000 s.

6. Summary, conclusions and next steps

Natural convection is an essential phenomenon, which plays a role in of a lot of industrial applications. The experimental test facility NOKO gives the possibility, to investigate heating up processes in a horizontal cylinder having a length of 6 m and a diameter of 2 m. Using the CFD code CFX-4, the simulation of the heating up process is possible, at least in qualitative manner, without additional models regarding the buoyant flow. The strong temperature stratification found in the experiments has been reproduced in the calculations,

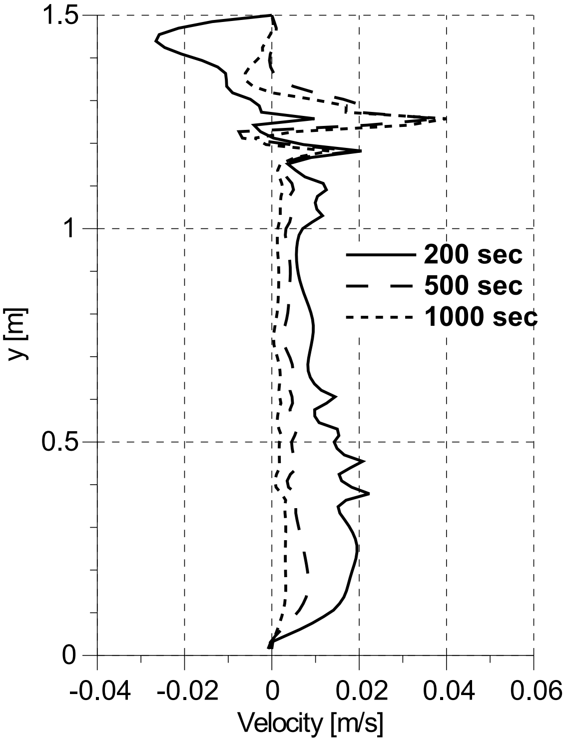


Fig. 13. Profile of the vertical velocity vy with guide plates (centre line C).

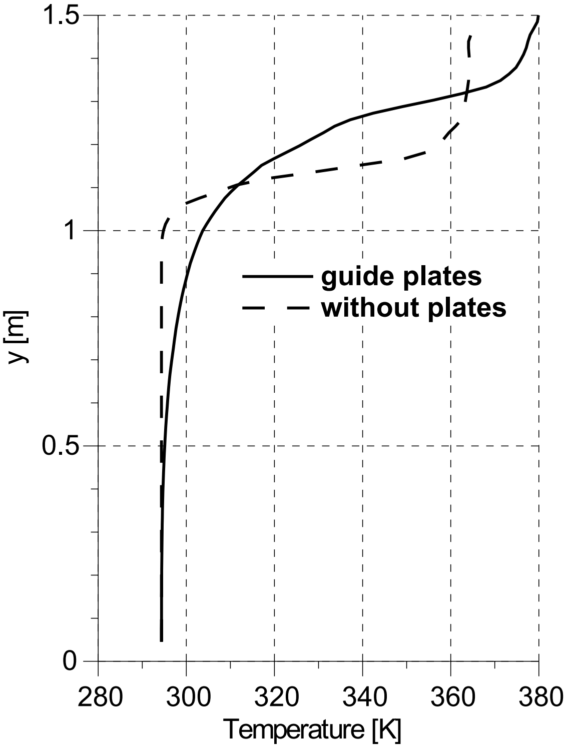


Fig. 14. Vertical temperature profile (centre line C).

too. Using the laminar approach, temperature oscillations caused by plumes could be simulated.

For an emergency condenser, the temperature stratification has important consequences. At the upper surface of the tank fluid boiling starts much earlier, as the mean pool temperature has reached the boiling point. In the case of an emergency condenser in a nuclear reactor, this effect has influence on the pressure increase in the containment and the operation conditions of other passive components. In later phases of the accident the pool coolant is designed for emergency core cooling. The temperature of the coolant has some influence on the neutron kinetic safety.

Therefore measures were investigated, to avoid the temperature stratification. The arrangement of guide plates, which should establish a natural circulation by chimney effect was taken into account as a passive measure. The insertion of straight vertical plates has been proven not to lead to the desired effect. An illustrative example for the influence of guide plates has been provided. Further optimization is necessary.

Further investigations should be concentrated on the improvement of the modelling of the heat transfer at the heated surface. To study later periods of the heating-up process, boiling has to be taken into account.

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