P. Pandazis and *B. Babcsány*

Numerical and experimental investigation of surface vortex formation in coolant reservoirs of reactor safety systems

The reliable operation of the emergency coolant pumps and passive gravitational injection systems are an important safety issue during accident scenarios with coolant loss in pressurized water reactors. Because of the pressure drop and flow disturbances surface vortices develops at the pump intakes if the water level decreasing below a critical value. The induced swirling flow and gas entrainment lead to flow limitation and to pump failures and damages. The prediction of the critical submergence to avoid surface vortex building is difficult because it depends on many geometrical and fluid dynamical parameters. An alternative and new method has been developed for the investigation of surface vortices. The method based on the combination of CFD results with the analytical vortex model of Burgers and Rott. For further investigation the small scale experiments from the Institute of Nuclear Techniques of the Budapest University of Technology and Economics are used which were inspired from flow limitation problems during the draining of the bubble condenser trays at a VVER type nuclear power plants.

Numerische und experimentelle Untersuchung von Oberflächenwirbelbildung in Kühlmittelbehältern von Sicherheitssystemen von Reaktoren. *Während eines Kühlmittelverluststörfalls ist der zuverlässige Betrieb von Not- und Nachkühlpumpen sowie von passiven Einspeisesystemen bei Druckwasserreaktoren ein wesentlicher sicherheitstechnischer Aspekt. Wenn der Wasserpegel im Behälter unter einen kritischen Wert sinkt, bilden sich an den Saugstutzen der Pumpen Oberflächenwirbel infolge von lokalen Druckabsenkungen und Strömungsinhomogenitäten aus. Dadurch kommt es zu einer Drallströmung sowie einem Lufteintrag in die Saugleitung, welche zu Einschränkungen in der Kühlmittelförderung oder zur Schädigung der Pumpe führen kann. Die Abschätzung der kritischen Überdeckung zur Vermeidung von Oberflächenwirbel ist schwierig, weil sie von zahlreichen geometrischen und strömungsmechanischen Parametern abhängt. Ein neues Verfahren, basierend auf der Kombination von CFD Ergebnissen und dem analytischen Wirbelmodell von Burgers und Rott wurde zur Untersuchung der Oberflächenwirbel entwickelt. Die Nachrechnung eines neuen Experiments der Technischen und Wirtschaftswissenschaftlichen Universität Budapest, das sich mit dem Einfluss der Wirbelbildung auf die Entleerung der WWER Komponente Bubble Condenser beschäftigt, mit diesem Verfahren, wird in diesem Beitrag beschrieben.*

1 Introduction

If the water level of a reservoir decreases below a critical value, the so-called critical submergence, surface vortices occur above the intake in consequence of the pressure drop. Disturbances, asymmetries and circulations in the inflow support vortex formation and increase the critical submergence. When the water level drops below the critical submergence a small dip on the water surface can be observed, which may develop into an air-cone. Figure 1 shows the phases of the vortex formation ordered by decreasing submergence. With reference to *Knauss* [1] they can be classified in 6 types. The small air-cone (vortex of type 2) can be stretched within a short time. By type 3 develop a continuous strong swirling dye core to intake. With further decreasing the water level it will be stronger and transport first the swimming floating thrash from the surface and after that as well as small air-bubbles into the intake. Finally developing a continuous gas core which reaches the pump intake and causes both swirl and gas entrainment into the pump (type 6).

Figure 2 shows the general setup of a surface vortex. The structure of the flow field can divided in two main parts. In the vicinity of the vortex axis there is a strong rotational region the so called vortex core. The vortex core is characterized with strong velocity gradients. Around of the core the flow region is almost a potential flow, enough far away from the core with a constant circulation.

In general a reliable pump operation requires a homogeneous, undisturbed inflow without vortices. The consequences of the disadvantageous inlet conditions are vibrations, increased rotor loads, noise or fluctuations of the pump-characteristic. These conditions can lead to damages of the pumps especially during a long-term operation. Moreover, gas entrainment caused by surface vortex formation can lead to a decrease or even a collapse of the flow rate. Surface vortex building above the draining intakes of passive safety systems are also an important safety risk in nuclear power plants. The gravitational draining of large water reservoirs are often affected from surface vortices which leads to a strong limitation in the draining mass flow [2]. Therefore, surface vortex formation at intakes must be avoided in general. That can be achieved with a minimum water level at which the formation of vortices of type 2 can be excluded. This water level called critical submergence.

1.1 Critical submergence in nuclear facilities

The determination of the critical submergence is an important issue for nuclear power plants. After Loss of Coolant Acci-

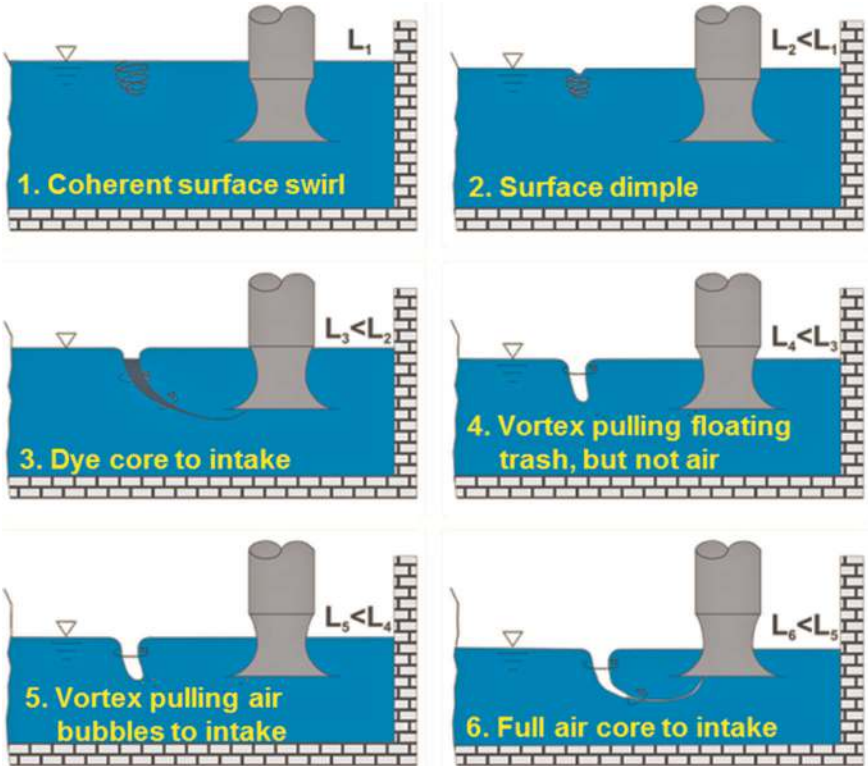

Fig. 1. Phases of surface vortex building by decreasing submergence

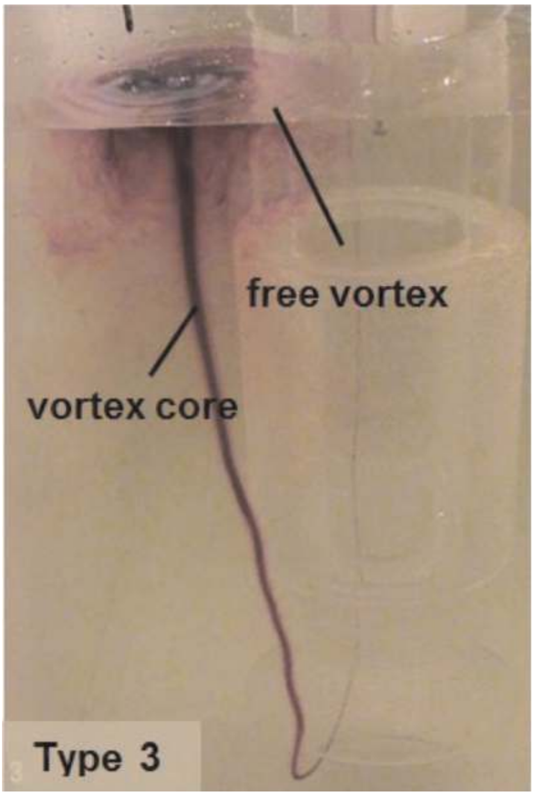

Fig. 2. Setup of a surface vortex [5]

dents (LOCA) in Light Water Reactors the heat removal systems provide the long-term cooling of reactor core. The heat removal pumps inject the coolant from the reservoirs and from the containment sump via the cooling systems into the primary circuit. These coolant reservoirs are the flooding tanks in Pressurized Water Reactors and the wet-well in Boiling Water Reactors. The reliable operation of the safety pumps is an important requirement for the undisturbed long-term recirculation of the coolant. Furthermore the critical submergence limits the available amount of coolant in these reservoirs and therefore the available time of an effective coolant injection.

By third generation reactors and newly investigated severe accident cooling strategies of existed reactors are often passive safety systems favorized. E.g. in AP1000 passively drained water from the large water tank (PCCS) on the top of the containment perform the long term cooling of the containment and ensure the depressurization of it. Furthermore i.a. the water in the trays of the bubble condenser in VVER-type reactors are foreseen for external cooling of the reactor pressure vessel after a severe accident. In this case the coolant are also transported gravitationally from the trays into the cavity. The successfully gravitational draining of available water reservoirs is an important part both of these strategies.

The prediction of the critical submergence is difficult, because it depend on many geometrical and fluid dynamical parameters. Numerous experimental and analytical investigations have been performed in the last decades to derive universal, conservative and easy-to-use correlations to calculate the critical submergence. However, these correlations are usually valid only on an individual limited range of applicability because of the complex nature of vortex formation. Therefore, there are well-established guidelines which contain conservative and easily usable correlations together with their application range and hints for the intake geometry design. The German Reactor Safety Commission (RSK 2005) [3] recommends the use of the conservative correlation from ANSI (American National Standards Institute) [4] in the nuclear supervising procedure. If more precise values are required or if correlations are not valid for the investigated parameter range, a complex and expensive experiment is required. The

ANSI correlation where the critical submergence h is only depends of the Froude number of the intake Fr_A and the diameter of the intake mouth d_A is:

$$(h / d_A)_{crit} = 1 + 2.3\,Fr_A \quad (1)$$

The surface vortex building was investigated with Computational Fluid Dynamic (CFD) simulations in the framework of the research project GUMP at TÜV NORD SysTec GmbH & Co. KG. Within this investigation an alternative and new way was investigated to calculate the critical submergence. The method based on the combination of the CFD results with the analytical vortex model of Burgers and Rott and offers an effective way to investigate surface vortices, also in the case of complex geometries, like a PWR containment sump [9].

To further investigation, validation as well as broadening the applicability of the developed combined method the results of experimental investigations of the Institute of Nuclear Techniques of the Budapest University of Technology and Economics has been used in the framework of an interinstitutional cooperation with the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH. In the following we describe the developed method to investigate the surface vortices. After that will be present the setup of the experiment and finally it will be show some validation results and the application of the combined method for the experimental investigated problem.

2 Combined method

The basic concept of the combined method was derived from two experiences. In one hand the CFD analysis with ANSYS CFX are shown that it is possible to compute the flow field in the free vortex region efficiently and in good approximation. However, a proper resolution of the vortex core region needs much more effort. In the other hand, the analytical vortex model of Burgers and Rott could calculate the vortex parameters in both of the region but it requires parameters from the free vortex region. Therefore, the basic concept of the combined method is the application of the CFD simulations to calculate the free vortex region (incl. flow disturbances and inflow structures) and the analytical vortex model to calculate the vortex core region. With this method is possible to calculate the gas core length of a surface vortex as well as the critical submergence.

An analytical vortex model was developed by Burgers and Rott which describes the flow field of stationary, axisymmetric vortices [1]. The model is derived from the incompressible Navier-Stokes equations and parameterized with the so-called suction parameter. The constant suction parameter (also called downward velocity gradient) represents the intensity of the pump suction for the actual intake. By knowing the suction parameter the model describe the tangential velocity distribution of a surface vortex. On the basis of the Burgers & Rott model Ito et al. [6] used a differential equation to describe the surface deformation. Integration of this equation yields a simple formula for the maximal surface deformation of the vortex, i. e. the gas-core length L_g:

$$L_g = \lim_{r\to\infty} h(r) - h(0) \approx \frac{a \cdot \ln(2)}{\nu \cdot g}\left(\frac{\Gamma_\infty}{4\pi}\right)^2, \text{ where } a = \frac{4 \cdot r_0^2}{\nu} \quad (2)$$

In Eq. (2) h characterizes the submergence, ν the viscosity, g the gravitational acceleration, r the radial coordinate, r_0 the specific vortex-core radius, Γ_∞ the circulation and a the suction parameter. The application of this analytical formula requires the knowledge of the suction parameter and the circulation and in the present investigations ANSYS CFX simulations are used to determine these parameters. The suction parameter describes the averaged downward velocity gradient which are calculates from CFX in all mesh cells. Hence the local values can be taken directly from numerical results. The local downward velocity gradients are averaged along the vortex core boundary near to the free surface. The boundary of the vortex core is determined by the well-known Q-criteria and the averaged tangential velocities far away from the vortex-core are used to calculate the circulation.

In summary, a CFX simulation is needed as first step of the combined method to calculate the gas-core lengths for a certain intake geometry and submergence. Afterwards the free parameters of the Burgers and Rott model can be obtained from the CFX results. Finally these parameters are inserted in the analytical model which yields the tangential velocity distribution and the gas-core length of the surface vortex by Equation (2).

The submergence achieves its critical value when the gas-core length of the vortex above the intake becomes larger than zero. Generally, at least two CFX simulations are necessary to determine the critical submergence, because two simulations are required whose boundary conditions are chosen such that they enclose the conditions for the critical submergence – one submergence above and one below the critical value. From these simulations at least two pairs of water levels and gas-core lengths are obtained which yield the critical submergence by interpolation. The critical suction parameter is also obtained by the same strategy. With the knowledge of this critical suction parameter it is possible to compute the critical submergence for other operation conditions without further CFX simulations. The basic idea is that Equation (2) should apply if the critical submergence and the suction parameter are known for one set of boundary conditions.

The experimental results of Anwar et al. [7] showed that the vortex core radius varies almost linearly with the height, i. e. the vortex-core radius r_0 is proportional to the critical submergence h_{crit}. Hence, the relation between r_0 and h_{crit} is given by the expansion constant C in Equation (3).

$$C = \frac{h_{crit}}{r_0} = \text{const.} \quad (3)$$

By introducing C in Equation (2) and using the relation between the suction parameter a and the vortex core radius r_0 an analytical correlation for the critical submergence h_{crit} can be derived (equation (4)) for the experimental setup shown in Fig. 2.

$$h_{crit} = \sqrt{C \cdot \frac{\dot{m} \cdot \tan\varphi}{2 \cdot \pi \cdot \rho} \cdot \left(\frac{\ln(2)}{\tau \cdot g}\right)^{\frac{1}{4}}} \quad (4)$$

Equation (4) provides a simple analytical correlation for vertical pump intakes to calculate the critical submergence for various intake velocities assuming constant density and inflow angle. The selected threshold value for critical submergence τ was chosen of 1 mm during the investigations.

3 Experiment and the CFD model

The VVER-440 type reactor in NPP Paks is equipped with a bubble condenser to containment depressurization purposes. The bubble condenser includes 12 trays which has a water content of about 1200 m^2. The draining of this water amount is necessary to handle with different severe accidents. The background of the experiment is provided from flow limitations at the intakes of the trays during supervising draining tests (2001). After 15–20 minutes a significant decreasing of the water massflow was observed. The ground for this were surface vortices with fully developed gas-core which caused a significant contraction in the flow cross section in the intake. To eliminate this problem so called vortex-breaker devices were mounted. The small scale experiments were dedicated to investigate this draining problem and the effectivity of the vortex-breaker devices with means of modern measuring techniques and in the same time to provide a validation basis for CFD codes [8].

3.1 Test facility

The main part of the test facility is a square glas tank with an central intake where the surface vortex can be observed and measured. The sqaure form was choosed because of the used optical measurement techniqe. The tank has a main dimension of 500 × 500 mm and the draining pipe has a diameter of 20 mm. The water has been drained through a vertical pipe in a further tank. With a pump the water could transported back in the draining tank, therefore it was possible to investigate the surface vortex also by contsant submergence. The water was lead back in separate part of the tank, from there this could flow slow and without any disturbance to the measuirng part. The setup of the experiment shows the Fig. 3.

Two type of test runs have been performed, gravitational draining tests and surface vortex investigations by constant submergence. The gravitational draining tests were performed like the original tests in NPP Paks. The draining was started by a water level of 110 mm and the mass flow and the drained water amount were measured. The developing of a surface vortex has been observed during the tests.

The second type of measurements was dedicated to the investigation of the structure of the surface vortex. During this tests a fully developed surfave vortex was generate above the intake by continuous draining but different constant submergence. The horizontal velocity field of the vortex was measured by PIV (Particle Image Velocimetry) in several vertical position. The resulted velocity distributions provide a good validation basis for CFD codes.

The combined method has been used to investigate the flow limitation problem during the draining of the bubble condenser trays according of this experiment. The first step for it was the CFD simulation of the experimental intake to determinate the suction parameter.

3.2 CFD model

The CFD calculations were performed with the code ANSYS CFX 14.5. During the experiment near stationary surface vortices arose in the centre of the square tank. The experimental results show a strong rotation also in the vicinity of the intake, that means a strong rotational symmetry in the whole investigated flow field (see Fig. 4). Used this we only calculated this

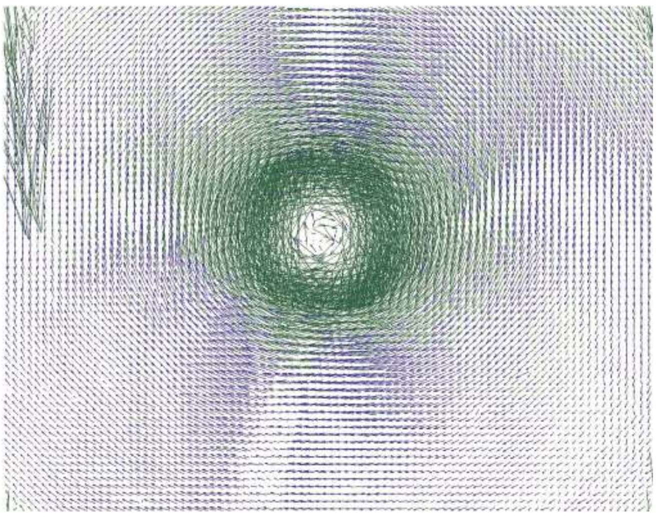

Fig. 4. The rotation symmetrical flow field measured in experiment with PIV [8]

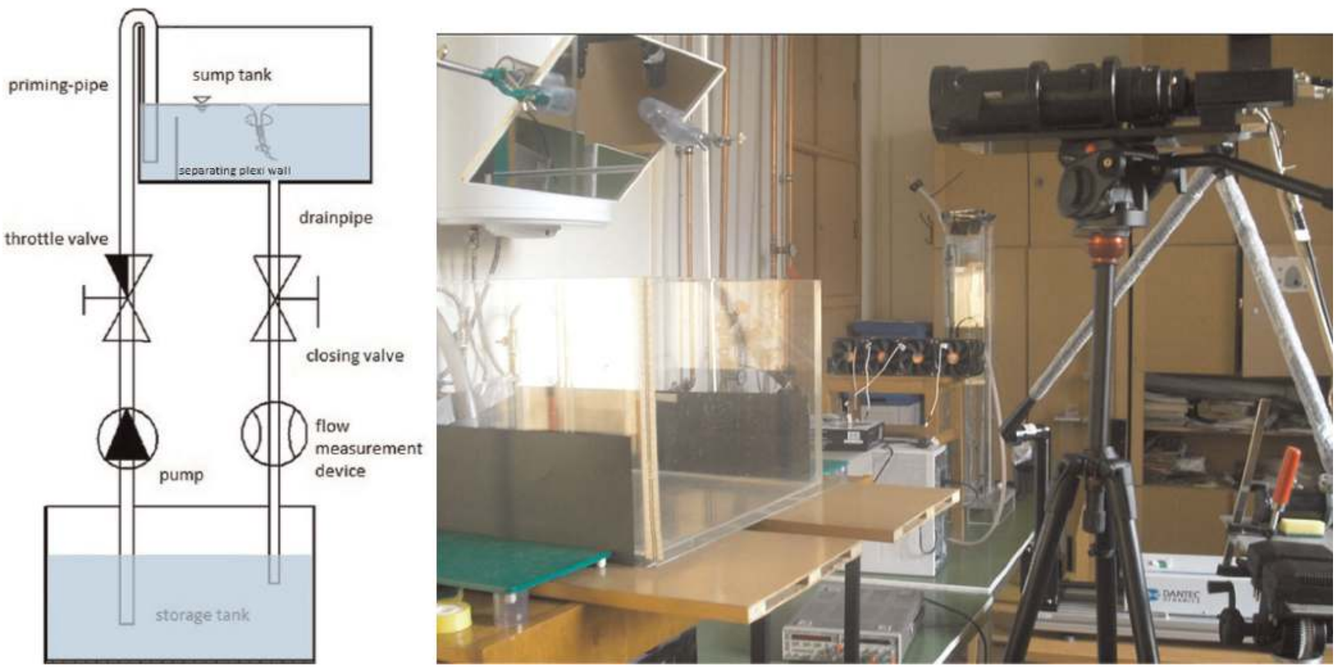

Fig. 3. Setup of the experiment and the PIV camera [8]

rotational symmetrical part of the experimental investigated flow field, i.e. the intake with a cylindrical flow fiel of 100 mm. To further reducing the computational effort only a 1.5 degree thin section of this cylindrical geometry has been modeled with periodic boundary conditions at the cut planes. According of previous validation this region is large enough to calculate the suction parameter of the intake [9].

The grid resolution, the physical model as well as the initial and boundary conditions were setup on the basis of previous validaton calculations [9]. The numerical grid was generated with hexahedral elements. The mesh was refined at the walls, at the water surface and in the vortex core which means a cell length in the core of about 1 mm in horizontal direction. Two-phase simulations with air and water were performed with the so called inhomogeneous model of the ANSYS CFX. The inhomogeneous model solves phase specific momentum equations by introducing the volume fractions in the conservation equations and provides a sharp interface and a good convergence in this case. Between the phases only momentum exchange had to be considered by a transfer term in the momentum equation, because no mass or energy transfer took place between water and air in this experiment. The interphase momentum transfer is modelled with the drag force. In the present case the drag coefficient was a constant value of 0.44 according to Newton's drag law. According of the preliminary calculations the turbulence was modelled. The SST turbulence model together with the so-called curvature correction to consider strongly swirling streamlines was applicate in the simulations.

Stationary calculations were performed with a submergence of 72 mm regarding of the experiment. The circulation was setup directly on the tank inlet boundary through the definition of the inflow angle. The simulation was run by different volume flows to determinate the critical suction parameter according of Chapter 2. The circulation value and therefore also the inflow angle was directly take from the experimental results.

4 Results

The first CFD simulations were performed with the volume flow where during the experiment a fully developed stationary vortex were observed. This means a submergence of 72 mm and a intake velocity of 0.44 m/s. The observed vortex and the CFD results are present in Fig. 5 and shows that the CFD simulation calculates qualitatively well the strong continuous gas core of the vortex. Also the expansion of the gas core in the intake because of flow separation after the sharp edge of the intake mouth shows the CFD results which is a relevante phenomena regarding of flow limitation.

To determinate the critical suction parameter at least two calculation are necessary one below and one above of the critical submergence (1 mm gas core length by critical submergence, see chapter 2). Instead of change the submergence (to avoid of the generating of new numerical grid) the intake velocity was reduced to simulate a draining without a surface vortex with gas core. The fully developed surface vortex by 0.44 m/s intake velocity is far away from the critical submergence. This is not optimal for the necessary interpolation, therefore two further simulations were performed with an inlet velocity of 0.25 and 0.1 m/s. Figure 6 shows the calculated interfaces by different intake velocities.

The CFD results show qualitatively good the development of the surface vortex by increasing intake velocity. The suction parameters were determined as described in Chapter 2 from the downward velocity gradients at the edge of vortex core 15 mm below of the water level. The accurate value of

Fig. 5. Calculated (left) and the during the experiment observed surface vortex (right) [8]

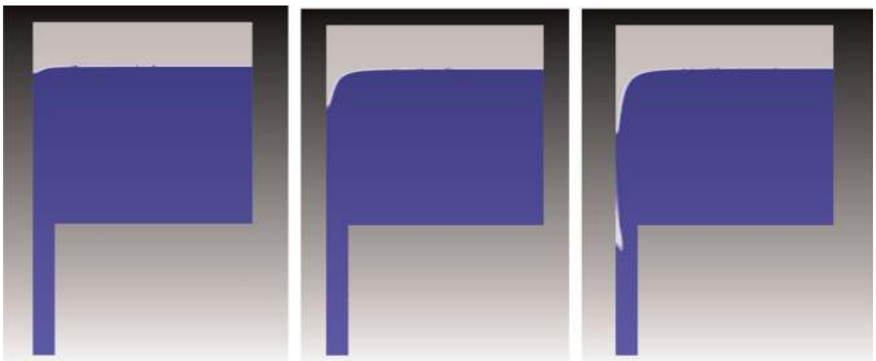

Fig. 6. Phase boundary at different intake velocities, blue: water and white: air (0.1, 0.25, 0.44 m/s)

the gas core lengths as well as the tangential velocities were calculated with the combned method. The tangential velocities were compared with the results of the PIV measurements in Fig. 7 by an intake velocity of 0.44 m/s.

The PIV results which were measured by different height shows that the tangential velocity is dependent of the vertical coordinate and not a constant as assumed in the Burgers and Rott model and therefore also in the combined method. For instance the maximal tangential velocity measured by 20 mm height is 0.15 m/s while by 60 mm reach a maximal value of 0.22 m/s. Hence the calculated tangential velocity distribution shows a good agreement with the experimental results. Regarding the critical submergence the neglecting of the height dependence causes no relevant effect. Figure 7 shows the tangential velocity distribution measured by 40 mm compared with the combined method results.

The suction parameters of the results of the simulations with 0.25 and 0.1 m/s were used to determinate the critical suction parameter which characterized the investigated intake. With the knowledge of the critical suction parameter the Equation (4) of the combined method were used to calculate the critical submergences of the intake. The calculated values are compared with the critical submergences determined with the ANSI correlation (Eq. (1)) and the experimental results of the draining tests in Fig. 8. The results of three draining test mark with the green lines. The curves show the limitation in the volume flow well. The intake velocity drops to about 50 % just directly by the beginning of the test because of surface vortex formation. This results means that the submergence of the intake at the beginning of the draining tests were below of the critical submergence. The critical

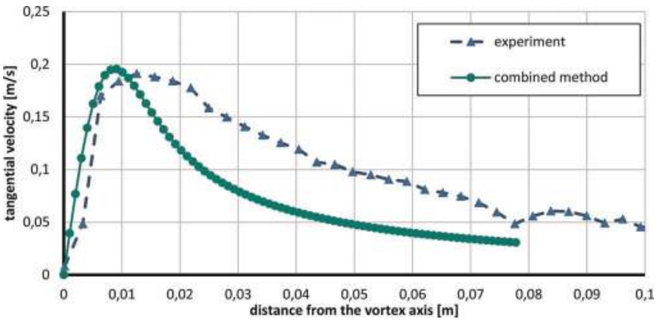

Fig. 7. Calculated and measured tangential velocity distribution (0.44 m/s)

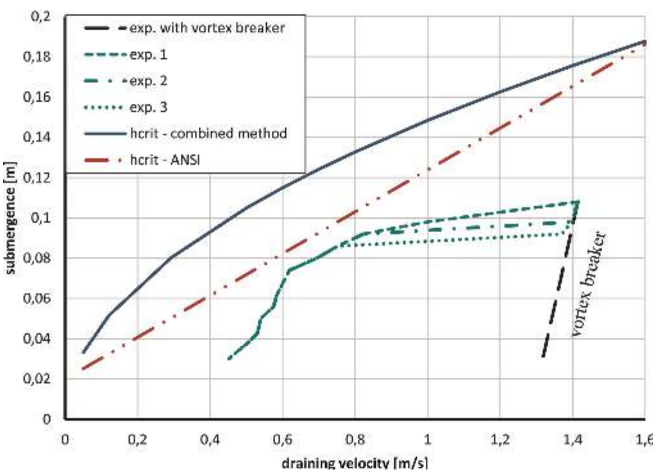

Fig. 8. Results of the draining tests and the critical submergence from combined method and ANSI correlation

submergence calculated with the combined method is mark with the blue line in Fig. 8. The diagram shows that the submergence during the experiment is significant lower in the experiments as the critical submergence. According of the calculations to avoid the surface vortex for this intake about 30 % higher water level is necessary. Another possible solution is the usage of vortex breaker devices.

In NPP Paks the bubble condenser trays are equipped with vortex breaker devices after the draining tests to ensure the necessary volume flow. The critical submergence is strong depending from the circulation in the flow field (see chapter 1). Vortex breaker devices decreased the circulation in the vicinity of the intake and therefore allowed a lower critical submergence. During the experiment the effectivity of the planned vortex breaker devices are also investigated. The black line in Fig. 8 shows the results of the draining tests with vortex breaker. It is clearly visible that the vortex breakers avoided effective the vortex formations and ensure a significant higher draining flow rate. To calculate the effectivity of vortex breaker devices is also possible with the combined method, through simulations with lower circulation. However the suction parameter is depending from the circulation, therefore further CFD calculations will be necessary to calculate the effect of vortex breakers.

The calculated critical submergence with the conservative correlation of ANSI are marked with the red curve in Fig. 8. Also these values predict surface vortex formation during the experiment. However ANSI calculates lower critical submergences than the combined method. The ANSI correlation is conservative but only valid for inflows with low circulation. Obviously in the investigated cases the circulation is larger than allowed for the ANSI correlation. The results show well the applicability limits of the ANSI correlation and at the same time the advantages of the newly developed combined method in case of gravitational draining.

5 Summary

An alternative and new method has been developed to investigate of surface vortex formation which based on the combination of the CFD code ANSYS CFX with the analytical vortex model of Burgers and Rott. The combined method provide an effective way to determinate the critical submergence of a water intake in a broad specific parameter range according of a few numerical simulation. Moreover the method provides information about the structure of the vortex through the determination of the tangential velocity distribution in the flow field.

In the framework of an interinstitutional cooperation the combined method was further investigated analysing of gravitational draining problems, broadening its applicability to support the work of nuclear safety authorities. The basis of the investigations provided the experimental results of the Institute of Nuclear Techniques of the Budapest University of Technology and Economics. These experiments were initially inspired by flow limitation problems induced by surface vortices during the draining of bubble condenser plates in VVER-type nuclear power plants.

The combined method was successfully used to calculate the critical submergence of the experimental water intake. The calculated results approved the experimental observations and showed the distance from the non-disturbed draining. The combined method predicted the formation of surface vortices at the defined submergence well. Moreover, the tangential velocity distribution calculated with the combined method shows a good agreement with the PIV results.

Summarized these investigation shows, that with the application of the combined method can successfully and effectively investigate the surface vortex formation. Through the calculation of the critical submergence could be predict, and with this to avoid i.a. flow limitation problems at gravitational drained water reservoirs, and therefore this method can help towards improve the nuclear safety.

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The authors of this contribution

Dipl. Ing. *Peter Pandazis* (corresponding author)
E-mail: peter.pandazis@grs.de
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Boltzmannstr. 14
85748 Garching b. München, Germany
M.Sc. Phys. Boglárka Babcsány
Institute of Nuclear Techniques, Budapest University of Technology and Economics
Műegyetem rkp. 9
1111 Budapest, Hungary

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Predisposal Management of Radioactive Waste from Nuclear Fuel Cycle Facilities. IAEA Safety Standards Series No. SSG-41. Published by the International Atomic Energy Agency, 2016, ISBN 978-92-0-110315-4, 93 pp., 43.00 EUR.

The objective of this Safety Guide is to provide operating organizations that generate and manage radioactive waste (including spent nuclear fuel declared as waste and high level radioactive waste), as well as regulatory bodies and government bodies, with recommendations on how to meet the requirements for the predisposal management of radioactive waste generated at nuclear fuel cycle facilities, excluding nuclear power plants, research reactors and facilities for the mining or processing of uranium ores or thorium ores. The waste may be managed either within larger nuclear fuel cycle facilities or at separate, dedicated waste management facilities, including centralized waste management facilities.

This Safety Guide provides guidance on the predisposal management of all types of radioactive waste (including spent nuclear fuel declared as waste and high level waste) generated at nuclear fuel cycle facilities. The waste may be managed at waste management facilities located within larger facilities or at separate, dedicated waste management facilities (including centralized waste management facilities). This Safety Guide covers all stages in the lifetime of a waste management facility, including its siting, design, construction, commissioning, operation, shutdown and decommissioning. It covers all steps earned out in the management of radioactive waste following its generation up to (but not including) disposal, including its processing (pretreatment. treatment and conditioning), storage and transport. It covers radioactive waste generated during normal operation and in accident conditions. While the recommendations of this Safety Guide are applicable to the generation and predisposal management of radioactive waste throughout the entire lifetime of the nuclear fuel cycle facility, other operational activities at nuclear fuel cycle faculties are outside the scope of this Safety Guide. A classification scheme for radioactive waste and recommendations on its application to the various types of radioactive waste are provided in IAEA Safety Standards Series No. GSG-1. Classification of Radioactive Waste.

This Safety Guide primarily addresses the situations that are typical at facilities for the predisposal management of radioactive waste arising from the nuclear fuel cycle and from facilities that produce medical isotopes from irradiation of nuclear material. The operating organization and the regulatory body should adopt a graded approach, taking account of the hazards, the complexity and stage in the lifetime of the facilities and activities, and the characteristics of the waste (see Section 3).

Section 2 of this Safety Guide provides recommendations on the protection of human health and protection of the environment. Section 3 addresses the roles and responsibilities of the government, the regulatory body and the operating organization. Section 4 provides recommendations on the integrated approach to safety. Section 5 provides recommendations on development of the safety case and supporting safety assessment, while Section 6 outlines general safety considerations over the lifetime of a waste management facility. Seven appendices are included, which set out examples relevant for the predisposal management of waste from nuclear fuel cycle facilities.