Nordic nuclear safety research

NKS-367
ISBN 978-87-7893-452-9

Pre-calculation of a PPOOLEX spray experiment

Timo Pättikangas

VTT Technical Research Centre of Finland

June 2016

Nordic nuclear safety research

Abstract

Pre-calculations have been performed for the spray experiments that are planned to be performed with the PPOOLEX test facility at the Lappeenranta University of Technology (LUT). PPOOLEX is a downscaled model of a BWR containment, which has pressurized drywell and wetwell compartments. Installation of sprays in the wetwell has been studied. The main interest was their interaction with the stratified pressure suppression pool.

The mixture of gas and liquid-water was described with Euler-Euler two-phase model, where the Discrete Particle Model (DPM) was used for spray droplets. The interaction of the droplets with the wetwell water pool was described with User-Defined Functions, where mass, momentum and enthalpy sources from the droplets to the water pool were modeled.

Initially, the water pool was assumed to be thermally stratified. Four spray nozzles installed close to the ceiling of the wetwell were considered. Each spray nozzle injected a mass flow rate of 17.8 liters/min, which corresponds to the rise of the water level by 1.5 cm within 60 s.

In the CFD simulation, the cooling of the water surface by the spray droplets was resolved. According to the simulation, the pool is partially mixed and the temperature at the pool bottom increases slightly. According to the simulation, it seems that the cooling of the pool surface by spray may eventually mix the pool. The length of the simulation is, however, only 60 s, which is fairly short. Longer simulation would be needed to see full mixing of the pool. In addition, grid sensitivity study should still be performed in order to rule out the role of numerical diffusion in the simulation result.

Key words

Spray, droplet, containment, nuclear reactor safety, NRS, computational fluid dynamics, CFD

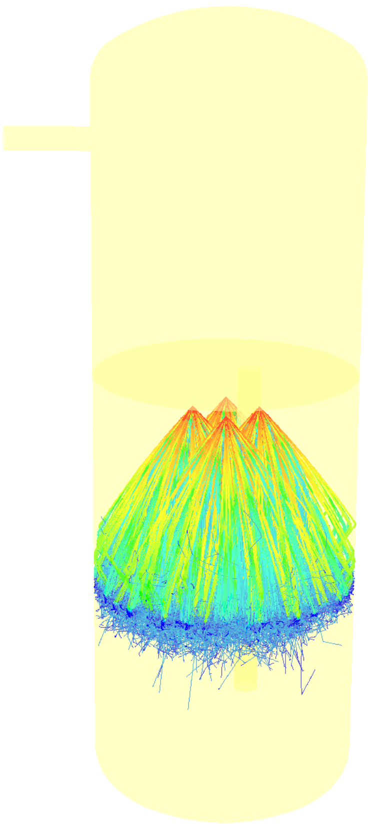
NKS-367
ISBN 978-87-7893-452-9
Electronic report, June 2016
NKS Secretariat
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4041
www.nks.org
e-mail nks@nks.org

Acknowledgment

NKS conveys its gratitude to all organisations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

RESEARCH REPORT

VTT-R-00793-16



Pre-calculation of a PPOOLEX spray experiment

Authors: Timo Pättikangas

Confidentiality: Public

Report's title	
Pre-calculation of a PPOOLEX spray experiment	
Customer, contact person, address	**Order reference**
1. Valtion ydinjätehuoltorahasto, Työ- ja elinkeinoministeriö, PL 32, 00023 VALTIONEUVOSTO 2. Nordic nuclear safety research (NKS), Emma Palm, Programme Manager NKS-R, Strålsäkerhetsmyndigheten, 171 16 Stockholm, SWEDEN	1. SAFIR2018 Programme: Dnro SAFIR 14/2015 2. NKS Contract no. AFT/NKS-R(15)114/3
Project name	**Project number/Short name**
Development and validation of CFD methods for nuclear reactor safety assessment	104836 / NURESA
Author(s)	**Pages**
Timo Pättikangas	15 p.
Keywords	**Report identification code**
Spray, droplet, containment, nuclear reactor safety, NRS, computational fluid dynamics, CFD	VTT-R-00793-16

Summary

Pre-calculations have been performed for the spray experiments that are planned to be performed with the PPOOLEX test facility at the Lappeenranta University of Technology (LUT). PPOOLEX is a downscaled model of a BWR containment, which has pressurized drywell and wetwell compartments. Installation of sprays in the wetwell has been studied. The main interest was their interaction with the stratified pressure suppression pool.

The mixture of gas and liquid-water was described with Euler-Euler two-phase model, where the Discrete Particle Model (DPM) was used for spray droplets. The interaction of the droplets with the wetwell water pool was described with User-Defined Functions, where mass, momentum and enthalpy sources from the droplets to the water pool were modeled.

Initially, the water pool was assumed to be thermally stratified. Four spray nozzles installed close to the ceiling of the wetwell were considered. Each spray nozzle injected a mass flow rate of 17.8 liters/min, which corresponds to the rise of the water level by 1.5 cm within 60 s.

In the CFD simulation, the cooling of the water surface by the spray droplets was resolved. According to the simulation, the pool is partially mixed and the temperature at the pool bottom increases slightly. According to the simulation, it seems that the cooling of the pool surface by spray may eventually mix the pool. The length of the simulation is, however, only 60 s, which is fairly short. Longer simulation would be needed to see full mixing of the pool. In addition, grid sensitivity study should still be performed in order to rule out the role of numerical diffusion in the simulation result.

Confidentiality	Public

Espoo, 29 April 2016

Written by	**Reviewed by**	**Accepted by**
Timo Pättikangas Principal Scientist	Mikko Manninen Principal Scientist	Lars Kjäldman Research Team Leader

VTT's contact address

VTT Technical Research Centre of Finland Ltd, P.O.B. 1000, FI-02044 VTT, Finland

Distribution (customer and VTT)

Emma Palm (NKS), STUK, Vesa Suolanen (VTT), Markku Puustinen (LUT), Heikki Purhonen (LUT), Lauri Pyy (LUT), SAFIR2018 Reference Group 4

Preface

This work has been carried out in the Work Package 2 of the NURESA project of the SAFIR2018 programme (The Finnish Research Programme on Nuclear Power Plant Safety). The project has been funded by Valtion ydinjätehuoltorahasto, VTT and NKS (Nordic nuclear safety research). The authors are grateful for comments obtained from the members of the SAFIR2018 Reference Group 4 and from the Northnet Roadmap 3 Reference Group.

Espoo, 29 April 2016

Authors

Contents

1. Introduction

Boiling Water Reactor (BWR) containment is a complex system that includes pressure suppression pool, blowdown pipes for rapid steam condensation, spray and containment venting systems for containment pressure control, spargers for the vessel pressure relief valves, and other components. In this work, the effect of sprays on the pressure suppression function of the containment is studied.

The present project aims to increase understanding of the phenomena related to BWR pressure suppression function to enhance capabilities to analyze Nordic BWR containments under transient and accident conditions. Particularly, additional information is needed on the spray efficiency in mixing of stratified gas layers and feedbacks between wetwell water pool and spray. This includes the formation and mixing of thermally stratified water layers in the pressure suppression pool due to spray operation.

This work is done in cooperation with the Lappeenranta University of Technology (LUT) and the Royal Institute of Technology (KTH). The experiments with sprays and spargers are performed at LUT (Laine, Puustinen and Räsänen, 2015) with the PPOOLEX test facility. Effective models for the simulation of thermal stratification and mixing are developed at KTH (Li, Villanueva and Kudinov, 2014) for the GOTHIC code. Computational Fluid Dynamics (CFD) simulations are performed at VTT Technical Research Centre of Finland.

At LUT, separate effect experiments have been performed where different spray nozzles have been tested. These nozzles could later be used in the PPOOLEX facility. The size distributions of the spray droplets have been measured with shadowgraphy. It is planned that sprays will be installed in the PPOOLEX test facility, which is a downscaled model of BWR containment. The behavior of the sprays in the wetwell compartment of PPOOLEX is of special interest. In the present work, pre-calculation is performed for one arrangement of the sprays in the wetwell.

So far, three different full cone spray nozzles have been tested at LUT in a separate test facility (Pyy et al., 2015, 2016). The CFD calculations of these separate effect tests were described in previous report (Pättikangas & Huhtanen, 2015). The largest of the nozzles had the capacity of 40 liters/min and its properties were estimated by using the information from the manufacturer of the nozzle (Spraying Systems Co, 2015; Schick, 2006). In addition, available information from experiments and literature was used in the estimation of the droplet size distribution (Brennen, 2005; Lefebvre, 1989). This characterization of the nozzle is used in the present work.

In the pre-calculation of the PPOOLEX experiment, four full cone nozzles were located near the ceiling of the wetwell of the facility. Suitable locations for the sprays were chosen, so that the spray cones hit on the water pool and not on the walls of the wetwell. Initially, the water pool was assumed to be stratified, when the sprays were turned on. The behavior of the pool and the gas space of the wetwell were calculated during the first minute of the spray operation. The aim was to study the effect of the sprays on the stratification of the pool.

In the present report, the pre-calculation of the PPOOLEX experiment is described. In Section 2, the estimated properties of the spray nozzles and the size distributions of the droplets are briefly reviewed. The arrangement chosen for the wetwell sprays is also presented. In Section 3, the CFD model for the experiment is described. The results of the pre-calculation are presented in Section 4. Finally, Section 5 contains summary and discussion.

2. A possible arrangement for wetwell sprays

At PPOOLEX test facility, it is planned that in future sprays will be installed both in the drywell and in the wetwell compartments. In the following, a possible arrangement for the spray nozzles in the wetwell is presented. The spray nozzle used in the arrangement was studied earlier by Pyy et al. (2016) and by Pättikangas and Huhtanen (2015).

The properties of the full cone spray nozzle B1/2HH-40 of Spraying Systems Co (2015) are used in the present study. The nominal diameter of the orifice of the nozzle is 6.2 mm. The pressure difference over the nozzle is 1 bar, which corresponds to a flow rate of 17.8 liters/min. The initial droplet velocity from the spray nozzle is 9.80 m/s. The main parameters of the nozzle are summarized in Table 1.

The volume (mass) of the droplets is assumed to obey the Rosin-Rammler distribution (Schick, 2006; Pättikangas and Huhtanen, 2015). The most probable droplet diameter of the distribution is 0.713 mm and the Sauter mean diameter of the droplets is 0.617 mm. The spread parameter of $n = 3.5$ describing the width of the distribution was used. The shape of the size distribution is illustrated in Figure 1.

Table 1. Estimated Sauter mean diameters and the most probable diameters for the spray droplets.

Nozzle type	**Orifice nom. *d* (mm)**	**Length *L* (mm)**	**Δp (bar)**	**$\dot{V}$ (l/min)**	**$v = \dot{V}/A$ (m/s)**	**We (–)**	**d_{32} (µm)**	**d_0 (µm)**
B1/2HH-40	6.2	30	1	17.8	9.80	1 010	617	713

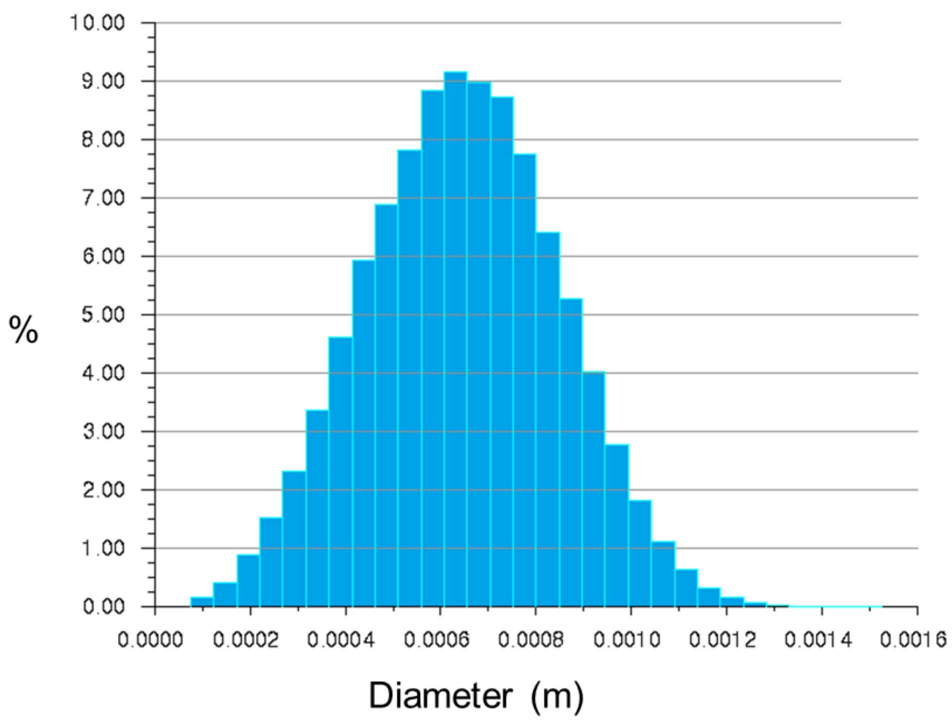


Figure 1. The Rosin-Rammler mass-weighted diameter distribution of droplets used for the full cone spray nozzle B1/2HH-40 in the CFD simulation. The Sauter mean droplet size is $d_{32} = 0.617$ *mm and the spread parameter is* $n = 3.5$.

The PPOOLEX test facility is a pressurized cylindrical vessel with a height of 7.45 m and a diameter of 2.4 m (Puustinen et al., 2007). The drywell and wetwell compartments are separated by the ceiling, which is located at a distance of 4.2 m from the bottom of the wetwell. In the present pre-calculation, the water level of the pressure suppression pool was 2.14 m. A vertical vent pipe penetrates from the drywell to the water pool of the wetwell, where its submergence depth was 1.05 m.

In the CFD calculation, four full cone spray nozzles located in the wetwell were considered. The four spray nozzles were located symmetrically at a distance of 300 mm from the axis of the cylindrical wetwell. The distance of the nozzle outlet orifices from the ceiling of the wetwell was 307 mm. The positions of the spray nozzles are summarized in Table 2.

The half angles of the spray cones were $\theta/2 = 44.75°$ (Spraying Systems Co, 2015). In the chosen arrangement, most of the spray droplets hit the water pool surface. Only small part of the droplets hit the side walls of the gas space of the wetwell. The arrangement is illustrated in Figure 2, where the droplets of the spray cone hitting on the pool surface are shown.

Table 2. Positions of the spray nozzles in the wetwell. Coordinates of the centers of the nozzle orifices are given. The origin of the coordinate system is located center of the wetwell bottom floor. The axis of the vent pipe is located at x = –212 mm, y = –212 mm.

Nozzle	**x (mm)**	**y (mm)**	***z (mm)***
1	–300	0	3900
2	0	–300	3900
3	300	0	3900
4	0	300	3900

3. CFD model for the wetwell sprays

Injections of the wetwell spray nozzles were included in the CFD model of the PPOOLEX facility. The numerical mesh consisted of only 140 000 hexahedral cells. A fairly coarse mesh was used for the present calculation because the transient simulations are fairly time consuming. The time step in the simulation was 0.01 s, which means that 8 000 time steps were needed for the simulation of 80 second transient. Bounded second order implicit method was used for the time discretization and QUICK was used for the spatial discretization of the transport equations.

The Euler-Euler two-phase model of Fluent was used for the modeling of gas phase and liquid water. The gas phase consisted of mixture of air and water vapor, where the mixture was modeled as compressible ideal gas. Floating operating pressure option of Fluent was used for the modeling of the closed vessel, where fluid volume is increasing during the simulation. Turbulence was modeled with k-ε model for the mixture of the phases, where enhanced wall treatment of Fluent was used for the boundary layers.

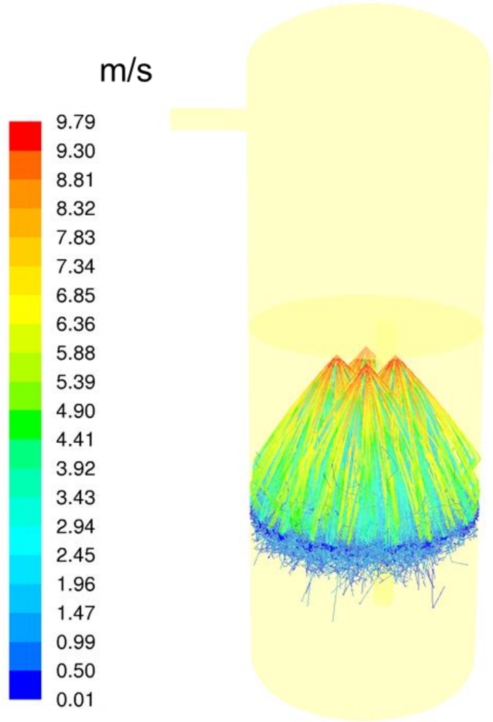


Figure 2. A possible arrangement of the PPOOLEX wetwell sprays, where four B1/2HH-40 spray nozzles are located near the ceiling of the wetwell. The droplet trajectories colored with the droplet velocity magnitude are shown.

The CFD calculation was performed with ANSYS Fluent version 17.0 (ANSYS, 2016). The injection of the spray droplets was performed by using the “Full Cone” model of Fluent, where the Rosin-Rammler model of Fluent was used. The spray droplets were described with the Discrete Particle Model (DPM) of Fluent, where 100 droplet streams were injected from each four spray nozzles. Each stream consisted of 10 different droplet diameters modeling the size distribution. The effect of turbulence on the droplet trajectories was taken into account by calculating 10 stochastic tries for each droplet stream and droplet size. Therefore, in total $4\times100\times10\times10$ = 40 000 droplet trajectories was calculated at every time step for the spray nozzles.

The injected spray droplets interact with the continuous gas phase by exchanging momentum according to the spherical drag law of Fluent. The droplets also exchange heat with the gas phase according to the inert cooling and heating law of Fluent. When the DPM droplets hit into the water pool, they release their mass, momentum and enthalpy to the Eulerian liquid phase. This is implemented as User-Defined Functions of Fluent, where the corresponding source terms for the Eulerian liquid phase are defined.

4. Results of the CFD simulation

4.1 Initialization of the CFD model

The initial state of the PPOOLEX facility was carefully initialized to a typical situation that occurs at late stage of recent pool stratification experiments (Laine et al., 2015). The initial pressure in the vessel was 2.75 bars. The temperature in the drywell was initially 133 °C and the drywell was filled with water vapor. The gas space of the wetwell was stratified: the temperature on the water surface was 40 °C and the temperature at the ceiling was 50 °C.

The water pool was also stratified: the temperature at the bottom of the pool was 25 °C and on the water surface 40 °C.

The initialized flow field was first calculated without any sprays for 21.5 s, which ensures formation of proper hydrostatic pressure in the water pool and the gas space of the wetwell. At time t = 21.5 s, the wetwell sprays were turned on. The flow rate of water from each spray nozzle was 17.8 liters/min, which means that within 60 s time the water level rises by 1.5 cm. In the simulation, the temperature of the spray droplets was 10 °C.

4.2 Results of the simulation

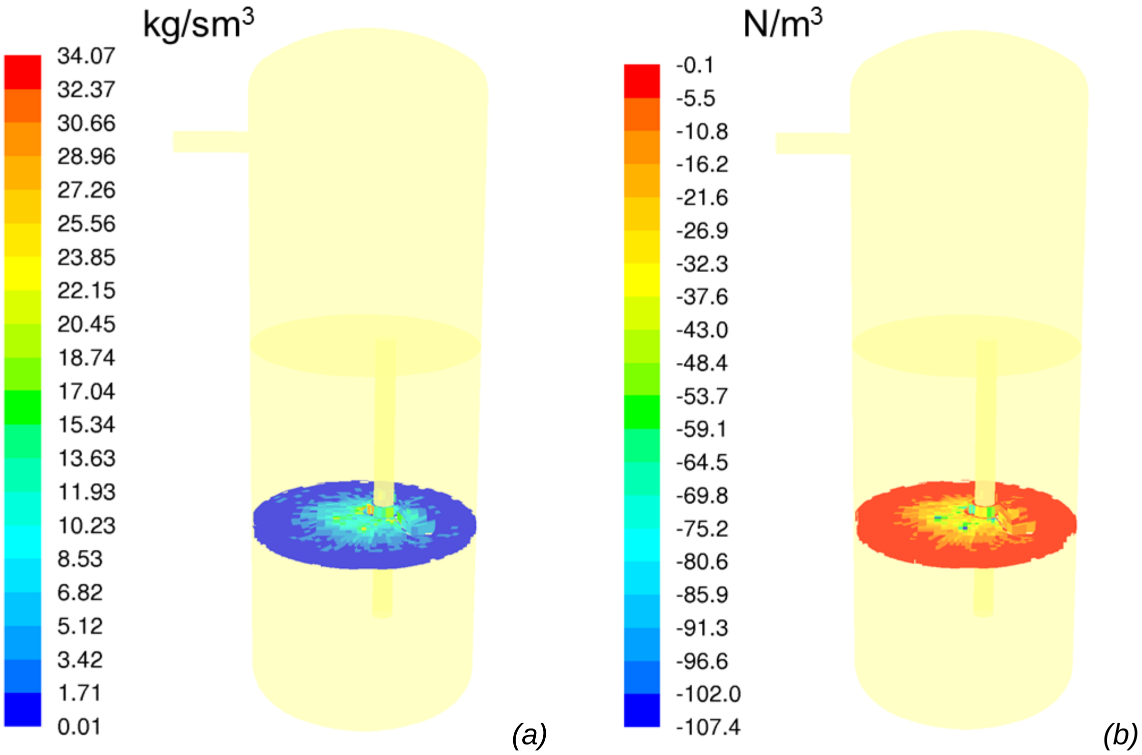
The arrangement of the wetwell sprays is shown in Figure 2, where the trajectories of the spray droplets colored with droplet velocities are presented. The initial velocity of the droplets is 9.8 m/s, but they slowdown in the gas space before hitting the water surface. Just before hitting the water surface the droplets have (mass weighted) average velocity of 3.0 m/s. When the droplets hit the water surface, they slowdown rapidly and transfer their mass, momentum and enthalpy to the liquid phase in the pool.

In Figure 3, the source terms of mass, momentum and energy from the spray droplets to the water pool are shown. The source terms have their maximum values near the vent pipe, where most of the droplets hit the water surface. Most of the droplets slowdown within one or two grid cells on the water surface.

The time evolution of liquid-water temperature during the spray injection is shown in Figure 4. At time t = 21.5 s, the initial state of the PPOOLEX wetwell before the spray injection can be seen. The stratification of the water pool between temperatures of 25…40 °C can be clearly seen below the horizontal line marking the initial water level. Above the water level, the gas space of the wetwell is initially stratified between temperatures of 40…50 °C.

When the spray injection starts at time t = 21.5 s, the first visible effect is cooling down of the air in the gas space of the wetwell. Stratification of the gas space vanishes and the temperature of the gas above the water level decreases to 25…30 °C. The response of the water pool to the spray injection is much slower than that of the gas space. The temperature of the water surface gradually decreases to about 31…34 °C. Simultaneously, the pool is partly mixed and the temperature at the pool bottom increases slightly. The temperature distribution at the pool bottom is somewhat asymmetric, which may be caused by the asymmetric location of the vent pipe that affects the sprays.

In Figure 5, the evolution of the temperature of liquid-water is shown in a horizontal plane slightly below the water surface. The initial temperature of the pool surface of 40 °C is still seen at time t = 24 s, which is 2.5 s after turning on the sprays. The cooling down at the pool surface is strongest around the vent pipe, where most the mass of the droplets hit. At the end of the simulation, the temperature of the pool surface varies between 31…34 °C.



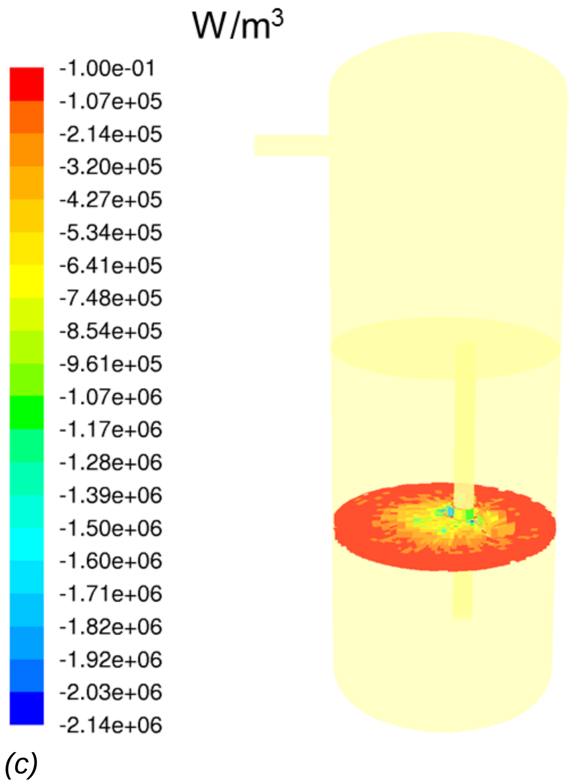


Figure 3. Source terms of mass, momentum and enthalpy from the spray droplets to the water pool surface: (a) mass source, (b) vertical component of the momentum source and (c) enthalpy source.

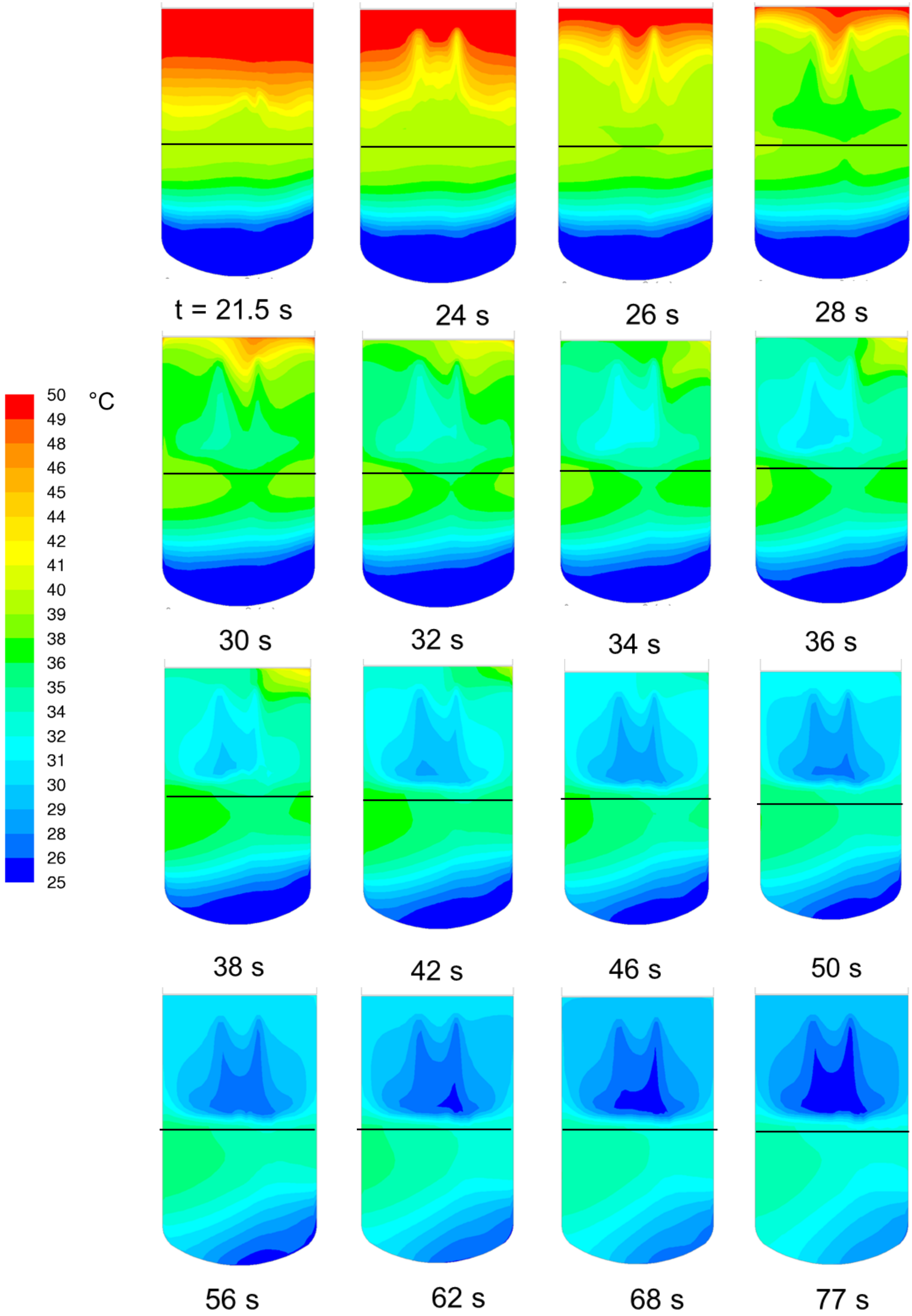


Figure 4. Temperature of water-liquid in the vertical center plane of the wetwell (x = 0). The initial position of the water surface is shown by a horizontal line.

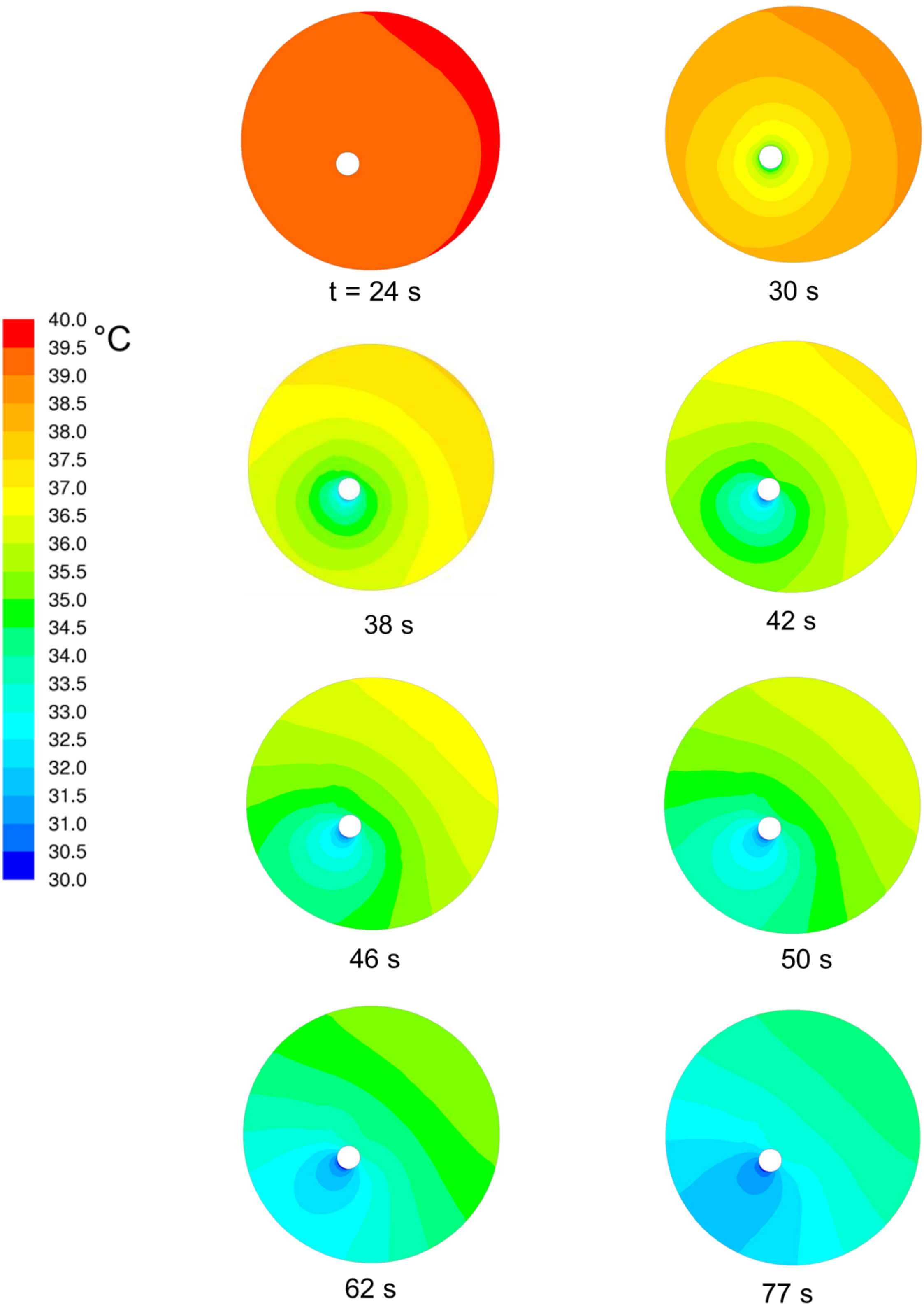


Figure 5. Temperature of liquid-water in the water pool near the pool surface (z = 207 cm).

5. Summary and discussion

Pre-calculations of spray experiments that are planned to be performed with the PPOOLEX test facility at the Lappeenranta University of Technology (LUT) have been performed. The PPOOLEX facility is a downscaled model of a BWR containment, which has pressurized drywell and wetwell compartments. Installation of sprays is planned both in the drywell and wetwell compartments. In the present study, a possible arrangement of sprays in the wetwell was investigated. The main interest was the interaction of sprays with the stratified pressure suppression pool.

Pre-calculation of an experiment was performed with the commercial CFD code ANSYS Fluent version 17.0. The mixture of gas and liquid-water was described with Euler-Euler two-phase model, where the Discrete Particle Model (DPM) was used for spray droplets. The interaction of the droplets and the wetwell water pool was described with User-Defined Functions, where mass, momentum and enthalpy sources from the droplets to the continuous liquid-water phase were modeled.

Initially, the water pool was assumed to be thermally stratified: the temperature at the bottom of the pool was 25 °C and at the water surface 40 °C. Four full cone spray nozzles installed close to the ceiling of the wetwell were considered. Each spray nozzle injected a mass flow rate of 17.8 liters/min, which corresponds to the rise of the water level by 1.5 cm within 60 s. The Sauter mean diameter of the droplets was 0.617 mm and the initial temperature of the droplets was 10 °C. The initial velocity of the droplets was 9.8 m/s and the mass weighted average velocity near the pool surface was 3.0 m/s.

In the CFD simulation, the cooling of the water surface by the spray droplets was resolved. When the sprays had operated for 60 s, the liquid-water temperature on the pool surface varied between 31…34 °C. According to the simulation, the pool is partially mixed and the temperature at the pool bottom increases slightly.

According to the simulation, it seems that the cooling of the pool surface by spray eventually mixes the pool. The length of the simulation is, however, only 60 s, which is fairly short. Longer simulation would be needed to see full mixing of the pool.

The numerical mesh used in the simulation was fairly coarse and had only 140 000 grid cells. The role of numerical diffusion in the mixing of the pool should still be examined. The beginning of the present simulation included 20 s period without sprays. No significant smoothing of the temperature stratification in the wetwell was observed at this stage. This suggests that no significant numerical diffusion occurred during this period. If finer mesh is used, even shorter time step is needed, which leads to even longer simulation time. Performing a grid sensitivity study was not possible in the present work but it should be considered at a later stage of the project.

In the simulations, the size distribution of the droplets was chosen based on experimental correlations. Rosin-Rammler distribution with Sauter mean diameter of 0.617 mm was used for the droplets in the simulation. According to the separate effect spray tests performed at LUT, the chosen mean diameter may be somewhat larger than the mean size of the chosen spray nozzle B1/2HH-40 (Spraying Systems Co, 2015). On the other hand, the mean diameter of droplets of the spray nozzles used in real BWRs is expected to be considerably larger (Foisscac et al., 2011). Therefore, the scaling of the experiments and simulations to plants needs to be carefully considered.

The pre-calculation of the PPOOLEX spray experiment showed that the suggested arrangement of wetwell sprays is appropriate for studying the effect of sprays on the mixing of the pressure suppression pool. The scaling of the spray droplet size from the experiment to the plant scale should, however, be considered carefully.

References

ANSYS Inc., 2016. ANSYS Fluent Theory Guide, Release 17.0, Section 16: Discrete Phase, USA.

Brennen, C.E., 2005. Fundamentals of Multiphase Flow, Section 12: Sprays, Cambridge University Press, New York, USA.

Foissac, A., Malet, J., Vetrano, M.R., Buchlin, J.-M., Mimouni, S., Feuillebois, F. and Simonin, O., 2011. Droplet size and velocity measurements at the outlet of a hollow cone spray nozzle, Atomization and Sprays **21,** 893–905.

Laine, J., Puustinen, M. and Räsänen, A., 2015. PPOOLEX experiments with a sparger. Nordic nuclear safety research, NKS-334.

Lefebvre, A.H., 1989. Atomization and Sprays, Hemisphere.

Li, H., Villanueva, W. and Kudinov, P., 2014. Effective Models for Simulation of Thermal Stratification and Mixing Induced by Steam Injection into a Large Pool of Water. Nordic nuclear safety research, NKS-316.

Puustinen, M., Partanen, H., Räsänen, A., Purhonen, H., 2007. PPOOLEX Facility Description. Lappeenranta University of Technology, Technical Report POOLEX 3/2006.

Pyy, L., 2015. First experiments with spray nozzles, private discussion in December 2015.

Pyy, L., 2016. Experiments with single spray testing station, private discussion in January 2016.

Pättikangas, T. and Huhtanen, R., 2015. CFD simulations of preliminary single spray experiments, VTT Research Report VTT-R-05311-15, Espoo, Finland, 25 p.

Schick, R.J., 2006. Spray technology reference guide: Understanding drop size, Spraying Systems Co., Bulletin No. 459B, USA 35 p.

Spraying Systems Co, 2015. Full cone spray nozzles, http://www.spray.com/spray_nozzles/standard_spray_nozzles.aspx.

Bibliographic Data Sheet **NKS-367**

Title	Pre-calculation of a PPOOLEX spray experiment
Author(s)	Timo Pättikangas
Affiliation(s)	VTT Technical Research Centre of Finland Ltd
ISBN	978-87-7893-452-9
Date	June 2016
Project	NKS-R / COPSAR
No. of pages	17
No. of tables	2
No. of illustrations	5
No. of references	12

Abstract
max. 2000 characters

Pre-calculations have been performed for the spray experiments that are planned to be performed with the PPOOLEX test facility at the Lappeenranta University of Technology (LUT). PPOOLEX is a downscaled model of a BWR containment, which has pressurized drywell and wetwell compartments. Installation of sprays in the wetwell has been studied. The main interest was their interaction with the stratified pressure suppression pool.

The mixture of gas and liquid-water was described with Euler-Euler two-phase model, where the Discrete Particle Model (DPM) was used for spray droplets. The interaction of the droplets with the wetwell water pool was described with User-Defined Functions, where mass, momentum and enthalpy sources from the droplets to the water pool were modeled.

Initially, the water pool was assumed to be thermally stratified. Four spray nozzles installed close to the ceiling of the wetwell were considered. Each spray nozzle injected a mass flow rate of 17.8 liters/min, which corresponds to the rise of the water level by 1.5 cm within 60 s.

In the CFD simulation, the cooling of the water surface by the spray droplets was resolved. According to the simulation, the pool is partially mixed and the temperature at the pool bottom increases slightly. According to the simulation, it seems that the cooling of the pool surface by spray may eventually mix the pool. The length of the simulation is, however, only 60 s, which is fairly short. Longer simulation would be needed to see full mixing of the pool. In addition, grid sensitivity study should still be performed in order to rule out the role of numerical diffusion in the simulation result.

Key words: Spray, droplet, containment, nuclear reactor safety, NRS, computational fluid dynamics, CFD

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4041, e-mail nks@nks.org, www.nks.org