The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-092

COMPUTATIONAL MODELS TO DETERMINE FLUIDDYNAMICAL TRANSIENTS DUE TO CONDENSATION INDUCED WATER HAMMER (CIWH)

H. Swidersky[1], A. Schaffrath[2] and A. Dudlik[3]
[1] TÜV SÜD Industrie Service GmbH, Munich, Germany
[2] TÜV NORD SysTec GmbH & Co. KG, Hamburg, Germany
[3] Fraunhofer Umsicht, Oberhausen, Germany
harald.swidersky@tuev-sued.de, aschaffrath@tuev-nord.de, andreas.dudlik@umsicht.fraunhofer.de

Abstract

Condensation induced water hammer (CIWH) represent a dangerous phenomenon in pipings, which can endanger the pipe integrity. If they cannot be excluded, they have to be taken into account for the integrity proof of components and pipe structures. Up to now, there exists no substantiated model, which sufficiently determines loads due to CIWH. Within the framework of the research alliance CIWA, a tool for estimating the potential and the amount of pressure loads will be developed based on theoretical work and supported by experimental results. This first study discusses used computational models, compares their results against experimental observations and gives an outlook onto future techniques.

Introduction

The basic theory on water hammer was developed in the second part of the 19th century (Kries, Allievi, Joukowsky) and focused on the determination of maximal pressure if a fluid column will be suddenly (de-)accelerated. The well known approach of Joukowsky (1898) [1] is commonly used up to now for determining sufficiently loads due to e.g. pump trip, valve closing or pipe ruptures in one-phase region of the fluid.

Two-phase flow also may induce pressure surges in branched piping e.g. during filling procedures. Therefore analytical and numerical computations play an important role in order to evaluate possible loads and to prevent structural damages. Detailed analyses have been carried out by the Electric Power Research Institute (EPRI) during 1992 [2] and 2002 [3]. Bergant et al. (2006) [4] gives a comprehensive historical overview about modelling slug-flow phenomena. The understanding, that classical one-dimensional approaches always overestimate pressure surges due to such events leads to 3D-CFD computations, which should produce more realistic results even they take into account phase changes. On the other hand, the capability of CFD for multiphase-flows with/without phase change is still in a controversial discussion. Also effects due to fluid-structure interaction (FSI) and pipe wall elasticity are not considered in most 3D-simulations. So the comparability of 1D- and 3D-approaches have to be checked carefully. However, from the present point of view there exist no secured and validated models which sufficiently determine dynamic loads in pipe systems due to direct condensation water hammer [5]. Against the background of several events from the 1970's up to now [3], the goal of the research alliance CIWA (Condensation Induced Water Hammer) is to develop a suitable tool for determination of the potential, the location and the amount of pressure loads due to condensation induced water hammer. The research alliance CIWA [6] was founded in 2010 and is sponsored by German Federal Ministry of Education and Research (BMBF) for a period of 3 years. The German research institution Fraunhofer UMSICHT, Technical University Munich, Technical University Hamburg-Harburg, University of the Germany Military (Munich) and the two inspection organizations TÜV NORD (Hamburg) and TÜV SÜD (Munich) are involved. In this period, experimental studies and theoretical works will be carried out at three test facilities.

1. Classification

Two-phase flow water hammer can be classified in different ways. The classification by EPRI (1996) [7] and Griffith (1997) [8] e. g. focuses on geometric aspects and filling procedures which result into slug-flow. The initial pressure surge is calculated with the Joukowsky approach taken into account the assumptions for slug-formation. In the publications of Bjorge and Griffith (1983) [9], Chun and Yu (2000) [10], condensation induced water hammer in horizontal pipes are classified regarding the potential of their occurrence depending on the sub-cooling, pressure and interfacial relative velocity of the two phases. The resulting pressure impact is not obtained in these investigations. It is evident, that e.g. these two approaches summarize only a few conditions which could produce a condensation induced water hammer. Because of the confusion existing in the literature about the difference between CIWH, slug-flow induced, and steam induced water hammer (SIWH) (the last two ones mean the same), the classification in this work follows the flow chart in Figure 1.

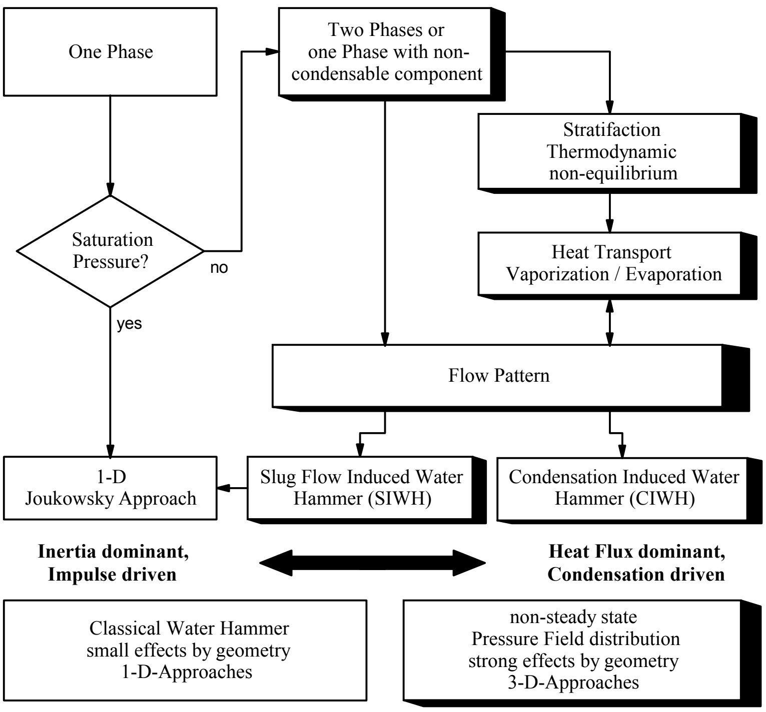

Figure 1: Influences and classification of water hammer

A strong distinction between impulse driven flow and condensation induced flow cannot be made for two-phase flows with condensation, because in most cases both effects are present simultaneously and varying with time. Therefore, an event known as SIWH is always the result of the immediate stop of a two-phase flow pattern but might be driven by different forces and effects. So the CIWH represents a special type which points out the source of the driving forces more exactly. In Figure 1, the shaded symbols highlight the related work fields which will be prepared in the framework of the CIWA-project.

2. Condensation induced water hammer (CIWH)

2.1 Physical phenomena

The pressure surges from two-phase flow water hammers might be higher than the pressure surges from operational load cases, such as pump trip or valve closing. The danger of CIWH occurs particularly during stagnation of the flow in horizontal pipe sections, especially when a stratified steam-water layer is formed. If no mixing takes place, a thermodynamic non-equilibrium state adjusts with stratification of the steam and liquid phase. With a disturbance of the separating layer, the steam mass might condense/collapse in a sudden and self-enforcing event. A CIWH event can be divided into a sequence of the following mechanism:

i. Disturbance of a stable thermodynamic non-equilibrium state: This is the initial ignition point for any CIWH. This might be a result of microscopic disturbances (a), injections that break up the interfacial surface (b) or a relative velocity between steam and liquid phase which induce waves due to friction and turbulence (c).

ii. Wave formation with increasing condensation: The pressure in the steam phase drops because of its decreasing steam mass. This induces a relative velocity between the phases and might enforce the breaking up of the isolating layer. If the difference of heat energy between the sub-cooled liquid and the steam phase is great enough, the condensation increases the fluid motion and therefore enlarges the surface where condensation takes place. The gravity force is not strong enough to close the broken surface and the mechanism will become self-enforcing.

iii. Possible transition to slug-flow: During this process the velocity of the steam flow increases over the top of the wave and induces a pressure difference between the up- and downstream wave surfaces. This sucks the liquid up to the upper wall of the pipe. Then the wave front sides are separated and react differently.

iv. Acceleration of the wave due to pressure drop while condensation: The wave will be accelerated until the volume flux from the steam into the liquid phase is equal to the volume flow of the liquid. The acceleration of the liquid molecules is limited by the capability of phase change due to condensation. This might result into a damping effect while compressing the steam phase.

v. Deceleration of the fluid by hitting structures or fluid column fronts, SIWH.

In many experimental studies it was observed that CIWH were not reproducible even if the same thermalhydraulic boundary conditions were present at the beginning. This leads to the understanding of a stochastic nature of CIWH. Therefore the effect i. has to be discussed in more detail: At zero flow the initial condition for a CIWH event is characterised by a thermodynamical non-equilibrium. In this state steam and condensate molecules continuously exchange energy inside a thin fluid layer between saturated steam and an underlying sub-cooled fluid phase. The molecules loose kinetic energy by collision. The frequency molecules of one domain reach the other phase directly and enforce the breaking up of the isolating layer which separates and isolates two domains with different temperatures is given by statistical probability. From the macroscopic point of view the whole fluid is in a stable state, although microscopic phase changes are present permanently. This situation changes drastically if external disturbances influence the isolating layer and the molecules are moved by momentum forces. Small particles as well as the pipe wall roughness might be a source for breaking up this isolating layer. Once started molecules with high enthalpy difference come into contact directly. Usually this process is self-enforcing.

Therefore, it is evident that CIWH have a stochastic nature and disturbances are needed to start the self-enforcing condensation. Also one can say this phenomenon represents an example of the transition from a stable state (attractor) inside a chaotic environment – but this interesting discussion is out of our scope.

2.2 Existing models and numerical methods

Several analytical models exist for analyzing individual effects as described in chapter 2. The formation of slugs is the most important mechanism for inducing pressure surges. Therefore, slug formation has been investigated in many experiments and empirical correlations were developed for this phenomenon. Sung et al. [11] give a comprehensive overview on the different modelling approaches. Many models do not take into account heat transfer, viscosity and turbulence. Because these models are mainly based on flow map correlations they are not valid for CIWH-computations. If condensation has to be considered, it is evident that the flow pattern might be completely different to slug-flow without condensation or two-phase flows with a large amount of non-condensables.

New 1D-approaches have been developed and published in the recent years to describe heat and mass transfer between the phases during CIWH. These approaches are a relaxation model [12] and a tripartite mass transfer model, the latter of which is presented during this meeting [13]. The relaxation model developed by Tiselj et al. [12] recognizes three flow regimes: dispersed flow, horizontally stratified flow and a transition regime between both. The classification depends on the so-called "stratification factor S" ($S = 0$ horizontally stratified flow, $0 < S < 1$ transition regime, $S = 1$). For each flow regime the liquid-to-interphase and the gas-to-interphase volumetric heat fluxes are determined by special models (e.g. homogeneous relaxation model (HRM) proposed Downar-Zapolski [14] and modified by Lemonnier [15]) or derived as approximations of the heat transfer coefficient for turbulent flow near a flat wall presented by Mills [16]. The developers state in [17] and [18] that such model can describe slugging satisfactorily and the models are solely able to forecast with great confidence if a CIWH happens in a flow system. However, the determination of the absolute magnitude of the pressure peak needs further improvements.

The 1D-thermalhydraulic analyses mostly use a finite volume technique whereas for fluid dynamics and pressure surge analyses finite difference schemes are preferred. The method of characteristics (MOC) is one of the most popular methods of this type for solving pressure surges and shock problems in 1D-piping after a SIWH took place. Mostly they solve a set of hyperbolic partial differential equations with a solver of first order. For reaching adequate accuracy the Courant-Friedrichs-Lewy condition must be full filled**.** Otherwise the solution might be unstable or gives unrealistic physical results. Solver of higher order, like the Lax-schemes, give better results for surge phenomena but tend to overestimate sharp discontinuities. In the past century, several variations and mixed solver types were developed. For a deep understanding the books of Tannehill, Anderson and Pletcher (1997) [19] and Laney (1998) [20] are recommended. For computing multi-phase flow phenomena in a 1D-pipe network, the set of equations is extended up to the number of phases/components which should be considered and solved separately. Two restrictions make the 1D-approach questionable for secured CIWH-computations. First, the heat transfer, i.e. the phase change between condensable gases, depends strongly on the timely varying structure of the interfacial surface area and is therefore a full 3D-mechanism. Empirical models such as flow maps, can only be used for a very small set of typical geometry and steady state thermalhydraulic conditions for which these correlation were derived. Second, the fluid properties have to be averaged in 1D-approaches because 1D-models can not consider interfacial areas. This makes it impossible to evaluate the driving forces for slug accelerations exactly.

3D-CFD codes use mostly the finite volume technique to solve the Navier-Stokes/Euler equations for each phase or component, respectively. The movement of interfacial areas can be trapped very efficiently by the volume of fluid method (VOF) with adaptive mesh refinement, marker and cell method (MAC) or the level set method (LSM). Theoretically, this allows sufficient computation of the interfacial heat and mass transfer, friction and turbulence in multi-phase flows while solving the fundamental physical equations. The book of Ferziger and Peri´c (2002) [21] is recommended for a deep understanding of CFD methods. However, up to now, empirical correlations are not thrown away. This makes sense unless the physical mechanism of CIWH is not understood completely. The validation of these methods is still in progress. Because of similar mechanisms during combustion and chemical reactions, the 3D-CIWH-approach might take advantage from developments in this field of interest. It should be noted that none of the mentioned literature above provide a cooking recipe for computation CIWH in 1D or 3D.

3. Existing experimental studies vs. computational results

Experimental reproducibility of CIWH can not be expected and this fact has to be accepted if we are not able to measure or are able to model all (small) disturbances exactly. So someone has to be careful to think that sophistic computational programs produce sufficiently realistic results. Especially in the case if numerical errors might dominate the physical effects we theoretically observe and measure. Also we have to be careful in valuing validations and comparisons against experimental results if boundary conditions are not clear or not documented completely, especially if no information is given about uncertainties.

Comparing documented CIWH-experiments show that the maximum pressure amplitudes differ in a wide range. Figure 2 shows interpolated isobars of measured peaks at the PMKII-test facility due to CIWH as function of system pressure and degree of sub-cooling. Obviously no clear relation between the parameter can be derived. It can be only observed that with higher system pressures the peaks become tendentious smaller.

Figure 3 shows one of the important measuring problems on CIWH. This is the small time width of the pressure peak, which is often around a few milliseconds. This is due to the fact that CIWH might occur only in a very small pipe region where at a certain time the pipe is totally filled with liquid. In certain small distance from the collapsing vapour bubble other vapour bubbles nearby the "CIWH-centre" may not be involved in the pressure increase, so that the measuring position becomes a measuring parameter itself.

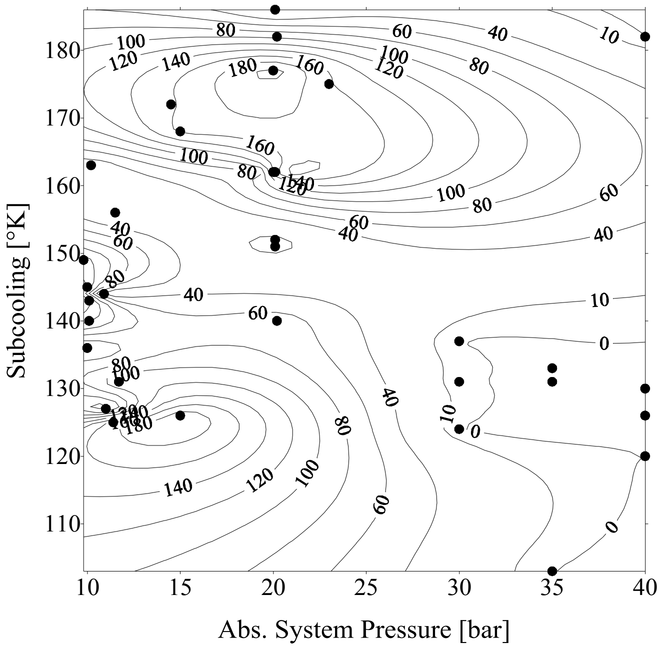

Figure 2: Interpolated isobars of measured pressure peaks (dots) at the PMKII-test facility

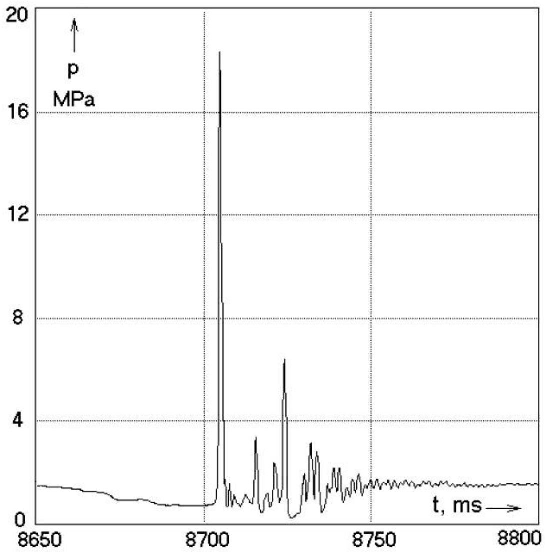

Figure 3: Pressure peaks due to CIWH at the PMKII-test facility [22]

For the comparison of experimental and analytical results it has to be considered that the measured peak might not be the peak in the centre of the collapsing bubble and that this peaks is a certain distance away from the pressure transducer. This problem can only be solved if several transducers in a pipe section are used in order to estimate the highest peak. With respect to pipe supports, it is obvious that force/accelerating measurements of the structure should have to be performed in order to get information about the "possible surge relevance" of the CIWH.

4. Concepts in modelling and computations

Firstly, a theoretical model, based on fundamental physical laws for heat and mass transfer during a CIWH, has to be developed. Thereby empirical correlations should be avoided. Also geometric scaling methods and their parameters have to be identified. The final CIWH-module should be accessible as standalone tool for steady-state analysis or as forecast function inside a thermalhydraulic- or CFD code during transient runs.

Additionally, it should be possible to detect and evaluate locations of potential CIWH at runtime (see chapter 4.2). The most important results are the degree of CIWH-potential, the condensable steam mass and the condensation rate.

4.1 Used codes

1-D numerical calculations will be carried out applying the system codes ATHLET [23] and RELAP5/MOD3 [24] which were developed for thermalhydraulic analyses of nuclear power plants. Also the fluid dynamic code DYVRO [13] which is based on WAHA [25] will be used. All these 1D codes use empirical models for heat transfer and phase change depending on flow pattern correlation (flow regime charts). These calculations will be carried out for a group of benchmarks (table 2). For the scheduled 3D-CFD calculations the codes ANSYS-CFX [26] and OpenFOAM [27] will be used.

4.2 Code-coupling techniques

The objective is to join the advantages of 1D-fluiddynamic codes with the 3D-CIWH-module. However, it is foreseeable that restrictions in resolution and accuracy have to be accepted because of practicability and computation time. Furthermore, the implementation of the CIWH-module into an existing application might be a huge challenge or might be impossible if a (commercial) source code is not accessible. Because the static implementation of the CIWH-code into an application would always be a one-way solution, the most interesting challenge lies in coupling different applications (executables) with a standard interface. This will not replace the necessity of validation of the core application but makes it easier to focus on modelling physical effects and validation work by skipping external code strips in the target application. Also the CIWH-module could be used to extend the capabilities of existing 3D-CFD applications using it as library with accessible functions called via high level languages. According to the well known CGNS standard [28] the CIWH-module will be based on this protocol structure. For the inter-communication between the processes parallelization techniques are used e.g. OpenMPI [29] because it is theoretically not restricted in running different codes in parallel. Details about this concept, functionality and the implemented interface will be discussed separately.

4.3 Validation procedures

A number of guidelines and standards exist for code validation procedures - especially for applications applied in the nuclear industry [30], [31]. These are useful to describe numerical errors, valuing validations, documentation and quality assurances from a global point of view. However, CFD computation of SIWH and CIWH is explicitly excluded in these guidelines because of insufficient CFD experiences. It is not the objective and not practical to fullfill all requirements found in the literature. Therefore, a CIWA-code validation specification will be prepared while adopting over main features from the ECORA-concept [31], [32]. The specification will include the most important requirements the code has to meet from the researcher and inspector point of view, considering e.g. errors in model, measuring, computational (numerical) errors, reproducibility and the practicability of the developed tool. The CIWA-module will finally be proofed against this base specification. Table 1 summarizes some important issues during the validation process.

Objective	**Criteria**
Numerical and model error estimation	Numerical sensitivity analyses of spatial and temporal discretization, iteration errors, numerical dispersion and diffusion errors. Sensitivity analyses of model errors in thermalhydraulic assumptions and geometry. Convergence analyses versus analytical solutions.
Experimental validation	Availability of data, quality and reproducibility, sensitivity analyses of measurement errors and uncertainties.
Benchmarks	Quality of documentation, accessibility of data, quality and reproducibility of experimental results.
Coding	Portability, code-transparency, documentation, practicability.
Documentation	Completeness of test case descriptions including geometry, boundary conditions, initial conditions, physical effects involved, used experimental data for comparisons, experimental data and numerical results.

Table 1: Steps in model validation

4.4 Benchmarks

The defined benchmarks take focus onto thermalhydraulic conditions as they might appear in light water reactors (LWR) and can be experimentally observed by the three CIWA-test facilities. These test cases focus on filling procedures and slug-flow formation with and without condensation. Details about the geometric definition, thermalhydraulic conditions and experimental results will be available at [6]. Table 2 gives a brief overview.

Benchmark group	**Description**	**Basic parameters**
SFF	SIWH, slug-flow formation in nearly horizontal pipes with/without condensation	water-air/steam-system, L/D, slope, interfacial velocity, degree of filling
ICW	injection of cold water into steam/cold water layer	temperature distribution, geometric types and direction of injection, injection mass flow rate
CFC	CIWH with counter flow and sub- cooled water layer	temperature distribution, interfacial velocity, degree of filling

Table 2: Benchmarks in the CIWA-Project

4.5 Experimental validation

The experiments will be carried out at three test facilities. This ensures a fundamental data base for the validation of the CIWH-module. The data is additionally needed for valuing different computational approaches actually used to describe CIWH-phenomena. Figure 3 shows the experimental setup at UMSICHT. The vapour filled pipe DN100 is equipped with steam traps to achieve a total pipe filling with saturated steam. The boundary condition pipe length is realized using two T-junctions at both ends of the test section. Hence, pressure waves will be reflected totally when CIWH occurs. Sub-cooled water is injected using different injection geometries that are typical for nuclear power plant conditions.

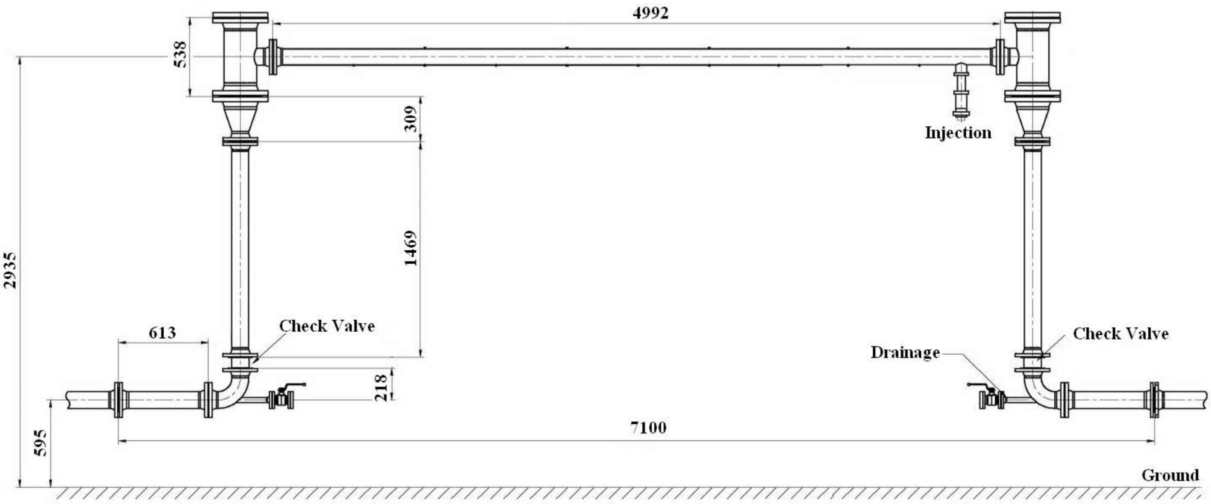

Figure 4: Test section of UMSICHT pilot plant setup

The horizontal test section between the T-junctions (see Fig. 4) is nearly identical with regard to all three setups. Nevertheless, it is planned to investigate different parameters simultaneously. The following parameters shall be varied at the first step of the investigation:

Basic parameters	**Variation**
pipe diameter	0.05 and 0.1 m
inclination angle	±5°
initial saturation conditions	0.1 - 4.0 MPa, 20°C - 250 °C
sub-cooling of the injected fluid	10 – 100 K
degree of filling	0 – 95 %
flow direction	stagnation, co- and counter current flow
fluid velocity, injected mass flow rate, wall surface roughness	not fixed yet

Table 3: Variation of basic experimental parameters

Counterpart tests are planned in order to find out measuring uncertainties. In a second step, several characteristic system parameters are fixed in order to visualize the phenomena using non-invasive, advanced measuring technology. Through this experimental strategy, it should be identified under which circumstances CIWH definitively occurs. Furthermore, validation procedures will be more sophisticated by using experimental data from three independent test facilities. A unique experimental data pool will be created with a presently unknown time and space resolution of the measurements. CIWH have a stochastic nature and both a complex and a transient change of the phase interfacial transport processes take place on the micrometer scale while local heat and mass transport processes dominate the large-scale velocity and concentration fields. Therefore, the development of models to describe the different phenomena of a CIWH requires measurements in different scales. This is the reason, why the test facilities (re)constructed within the research alliance CIWA, contain numerous opportunities to introduce advanced two phase measurements.

4.6 Uncertainties

Experiments might not allow locating the ignition point of CIWH and the maximum pressure peak inside the collapsing steam volume because of the measurement uncertainties (see chapter 3). So one might only measure a pressure peak transported through the slug-flow front. Then, one has to get to know if a repetition of experiments is possible at all, using the same boundary conditions. With regard to validation, the boundaries shall be as comprehensive as possible, so that effects like fluid-structure interaction (by using "stiff" pipe supports), degassing (by using de-aerated water) and the total pipe length (by using suitable dimensioned T-junctions for fixed pressure conditions) shall be neglected in the first step.

5. Conclusion

Condensation induced water hammer are dangerous for pipings. If they cannot be excluded, they have to be taken into account for the integrity proves for components and pipe structures. Two approaches (a 1D and a 3D) exist for this purpose. Comparisons between 1D- and 3D-methods have to be done carefully. Disadvantages of 1D-approaches might lie in simplifying the interfacial surface area and therefore the amount of heat transfer. But mostly these 1D-models are able to take into account effects due to FSI and pipe wall elasticity. which could play an important role. For more detailed analyses, 3D-approaches need fine meshes at the interface layer and therefore might not be practical. All existing 1D- and 3D- approaches based on flow maps are questionable if they can not take into account the timely varying development of the interfacial surface area accurately. Past experimental results show a width range in occurrence and magnitude of pressure loads. Measurements might not represent the maximum of the pressure peak which occur in the centre of the collapsing bubble. Due to the limited number of transducers and their locations along the test section, past measurements did not meet the ignition point for the CIWH. From the present point of view there exist no secured and validated models which sufficiently determine dynamic loads in pipe systems due to CIWH. Within the framework of the research alliance CIWA, experimental studies at three test facilities will be carried out. Advanced two-phase flow instrumentation (e.g. particle image velocimetry) will be used. These experiments are the basis for the development of a practical tool which will finally be qualified and applied by the inspection organizations involved in nuclear and conventional power plant technology. This will hopefully enhance future developments and definitions of international technical standards and regulatory guides of CIWH.

Acknowledgement

This work is sponsored by the German Federal Ministry of Education and Research (BMBF) under the contract number 02NUK011.

6. References

[1] N. Joukowsky, "Über den hydraulischen Stoss in Wasserleitungsröhren", (transl.: "On the hydraulic hammer in water supply pipes"), Mémoires de l'Académie Impériale des Sciences de St.-Pétersbourg, Series 8, 9(5), 1898, pp. 171.

[2] D. A. Van Duyne and M. Merilo (Editors), "Water Hammer Prevention Mitigation, and Accomodation", Electric Power Research Institute (EPRI), Final Report, NP-6766, Vol. 1-6, Research Project 2856-03, 1992.

[3] Electric Power Research Institute (EPRI), "GenericLetter 96-06 Waterhammer Issues Resolution", Final Report, Palo Alto, 2002.

[4] A. Bergant, A.R. Simpson and A.S. Tijsseling, "Water hammer with column separation; A historical review", *Journal of Fluids and Structures*, Vol. 22, 2006, pp. 135-171.

[5] L. Strubelj, G. Ézsöl and I. Tiselj, "Direct contact condensation induced transition from stratified to slug flow", *Nuclear Engineering and Design*, Vol. 240, 2010, pp. 266-274.

[6] CIWA-Project, Web-Page, http://www.tu-harburg.de/ciwa.html.

[7] D. A. Van Duyne and M. Merilo (Editors),"Water Hammer Handbook for Nuclear Plant Engineers and Operators", Electric Power Research Institute (EPRI), TR-106438, 1996.

[8] P. Griffith, "Screening Reactor Steam/Water Piping Systems for Water Hammer", NUREG/CR-6519, Massachusetts Institute of Technology, 1997.

[9] R. W. Bjorge and P. Griffith, "Initiation of water hammer in horizontal and nearly horizontal pipes containing steam and subcooled water", *ASME Journal Heat Transfer*, Vol. 106, 1983, pp 835-840.

[10] M.-H. Chun and S.-O. Yu, "A parametric study and guide chart to avoid condensation-induced water hammer in a horizontal pipe", *Nuclear Engineering and Design*, Vol. 201, 2000, pp. 239-257.

[11] C.-K. Sung and M.-H. Chun, "Onset Slugging Criterion Based on Singular Points and Stability Analyses of Transient One-Dimensional Two-Phase Flow Equations of Two-Fluid Model", *Journal of the Korean Nuclear Society*, Vol. 28, No. 3, 1996, pp. 299-310.

[12] I. Tiselj et al., "WAHALoads – Two-Phase Flow Water Hammer Transients and Induced Loads on Materials and structures of Nuclear Power Plants", JSI-Report, IJS-DP-8841, Rev. Mar-04., Ljubljana, 2004.

[13] T. Neuhaus and A. Schaffrath, "Tripartite Mass Transfer Model: Development, Implementation in DYVRO, Verification and Validation", Proceedings of the 14th International Topical Meeting an Nuclear Reactor Thermalhyraulics NURETH-14, Toronto, Canada, September 25 –30, 2011.

[14] P. Downar-Zapolski, Z. Bilicki, L. Bolle and J. Franco, "The non-equilibrium relaxation model for one-dimensional flashing liquid flow, *International Journal of Multiphase Flow*, 22 (3), 1996, pp. 473-483.

[15] H. Lemmonier, "An attempt to apply the homogeneous relaxation model to the WAHA-loads benchmark tests with interaction with the mechanical structure", CEAT3.3-D61-200302, WAHALoads project deliverable D61, 2002.

[16] A.F. Mills, "Heat Transfer", 2nd Edition, Prentice Hall, 1999.

[17] J. Gale, I. Tiselj, "WAHA (Water Hammer) computer code, The Practical Application of Surge Analysis for Design and Operation", Proceedings of the 9th International Conference on Pressure Surges, Vol. 2, Chester, UK, 24-26 March 2004, pp. 619-632.

[18] I. F. Barna, A.R. Imre, G. Baranyai and G. Ézsöl, "Experimental and theoretical study of steam condensation induced water hammer phenomena", *Nuclear Engineering and Design*, 240, 2010, pp. 146–150.

[19] J.C. Tannehill, D.A. Anderson and R.H. Pletcher, "Computational Fluid Mechanics and Heat Transfer", 2nd Edition, 1997, Taylor & Francis.

[20] C.B. Laney, "Computational Gasdynamics", Cambridge University Press, 1998.

[21] J.H. Ferziger and M. Peric´, "Computational Methods for Fluid Dynamics", 3rd rev. Edition, Springer, Berlin, Heidelberg, New York, 2002.

[22] H.-M. Prasser, Gy. Ézsöl, G. Baranyai and T. Sühnel, "Spontaneous water hammers in a steam line in case of cold water ingress", *Multiphase Science and Technology*, 20, pp. 265-289, 2008.

[23] G. Lerchel and H. Augustregesilo, "ATHLET User's Manual, ATHLET Mod 2.0, Cycle A", Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), 2003.

[24] Information System Laboratories, "RELAP5/MOD3.3 Code Manual", NUREG/CR-5535, Vol. 1-8, 2001.

[25] M. Giot et al., "Two-Phase Flow Water Hammer Transients and Induced Loads on Materials and Structures of Nuclear Power Plants (WAHALoads)", Final Report, 2004.

[26] ANSYS CFX, http://www.ansys.com.

[27] OpenFOAM, http://www.openfoam.com.

[28] CGNS, CFD General Notation System, Version 2.5, http://cgns.sourceforge.net.

[29] OpenMPI, Message Passing Interface, http://www.open-mpi.org.

[30] J. Mahaffy, "Development of Best Practice Guidelines for CFD in Nuclear Reactor Safety", *Nuclear Engineering and Design*, Vol. 42, No. 4, 2010, pp. 377-381.

[31] F. Menter et al., "CFD Best Practice Guidelines for CFD Validation for Reactor Safety Applications", 5th EURATOM Framework Programme, ECORA, Contract No. FIKS-CT-2001-00154, European Commission, 2002.

[32] D. Bestion et al., "Recommendation on Use of CFD Codes for Nuclear Reactor Safety Analysis", 5th EURATOM Framework Programme, ECORA, Contract No. FIKS-CT-2001-00154, European Commission, 2004.