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Condensation-Induced Water Hammer – Overview and own Experiments

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Abstract

A condensation induced water hammer is a severe effect that has caused damages and even fatalities worldwide. This effect is not limited to the nuclear industry only. Generally it can occur in every pipe that contains water and steam (two-phase-flow). To date many experiments were executed to study this effect and to validate existing water hammer codes. But theoretically versus measured results show a very high degree of deviation. Information about those experiments was obtained by literature review. This information is presented additionally to a test facility, which has been developed in order to generate water hammers. The test device is introduced in this paper and its main functions are briefly explained.

In contrast to other experiments, water hammers at the UniBw are performed under controlled conditions. Air in water is a disruptive parameter that causes vigorous deviations between the theoretical system code and the experimental measurements. As in the test device presented in this paper, deionised water without air is used, this effect is ruled out. Furthermore the inception of a water hammer is controlled by a scientist. The experimental results will characterise the dynamic response of the test device as a function of system pressure, filling degree and sub-cooling.

Keywords: water hammer, condensation, two phase flow

Introduction

Whenever a two phase flow of sub-cooled water and steam appears in a pipe, a dangerous phenomenon may happen. It is the so called condensation induced water hammer (CIWH) or the pressurised thermal shock. This effect occurs often in the nuclear industry in case of emergency core cooling. Nevertheless this effect has caused severe damages in other civil facilities like the “New York steam explosion” in 2007. The high destruction potential of a water hammer is the reason why to date great efforts are made to investigate this effect. Nevertheless it is still not possible to simulate a condensation induced water hammer precisely enough by a computer model. This paper shall give an overview about water hammer experiments and presents a concept for a complete new test apparatus, which is currently under construction at the UniBw. In contrast to most other experiments the water hammer at UniBw is planned to be generated in a controllable mode. The UniBw test apparatus offers different possible procedural methods to generate a condensation induced water hammer.

1. Overview of water hammer experiments

This section gives a short overview about experiments that have performed condensation induced water hammers. Though a wide variety of pressure surge codes exists, to date forecasting the inception and intensity of a water hammer is not exactly possible. As in two phase flows very complex phenomena take place, a serious calculation needs to consider effects such as thermal resistance or development of the interaction between the two phases. Even three dimensional codes are not capable to calculate water hammer in the favoured precision. These complex phenomena are tried to being validated with empirical correlations which are obtained from experiments. In this paper literature is presented that describes real water hammer pressure increases, since the new test apparatus at the UniBw can be compared to these facilities.

1.1 PMK-2 test facility

The test section PMK-2 is located at the KFKI Atomic Energy Research Institute in Budapest, Hungary. It consists of a 2.87 m long pipe with an inner diameter of 73 mm. PMK-2 is designed for a maximum pressure of 16 MPa (1).
Table 1 shows the essential part of the PMK-2 test device. Steam comes from a dome and is generated by a steam generator. Water is taken from a 75 l water tank, which is pressurised with nitrogen. The experiments were carried out under a counter current flow regime.

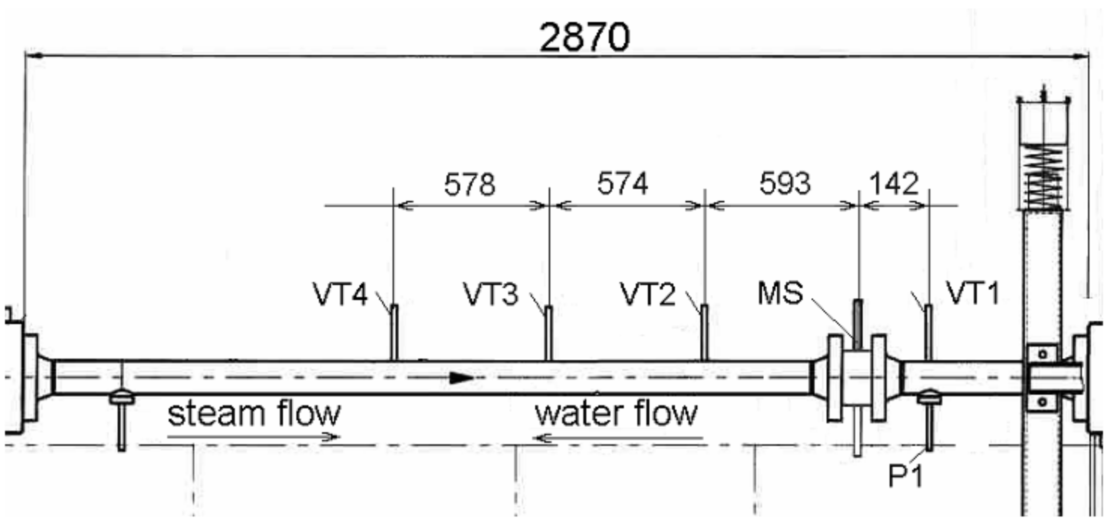


Figure 1: Test section of PMK-2, VT 1-4 void probes, P1 pressure transducer (1)

The temperature is measured by void probes with integrated thermocouples and the pressure by two pressure transducers. Water hammers were measured according to sub-cooling, system pressure and water inflow rate. The
Table 1 shows some pressure peaks measured with the PMK-2 test device. At PMK-2 a pressure increase of nearly 17 MPa has been realised. As figure 2 shows, the pressure peak of the water hammer is very short. The duration of a water hammer is about 1-2 ms.

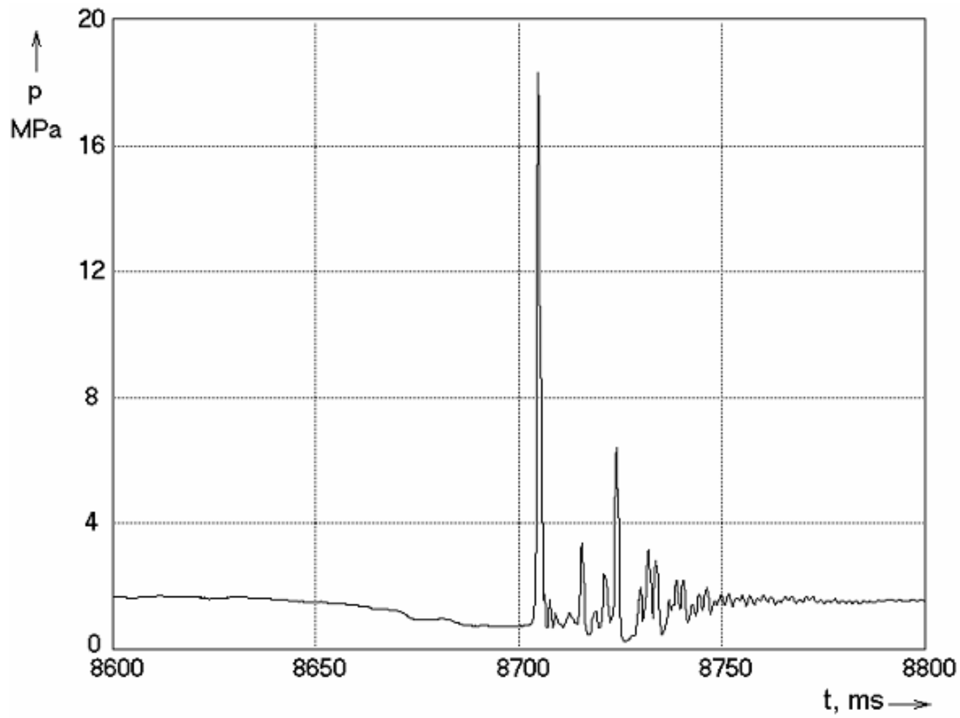


Figure 2: Pressure increase at the PMK-2

Number	Steam pressure	Inflow water	Water temperature	Water hammer
	MPa	kg/s	C°	MPa
AEKI_Exp03	0.98	1.20	30	12.01
AEKI_Exp04	1.15	0.66	30	1.6
AEKI_Exp05	1.45	1.01	25	15.98
AEKI_Exp06	1.50	1.66	30	16.85

Table 1: Data of measured water hammer at PMK-2

1.2 ROSA / LSTF facility

ROSA means rig of safety assessment and is a program initiated by the Japan Atomic Energy Agency. Beside several topics as thermal stratification or natural circulation after an ECCS event (ECCS = Emergency Core Cooling System), destructive phenomena like the condensation induced water hammer have been investigated.

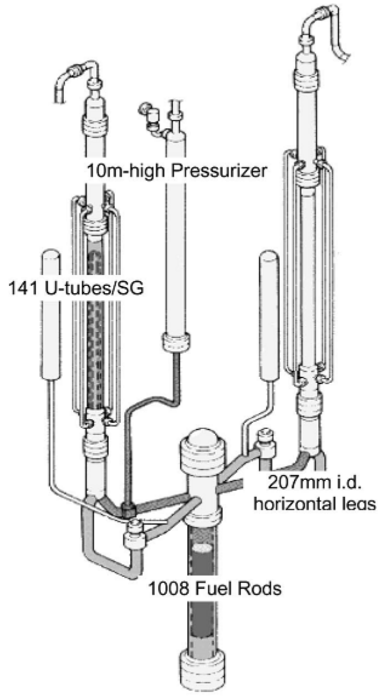


Figure 3: Sketch of ROSA/LSTF(2)

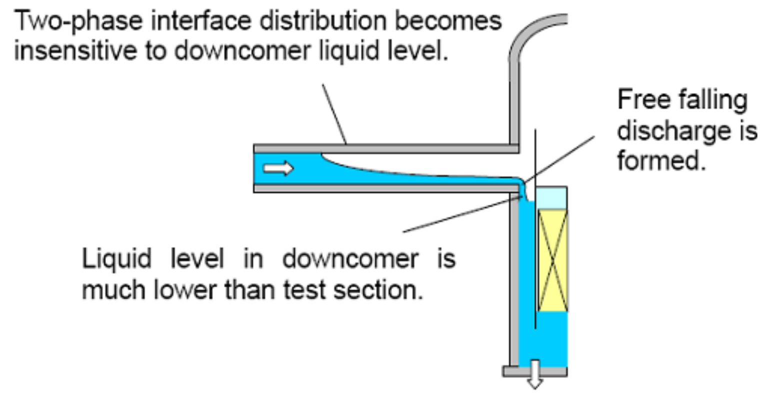


Figure 4: Sketch of ROSA test section (3)

Figure 3 and Figure 4 show a draft of the ROSA test section. In the downcomer a high power heater is installed which simulates a reactor core. In case of ECCS water at ambient temperature is injected into the cold leg in order to cool the reactor core. A flow regime of sub-cooled water and steam like in figure 3 can occur and lead to a water hammer. The experiments investigated the influence of the system pressure to the water hammer effect.

The outcome of the experiments was that the water hammers had their maximum pressure increase at a system pressure of 1 MPa. The pressure peaks decreased beyond a system pressure of 4 MPa and disappeared at 7 MPa.

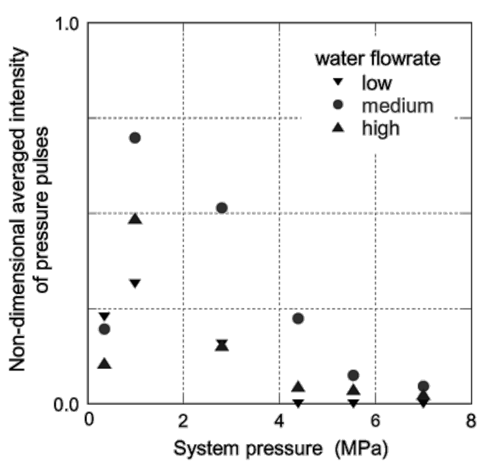


Figure 5: Effect of system pressure on water hammers (2)

This result differs to the tests made at the PMK-2 in Budapest. At the PMK-2 facility no pressure peak was measured at a system pressure of 3 MPa or higher. Experiments carried out at a system pressure of 2.8 MPa showed a pressure increase of up to 32 MPa (3). Figure 6 shows that water hammers occur in the complete range from 0-32 MPa.

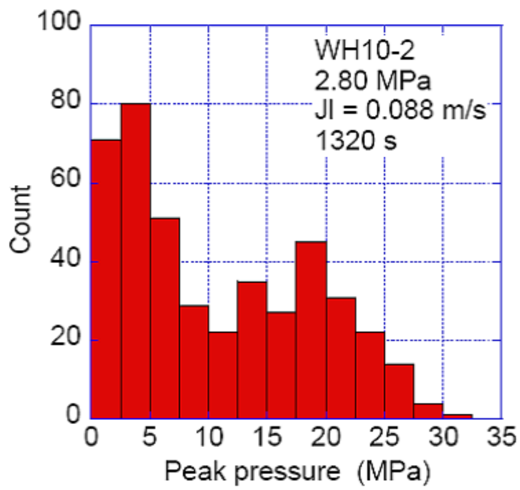
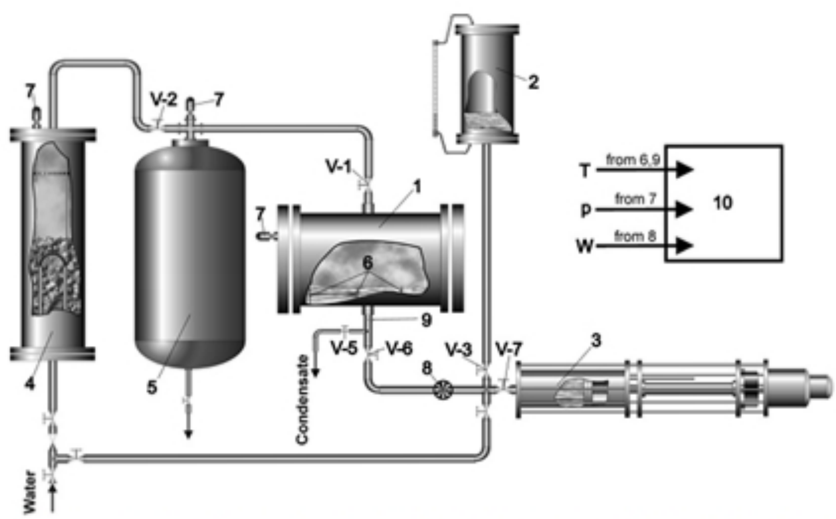


Figure 6: Water hammer at ROSA **(3)**

1.3 Pulser Test Facility LEI MOD2

Condensation induced water hammers occur stochastically as the results of PMK-2 and ROSA test facility have shown. At the PMK-2 it happened that the pressure increase was completely different for exact same parameters. In report (4) it is written “For instance, the particular experiment considered in the present paper with the same initial and boundary conditions was repeated twice with the pressure peak 102 bar in one case and 216 bar in the other case.”
This result has documented outstandingly the incalculability of water hammers. Therefore experiments are desired which are able to produce a controllable water hammer. This aim could be realised with the following test apparatus (5).



MOD2 Pulser Test Facility. 1, pulser; 2, water supply tank; 3, cylinder-piston with motor; 4, steam boiler; 5, steam hold-up tank; 6, 9, thermocouples; 7, pressure transducers; 8, flow meter; 10, data acquisition system.

Figure 7: MOD Pulser Test Facility, apparatus for generating implosions (5)

This device was considered to generate implosions only, but these are controllable. The test section was 0.51 m long with an inner diameter of 0.26 m, an atypical geometry for the simulation of classical water hammers. This geometry prevents slug flow and thus no water impact happens after the implosion. Therefore, there were no water hammers.
The experiment was carried out in the following way. The test section (no. 6 in Figure 7) is filled up with steam. Steam is provided by a steam boiler. Cold water (10-12 °C) was supplied by a tank and could be injected into the test section from below by a screw-driven piston cylinder at a preset rate. During a test the valves were adjusted that the test section could get steam from the steam hold-up tank and water from the cylinder-piston. Two kg of cold water were injected into the Pulser test facility. The following two essential requirements have to be fulfilled in order to generate an implosion:

1) The water must be able to absorb the condensation energy of steam which condenses. That means that the energy difference of the water from its saturated conditions has to be large enough to generate a significant pressure decrease. In report (5) the following modified Ja number has been used to quantify this condition:

$$Ja = \frac{M_f \cdot c_{p,f} \cdot (T_{sat}(p) - T_f)}{M_g \cdot h_{fg}}; \quad (5)$$

M: mass, C: heat capacity, f and g: fluid or gas respectively.
The colder the water is, the higher is the Ja number, as the energy difference versus the saturated conditions increases.

2) The second requirement is the relation between the rate of condensation and the rate of increase of the interfacial area. The interfacial area is assumed as a smooth interface between water and steam. Because of the curvature of the test section, which is a cylinder, the interfacial area rises with the water level. The rate of condensation is coupled with the interfacial area. A larger interfacial area results in a higher condensation rate. If the ratio between these two parameters remains constant during the whole test, no implosion occurs. But a sudden over linear increase of the condensation rate can result in an implosion. This effected was registered at a water inflow rate of at least 0.033 kg/s.

Figure 9 shows the pressure decrease very clearly between 45 – 60 seconds.

The heat transfer coefficient is a key parameter for the appearance of implosions. It was experimentally determined by measuring the steam flow rate, which was equalled to the condensation rate.
Furthermore the mean temperatures of the distributed thermocouples were used. Figure 8 shows a correlation between implosions and development of the heat transfer. $M_f(t) / M_{f,tot}$ is the relative water level. This allows a comparison of the heat transfer at equivalent interface areas. Water inflow rates of 0.041 kg/s led to an increase of the heat transfer of more than 4000 W/(m²K). At this water inflow rate also an implosion happened.

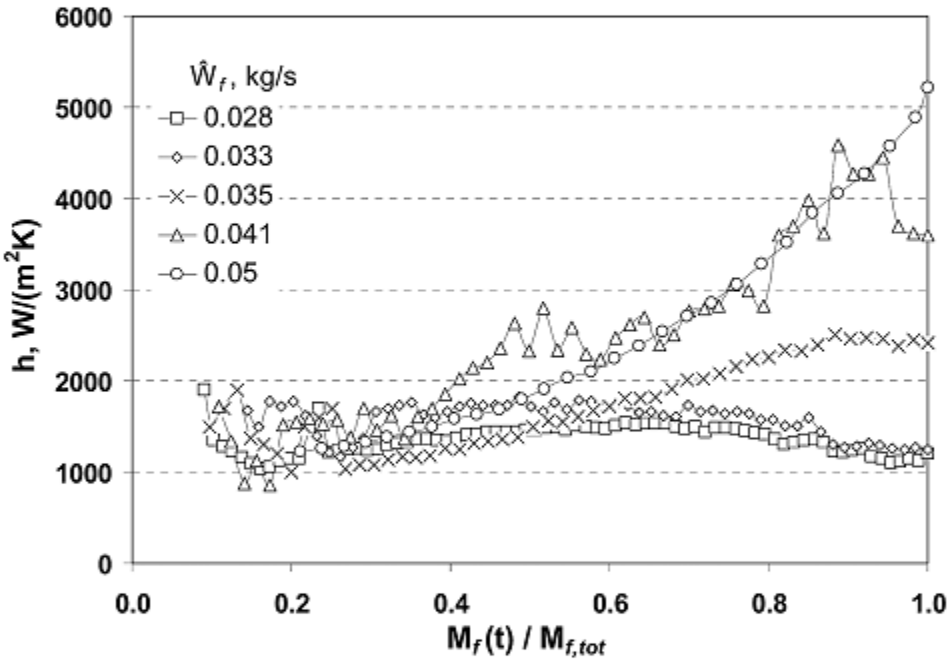


Figure 8: Heat transfer and relative water level of different water inflow rates (air concentration less than 0.001).

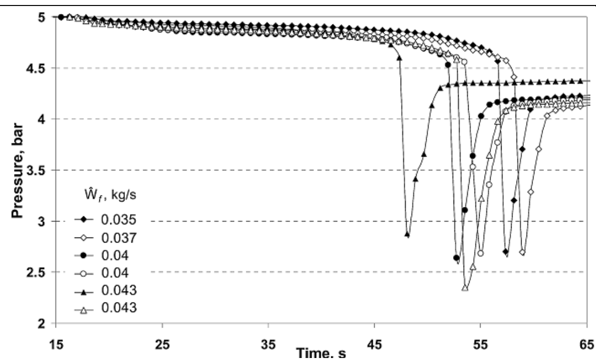


Figure 9: Time-pressure curves for different water inflow rates (5)

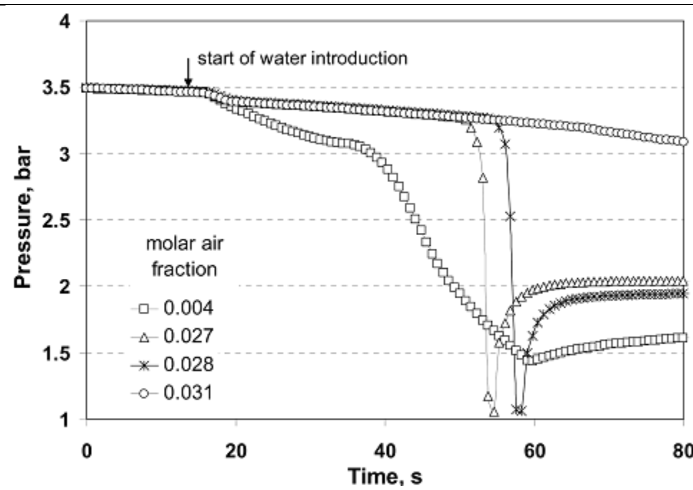


Figure 10: Time-pressure curves for different molar air fractions (5)

A remarkable result is visible in Figure 10. Usually air in steam dampens the pressure increase at water hammer experiments. At the Pulser test facility however, the influence of air has to be considered in a differentiated way. At higher molar air fractions (0.031) no implosion is visible. This result is well known from other water hammer experiments. But the test run with the lowest molar air fraction did not result in the highest pressure decrease. The values 0.027 or 0.028 have generated a higher pressure decrease than the test run with 0.004. The reason for this effect is the isolation of the two phases. Air influences the heat transfer and can isolate these two phases. That is why a small amount of air can further the event of implosions. This effect is clearly visible in figure 11.

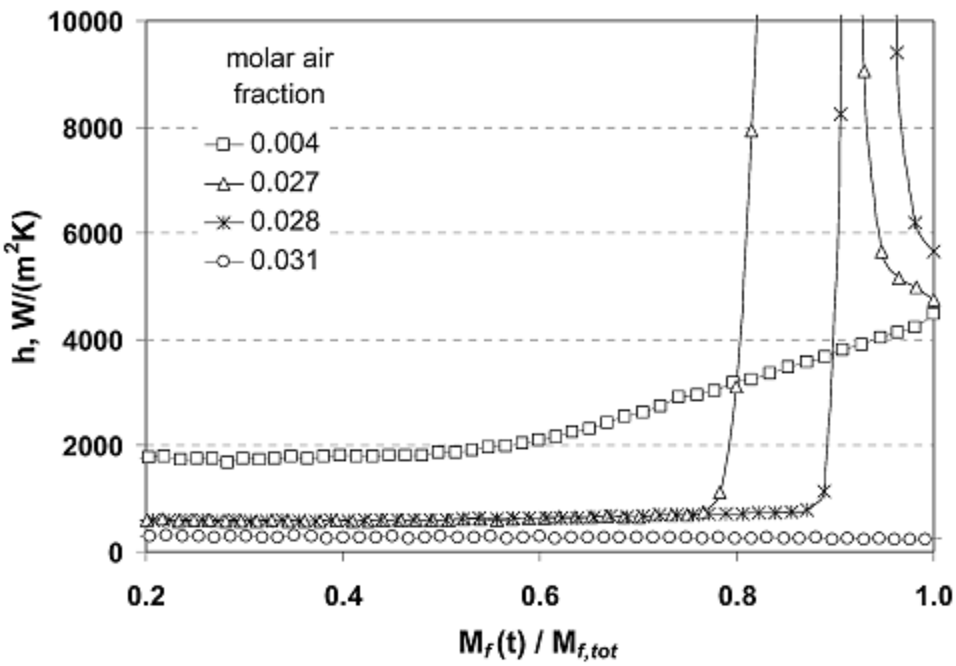


Figure 11: Influence of air on the heat transfer coefficient h

The heat transfer coefficient changes rapidly within a range of approximately 0.027 to 0.028. At high molar air fractions the heat transfer coefficient is so low that no relevant interactions took place. In case of molar air fractions below 0.004, the heat transfer was so high that the water was heated and additionally condensation took place during the filling process. This condensation reduced the pressure in the pulser and the storage tank and lowered $T_{sat}(t)$ of the water. These two effects reduced the potential to create an implosion. Simply said, the energy for the implosion was already “lost”.

2. Test facility at the UniBw

At the UniBw in Neubiberg, Germany, a completely new test apparatus for generating water hammers is under construction. This new device is considered to generate condensation induced water hammers in a controllable way like at the Pulser test facility for implosions. Figure 12 shows the principle of this test device. The entire test device is a closed system. The water which is used for the tests is always the same. It is intended to use water with no air so that the destructive influence of air is ruled out. The test parameters will be chosen in a way that pressure peaks will be within 4 MPa for safety and economic reasons. The horizontal test section is about 5 m long, the vertical about 2.5 m. The pipes have an inner diameter of 102 mm and a thickness of 6 mm (DN100, German standard). The water supply tank and therefore the whole apparatus can be pressurised with nitrogen. A circulating pump allows adjusting a preset flow rate. In the vertical pipe section a heating rod with a power of 18 kW supplies the needed energy for heating up the water to saturated conditions. Thereby heating the water in the supply tank is optional. It is a degree of freedom to integrate the water tank into the water circulation. Cooling elements in the horizontal and vertical sections should create a degree of sub-cooling of at least 20 K. In a further phase of the experiments a glass tube should be installed. This would allow to visualise the water hammer and to use a special thermo camera. With this camera it is possible to measure a whole temperature field. Furthermore the usual measuring devices will be installed:

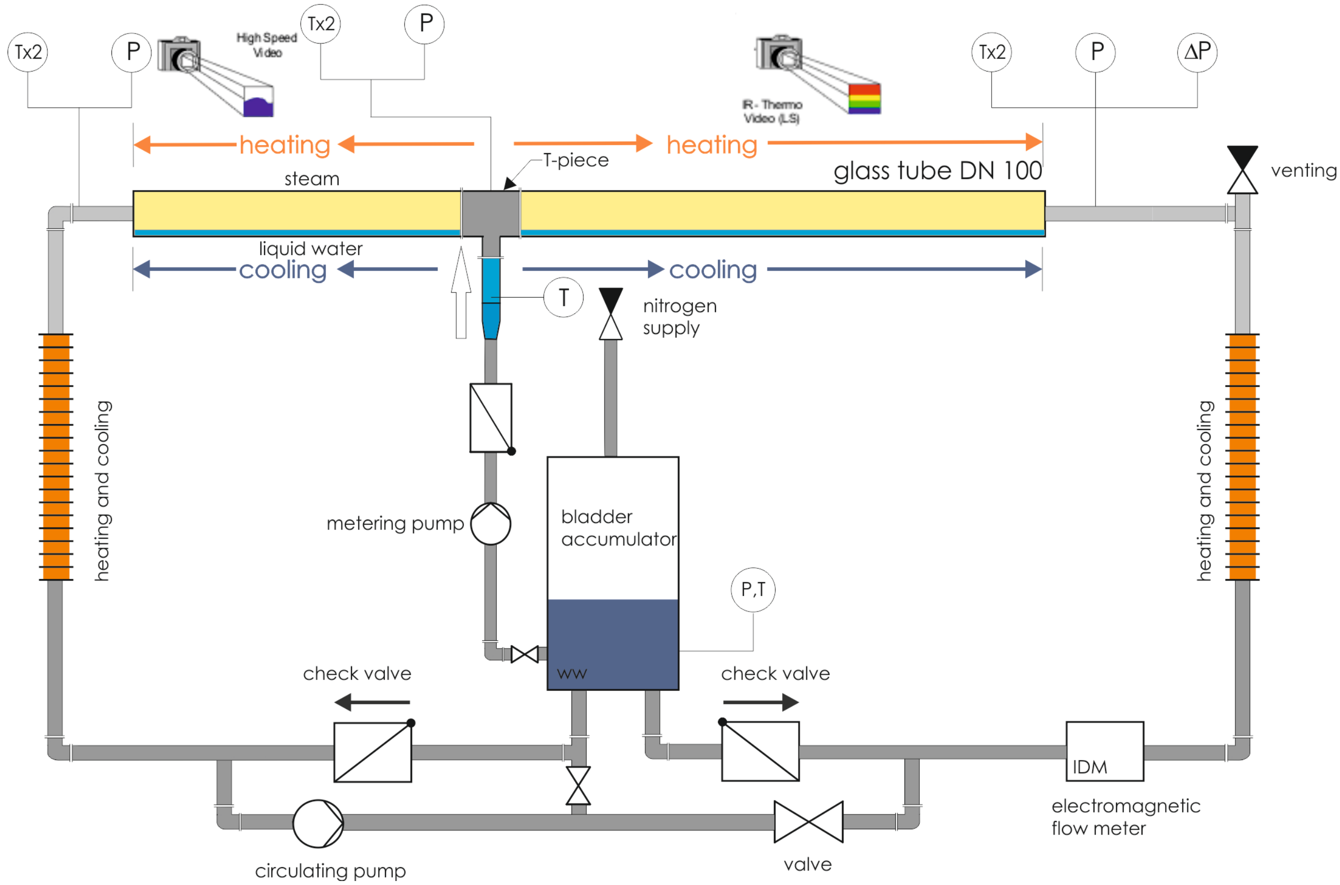


Figure 12: UniBw test apparatus for generating controllable water hammers

- several thermocouples in the test section, one at the water supply tank; as thermocouples PT100 elements will be used.
- several pressure transducers, two at each end of the test section, one in the middle at the T-piece and one at the water supply tank
- water level will be measured with an ultrasonic device

The first tests will be conducted with a usual steel pipe. After sufficient experiences, when controllable water hammers can be realised the glass tube will be applied. The UniBw concept allows creating water hammers in three different ways:

1) Operating mode 1

At first the water will be heated to its boiling point during pumping. Thereby only the circulating pump is running, so water flows in the outer circle during heating. When boiling of the water starts, the circulating pump will be switched off and heating will be continued until the desired amount of steam is present in the horizontal test section. In operating mode 1 the amount of steam will be low, about 10% of the inner diameter. At this point the cooling will be activated in the horizontal test section and optionally also in the vertical section(s). The heat rods in the vertical pipe will be turned off. In order to keep steam at saturated conditions umbrella heaters above the horizontal test section can keep the upper part of this pipe hot. The purpose of method is to produce a two phase mixture in the horizontal test section. The saturated water layer between water and steam isolates these two phases.

This isolation can be destroyed by injecting cold water from below with an injecting pump. This disturbance activates the condensation induced water hammer.

2) Operating mode 2

The way of generating water hammer in this operating mode is similar to the method explained in (5). Steam will be generated as explained in operating mode 1 until the whole test section is filled with steam. Cold water from the bladder accumulator will be injected into the test section from below. In (5) a lower bound of water injection rate existed, where implosions happened. In case of the UniBw test section the space of the collapsing steam can be filled with water from the bladder accumulator and therefore a CIWH will be induced.

3) Operating mode 3

This method is similar to most of the common ways to generate water hammers. Steam will be produced as before in mode 1 and 2. Once sufficient steam has been generated, the pump is switched off and the cooling system will be activated. The umbrella heaters keep the steam hot. The heating of the steam and the cooling of the water produces an energy difference. Once the desired temperature difference is present, the circulating pump is switched on again. With an appropriate flow rate slug flow will be established leading finally to a CIWH. This flow regime is supposed to be a typical precursor of a condensation induced water hammer in the appropriate literature (for example see (6)).

The UniBw test apparatus has some advantages compared to usual test devices that shall make controllable condensation induced water hammer possible.

- Data acquisition system
  The data acquisition systems offers 16 analogue input channels. Each of them has a frequency of 500 kHz and an own analogue digital converter. This ensures that the short time events that happen during a water hammer event can be measured.
- Closed System
  The UniBw test apparatus has a closed water cycle. This ensures that always the same quality of water is used. At the UniBw it is intended to use tap water and demineralised water. A decision for the liquid will be made after the comparison between tap and demineralised water. Thus the influence of the water quality will be investigated.
- Pipe system with flexible connectors
  The UniBw test apparatus is not completely fixed after its installation.

Figure 13: flexible connector

The pipes will be connected with flexible coupler elements, see Figure 13. They allow a reconstruction of the apparatus and therefore a flexible procedure is possible.

- Opportunity for using a thermo camera and a high speed camera
  In later experiments a glass tube is supposed to be used in the test section. The process of a condensation induced water hammer can be visualised with a high speed camera and additionally a thermo camera can be used. This kind of camera is able to scan a complete temperature field. It would be possible to get the whole temperature distribution across the pipe.

3. Summary and conclusion

An overview about important water hammer experiments (PMK-2, ROSA and Pulser Test Facility) is presented. As water hammer experiments show a very high degree of variation in the pressure peaks, it would be useful to make experiments in this matter more controllable. The Pulser Test Facility is a step into more control but is presently limited to implosions only. Therefore at UniBw a complete new test apparatus is currently under construction. This new test device is designed to allow the generation of water hammers by different operating modes. They are explained in this paper. Two out of the three possibilities for generating a condensation induced water hammer should allow to achieve controllable pressure peaks instead of a stochastic water hammer. Controllable water hammer events would be very helpful for the code validation of CIWH simulating codes.

4. Nomenclature

M_f: Mass of water [kg]
M_g: Mass of steam [kg]
$C_{p,f}$: Heat capacity of water [J / (kg K)]
W_f: Water inflow rate [kg/s]
T_f : Temperature of water [K]
h_{fg}: Enthalpy difference between water and steam [J/kg]
T_{sat}: Saturated temperature of water [K]
Ja: Jacobs-number [-]

5. Acknowledgements

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