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High Speed PIV Measurements in Water Hammer

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Abstract

An experimental study addressing the challenge to measure relaxation coefficient of very fast phenomena such as water hammers is presented. An acrylic projectile containing water is accelerated and impacts a metal wall creating a water hammer. State of the art laser measurements techniques will be deployed in order to achieve such goal. A compressed air custom built cannon is used to accelerate the projectile and create the impact leading to the water hammer. First experimental results for Shadowgraphy and PIV measurements are presented and discussed with focus on the future development for the presented facility.

1 Introduction

The RELAP-7 code is the next-generation nuclear reactor system safety analysis code being developed at Idaho National Laboratory (Berry et al., 2013, 2018, 2015). In RELAP-7, the comprehensive Seven-Equation multiphase model is used to represent quasi-one-dimensional gas-liquid flows for problems with varying cross-sectional areas. For fast transients (such as water hammer or steam explosion) in water, the Seven-Equation model takes into account non-equilibrium processes through relaxation rate terms.

Due to the complex polar and tri-atomic nature of the H2O molecules, the relaxation rate terms in the seven-equation model rely on simplified models and limited data. There is therefore significant empiricism and knowledge gap in those terms that limits the application domain of RELAP-7 for fast transients. Unfortunately, no analytical model describes H2O satisfactorily over the range of parameters considered here because of its complex geometry and polar nature. Therefore, one must rely on a combination of experiments and molecular dynamic simulations (partly calibrated by experimental results) to estimate the relaxation times.

To measure return to equilibrium, an experiment should therefore resolve independently rotational and vibrational temperatures, the relaxation time will be the time at which the two temperatures agree. Therefore, the thermal and mechanical relaxation times will be determined experimentally. They depend on temperature and pressure and are on the order of tenth of microseconds or longer for the experimental cases that will be considered here. The work presented in this paper represents a first effort in the characterization of the water hammer realized in a new experimental facility by using laser measurements techniques. The facility is based on the Rich pipe concept. However, instead of using a drop tower, a compressed air cannon has been constructed. It consists of a driver volume and a barrel. The projectile is a titanium pipe filled with water that will go water hammer when the pipe hits a solid obstacle. As a first step for the visualization of the water flow undergoing water hammer a Shadowgraphy technique has been implemented. Then a first of a kind very high-speed PIV technique has been implemented allowing to reach more than 100 frame/s. This temporal resolution is required in order to resolve very fast transients involved in water hammer phenomena. Important challenges were solved in order to perform high speed PIV measurements on a moving target, and they will be illustrated in this paper. To the author knowledge the implementation of PIV measurements at this temporal resolution represent a first of a kind. Some work has been done on water hammer PIV measurements, with focus in the spatial resolution, but at low time resolution (15 Hz) as described in Brito et al. (2014).

First the experimental facility and its main characteristics will be presented, then the laser setup and the challenge due to the specific configuration will be illustrated. Finally, main results obtained with both Shadowgraphy and PIV techniques will be illustrated. Finally, discussion will be opened on the further steps for quantitative measurements of relaxation constants by using advanced techniques such as Ultrafast Absorption Spectroscopy with Femtosecond Lasers.

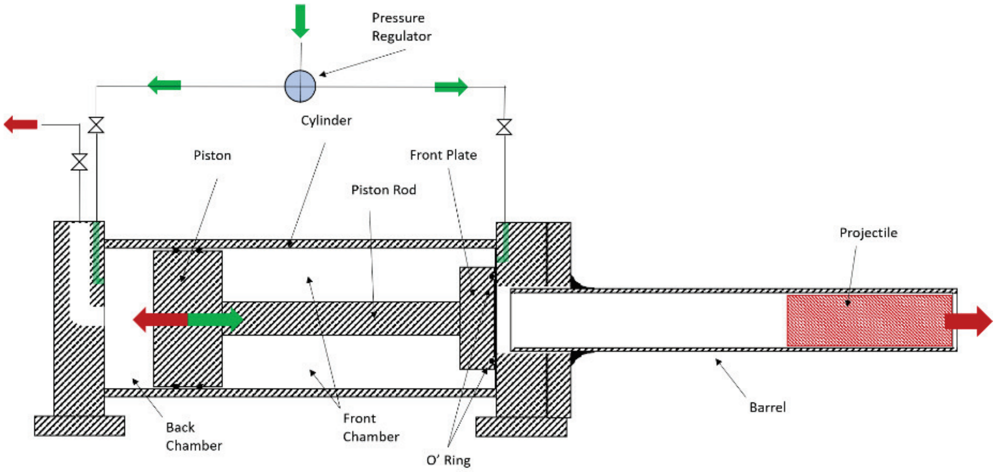

Figure 1: Schematic view of the compressed air cannon.

2 Experimental Facility

As already mentioned above, the facility consists of a compressed air cannon. This design has been chosen in order to improve the repeatability of the experiments and to have the final velocity and direction of the projectile to be identical at each shot as much as possible. Some modifications have been done on the piston and cylinder system in order to improve the repeatability and to maximize the discharge speed of the chambers.

In other standard applications (Rohrbach et al., 2012) we usually find a valve which brings the air into the barrel and which gives thus the trust force to the projectile. Since, for our application we are in the conditions of chocked regime, this means the air mass flow rate ($\dot{m}$) directly depends on the diameter of the valve, as expressed by equation of the chocked regime:

$$\dot{m} = C_d A \sqrt{\rho\gamma(P_1 - P_{atm})\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

where P_1 is the pressure of the front chamber, P_{atm} is the atmospheric pressure at the outlet of the barrel, C_d is a dimensionless discharge coefficient, ρ is the density of the gas and $\gamma = C_p/C_v$ ratio of the gas and A is the cross section of the barrel (or of the valve in other situations).

Since commercial solenoid valves have by design a very narrow cross section, this means that the mass flow rate of the discharge chocked flow will be very limited, so meaning that the pressure differential that the projectile experience will be not the total pressure difference between the front chamber and the atmospheric pressure. In order to have a trust force the most efficient, we want the projectile to experience the whole pressure difference ideally instantaneously. We cannot achieve the instantaneity but increasing the cross sections we can increase the discharge flow rate. So, the maximum we can achieve, is when the front chamber directly discharges into the barrel.

In order to achieve this goal, the piston rod has been modified (shortened) and a front plate is added to the piston rod (with an O' Ring for the sealing.). So now the cylinder has two chambers, the back chamber and the front chamber. The front chamber is the chamber where all the gas which will fire the projectile is stored, while the back chamber is needed to push the front plate of the cylinder rod towards the wall of the barrel for sealing the front chamber.

For the same reasons, the outlet nozzle of the back chamber is much larger than the inlet nozzle, so the back chamber could be emptied as fast as possible. In order to minimize the time for the gas to flow from the back chamber, and also to maximize the volume of the front chamber, we want the volume of the back chamber to be as small as possible.

After all these design considerations have been done, we were able to design the size of our system. A cylinder of 15.24 cm diameter with a 35.56 cm stroke has been used. The piston rod and the piston have a total length of 30.48 cm, which thus leaves a back chamber of 5.08 cm long and a front chamber of 25.4 cm

Figure 2: Picture of the assembled air cannon.

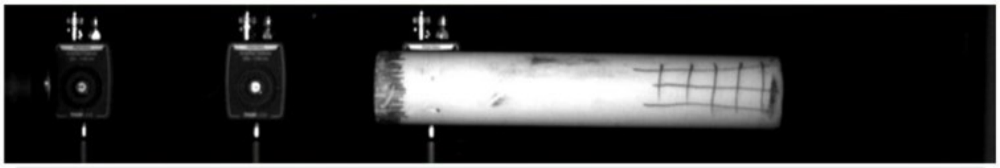

Figure 3: Frame of the projectile exiting the barrel.

long. A very high precision barrel has been used with an inner diameter of $5.08762\text{ cm} + 0.01778\text{ cm} - 0.000\text{ cm}$ and 2 m long. The maximum service pressure of the chambers is 1.7 MPa, which is thus capable of firing a projectile of about 2 kg at a velocity of about 70 m/s (at the outlet of the barrel).

One can thus imagine that the pressure on the back chamber should be greater than the pressure in the front chamber in order to insure the sealing of the front chamber. One should remark that since the front plate also experiences a pressure gap, the active surface where the front chamber pushes is smaller than the surface of the back chamber, then this means that even without any pressure difference between the back and the front chamber we will have resultant force which pushes the front plate towards the wall. After a quick calculation, it results that at the service pressure of 1.7 MPa in both chambers, a net force of about 4000 N results in the direction of the barrel. This force is more than the double of the force needed to guarantee the sealing of the O' ring. We can thus use the same pressure in both chamber, which allow to simplify the design of the piping and to use only one gas tank for feeding the whole system.

The pressure inside the chamber is controlled with two pressure sensors which have an error less than 0.1% thus allowing to have a very accurate control of the initial conditions of our experiments, and thus to insure a good repeatability of the tests.

Finally, the compressed air cannon is mounted to a 10 inch I-beam, itself mounted on a frame to bring the barrel to the height of the laser. The I-beam was necessary to add mass to the overall assembly and minimize recoil of the system. Also, it will serve as a support to mount a solid obstacle to intercept the projectile (see Figure 2).

To monitor the projectile speed exiting the barrel, a series of 3 fast photodiodes are positioned at the exit of the barrel. They have a rise time of less than 1 ns and will capture precisely the front of the projectile. They are connected an oscilloscope to measure the outlet velocity of the projectile. The photodiodes will serve as a trigger signal to start the acquisition of the instruments that will be deployed in the water hammer projectile. Tests have been performed to assess the repeatability of the velocity between different shots with a dummy projectile made of Teflon (as shown in Figure 3).

In Figure 4 the measured velocity for 15 different tests performed at the same nominal conditions of 3bar in the front chamber and 3.2 bar on the back chamber are shown. With the current design we can obtain a precision of about 0.5% at 95% confidence.

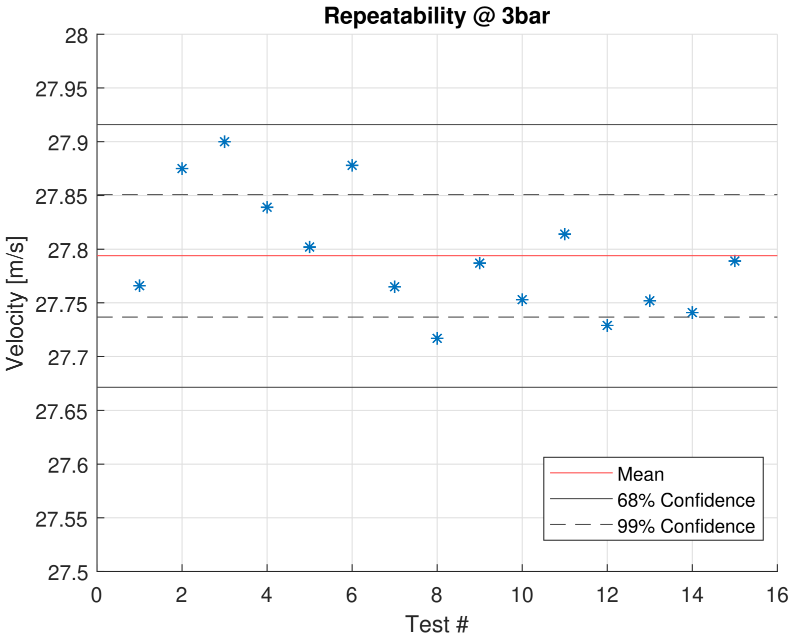

Figure 4: Frame of the projectile exiting the barrel.

3 PIV and Shadowgraphy setup

First tests with Shadowgraphy and PIV measurements are performed by using a test projectile made of acrylic and filled with distilled water inside (as shown in Figure 5). PIV silver coated particles with a diameter of 2 μm have been used as a tracer for the flow.

This projectile is used for the first tests because it is cheap and easy to build, but it can be destroyed during tests due to its fragility. The choice to use a cheap test projectile, is dictated to the elevated number of tests needed for synchronization and calibration of all the tools necessary for deploying PIV in such a challenging environment. For final quantitative measurements a new titanium body projectile is designed in order to resist several shots without breaking.

The first measurement technique implemented is the Shadowgraphy which allows to visualize the dynamic of the projectile and the water flow inside it. The Shadowgraphy technique is simple to implement and consists of a powerful LED lamp placed in front of a camera and the trajectory of the moving target is placed in between the camera and the light. For our application the High-Speed camera Phantom v.710 is used with a resolution of 640×256 pixels and an exposure time of 3 μs leading to an acquisition rate of 40000 fps. The physical resolution obtained by using a 200 mm Nikon lens at 2 m from the target is 208μm/pixel resulting in a magnification of $M = 0.096$. The LED lamp used is a Veritas Constellation Model 120 giving 12000 lumen of light intensity, used in continuous mode (it could be used in strobe mode up to 100 kHz) and placed about 1 m away from the target.

Later, a PIV technique has been implemented in order to perform time resolved measurements of the flow field undergoing water hammer. The implementation of a PIV technique in water hammer represents a big challenge due to the very fast involved phenomena, and to the authors knowledge time resolved PIV in water hammer at very high frequencies have never been performed. A very powerful and fast laser was needed in order to have a repetition rate high enough to temporally resolve the transients involved in a water hammer.

The Spectral Energies Quasimodo Pulse Burst Laser has been used for this setup, which allows a repetition rate up to 1 MHz with a pulse length of 1 ns at 532 nm. Due to the high repetition rate, the laser can only work for 10 ms and needs a cooling time of about 10 s in between each burst. The energy of each burst is of 16 J/burst, giving thus an energy of 0.16 mJ/pulse. This represented a synchronization challenge, meaning that the trigger of the laser must be perfectly synchronized with the impact of the projectile on the solid wall. The high-speed camera used for the PIV measurements is an IDT Y7-S3 with a reduced resolution of 1920200 pixels allowing an acquisition rate of 100000 fps with an exposure time of 8 μs. A 60 mm

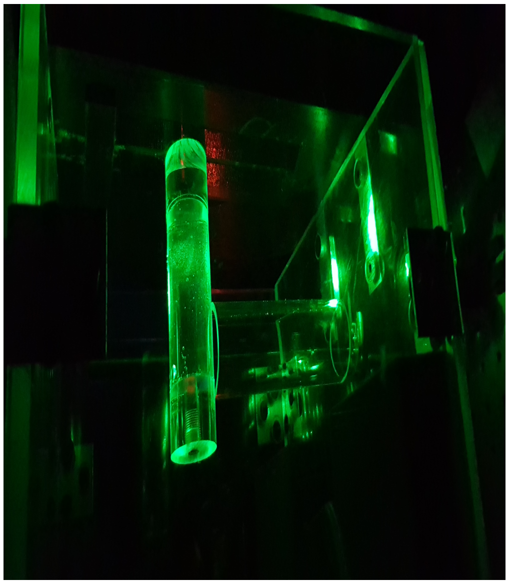

Figure 5: Laser alignment on the impact area for PIV measurements.

Nikon lens has been used with the camera placed at about 50 cm from the target resulting in a resolution of 24 µ/pixel and a magnification $M = 0.29$. A system of 3 mirrors and a cylindrical and a spherical lens has been used in order to bring the laser light into the impact point and to create a laser sheet of about 0.5 mm thickness (as shown in Figure 5).

The master clock of the laser system has been used for synchronizing the camera acquisition and exposure with the laser pulses, and a fast photodiode (Thorlabs PDA10A) with a laser pointer placed 5 cm form the impact area has been used to trigger both the laser and the camera.

4 Results

At this stage preliminary results are shown. In Figure 6 the water hammer recorded with the Shadowgraphy technique by the Phantom camera at a 40000 fps is reported. The rarefaction wave produced cavitation bubble which are visible in 6 different frames, and this allows to have a rough estimation of the shock wave speed inside the projectile which about 900 m/s. This estimation agrees with the calculated value for the shock wave travelling in water inside an acrylic pipe which is of 980 m/s.

The Shadowgraphy measurements allowed for the first time (to the authors knowledge) do visualized the rarefication wave inside a transparent projectile undergoing water hammer, and also proved that the experimental facility and the available tools are suitable for the purpose non-intrusive measurements in a water hammer. However, due to the very high speed of the shock wave due to the water hammer, an acquisition rate of 40000 fps is not enough to completely resolve the flow field undergoing water hammer, thus a better high-speed camera has been chosen for the PIV measurements (as discussed above).

Some of the PIV raw images collected with the IDT camera at 100000 fps are shown in Figure 7. At this stage only some qualitative analysis has been performed on these images, but with the implemented PIV technique we are able to visualize and follow the water flow field undergoing water hammer. The presence of some bubbles due to the rarefication wave is evident. Some PIV software could be used to compute the time resolved local flow velocities inside the projectile undergoing water hammer.

5 Conclusions

A new experimental facility that address the challenge to measure relaxation coefficient of very fast phenomena such as water hammers has been presented in this paper. A first of a kind very fast Shadowgraphy and PIV techniques have been deployed for the measurements of such fast phenomena. It has been demonstrated that the tools used for these measurements give useful results for the understanding of the flow fields

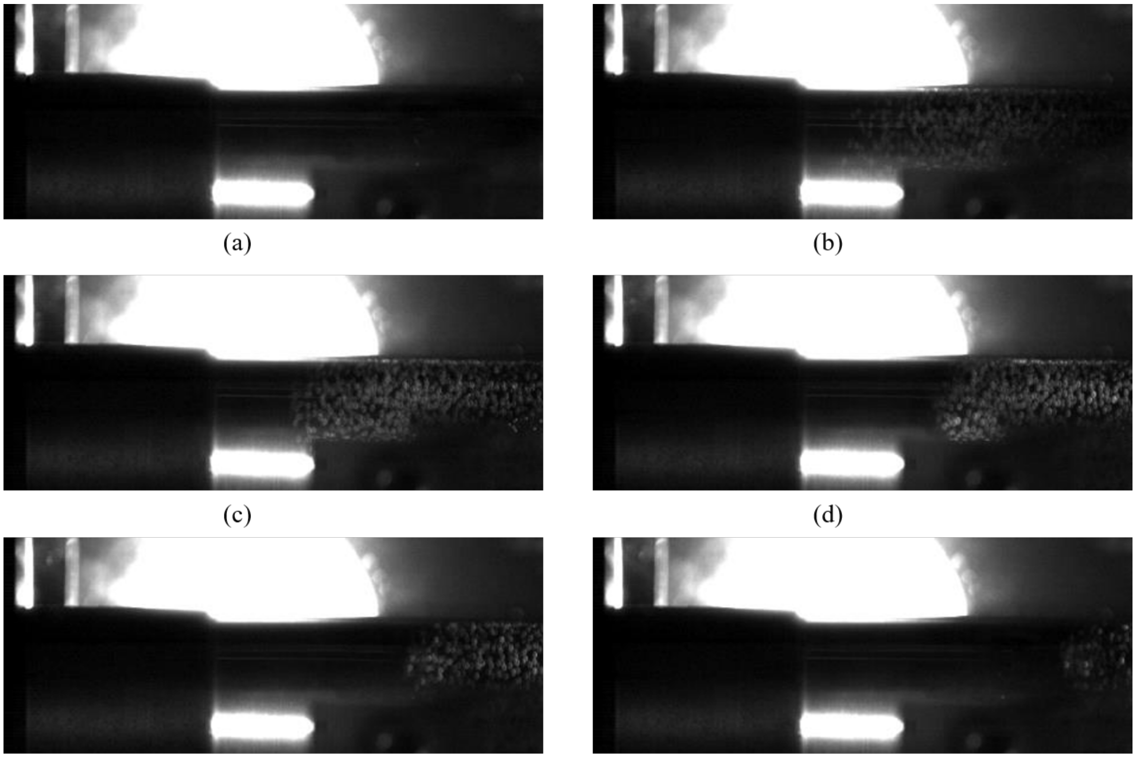
(a) (b) (c) (d) (e) (f)

Figure 6: Shadowgraphy images of water hammer: (a) Frame 1; (b) Frame 2; (c) Frame 3; (d) Frame 4; (e) Frame 5; (f) Frame 6.

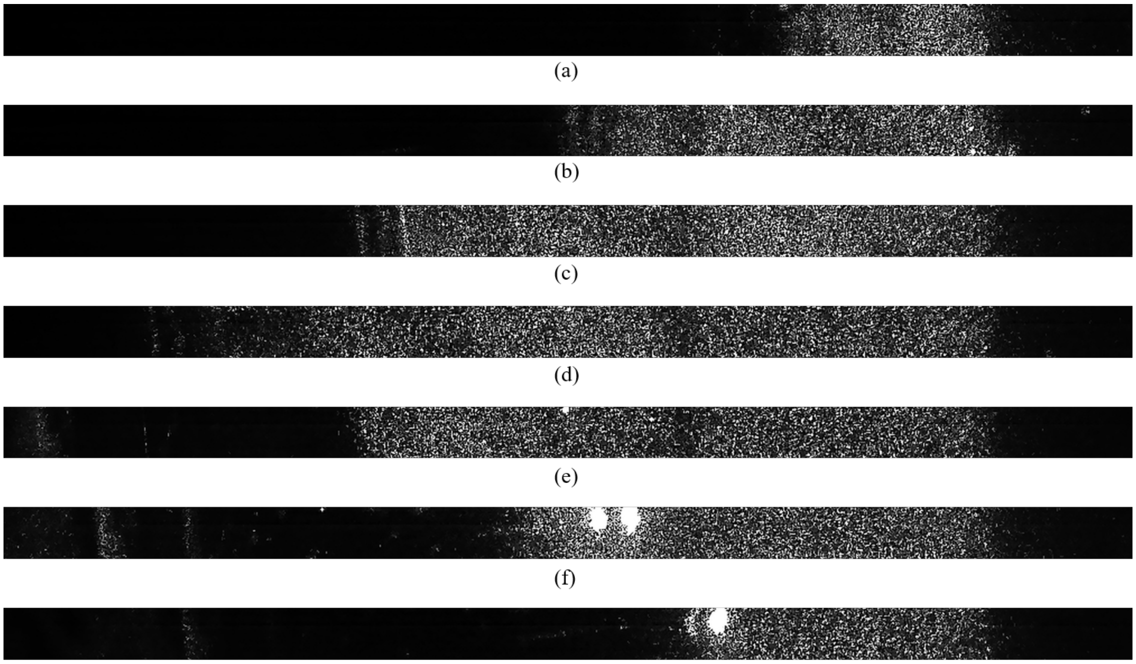
(a) (b) (c) (d) (e) (f) (g)

Figure 7: PIV raw images of water hammer: (a) Frame 400; (b) Frame 450; (c) Frame 500; (d) Frame 550; (e) Frame 600; (f) Frame 650; (g) Frame 700.

in a water hammer a represent a first step in the development of further techniques for the measurement of relaxation coefficients. Several challenges have been overcome in order to trigger and synchronize in a very precise way all the tools used for the PIV measurements.

Further PIV measurements will be performed on a new projectile, which will allow to have several repetitions of the measurements, acquiring a statistic on the measurements. The new projectile has a Titanium body to resist the strong impacts and a Sapphire tube to resist the internal pressure and allow UV light to pass trough (needed for eventual Absorption Spectroscopy measurements).

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