IMPACT OF A HIGH TEMPERATURE SODIUM SPRAY ON A TARGET: PDA PRELIMINARY CHARACTERIZATION.

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ABSTRACT
The behaviour of high temperature sodium when spread into air is not well known, although of capital interest in preparing safety systems in plants that use large amounts of it. A new set-up was built to produce high temperature liquid sodium sprays and jets, that were observed when produced in nitrogen inert atmosphere and in air. Sodium sprays were produced by sub-millimetric nozzles simulating a small leakage, while a rupture diaphragm of 30 millimetres diameter simulated a more severe failure. Sodium was pressurised up to 9 bar, and heated up to 550°C, while the surrounding gas, nitrogen or air, was kept at atmospheric conditions. High speed cinematography was used to observe the liquid macroscopic behaviours, while Phase Doppler Interpherometry was used to measure the sodium droplets velocity and size, when possible. Particular care was put in preparing this new experimental set-up, because of the partially unknown and potentially dangerous phenomena involved, requiring double confinement of the spray set-up and remote controlled operations. Spray macroscopic shape and some granulometric characteristics could be measured, and are reported together with occurrence of ignition.

INTRODUCTION

Liquid Sodium is already used in some applications and studied as cooling fluid for high temperature applications like in the nuclear IV Gen and fast reactors thanks to its favourable physical characteristics. Nevertheless it strong chemical reactivity requires extreme care for its use. Its liquid state temperature range is wide and quite convenient for mid and high temperature cycles, its density and viscosity are much lower than those of other low melting metals or salts, and close to water's ones, and its thermal properties values are quite attracting.

Melting Temperature	371 [K]
Boiling Temperature	1155 [K]
Density at 800 K	828 [kg m^{-3}]
Dynamic viscosity at 800 K	$2.27 \cdot 10^{-4}$ [Pa s]
Heat Capacity at 800 K	1260 [J kg^{-1} K^{-1}]
Thermal conductivity at 800 K	62.9 [W m^{-1} K^{-1}]

Table 1: Sodium physical properties, from [1]

On the other hand, sodium reacts strongly with water and oxygen, so a small leakage from a liquid sodium duct or vessel is potentially dangerous, but information about its behaviour when spread in air is quite limited or not available. Hence the present work aimed to gain basic knowledge on the evolution of a sodium jet or spray above 500°C, its shape, characteristics, granulometry, with injection pressure up to 9 bar, both in nitrogen, to avoid combustion, and in air, to observe if ignition occurs.

EXPERIMENTAL SET-UP

The injection systems

The injection systems used in the present experiment were purposely designed at RSE since commercial systems for this peculiar application do not exist. Four similar devices where built, each composed by a small pressurized recipient, a valve with a pneumatic actuator, and each one with a different nozzle.

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Figure 1: The injection system after its use. The heater had been removed and is not shown.

All hot components are manufactured with stainless steel and can be heated up to 550°C by an electric heater controlled by a PID system connected to a thermocouple immersed into the liquid metal. The recipient has the inner volume of about 200 cm^3 containing the molten sodium, and can be

pressurized up to 9 bar by nitrogen. The valve is connected directly below the recipient, and its pneumatic actuator is mounted with a spacer to keep it at lower temperature. The nozzle is nitrogen flushed while not in use to avoid its clogging. The available nozzles had 0.25, 0.40 and 0.50 mm diameter, used to produce small jets or sprays. The last system instead of the nozzle had a rupture diaphragm with 30 millimetres diameter and rupture pressure 6 bar.

The three nozzles were not designed to produce a jet or spray with specific granulometric requirements, but to generate different kinds of jet to have different characteristics to be tested.

The targets

Two different targets were used. The first target for spray testing is a flat disk (diameter 20 centimetres, thickness 2 centimetres) composed of concrete, with the aim of testing the material resistance to the sodium chemical attack at high temperature. The second target is a concrete pan (diameter 15 centimetres, thickness 2 centimetres), whose primary aim was to collect the large sodium ejection of the rupture disk test and avoid its spreading in the test cell, and at the same time to test the concrete resistance.

The controlled atmosphere test cell

A controlled atmosphere test cell was designed by RSE and used to host the experiment. It is shaped as a cube with side length 80 cm, made in stainless steel, with two large, opening and transparent observation windows, facing each other on two sides of the cube, equipped with double layer safety glasses (70x70 cm, total thickness 20 mm). Other two smaller circular window (D=100 mm, thickness 50 mm) are located on one side of the cell and are used for laser diagnostics, being equipped with high quality optical glasses already tested in combustion environment. The test cell is equipped with temperature sensors, oxygen sensor, venting lines to flush it continuously with nitrogen or air; it is not designed to withstand over pressures. Preliminary extinction tests with nitrogen showed that the oxygen content can be lowered from atmospheric condition to less than 10% in less than 20 seconds.

Figure 2: The test cell. The injection system is mounted to spray downward. The concrete target lays on the cell floor.

The "Chamber Vent Explosion" facility

The test cell and most of the measurement instrument were installed in a the "Chamber Vent Explosion" facility available at the University of Pisa, Italy. It is a large chamber designed for deflagration tests, cubic shaped with 3 meters side, built with iron walls and large safety windows. It is designed to withstand over-pressures up to 300 mbar, above which two lateral walls are detached and the chamber results fully vented to the atmosphere. The chamber is mounted on rail to translate it easily outside of the laboratory building to allow its use in open field. All operations are remoted in the control room inside the laboratory.

Figure 3: The "Chamber Vent Explosion" inside the laboratory.

The high speed recording system

To record the experiment, the high speed video camera available at the Politecnico di Milano, Department of Energy, was used. It is a Phantom V5.1 camera, equipped with a 1.2 Mpixel CMOS sensor, capable of a frame rate up to 1200 Hz at full resolution, with tuneable exposure time. It has 4 GB of on board memory to temporary store the images, and a GLan connection to transfer the data to a PC.

High speed imaging requires illumination with high power and stability, the risk being to observe the 100 Hz light fluctuation caused by the 50 Hz mains supply. Lighting was provided by one 800W 220V halogen lamps, having a large filament with sufficient thermal inertia to attenuate the 50 Hz oscillation, and two 100 W 12V DC halogen lamps. All lamps were switched on few seconds before the experiment to avoid window overheating.

A traditional video recorder and closed circuit TV are used to monitor and record the tests from the control room.

LDV and PDA instrumentation

A combined LDV + PDA system set-up was used for this experiment.

The laser source used is a continuous Melles Griot 43 series Argon-ion laser used at its maximum power of 300 mW. The optic hardware is made by Dantec, and comprises a Bragg cell and beam splitter system, a Fiber LDV transmitting optic with integrated back-scatter receiving optic, a Fiber PDA receiving optic, a 58N70 Detector Unit with the photomultipliers, an additional external photomultiplier, a 2D BSA P60 Flow and Particle Processor, and a PC with the acquisition software. The optics were mounted on a traverse system for easy and remote positioning of the measurement point.

The sprays to be analysed were not known a-priori, and it was not know if spherical particles had to be expect, allowing to measure their diameter by the PDA, or other kind of particles of which only the velocity could be measured. In any case, the tests were limited, so all possible data had to be acquired to obtain better statistics. Form this last point of view a back scatter LDV system has a larger measurement volume, the whole two beams intersection region, while the PDA optics uses only a narrow section of it [2, 3], thus decreasing the sampled data. The strategy was to implement both systems at the same time.

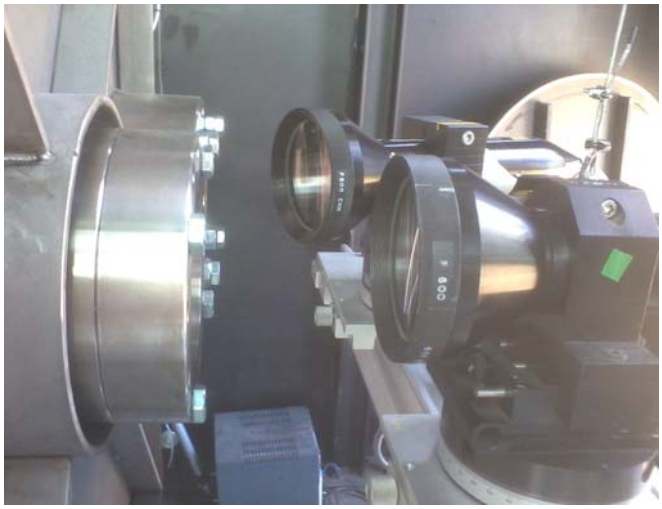


Figure 4: The optics: in front the PDA receiver, behind the LDV transmitter.

A traditional PDA system was set-up; with its receiving optics and detector unit. The spray axial velocity is measured a first time by the acquisition channel 1 (1st photomultiplier and 1st FFT processor board); the channels 2 and 3 are used together with channel 1 to measure and verify the particle diameter. A fourth external photomultiplier and the processor 4th board, normally used to measure a different velocity component, were here used to measure the axial velocity component from the particles seen by the back-scatter lens of the transmitting optics. In the following text, the two measured velocity will be called LDV-velocity (or LDA-1 by the Dantec software, from Laser Doppler Anemometry board 1), and PDA-velocity (or LDA-4); they are in principle the same axial velocity component of the particle seen by the two optics, with lower probability to detect particles by the PDA system, and also lower validation because non spherical particles are discarded.

Table1: LDV and PDA set-up

Laser: argon-ion, used on the green line (514.5 nm), for axial velocity component and diameter measurement
Bragg cell frequency (frequency shift): 40 MHz
Transmitting (and LDV receiving) optic focal length: 600 mm
Beam separation at the frontal lens: 38 mm
Nominal beam diameter ($1/e^2$) at the frontal lens: 1.35 mm
Nominal measurement volume size 290 290 9000 μm
Velocity range: -10 ÷ 30 m/s
PDA Receiving optic focal length: 600 mm
Scattering angle: 150º
Sensor order: reflection
Sensor aperture: mask A
Diameter range: up to 900 μm,

EXPERIMENTAL RESULTS

Preliminary test with water

To acquire some preliminary information about the jet brake-up pattern, few preliminary test were conducted at the Politecnico di Milano Department of Energy, on the three available nozzles, using water as test fluid. Since liquid sodium rheological properties are quite similar to water's ones, it can be expected that similar patterns, particle or droplet with similar velocity and diameters will be produced when using liquid sodium.

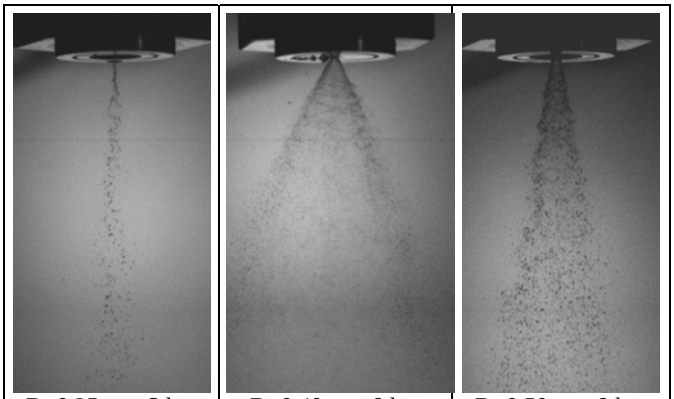


Figure 5: The three nozzles tested with water at different pressures. The nozzle cylindrical body has external diameter 20 mm

The PDA measurement volume was located along the geometrical injector axis, 80 millimetres downstream of the nozzle.

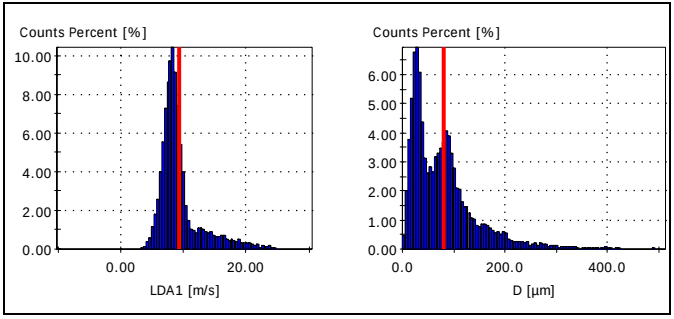


Figure 6: Nozzle D=0.50mm: example of velocity and diameter histogram with water at 9 bar.

Test with liquid sodium, overview

Five test were conducted on the four available injectors. The ambient gas, nitrogen or air, was always at atmospheric pressure and temperature (25-35°C).

Nozzle 0.25 was tested in nitrogen, with sodium at 550°C, 3 bar gauge (relative) pressure.

Nozzle 0.50 was tested in nitrogen with sodium at 550°C, 9 bar gauge pressure.

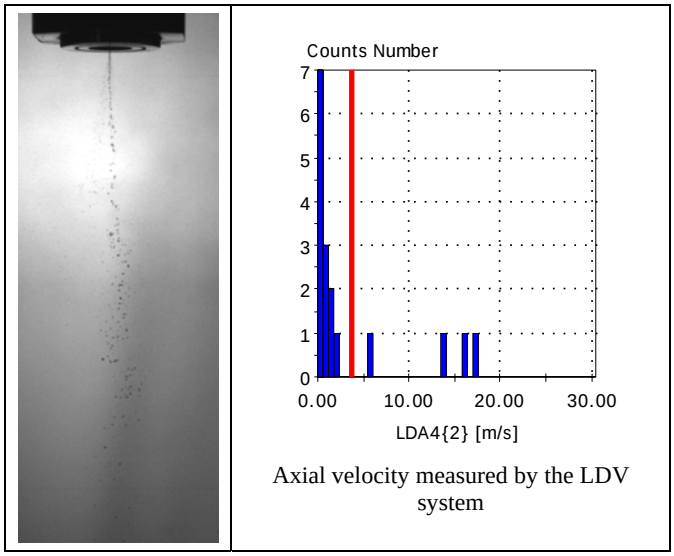
Nozzle 0.40 was tested in air, with sodium at 550°C, 9 and 6 bar gauge pressure.

The rupture diaphragm was tested in air, with sodium at 500°C, 6 bar gauge pressure. Ignition occurred only in this test.

For each test condition the results presented, are still images to observe the spray or jet pattern, LDV and PDA results, if available, and some comments and comparison with water results. The PDA measurement volume was located along the geometrical injector axis, 80 millimetres downstream of the nozzle. This distance is different from that of the water tests since the optical windows aperture of the test cell limited the accessible region of the spray.

Nozzle 0.25, in nitrogen, sodium at 3 bar

This nozzle was quite small, and got clogged quite soon. The jet produced showed a break-up process in the Rayleigh regime, with few particles produced with size comparable or larger than the nozzle diameter. PDA measurement gave no results since the few droplet produced did not cross the measurement volume. Few LDV results measured few particles at 15 to 20 m/s (where Bernoulli limit is 27 m/s), and a dozen of nearly standing particles.



Axial velocity measured by the LDV system

Figure 7: Results from Nozzle 0.25 mm, in nitrogen, sodium at 3 bar.

The atomization pattern is quite similar to the one obtained with water, with larger particles and poor atomization. No immediate chemical reactions were observed on the concrete target.

Nozzle 0.50, in nitrogen, sodium at 9 bar

The spray produced in this test was successfully measured with all the techniques used. The initial liquid break-up generated a conical sheet and then a spray; after few seconds the atomization became poor and switched to the Rayleigh break-up regime [4].

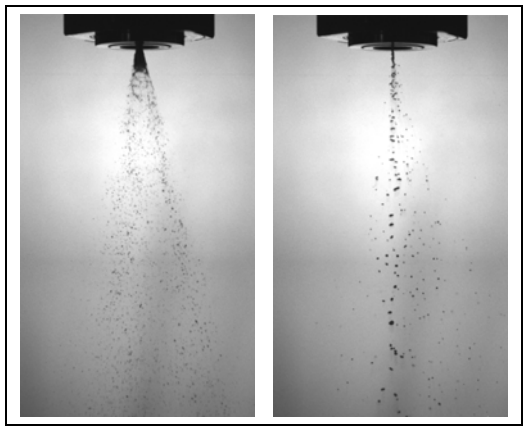


Figure 8: Two images from Nozzle 0.50 mm, in nitrogen, sodium at 9 bar. Initial spray (left) and after few seconds (right)

The LDV and PDA systems sampled enough droplets to calculate meaningful statistic values, presented by histograms. Axial velocity ranged up to 30 m/s, with the average value around 12 m/s. Droplet diameter show the typical spray log-normal distribution, here with a peak around 120 microns and maximum measured value up to 900 microns. The average calculated moments are: D_{10} = 177 µm, D_{20} = 240 µm, D_{30} = 301 µm, D_{32} = 472 µm (for a definition of droplet moments refer e.g. to [4, 5, 6]).

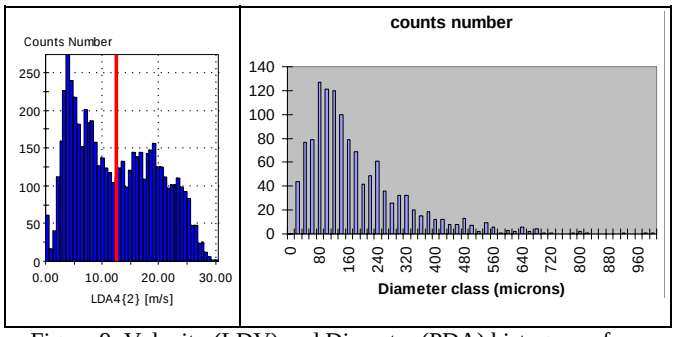


Figure 9: Velocity (LDV) and Diameter (PDA) histograms from Nozzle 0.50 mm, in nitrogen, sodium at 9 bar.

The initial spray angle is similar to that obtained with water, but with larger particles, then the nozzle probably started to get clogged.

Nozzle 0.40, in air, sodium at 9 and 6 bar

The break up pattern of this jet showed the typical behaviour of a swirled spray development. Compared to water, the spray angle is narrower and the particles are larger. The particle shape is not always spherical, probably the fast cooling in cold air is affecting the liquid viscosity and surface tension.

The sodium pressure was then lowered to 6 bar without interruption, and the spray kept stable for a few seconds, but no images are available since the camera memory was full. Later the nozzle started clogging, and the shape of the jet turned to something similar to an extrusion of high viscosity liquid, with a residual swirl, as shown by the following figures.

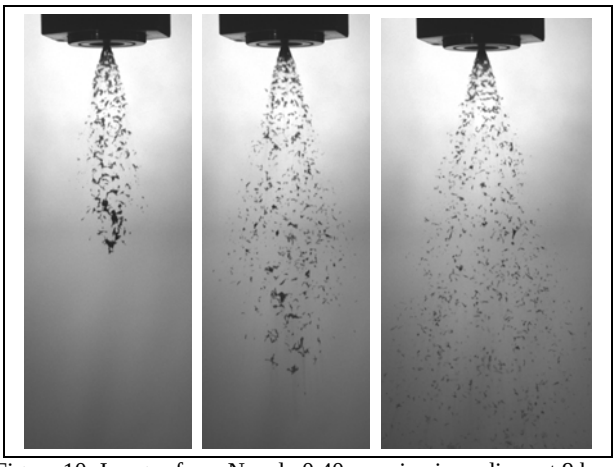


Figure 10: Images from Nozzle 0.40 mm, in air, sodium at 9 bar. initial spray development

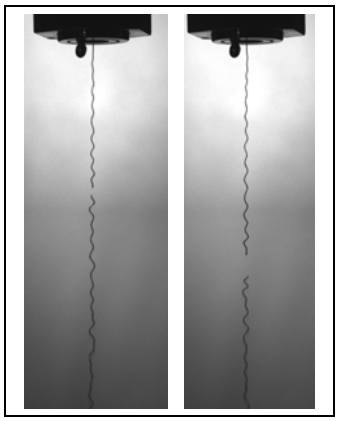
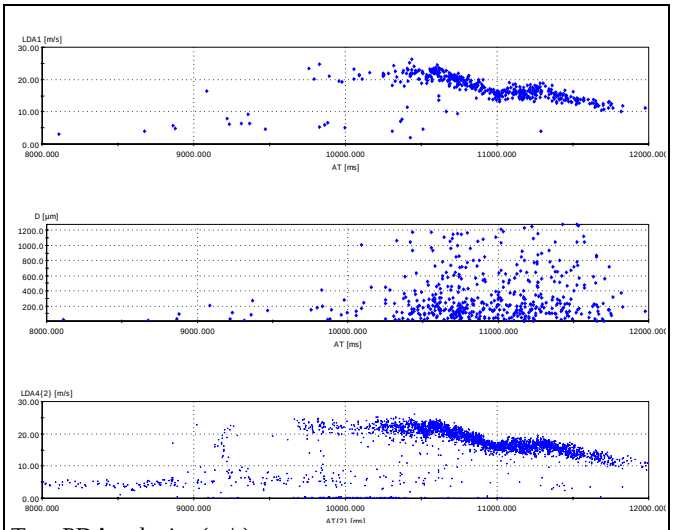


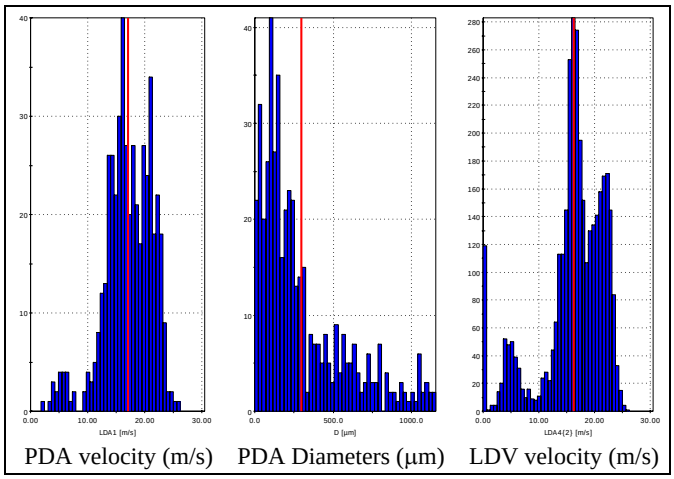
Figure 11: Images from Nozzle 0.40 mm, in air, sodium at 6 bar. Nozzle getting clogged. A small leakage is also visible close to the nozzle.

The LDV system collected sufficient data during the spraying stage, with velocity ranging from 0 to 25 m/s. The time evolution clearly shows the velocity decrease when passing from 9 to 6 bar; in the histograms this appears as two peaks around 16 and 25 m/s.



Top; PDA velocity (m/s)
Centre: PDA Diameters (µm)
Bottom: LDV velocity (m/s)

Figure 12: Results from Nozzle 0.40 mm, in air, sodium at 9 and 6 bar. Velocity and diameter time evolution. Each dot is one detected particle.



PDA velocity (m/s) PDA Diameters (µm) LDV velocity (m/s)

Figure 13: Results from Nozzle 0.40 mm, in air, sodium at 9 and 6 bar. Velocity and diameter histograms

The velocity data form LDV and PDA are well matching, with LDV data being 10 times more numerous. Diameters went slightly out of range, so accurate average values can not be calculated

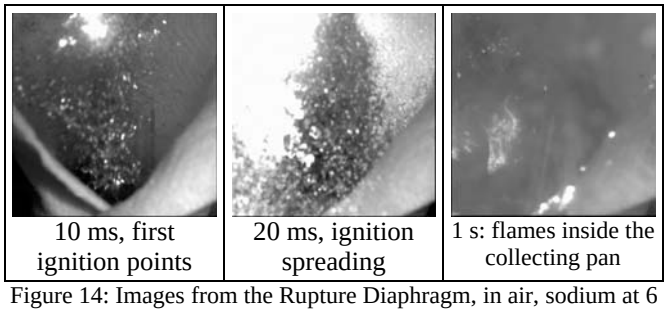
It is important to note that no ignition occurred in this test in air.

Rupture diaphragm, in air, sodium at 6 bar

For this test the LDV-PDA system was removed, since no particles suitable for this instrument can be expected, while the large amount of sodium to be ejected at once would have exposed the instrument to useless risks.

The collecting pan placed below the injector was also surrounded by glass-wool to reduce possible spreading of sodium droplets toward the observation windows.

Ignition started already from a small leakage before reaching the target temperature of 500°C. When pressure was applied and the diaphragm broke, ignition occurred in many point of the jet before it could reach the collecting pan, that is in less than 10 ms. After 20 ms the ignition had propagated to most of the jet. After 30 ms all the ejected sodium was burning, the video camera was completely saturated and could not deliver useful images for 1 second, after which a flame was clearly visible inside the collecting pan, but image quality was lowered by the deposition of smoke on the observing window. Than the cell was purged with nitrogen up to flame extinction.



10 ms, first ignition points | 20 ms, ignition spreading | 1 s: flames inside the collecting pan

Figure 14: Images from the Rupture Diaphragm, in air, sodium at 6 bar. Time is given approximatively after the rupture.

CONCLUSION

A first test was performed on liquid sodium with high speed cinematography and Laser Doppler and Phase Doppler measurements. The procedure and the measurement systems were successfully implemented, with a new peculiar

LDV+PDA implementation that can be easily obtained with the commercial existent instruments. The results show that the molten sodium in some condition behaves like water as regard the break-up patterns, but poorer atomization and larger particles. Velocity and size of sodium droplet are measured for the first time. About the ignition, it did not occur when the injected sodium flow was quite small, while it occurred immediately and strongly when a large amount of sodium was delivered at once.

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