BENCHMARK TESTS OF THE PRESSURE SENSITIVE PAINT SYSTEMS DEVELOPED WITHIN THE EUROPEAN WINDTUNNEL ASSOCIATION (EWA)

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OVERVIEW

A description of a series of benchmark tests that has been undertaken on the PSP systems currently under development within the European Windtunnel Association (EWA) is given. These systems are used to provide global surface pressure measurements on models tested in European wind tunnels. Systems utilising the intensity and lifetime techniques were included in these tests. The test programme was specified to investigate all aspects of system performance under accurate laboratory conditions, e.g. accuracy and the speed of data processing, and also issues that are experienced with system use, e.g. reflection and temperature hysterysis effects. The tests also included an investigation of calibration chamber performance. Analysis of the acquired data has demonstrated a high capability in the use of the PSP technique within the EWA community.

1. INTRODUCTION

The use of pressure sensitive paint (PSP) can provide significant advantages over traditional transducer based surface pressure measurement techniques. The potential benefits have resulted in the development of several PSP systems within Europe.

It was decided to undertake a series of benchmark tests of the systems developed within the EWA network to allow an accurate assessment of the relative performance of each system. The aim of the programme was to generate a test set that represented those issues commonly experienced when operating PSP systems in wind tunnels. These issues include temperature hysteresis effects, reflection and shadow issues as well as model deformation in non-uniform light fields. By separating the test sets it would be possible to address and quantify each issue in isolation thereby simplifying the development process.

The benchmark test programme presented in this paper was undertaken during 2006 and systems from the following organisations were included:

BAE Systems
CIRA
DLR
DNW
ONERA
Von Karman Institute.

All of the systems were of the intensity type apart from the BAE Systems system which used the lifetime technique. Information about these systems can be found in References 1 –9.

The tests were carried out using test pieces mounted in a calibration chamber where the effects of changes in test conditions, e.g. temperature, pressure and illumination angle could be examined under accurately controlled and repeatable laboratory test conditions. The chamber had to be capable of generating the temperature and pressure conditions produced in a wide range of wind tunnels.

The calibration chamber is a very important tool in the use of pressure sensitive paint. It was therefore decided that the PSP system benchmark tests were to be preceded by a series of calibration chamber benchmark tests. These tests are presented in Section 2.

The PSP system benchmark tests are discussed in Sections 3 and 4.

2. CALIBRATION CHAMBER BENCHMARK TESTS

The calibration chambers included in this phase of the tests were provided by BAE Systems and DLR.

These two chambers are of very different design, DLR – small volume and BAE Systems – relatively large volume. The benchmark tests provided an opportunity to assess the performance of these two design approaches.

2.1. BAE Systems Calibration Chamber

The BAE Systems calibration chamber is shown in Fig. 1 and its specification is as follows:

Pressure Range:	0 – 3 bar
Temperature Range:	-20 ^{0}C to +50 ^{0}C
Other Requirements:	Standard UK 13A 240V, dry air supply.

The main viewing panel at the front of the chamber is 150mm diameter. All the viewing panels are made from fused silica for good transmission at visible wavelengths. The test pieces were mounted on a 35mm diameter turntable.

The BAE approach is to control the temperature of an intermediate fluid via a cooler and a heater. The fluid circulates through a heat exchanger at the rear of the chamber, and a fan circulates the air in the chamber over the test piece and holder mechanism. There are two thermal breaks to ensure that the air is at a constant temperature and the PRT transducer is mounted in the airflow at the sample location. A schematic view of the chamber is shown in Fig. 2.

A Druck PDCR910 pressure transducer is used for pressure measurement and a 100 ohm Platinum Resistance Thermometer (PRT) for temperature measurement. The pressure transducer is placed in the supply line to the chamber which is at the chamber pressure.

It can be seen that the BAE Systems chamber has a relatively large volume of accurately known conditions. This enables 3-D shapes, such as cylindrical test pieces to be calibrated.

2.2. DLR Calibration Chamber

The DLR calibration chamber is shown in Figs. 3 and 4 and has the following specification:

Pressure Range:	0 – 3.5 bar
Temperature Range:	0 ^{0}C to +60 ^{0}C
Other Requirements:	Power supply (240V), water for Peltier device.

The quartz viewing window has a diameter of 75mm and the chamber has a depth of 50mm. Primary temperature control is achieved through heating and cooling of a large copper block on which the sample is placed in good thermal contact. The heating and cooling is achieved with a Peltier effect cooler/heater with cooling water for heat rejection. The volume of the DLR chamber is deliberately kept small to enable precise control of pressure and provide a rapid temperature change capability. This limits its use to the calibration of flat test pieces. The chamber is controlled by computer and the overall system is shown in Fig. 5.

2.3. Test Instrumentation

The primary instrumentation used for validation of the results from the chambers was an Agema infrared camera.

2.4. Calibration Chamber Tests

The calibration chamber benchmark tests were performed using the intensity method with the standard set up of DLR using a 12bit PCO Sensicam CCD camera equipped with a 650FS80 filter and an Xe flash lamp equipped with FITCA-40 bandpass filters for the emission of blue excitation light.

A steel test piece painted with PtTFPP based paint was used in this test programme. The dimensions of the test piece were 300mm square and 3mm thick.

The main item of instrumentation used to compare the temperature profiles in the chambers was an IR camera.

The data were acquired for a large number of test points within the following range:

Temperature	-10^0C to 40^0C
Pressure	1000 mbar to 3000 mbar

3. PSP BENCHMARK TESTS

3.1. Test Pieces

The following four test pieces were used in the benchmark tests. They are shown painted with PSP and the positional markers fitted in Fig. 6.

Each test piece was designed to investigate one particular area of uncertainty in the application of PSP. Thus the flat plate investigated thermal effects, the 90^0 corner test piece the reflection problem, the cylindrical test piece the effects of surface curvature and the excrescence test piece the effects of model movement and deformation.

The size of the test pieces was determined by the dimensions of the BAE Systems calibration chamber and they were of a suitable design, e.g. low thermal capacity, to minimize problems due to temperature effects.

1) Flat plate test piece.

The steel plate was 30mm square and 3mm thick.

2) 90^0 corner test piece.

The steel test piece comprised of two 30mm square plates at 90^0 degrees to each other. The plates were 3mm thick.

3) Circular cylinder test piece.

The test piece was of varying diameter 10mm, 20mm and 40mm. Each section of the steel test piece had a height of 10mm.

4) Excrescence test piece.

This test piece was a 30mm square plate with a cylinder of 5mm diameter extending 20mm from the centre. The cylinder was present to produce a shadow over the area of interest. The plate was 3mm thick.

Each test piece was positioned in the calibration chamber using a single mount which had been designed for use with all the test pieces. This ensured accurate positioning of the test pieces throughout the test programme.

3.2. Paints

The paints tested by each test participant were as follows:

BAE Systems	BAE 2577/92/200.
CIRA	ISSI Unicoat 405 and ISSI BUNC405.
DNW	DLR02 and ISSI BUNC405.
ONERA	ON1.
VKI	ISSI Unicoat.

3.3. Calibration Chamber

The BAE Systems calibration chamber allowed the testing of this range of test pieces and it was therefore decided to use this chamber during these paint characterization tests.

4. TEST PROGRAMME

A test programme was agreed by all test participants which would provide a thorough examination of the performance of each pressure sensitive paint system and its ability to overcome the major problems encountered when using the PSP technique. The PSP systems were benchmarked under a range of test conditions, representative of both low and high speed testing. The temperature of the chamber was varied between -10^0 and 40^0 and the pressure between 200mbar and 3000mbar.

The following section gives a description of the topics that were investigated:

a) Temperature and Pressure Calibration.

The flat plate test piece was installed in the calibration chamber to allow a thorough calibration of the paint to be undertaken. Data were acquired for a large series of temperatures and pressures representative of a wide range of wind tunnel test conditions. Analysis of the results would identify any pressure, or more likely, temperature hysterysis effects.

b) Light Intrusion/Filter Leakage Effects

Interference filters are very efficient. However, they are sensitive to the angle of incidence of the incoming light. As the angle moves away from 90^0, then more and more of the unwanted light strays through. So, in the case of a camera lens, if the filter is placed in an area of parallel light then the system operates satisfactorily. However, if it is placed in a converging area, the edges start to leak light. With a badly designed camera arrangement, areas of the image towards the edges of the field of view will display the wrong pressure. The camera was positioned close to the chamber window so that the flat plate filled the field of view. The acquired images were examined to determine if any pressure gradients were displayed, especially towards the edges of the field of view.

c) Self Illumination - also known as the reflection problem

This test investigated the case of a low pressure region on a wing (which emits brightly) reflecting on the nearby fuselage and creating a ‘ghost’ pressure map. A similar effect can happen when, due to model deflection, the intensity on a particular area increases due to reflection from a nearby component which has moved.

This effect was replicated by using the 90 degree corner test piece. A small nitrogen jet was applied to one face to increase the intensity of the paint. The other face was examined to determine if a ghost image had been formed. A 0.5mm hypodermic tube and compressed nitrogen supply were used to create the jet. The use of a mounting block ensured that the hypodermic tube was always in the same position throughout the series of tests.

This test was undertaken outside the calibration chamber because of the effects that would be introduced by the addition of the nitrogen in the jet into the volume surrounding the test piece.

d) Effects of Surface Curvature on Accuracy

The measurement of steep pressure gradients on highly curved surfaces is of interest, e.g. leading edges. This test was included to examine the ability of each system to correct for, or determine insensitivity to, surface curvature. The test was undertaken using the cylinder test piece. The performance of the systems can be reduced when viewing the area of interest at oblique angles due to the elongation of the laser spot or image pixel.

The sensitivities of the systems to this problem were investigated by undertaking tests during which small pressure changes, 10 mbar steps, were produced.

e) Model Deformation Image Registration Problem

The effect of model movement due to, for example strut deflection, was investigated using the excrescence test piece. The camera and light source were attached to an accurate micrometer mount to ensure that good positional repeatability was achieved. They were translated by small distances e.g. 1mm, to mimic model movement. The cylinder had been added to create a shadow, and changes in the shadow position made any problems more apparent.

5. DISCUSSION OF TEST RESULTS

This series of benchmark tests has enabled an examination of the status of the PSP technique within the EWA network together with the identification of areas that require further technique development. The tests and test pieces were configured to investigate those problems that may typically occur during a PSP wind tunnel test including reflection, temperature hysterysis and changes in paint illumination resulting from model or light source movement.

A large amount of information about the performance of the paints was obtained during these tests.

The results obtained during this test programme demonstrated that cameras with a minimum of 14-bit resolution are required to resolve small pressure changes.

The following section gives a description of the major results and conclusions.

5.1. Calibration Chambers

A comparison of two environmental chambers used for the calibration of pressure sensitive paint has been undertaken. The chambers were provided by BAE Systems and DLR. They are shown in Figs. 1- 5.

The chambers are fundamentally different in the way in which they control temperature.

The BAE chamber needed much longer, especially to change temperature set point, than the DLR chamber, but it's bigger volume allowed the use of various samples with special geometries and was thus the better choice for use in this series of tests.

The acquired data showed that both chambers provided a similar performance.

It has been shown that the temperature validation method, using an IR camera, can be in error due to the way in which IR cameras acquire data. The camera records total IR radiation on a pixel – this can then be approximated to temperature through some assumptions. In this case, the assumption of emmissivity of the paint was in error. The measurement of apparent temperature gradients within the chambers is more worrying and suggests that problems exist with the IR measurement technique in tests of this kind.

5.2. System Benchmark Tests

A typical test set up used during the tests is shown in Fig. 7. The calibration chamber, camera and illumination source are displayed. Fig. 8 shows a close-up view of the camera, fitted with filters, and illumination source.

5.2.1. Temperature

A series of tests was undertaken in which data were acquired at a baseline condition of 1000mbar and 10^0C. The sample was then sequentially heated to 20^0C, 30^0C and 40^0C at constant pressure, and returned to the baseline condition between each temperature point. Data were acquired at each test condition. This test allowed the examination of the effect of temperature on sensitivity and the determination of any temperature hysterysis effects.

The variation of temperature did cause a change in the sensitivity of the paints. A typical value of 0.5% / ^{0}C was observed.

Temperature hysterysis of typically 1.5% was observed during these tests. This creates errors in the data acquired and is a subject that requires further investigation in order to determine the causes of the problem. It is thought to arise from changes in the polymer structure of the paint.

5.2.2. Pressure

The pressure was varied within the range 200 mbar to 3000 mbar. It was found that the pressure sensitivity of the paints was in the range 0.055% to 0.07% / mbar.

Only one system / paint combination showed any pressure hysterysis. This result was not expected and is currently being investigated.

All systems showed that at low pressures the larger luminescence signal resulted in improved pressure resolution compared to ambient conditions.

5.2.3. Surface Curvature

All systems and paint combinations performed well and could extract useful pressure data up to highly oblique viewing angles. However, the effects of sample movement reduced the effective viewing angles and introduced some unwanted effects.

5.2.4. Self-Illumination

In general, the results displayed problems when self illumination was investigated using the 90^0 corner model. A 'ghost' image was produced in some cases on the opposing face of the model. This resulted in the generation of inaccurate results in the affected area. The magnitude of the problem depended on the surface finish of the paint and was significantly reduced by ensuring that the paint surface was of a matt nature. The effect can be seen clearly in Fig. 9 where the left image displays the results obtained with a gloss surface finish and the right with a matt finish. The effect can also be reduced within the analysis software in the case of diffuse paints. This problem is encountered in several areas over the model surface, e.g. wing body junctions, and is a topic in which the technique requires further development to allow accurate data to be obtained in these important parts of the model.

5.2.5. Illumination and Camera Movement

This phenomenon was investigated using two of the models – the circular test piece and the excrescence test piece. In both cases, both camera and light source were moved by small and precise distances on micrometer controlled translation stages. Images were taken at both baseline and deflected conditions. A set of images was taken at the base line positions immediately after return from each light / camera movement. The tests replicated the effects of model and sting deflection within non-uniform light fields in working sections. The separation of camera movement from light source movement allowed the effects of pixel-pixel variations to be eliminated.

A lot of difficulty was caused by reflections in the viewing window. This was surprising considering the ideal conditions, i.e. small time delay between each acquisition and the highly repeatable lighting conditions.

The systems performed well and produced satisfactory results when the position of the camera was altered. However, the movement of the light source resulted in the creation of inaccurate results. Binary paints have been developed, together with the appropriate analysis software, to remove problems associated with changes in illumination. The results acquired during these tests suggest that this approach requires further attention.

As expected for an optical diagnostic system, none of the PSP systems allowed the measurement of surface pressure within the area of a shadow.

6. CONCLUSIONS

This series of tests have provided a large amount of information about the current status of the PSP capability within the EWA network. They have also promoted significant cooperation and collaboration between the different development groups. Of critical importance was the generation of a standardised set of test geometries that can be used to quantitatively investigate the problem areas commonly encountered during wind tunnel tests using PSP. These data sets, test pieces and test procedures have provided a quantum leap in the development of PSP systems by providing a sound basis for comparison of systems and by allowing the separation of the complex environmental interactions encountered in wind tunnel testing.

Another series of benchmark tests is currently being undertaken in which the following topics are being examined:

1) Data processing.

a) Synthetic images will be produced to allow an investigation of the capability of the different software packages to remove errors.

b) A set of representative measured images obtained during a wind tunnel test will be analysed by each system.

2) Unsteady pressure measurement.

The time response of the systems will be examined to determine the capability of each system to measure unsteady surface pressures. The ability to measure unsteady pressures up to the kHz range will be investigated.

3) Further analysis of temperature hysterysis effects.

7. REFERENCES

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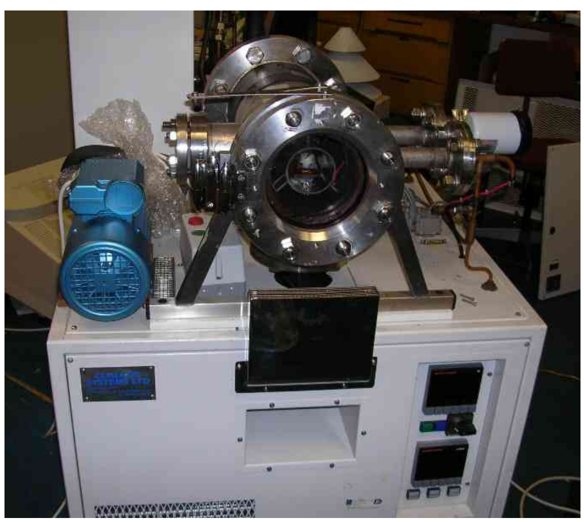


Fig. 1. Photograph of the BAE SYSTEMS Calibration Chamber.

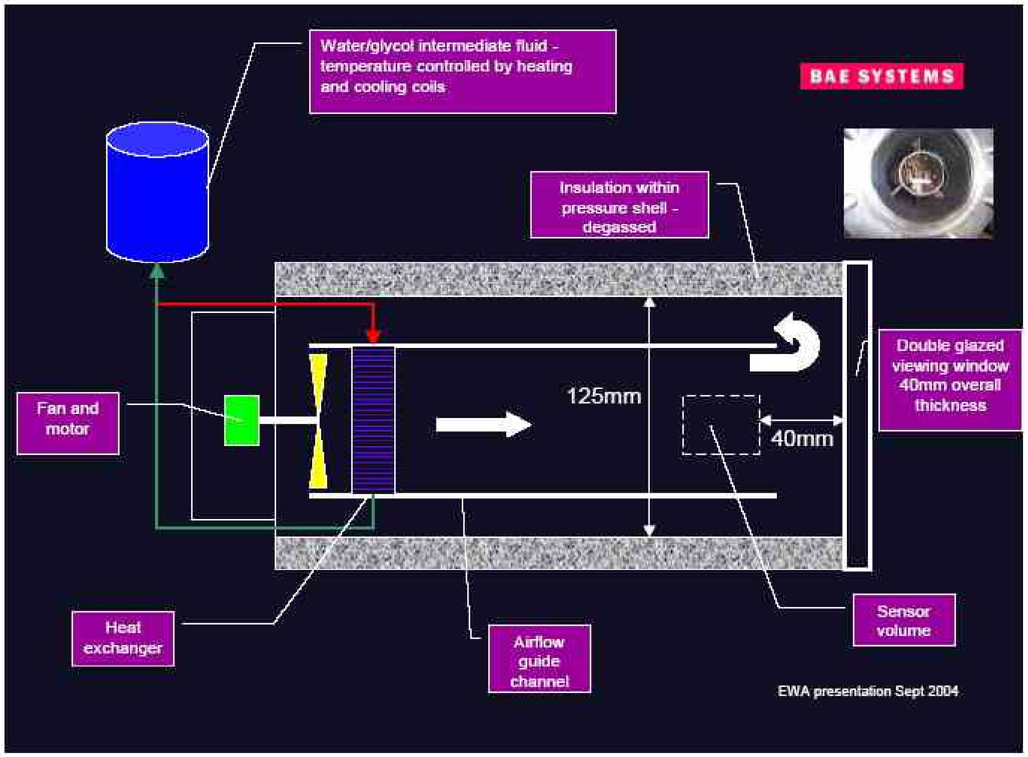
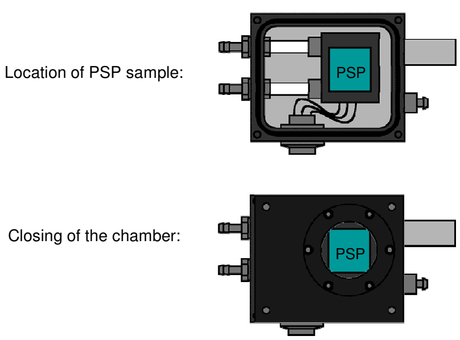


Fig. 2. Schematic of the BAE SYSTEMS Calibration Chamber System.



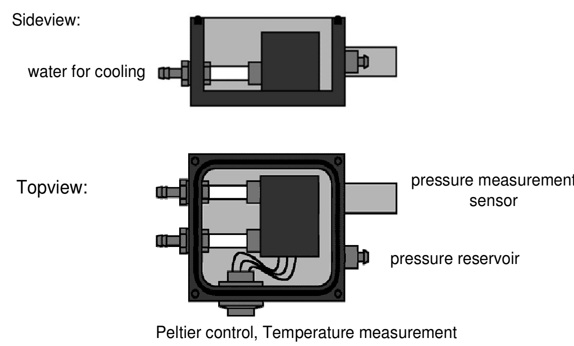


Fig. 4. DLR Calibration Chamber.

Fig. 3. DLR Calibration Chamber.

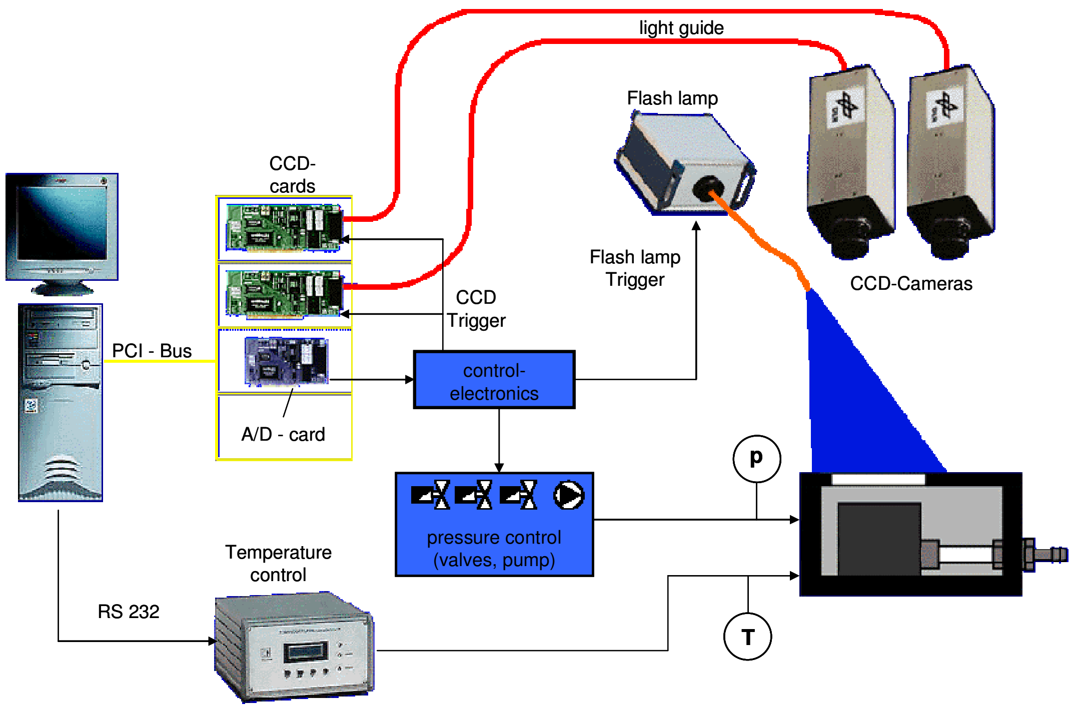


Fig. 5. Set up of the DLR Calibration Chamber.

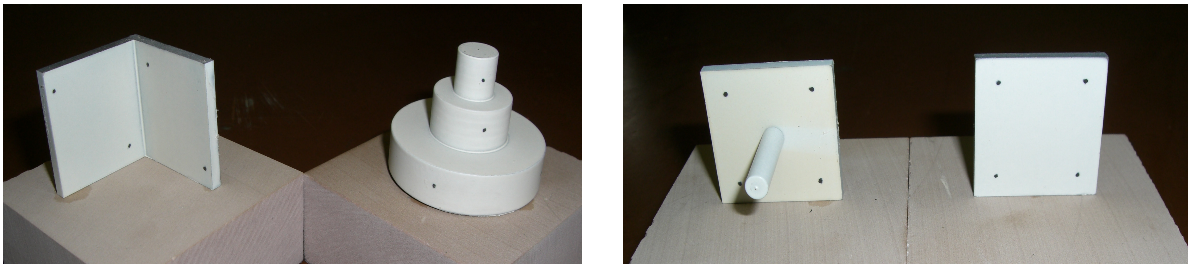


Fig. 6. Painted test pieces.

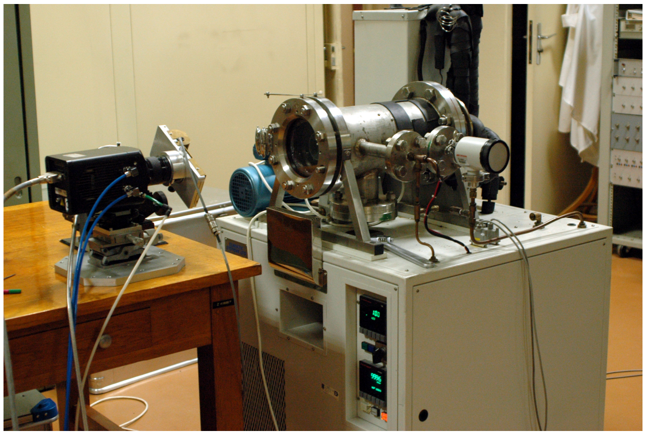


Fig. 7. Typical view of the test setup.

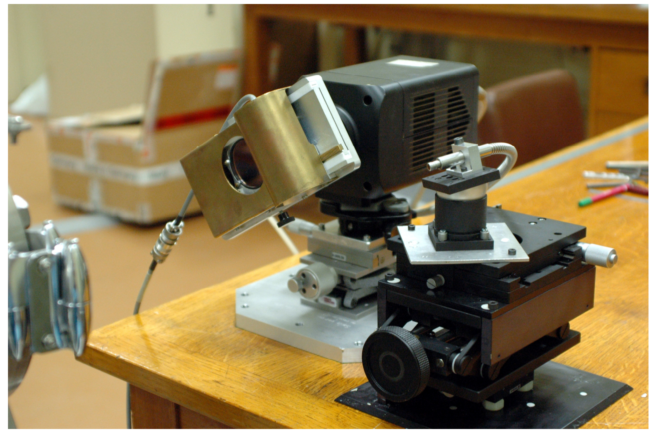


Fig. 8. View of the camera and optical fibre.

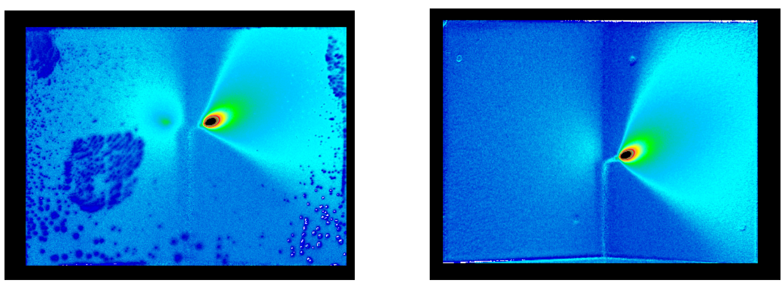


Fig. 9. Nitrogen jet on the corner test piece.