Session 5 - Optical Measurements

BOUNDARY LAYER TRANSITION DETECTION IN TRANSONIC FLOWS BY LASER TRANSIT VELOCIMETRY

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1. INTRODUCTION

In order to develop transonic profiles for which the boundary layer is relaminarized by suction, the location where the boundary layer naturally transits from laminar to turbulent has to be known. Mechanical probes, such as hot wires probes, suffer from interaction between the probe and the boundary layer. Especially at transonic velocity the physical presence of such probes may affect the whole flow field.

Optical velocimeters, such as laser doppler anemometers (LDA) and laser transit anemometers (LTV), also called laser dual focus anemometers (L2F), are now commonly used to explore a flow field. The LDA can be used in very turbulent flows and even in regions where the flow is completely separated. One of the drawbacks of the LTV is the maximum turbulence level of the flow that can be achieved. Because of the requirement to align both light spots of the control volume with the velocity vector, only flows with low turbulence level can be examined with such a system. However, the LTV can be extremely useful when low levels of turbulence are to be measured. This ability to measure very low turbulence intensities allows to determine where transition from laminar to turbulent will take place.

2. CORRELATION COEFFICIENT AND TURBULENCE LEVEL

Applying LDV close to solid walls results in erroneous turbulence levels. As a matter of fact, the velocity gradient inside the boundary layer will be interpreted as a pseudo-turbulence. Compared to a LDV, a LTV has an extremely small probe volume. It consists of two light spots wherein all of the laser light is concentrated, allowing particles, even of a diameter of the order of 0.1 μm, to be detected. Using high quality optics, a spot diameter as low as 5 μm can be obtained, allowing to carry out correct measurements very close to the model.

Conventional laser transit velocimeters have a spot distance of the order of 0.5 mm. In order to increase the sensitivity to low turbulence intensities, the distance between both spots must be higher. Typically in our application the spot distance is between 2 and 3 millimeters. At low turbulence levels it is extremely difficult or even impossible to obtain reliable turbulence intensities from the velocity histograms. Therefore the signals $g_1(t)$ and $g_2(t)$, generated at the output of the photomultipliers, are cross-correlated according to the following expression:

$$F(\tau) = [\int_0^T g_1(t).g_2(t+\tau)dt] / T$$

where $F(\tau)$ is the correlation function, τ a time delay and T the integration time. The maximum of the correlation function is in relation to the turbulence intensity. When the boundary layer changes from laminar to turbulent a steep decrease of the magnitude of the correlation function is notified. In order to investigate the parameters having an influence on this property, in a first step, a theoretical model was used, based on a paper written by ERDMANN (Ref 1). In Ref 1 and 2 it is explained that the maximum of the correlation function (F_{max}) is given by:

$$F_{max} = A + B/(T*I)$$

In this equation A an B are constants related to the geometrical characteristics of the probe volume, T is the time of flight at which the correlation function is maximum and I is the turbulence intensity. With a suitable choice of A and B, it is possible to have an arrangement such as F_{max} varies rapidly with increasing turbulence intensity.

It is more convenient to transform the correlation function and to define the dimensionless correlation coefficient $CC(\tau)$ according to:

$$CC(\tau) = [\int_0^T g_1(t).g_2(t+\tau)dt] / \sqrt{\int_0^T g_1{}^2(t)dt \,.\int_0^T g_2{}^2(t+\tau)dt}$$

The correlation coefficient exhibits the same trend as the correlation function. An example of such an analytical calculation is given on Fig 1. The magnitude of its maximum drops abruptly when the turbulence increases. The width of the curve varies only slightly.

3. NUMERICAL SIMULATION

Although numerous papers are published on the working principle of transit velocimeters, it is not easy to discover fundamental theoretical work on particle statistics applied to transit velocimetry.

A numerical simulation of the method has been performed at the VKI by Prof Riethmuller (Ref 2,3) in order to evaluate the influence of several parameters such as the spot diameter, the spot distance, the particle concentration... Such a simulation allows the validation of the computer program, written to analyse the signals . A random number generator produces a large amount of tracers characterized by arbitrary values of their spatial position, velocity and life time. When a tracer crosses one of the "light spots" a clock is read and the result stored in the corresponding table for that spot. After the simulation, both tables are cross-correlated and the correlation coefficient is calculated. A result is shown on Fig 2, while the maximum of the correlation coefficient is plotted against the turbulence intensity on Fig 3. A decrease of 50% of the correlation coefficient is notified when the turbulence intensity changes from 0.1 to 0.2%. From such calculations one can conclude that the method is very sensitive to variations of the turbulence intensity.

4. Optics

Once it was decided, based on the theoretical results, to build a LTV suitable to detect very low turbulence intensities, the first step was to develop an optical head achieving the requirement of having a spot distance of the order of 2 or 3 mm with a spot size as small as possible. A lay-out of the first optical head used for this application is shown on Fig 4.

A quarter wave plate changes the laser light from linear polarization into circular. A Rochon prism generates two equal intensity beams. The angle between both beams is only 1°. A microscope lens with a focal distance of 4mm produces two focal points. With two mirrors and two lenses a real image of the light spots is projected into the test section. Light scattered by the tracers is collected by the same lenses, and by means of a second microscope objective an image of the test section spots is produced on the input of two optic fibers, each of them connected to a photomultiplier. A stepping motor allows to align the probe volume with the velocity and a mechanical transmission system assures correct light input into the optic fibers.

5. SUBSONIC VALIDATION

The technique was first applied to determine the transition along the center line of a horizontal pipe. The internal diameter was 14.2 mm. Water is supplied to the pipe by a reservoir with stabilized water level. The flow is realized only by gravity. There is no pump between the pipe and the liquid tank in order to avoid additional turbulence. The water level of the supply tank can be modified, allowing the velocity in the pipe and therefore the Reynolds number, to be changed.

First, using a laser **doppler** anemometer, the critical Reynolds number was determined at which the flow changes from laminar to turbulent regime. This was obtained by measuring the turbulence level and the velocity along the center line. Fig 5 shows the result. From this figure we could conclude that transition occurs at a Reynolds number between 1600 and 2300.

In the same test conditions the laser **transit** velocimeter was used in order to obtain the maximum value of the cross correlation coefficient. Fig 6 represents its magnitude as a function of the Reynolds number. The maximum drops abrubtly from 37% at Re=1750 to 10% at Re=2300. This allows to determine precisely where transition takes place.

6. TRANSONIC VALIDATION

A limited number of tests have been carried out at the CEAT in Poitiers. The model is a flat plate placed in the center of the test section. The free stream Mach number is 0.8. Suction is applied to remove the boundary layer along the tunnel walls. A Schlieren picture of the flow is given on Fig 7 and indicates that transition occurs at approximately 50 mm from the leading edge.

The probe volume is placed at 75 mm from the leading edge. The height (h) above the plate can be varied in such a way that measurements can be taken at different stations inside the boundary layer and in the main flow. At the moment the spot size is 20 μm, which is too important to detect the transition point based on the method explained in the present paper. However, the time of flight histograms , taken at different positions above the model, (Fig 8) clearly show that the turbulence decreases when the probe volume is displaced towards the undisturbed flow region. Near the wall 66% of the particles have a time of flight between 7.5 and 10 μs. Outside the boundary layer, where the flow has only very little turbulence, 70% of the particles have a transit time of 5 μs. In the main flow the number of counted particles is more important and the acquisition time less, compared to the measurements inside the boundary layer. There are two reasons for this: the turbulence intensity and the quality of the seeding. The correlation coefficient changes from 5.4% to 33% when moving the probe volume from h=0.8mm (inside the boundary layer) to 1.35 mm (in the main flow) above the model. Such values are quite reasonable.

7. CONCLUSION

The ability to detect low levels of turbulence by measuring the correlation coefficient of the time of arrival of particles through both light spots of a LTV permits to locate the transition point. This property has been demonstrated by a numerical simulation and validated by tests in a water tube. Priliminary tests in the transonic tunnel show an important difference between the histograms obtained inside and outside the turbulent boundary layer.

In the next future the optical head will be modified in order to decrease the spot size with a view to improve further the sensitivity of the present system.

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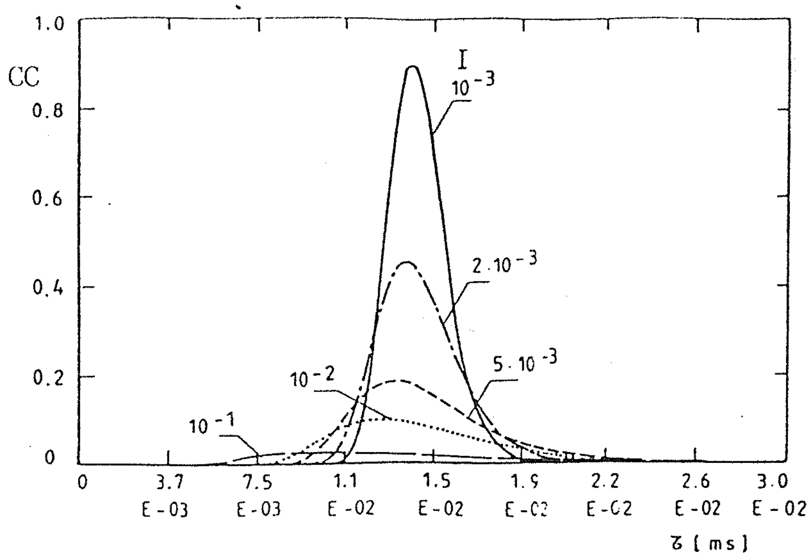


Fig 1

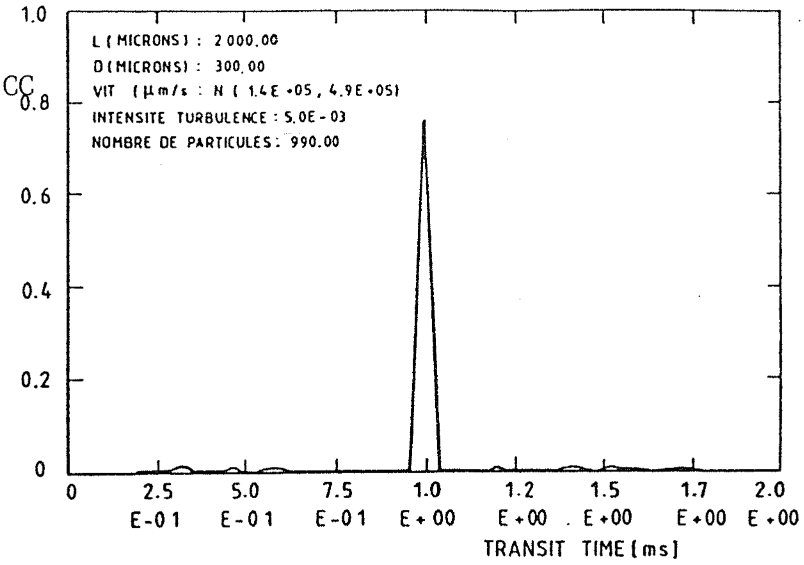


Fig 2

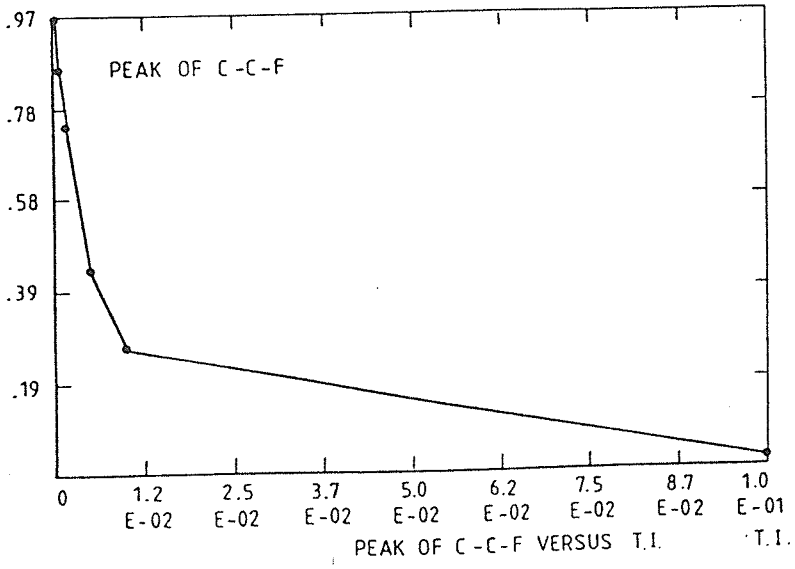
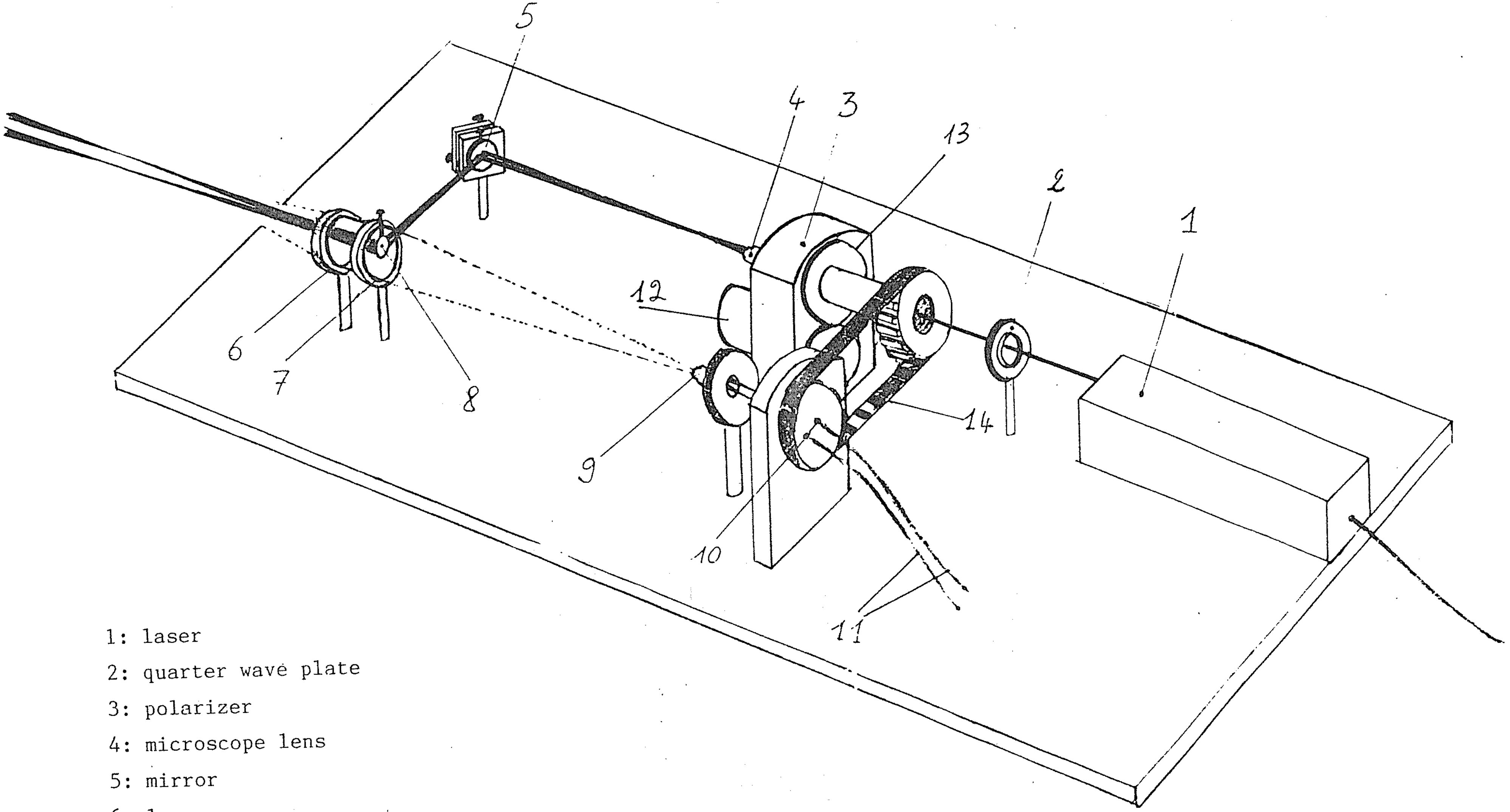


Fig 3



1: laser
2: quarter wave plate
3: polarizer
4: microscope lens
5: mirror
6: lens
7: lens
8: mirror
9: microscope lens
10: input couplers
11: optic fibres

Fig 4

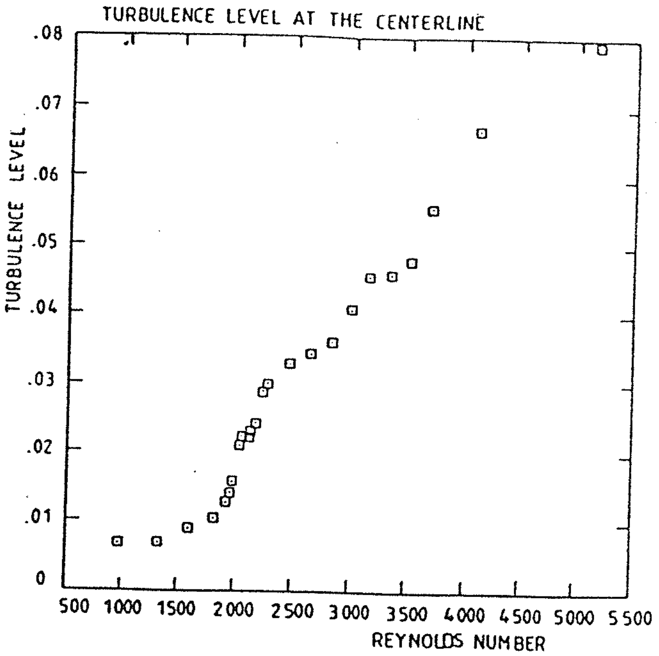


Fig 5

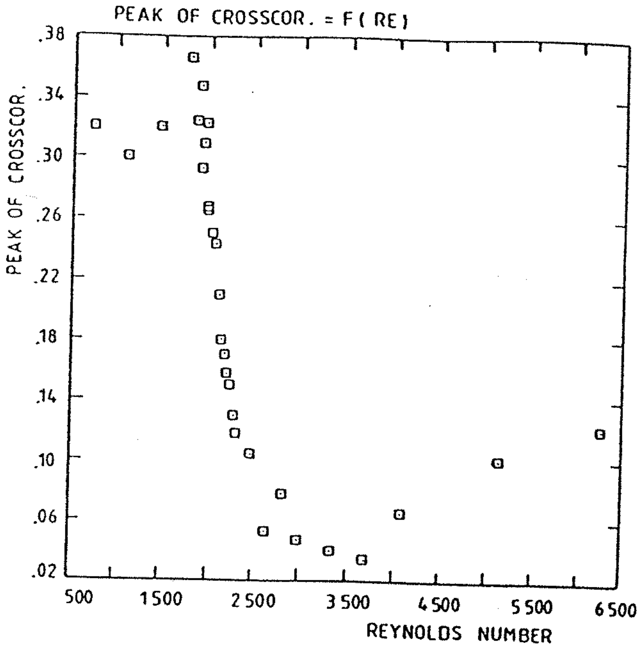


Fig 6

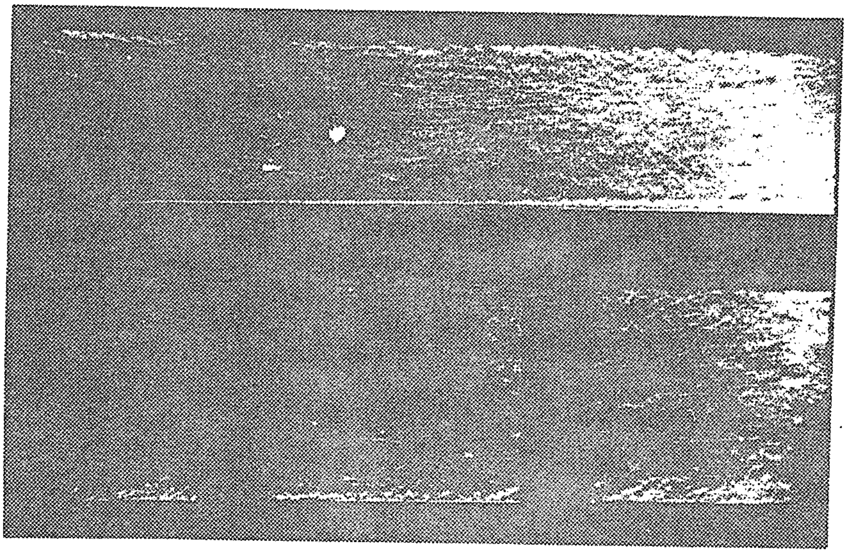


Fig 7

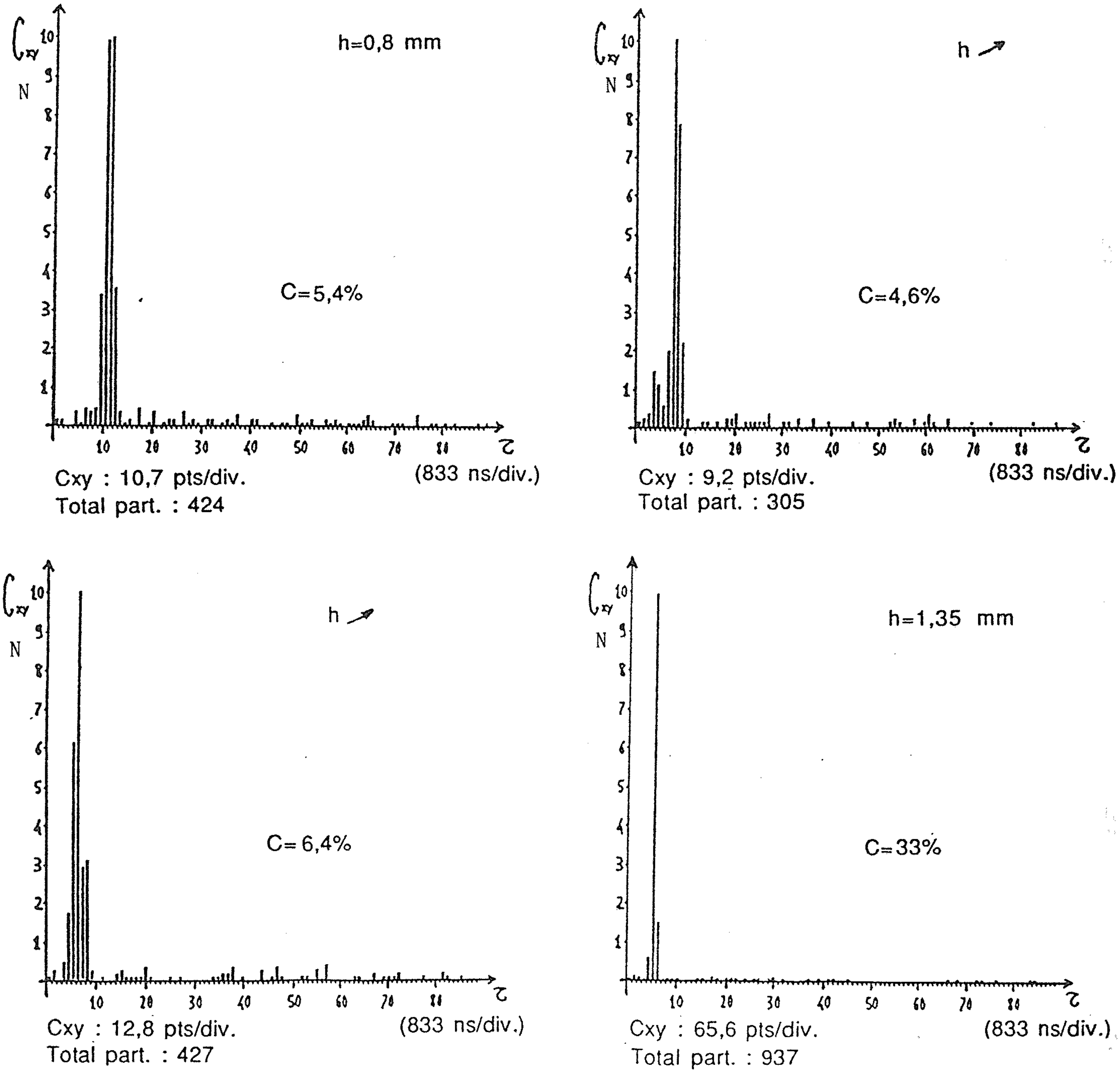

C_{xy}
N
1
2
3
4
5
6
7
8
9
10
h=0,8 mm
C=5,4%
10
20
30
40
50
60
70
80
τ
Cxy : 10,7 pts/div.
(833 ns/div.)
Total part. : 424
C_{xy}
N
h ↗
C=4,6%
τ
Cxy : 9,2 pts/div.
(833 ns/div.)
Total part. : 305
C_{xy}
N
h ↗
C= 6,4%
τ
Cxy : 12,8 pts/div.
(833 ns/div.)
Total part. : 427
C_{xy}
N
h=1,35 mm
C=33%
τ
Cxy : 65,6 pts/div.
(833 ns/div.)
Total part. : 937

Fig 8