Use of an isokinetic sampling probe.
Results in a cyclone

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Abstract.

To deepen our knowledge of the flow in cyclones, flow velocity and local solids concentration measurement techniques were developed. The flow consists of a high mass concentration gas-solid suspension (up to 2 kg of material per kg of gas) and a vortex generated by the cyclone. Sampling is a direct and simple method which doesn't require any calibration and enables to carry out chemical and grain size analyses on the collected samples. The descriptions of the probe used and of the testing procedure are followed by the presentation of results obtained in a cyclone. An analysis has permitted to characterize the inlet conditions of the suspension in the cyclone and to identify the characteristics of the vortex flow. Investigation of the efficiency per grain size range allows quantifying the phenomena revealed by the solids concentration measurements. The structure of the flow, identified owing to the experimental measurements, is closely dependent on cyclone geometry.

1. INTRODUCTION.

The study of a gas-solid suspension flow often requires expensive measurement means not really adapted to an industrial scale. LASER, for example, used in laboratories requires low solids concentration and very restricting testing conditions. Nieuwland et al. [1] compared quickly several measurement methods used for gas-solid two-phase flows. The optical-fiber probes, using transmission or reflection of the light, have to be calibrated. Strain gauge probes have the same drawback and are only used with small particles (Mann and Crosby [2]). The use of Capacitive probes is not suitable when electrostatic phenomena can occur (Hartge and al. [3]). Acoustic methods are, at present, developed to measure velocity suspension but require a second measurement method to determine solids concentration (Sheen and Raptis [4]).
For probes needing calibration, measurement accuracy is closely linked to the calibration quality.
Sampling is a cheap, simple and direct method. Aguillon and al. [5] have studied the influence of the probe tip geometry and of the extracting velocity on the measurement of solids concentration, but only in a circulating fluidized bed. Rhodes [6] has proved that, within specific conditions, isokinetism is not necessary to measure the local material concentration correctly.
This work deals with the creation and the use, within particular conditions, of an isokinetic sampling probe. A geometrical description of the probe and its principle are presented. This probe enables simultaneous evaluations of local concentration and suspension velocity.
After an explanation of the measurement procedure, we will present concentration and velocity profiles measured in a cyclone.

2. Measurement method.

The method enables the isolation of gas-solid flow from the main stream without disturbing the flow around the probe by ensuring isokinetism (the extraction velocity is equal to the velocity of the suspension at the measurement point). Probes used by Rhodes [6] and Aiguillon and al. [5], drawn in figures 1 and 2, are unable to obtain isokinetism. Velocity field characterization is required before concentration measurements.

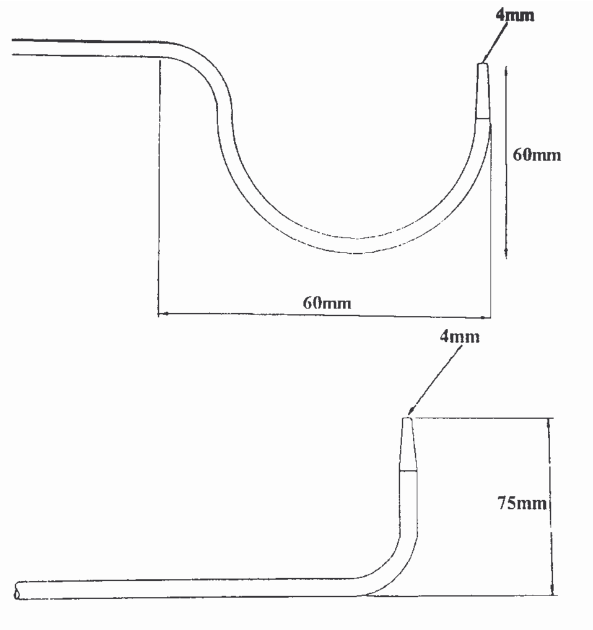


Figure 1: *Rhodes probes [6].*

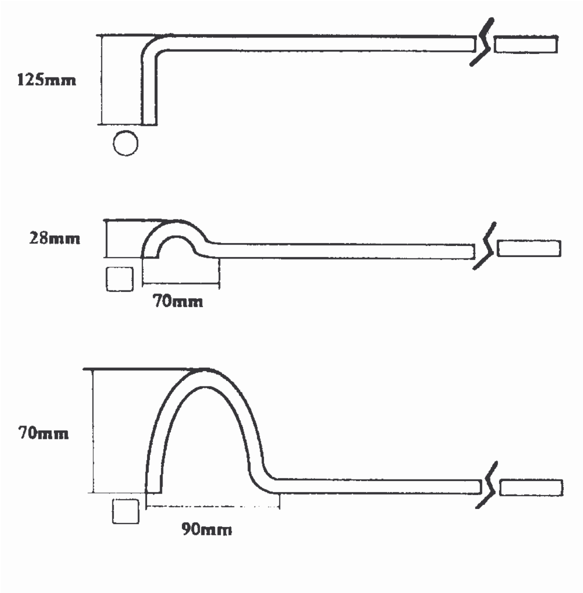


Figure 2: *Aiguillon and al. Probes [5].*

2.1. Equipment.

The probe is composed of a tip, placed in front of the flow, a filter element which separates the material from the gas (in our case, a microcyclone), a nozzle that measures the sampled gas flow rate and a jet vacuum pump that generates the negative pressure necessary for the extraction (figure 3). The filter and negative pressure generation elements have been borrowed from a Prat-Daniel probe.

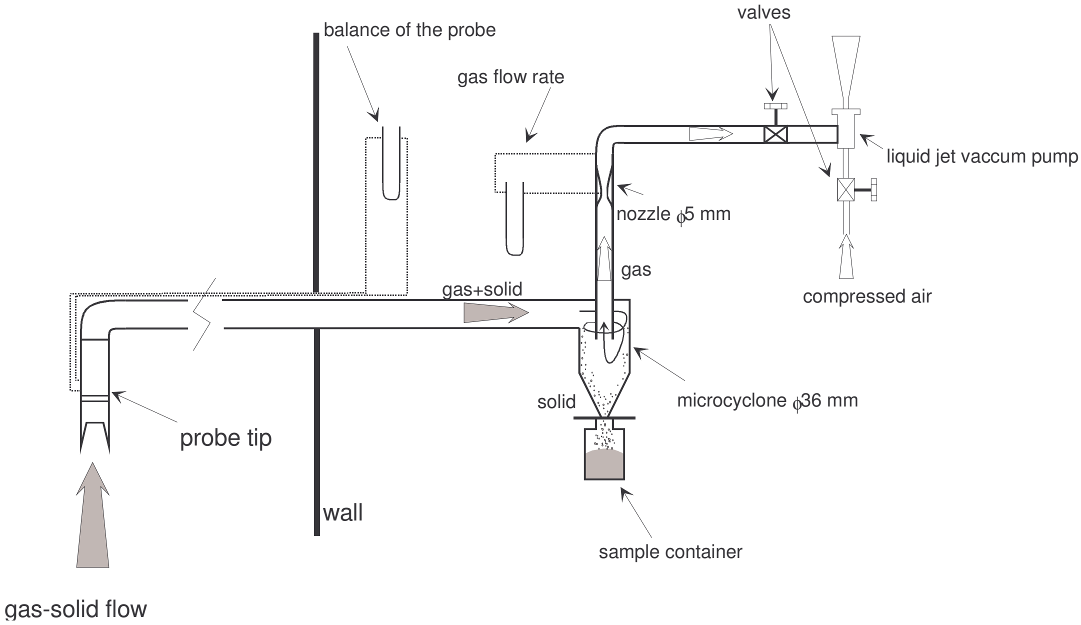


Figure 3: *Probe design.*

2.2. Operating mode.

The probe tip has two pressure intakes (P1 and P2). The geometry of the tip used is described in figure 4.

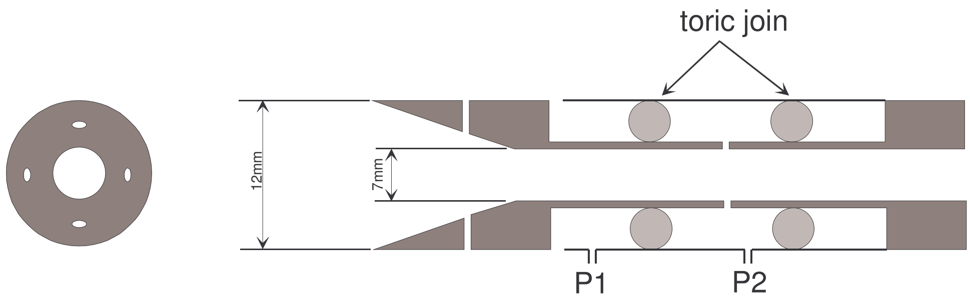


Figure 4: *Probe tip design.*

Pressure P1 represents the static pressure of the flow outside the probe, and P2 that of the inside flow. As the total pressure is the same for both flows, when static pressures P1 and P2 are equal, velocities of the suspension inside and outside the probe are equal too. The probe is then said to be ″balanced″.

Two regulating valves are available to balance the probe. The first one, on the compressed air circuit, controls the negative pressure of the jet vacuum pump, whereas the second, on the probe circuit, controls the extracted flow rate.

Once the material is separated in the microcyclone, it is collected in a container. Which is replaced at each measurement point.

The pressure drop of the nozzle, which has to be calibrated beforehand, gives information about the extracted gas flow.

2.3. Procedure.

The testing procedure of concentration and velocity measurement with the isokinetic sampling probe consits of :

- ⓿ placing the probe in the flow,
- ❶ balancing the probe with the regulating valves,
- ❷ shutting off the compressed air without resetting the valves, once equilibrium has been obtained (P1=P2),
- ❸ replacing the container under the microcyclone,
- ❹ turning on the compressed air (therefore, the probe is balanced),
- ❺ extracting the gas-solid flow during a period of time that should be measured with a chronometer,
- ❻ noting the nozzle pressure drop,
- ❼ shutting off the compressed air, as soon as an adequate quantity of material has been collected,
- ❽ replacing the container,
- ❾ repositioning the probe,
- ❿ repeating the operation.

The weight of the sample collected and the extraction time enables evaluation of the material flow rate whereas the gas flow rate is determined from the nozzle pressure drop. A simple division gives the local material concentration. The suspension velocity at the measurement point is equal to the extracting velocity since the probe is balanced.
Only the nozzle of the probe should be calibrated beforehand. This calibration can be carried out at an ambient temperature (figure 5).
Comparing the grain size of the product taken by the probe with that of the product collected in the container shows the separating capacity of the microcyclone (figure 6).

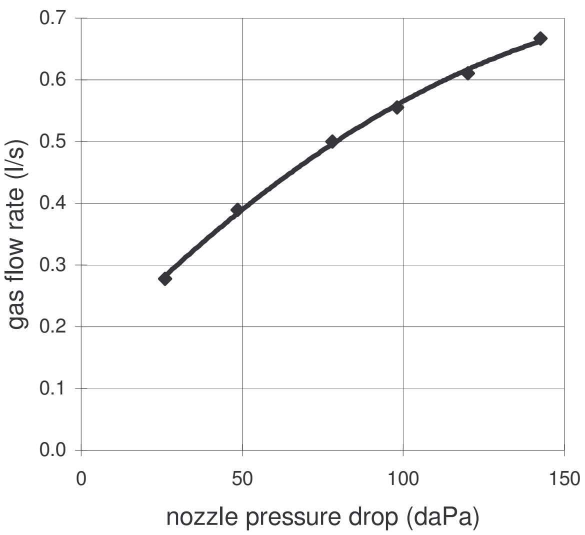


Figure 5: *Nozzle calibration at 20°C.*

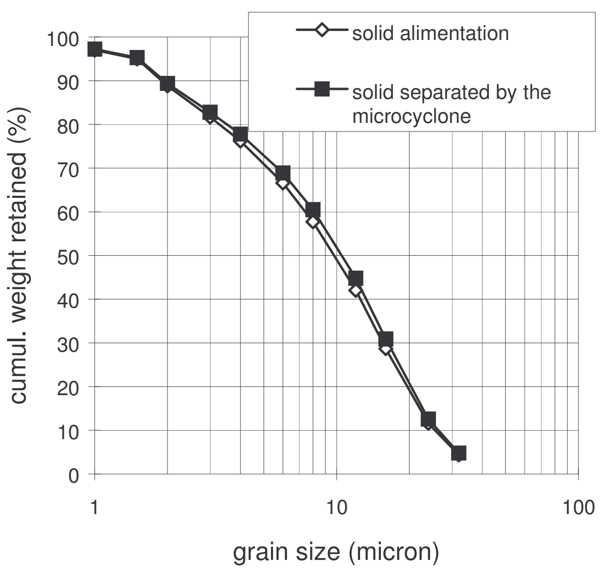
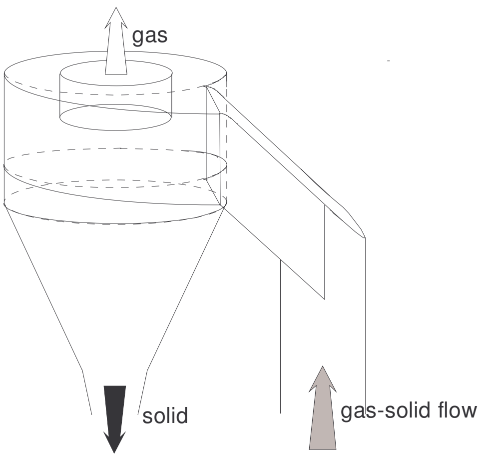


Figure 6: *Sample grain size distribution.*

3. Measurements in cyclone.

The measuring method enables structure analysis of the flow in a cyclone. Inlet conditions have been characterized. Measurements of concentration are made in a cyclone of diameter 835 mm.
The material used for this measurement test is silica of grain size ranges from 0 to 50µm with a mean diameter of 12µm. The specific gravity of the product is 2650 kg/m^3. Moreover, mean loading equals 1 kg of material per kg of gas and the flow rate equals 7000 m^3/h, i.e. cyclone inlet velocity of 10 m/s.
See figure 7 for the cyclone design, used for the measurements.



The inlet pipe feeds the cyclone with upward gas-solid suspension.

Figure 7: *Cyclone design.*

The cyclone is placed in a testing loop that allows a closed-circuit operation (figure 8). All the operating parameters (gas and material flow rates, gas temperature) are supervised and stocked.

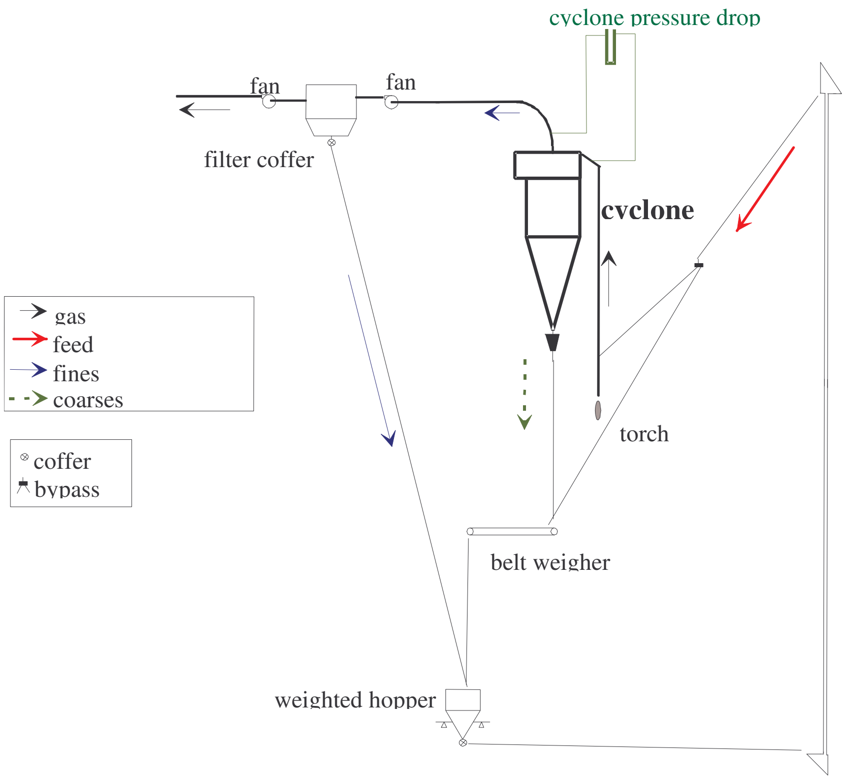


Figure 8: *Testing loop.*

3.1. Characterization of inlet conditions.

The cyclone inlet conditions are characterized according to a vertical line placed in the centre of the inlet section by evaluating the local solids concentration (Figure 9).

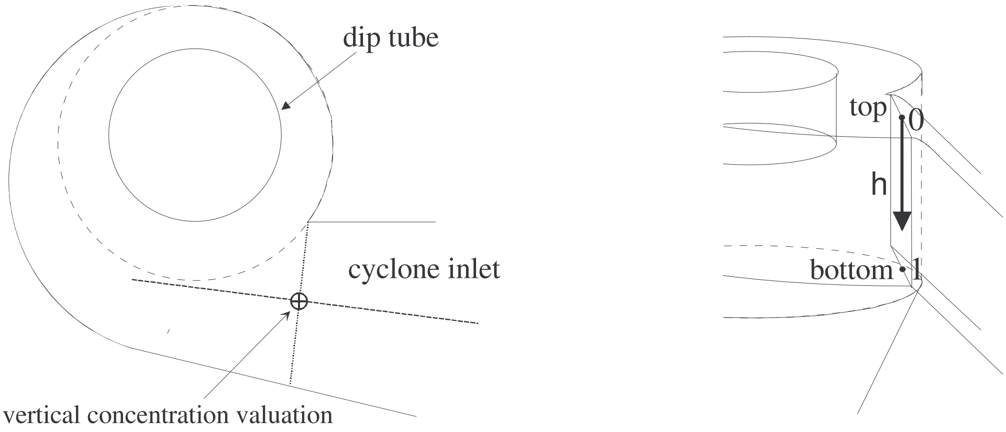


Figure 9: *Inlet conditions characterization.*

Results of concentration measurements are shown in Figure 10. The maximum material concentration is obtained in the top part of the section because of the inlet pipe geometry that centrifuges the material a first time before it enters the cyclone. The concentration then reaches 150% of the average inlet solids concentration whereas it is only 50% in the bottom.
The sample grain size analysis at points A, B and C, of figure 10, leads to the conclusion that the grain size is not dependent on its position in the cyclone inlet (Figure 11). Therefore, there is no grain size discrimination with height h.

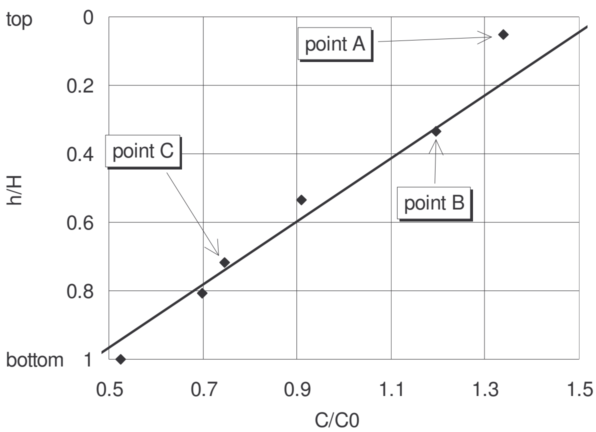


Figure 10: *Cyclone inlet concentration profiles.*

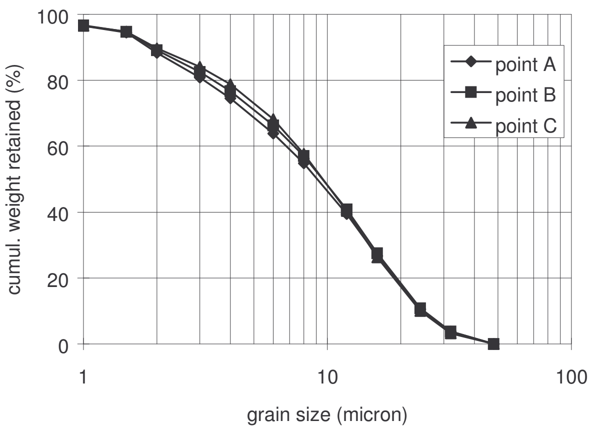


Figure 11: *Sample collected grain size profiles.*

Integrating the concentration ratio C/C_0 along the height of the section, h, leads to a value of 1.0. The mean inlet solids concentration, C_0, is the ratio of cyclone inlet mean material and gas flow rates.
This result confirms the accuracy of the measurement method. The measurement error is estimated at 3% of the measured value.

3.2. *Characterization of the vortex.*

Concentration measurements have been made in the cyclone along several geometrical radii. Analysis of velocity measurements conclude that the probe should be vertical, facing the tangential component of the velocity as shown in figure 12 (Reinhardt [7]).

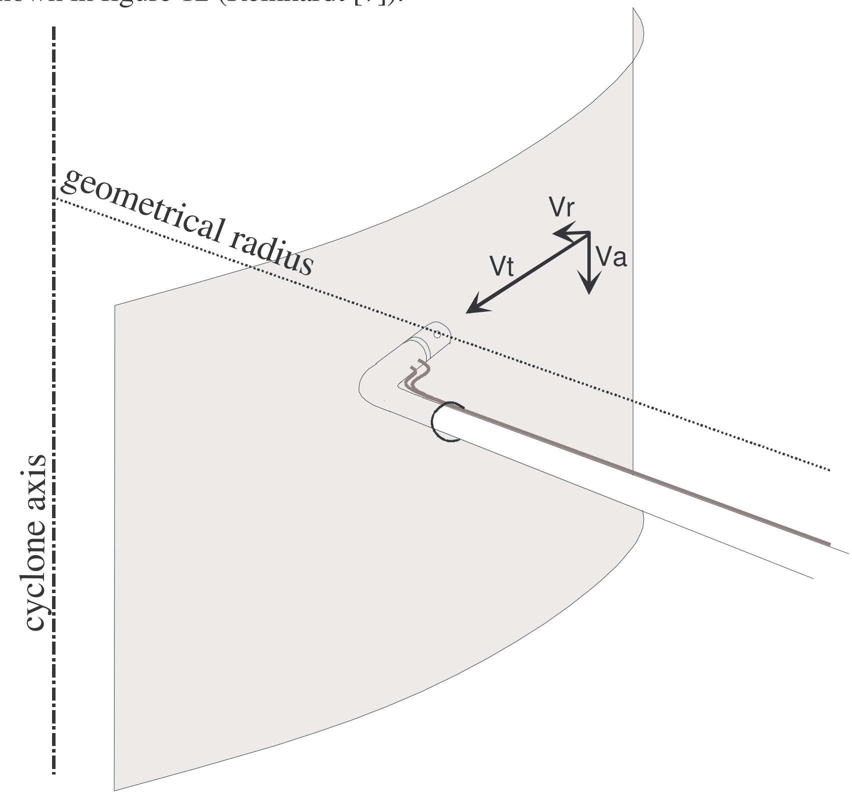


Figure 12: *Probe positioning.*

Measurements obtained at several heights in the cyclone enable identification of the flow characteristics.

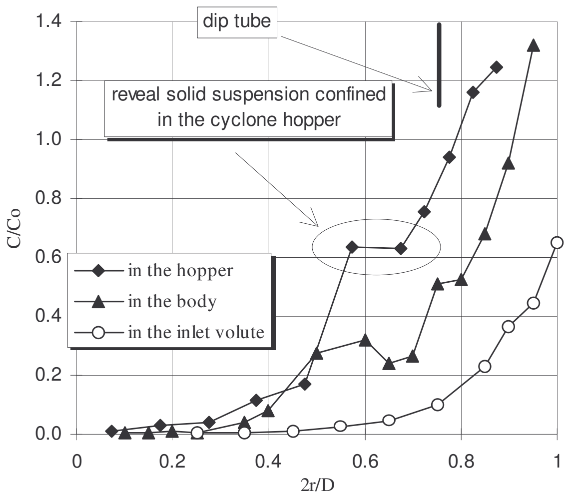


Figure 13: *Material circulation in bottom part of the cyclone.*

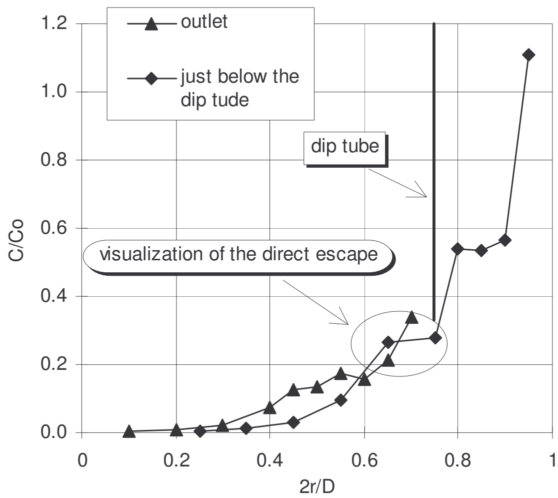


Figure 14: *Material Direct bypass.*

Profiles obtained in the inlet volute, in the body and in the hopper reveal a circulation of material that remains confined to the bottom of the cyclone (Figure 13). Actually, concentrations in the body and in the hopper of the cyclone away from the wall (2r/D between 0.5 and 0.7) represent respectively 30 and 60% of the mean inlet concentration.

This observation agrees with the formation of secondary flows already identified by Nagel [8] near the hopper wall (figure 15).

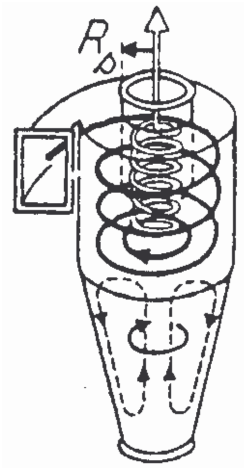


Figure 15: *Secondary flows (Nagel [8]).*

A direct escape of material from the inlet of the cyclone towards its outlet is also identified by comparing the concentration profiles just below the dip tube and at the cyclone outlet (Figure 14).

The comparison of the concentration profiles obtained in a single plane but at different angular positions (figure 16) reveals a suspension asymmetry generated by the geometry itself of the inlet volute (Figures 17 and 18).

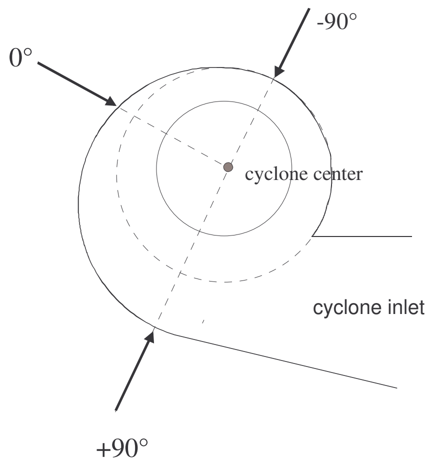


Figure 16: *angular positions.*

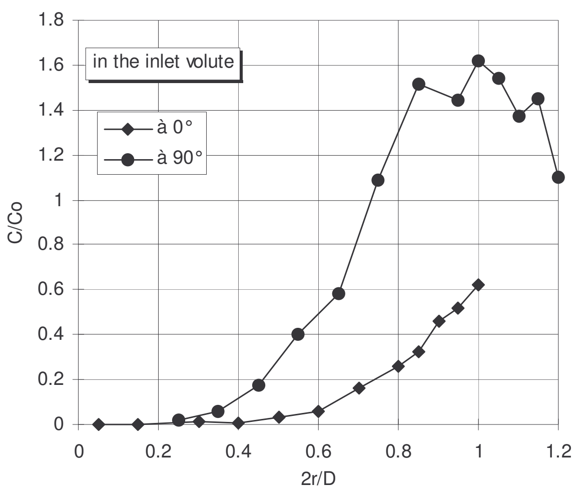


Figure 17: *Inlet volute concentration profiles.*

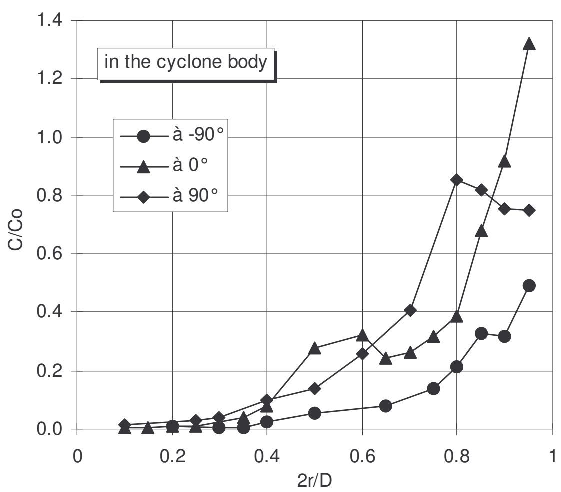


Figure 18: *Body concentration profiles.*

A certain quantity of material is projected on wall as soon as it enters the cyclone ; referred to hereafter as "dense phase". This phenomenon is closely linked with the inlet pipe design.

The dense phase moves down along the wall in a spiral course that can be followed by observing the concentration profiles near the wall (figure 19).

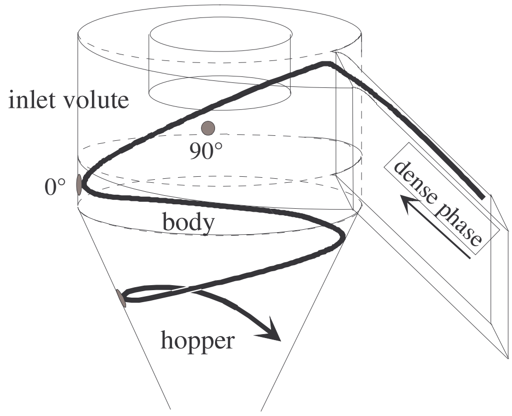


Figure 19: *"dense phase" spiral course.*

The proportion of the above described phenomena can be quantified by analyzing efficiency curves (Figure 20).

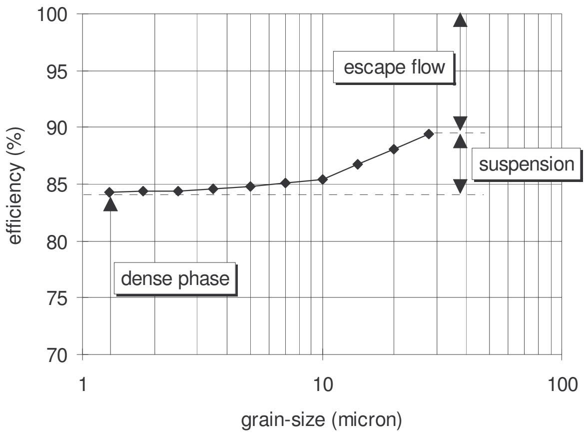


Figure 20: *Efficiency curve Analyzing.*

The escape flow rate is characterized by the efficiency of the coarsest particles whereas the material flow rate concerned by the formation of the dense phase is characterized by the efficiency of the smallest particles.
This study (Reinhardt and al. [9]) has shown that the higher the inlet solids concentration is, the smaller the quantity of material in suspension submitted to the centrifugation is (in % of the feed material flow rate).

The extracted sampling grain size analysis at the cyclone outlet allows us to plot profiles of concentration ratio profiles C/C_0 per grain size ranges according to the radial position (figure 21). All grain size ranges have the same weight. If we compare this graph with the centrifugation efficiency curve (separation efficiency of the amount of material in suspension), we note that the results correspond, particularly as regards the 14µm cut diameter (figure 22). In figure 21, profiles obtained for average diameters < 14µm merge. Above 14µm, concentrations decrease.

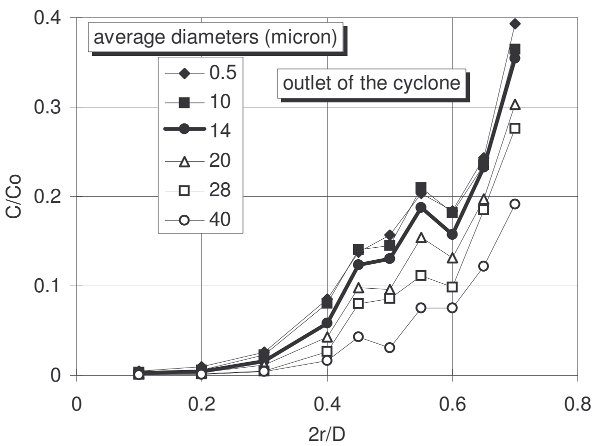


Figure 21: *Cyclone outlet concentration per grain size ranges profiles.*

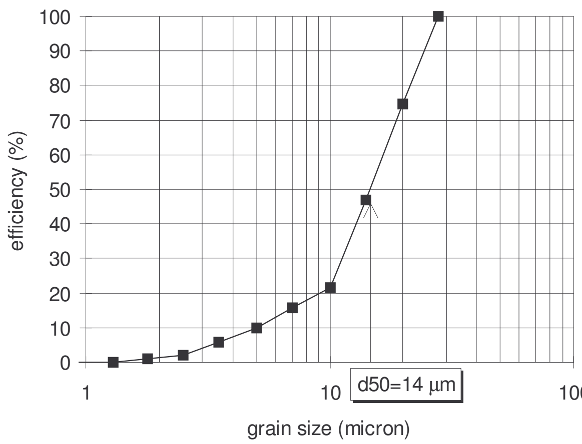


Figure 22: *Centrifugation efficiency curve.*

The measurement method also determines the suspension velocity that corresponds, once the probe has been balanced, to extracting velocity. Velocity measurements made by Reinhardt [7] with a sturdy hot-wire probe has enabled to show that maximum tangential velocity has a 60% drop (without any modification of the corresponding radius) for an inlet solids concentration in the order of 1 kg/kg.

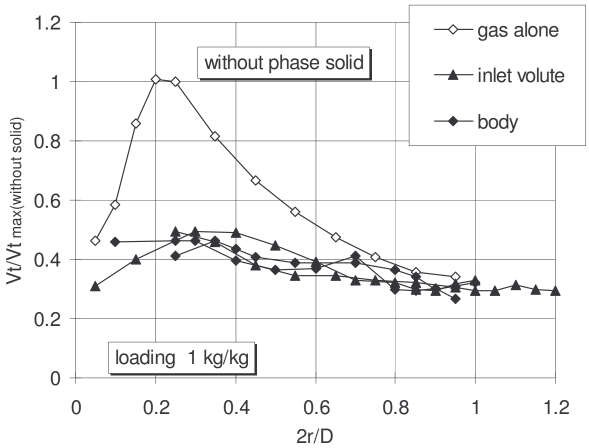


Figure 23 shows the whole of the results divided by the maximum velocity obtained when operating the cyclone without material.
The "without phase solid" profile characterizes the vortex development without material in suspension (Reinhardt [7]). This one represents the mean of all profiles obtained in the cyclone (inlet volute, body, hopper and for different angular positions).

Figure 23: *Tangential velocity profiles.*

The isokinetic sampling probe enables us to estimate the suspension velocity at the measurement point but is less accurate than a pressure probe method. The first purpose of the probe is to evaluate the local concentration of material in suspension.
All the measurements have been made at an ambient temperature. When the probe is used in a hot gas, additional cautions are required. It may be necessary to lag the downstream part because of a risk of gas condensation in the probe. The cyclone inlet suspension temperature can be reduced by dilution with ambient gas to keep the separator efficiency at a good value and to protect the upstream equipment. At high temperatures, the microcyclone will be advantageously followed by a filter to clean completely the gas. A cold-calibrated probe can be used in hot conditions.
On-site measurements in large cyclones operated at high temperatures have been planned.
Of course, the probe tip dimensions and the separating unit (microcyclone, filters,...) are dependent on the measuring conditions (suspension velocity, solids concentration level, gas temperature, gas and material nature). The tip must be chosen so that the inlet velocity in the microcyclone stays between 15 and 30 m/s to keep good efficiency.

4. Conclusions.

An isokinetic sampling probe allows us to measure concentration, up to 2 kg of material per kg of gas, without prior calibration since the measurement method is direct. Measurements made with a FCB isokinetic sampling probe have revealed the suspension-type flow structure in a cyclone. Inlet conditions characterizations reveal no uniform solids concentration and no grain size discrimination with inlet height, h. A direct escape of material from the cyclone inlet toward its outlet, prior to any centrifugation, has been identified. A dense phase, material projected on the wall as soon as it enters the cyclone, moves down the wall in a spiral flux that can be followed by observing the solids concentration profiles near the wall. Phenomena revealed thanks to the concentration measurements are quantifiable from the efficiency curve (escape of material, dense phase and suspension).
Finally, a sample of material is taken at each measuring point, which enables us to make a grain size or chemical analysis.

5. List of symbols.

C	local solids concentration (kg/kg),
C_0	cyclone inlet mean concentration (kg/kg),
D	cyclone diameter (mm),
h	cyclone inlet vertical position (mm),
H	inlet height (mm),
P_1	external flow static pressure,
P_2	internal flow static pressure,
r	radial position (mm),
V_t	tangential velocity (m/s),
$V_{t\ max}$(without material)	maximum tangential velocity in pure air.

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