Numerical and experimental studies on mini electro-cyclones for bioaerosol collection at individual level

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Résumé – Les risques biologiques se fondent sur la notion de dose pathogène absorbée. La connaissance de cette dose est fondamentale afin de définir aussi tôt que possible les contre-mesures médicales adaptées. L'objectif du projet WHIFF est de développer un bio-collecteur ayant un débit similaire à celui de la respiration humaine, qui pourra être porté ou intégré à la tenue de travail d'un primo-intervenant et qui effectuera des collectes d'aérosols durant sa mission. Ce bio-collecteur personnel permettra de mieux cerner la dose absorbée par le porteur. A la différence des collecteurs basés sur les principes d'impaction et de filtration, le cyclone se distingue par sa meilleure viabilité biologique grâce au « soft landing » des aérosols sur la paroi, son meilleur rapport performance/consommation et sa facilité d'entretien. Par ailleurs, le cyclone pose moins de problèmes de saturation dans un environnement lourdement chargé en poussière. L'ajout de champs électrostatiques au cyclone pourra avantageusement augmenter l'efficacité de collecte des particules submicroniques. Dans un premier temps, une étude de la miniaturisation de cyclone a été menée à l'aide de cinq modèles de calcul. Les résultats de ces modélisations nous ont conduits à choisir finalement deux mini cyclones, le BT-10 et le BT-20. Une série d'essais a ensuite été effectuée sur les 2 prototypes au sein du laboratoire de Bertin et celui de l'ENS. Les bons résultats expérimentaux obtenus ont confirmé nos choix dimensionnels pour les 2 prototypes. Dans un deuxième temps, nous avons étudié numériquement le gain fourni par les champs électrostatiques sur les rendements des mini-cyclones à partir de deux modèles, celui de Dietz (1982) et celui de Plucinski (1989). Les résultats des simulations ont mis en évidence une amélioration sensible de l'efficacité de collecte du mini cyclone BT-20 lorsqu'il y a présence des champs électrostatiques. En outre, ils ont montré que ce renforcement augmente à mesure que le débit d'air diminue. A faible débit, les forces électrostatiques sont en effet dominantes devant les forces centrifuges. De plus, à faible débit les pertes de charge sont très significativement réduites dans le cyclone et par conséquent la consommation énergétique est plus faible. Il s'en suit qu'à un niveau de consommation énergétique équivalent, la technologie d'électro-cyclone nous permet d'obtenir des bio-collecteurs personnels plus efficaces.

Abstract – Dangers caused by biological agents depend upon the pathogen dose taken in by an individual. The knowledge of the dose is crucial for conducting corresponding medical treatment as soon as possible. The objective of WHIFF project is to develop a biological air sampler having the same air flow rate as that of human breathing, which will be carried or integrated into a first-responder's protective suit and will allow a continuous aerosol collection during his/her mission. Compared to other air samplers based on impaction and filtration, the cyclone distinguishes itself by its higher biological viability as a result of "soft landing" of aerosols onto the wall, its better performance/consumption ratio, as well as its easier maintenance. In addition, there is less saturation problems in a cyclone when the sampling takes place in a dusty environment. Firstly, cyclone miniaturization has been theoretically studied by using 5 different models. The simulation results have led to the designs of two mini cyclones, BT-10 and BT-20. Then, following their manufacturing, a series of tests has been conducted both in Bertin and in ENS. The good experimental results have confirmed their successful designs. Secondly, the theoretical studies and modelling have been carried out to better understand the effect of induced electrostatic field in the mini cyclones BT-20. The simulation results, obtained by using Dietz (1982) and Plucinski (1989) models, show that the mini cyclone collection efficiencies have been significantly improved by the presence of electric forces. This efficiency enhancement is even more remarkable at lower flow rates, where the electric force is dominating over the centrifugal force. Lower flow rate means less pressure drop in cyclones, and hence less power needed. The electro-cyclone technology can allow us to have more efficient personal aerosol samplers at equivalent energy consumption.

1. Introduction

The emergence of biological threats became a reality when the world witnessed the Anthrax attacks in 2001. Biological hazards, like ionising radiation and many chemical hazards cannot be directly detected by human senses and therefore can go unnoticed. Moreover, the level of danger relies on the absorbed pathogen dose. Consequently, quick knowledge of an individual’s exposure and in time medical treatment can make the difference between the life and death.

WHIFF project aims at improving first responder clothing with the integration of a compact, lightweight and non-intrusive personal sampler of high performance, permitting the discovery of airborne biohazards at the individual level. Periodic reading of these samplers can then provide evidence of biological incident that would have been unnoticed or unexpected and therefore lead to appropriate protective action.

The output of the project can benefit the entire society in terms of routine environment surveillance in hospitals, schools and work-places. In case of accidents or epidemic explosions, personal bioaerosol samplers can help the government to make the right decision on isolating the contaminated people from non-exposed ones, anticipating the first protection and putting further medical treatments in place. It is also a significant advance in individual protection.

Bioaerosol sampling is a multifaceted challenge that requires the considerations not only on the physical collecting efficiency, but also on the biological viability which depends on the origin, composition and aerodynamic behaviour of bioaerosols. Many sampling and analytical methods are available to collect and assay air samples for biological agents. These methods vary in their suitability for the study of particular biological agents. Decisions on what agents to study as well as where and when to collect samples are as critical as bioaerosol sampler selection. Minimizing the environmental stress on the organisms collected under different operating conditions is a big concern. There is no single sampling method that is suitable to all occasions. No single currently available bioaerosol sampler is optimal for all applications [1].

With appropriate filter media, filter samples can be collected in almost any form, quantity and state. The collecting efficiency depends upon face velocity, particle size, and filter medium. No single filter medium is appropriate to all problems. The face velocity is relatively low and the pressure drop is relatively high. Impactors and cyclones collect particles in an accelerating air flow wherein the particles by virtue of their inertia cannot follow the flow streamlines, and deposit on a collecting surface. Unlike impactors, cyclones allow a more soft landing for particles despite their high velocities because the perpendicular impact between particles and collecting surfaces is avoided. Electrostatic precipitator samplers for aerosols are based on the well-established principles of charges particle drift in electric fields. A number of devices that employ electrostatic collection have been designed and used in the past. A major advantage of such devices is the absence of high impact collection velocities which may fracture or deform particles.

The technology of the combination of the cyclone and electrostatic attraction has been applied in exhaust gas treatment [2-6]. The significant increases of collecting efficiency of cyclone with the help of electrostatic attraction have been demonstrated. To our knowledge, there is no electro-cyclone system for bio-aerosol sampling. In recent years, the use of wetted-wall cyclone for bioaerosol sampling has been pioneered by Bertin Technologies [7]. A commercial device for hospital and environmental monitoring uses, called CORIOLIS, has been developed with success. In parallel, ENSL has conducted electrostatic studies and are leading 2 research programs in bio-aerosol sampling with electrostatic principle. The state of the art analysis plus the experiences of Bertin and ENSL orientate us to make the choice of 2 technologies: mini-cyclone plus electrostatic precipitation [8].

2. Theoretical modeling of mini-cyclone performance

Cyclones have several advantages in air sampling, including their relatively low cost of construction and ease of operation. As they have no moving parts, their maintenances are very easy. Above all, cyclones samplers have the highest ratio of performance to energy consumption, compared to other sampling technologies.

Cyclone separation is an inertial method of removing particles from air, gas or liquid stream, without the use of filters, through vortex separation. A typical “reverse flow” cyclone is illustrated in FIG.1.

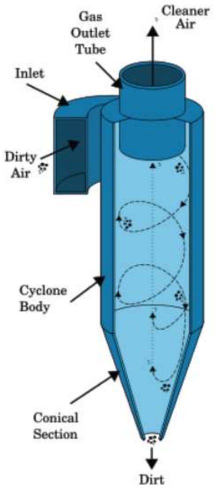

FIG. 1 : Schematic of typical cyclone separator

Air is introduced tangentially near the top, creating a double vortex flow within the cyclone body. The flow spirals down the outer porting of the chamber and then reverses and spirals up the inner core to the exit tube. Particles having sufficient inertia are unable to follow the air streamlines, and they impact onto the cyclone walls. The particles are either retained on the cyclone wall, or they migrate to the bottom of the cyclone cone. A balance between the centrifugal force and the drag force on a particle governs a cyclone sampler performance.

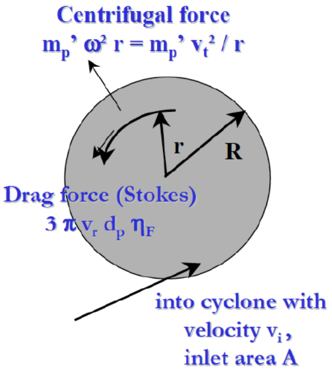

FIG. 2: Governing forces in a cyclone

Cyclones are characterized by a collection efficiency curve. The particle size collected with an efficiency of 50% is referred to as the cutpoint of the cyclone, or cut-off diameter d_{50}. The collection efficiency depends on the cyclone dimensions and flow rate. Over the years, several models have been proposed to predict cyclone performance. Because the flow pattern inside cyclones is complex, the particle collection characteristics are not easily worked out. The various cyclone models present somewhat different expression for the dependence of cyclone cutpoints on the cyclone dimensions, flow rate, gas viscosity, and temperature. At present, there is no generally accepted fundamental relationship to describe cyclone performance. Five currently used cyclone performance models developed for relatively big cyclones in industrial exhaust gas treatment systems, including those of Plucinski (1989), Lapple (1951), Iozia & Leith (1972), Leith & Licht (1990) and Dietz (1982) have been used to predict the performances of mini cyclones. Despite the fact that they are based on big cyclone data, the simulation results from these models can be served as guidelines in the design of mini cyclones. With the help of modeling, we have indeed achieved the sizing of 2 mini-cyclones, BT-10 and BT-20, for WHIFF project. FIG.3 illustrates their simulated performance curves by using the five models. We can observe that Dietz (1982) model always gives the most optimistic prediction whilst the Plucinski (1989) model the most pessimistic one. The upper and lower cut-off diameters of BT-10 are 0.53µm and 1.36 at a flow rate of 10 l/min and 0.43µm and 1.11µm at a flow rate of 15l/min. As far as BT-20 is concerned, the cut-off diameter varies from 0.72µm to 1.60 µm in at a flow rate of 30 l/min and from 0.56µm to 1.24 µm at 50 l/min.

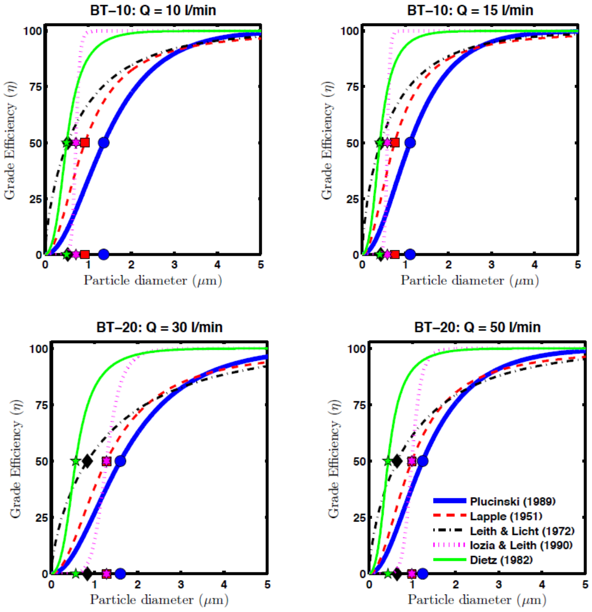

FIG. 3: Simulation results of mini cyclones BT-10 and BT-20

3. Experimental study on midi-cyclones

Theoretical study and modeling enable us to complete two mini cyclones designs, BT-20 and BT-10. They have then be manufactured by “rapid prototyping” technology. Despite the fact that these models have been successfully used in the industrial cyclone performance predictions, it’s still the experimental testing that tells the real performance, especially for the miniaturized cyclones which have never been realized and used before.

A test loop bas been built for the testing of biological samplers in Bertin Technologies. It is composed of two test chambers of 1.08 m3 and 0.061 m3 respectively. They are isolated by HEPA filters from the environment. Tow fans connected to the chambers allowing ventilating of either or both of the chambers before and after tests. Aerosol generation is achieved with a 6-jet Collision nebulizer (BGI Inc. Model CN25J). Tow laser light scattering particle counters, type HHPC-6, were used to monitor the particle concentrations at the inlet and outlet of the sampler.

During the test, particle concentrations upstream and downstream the sampler at every time step Δt are given and recorded simultaneously by the 2 identical particle counters placed at the inlet and outlet of the sampler. The stepwise η can be calculated from the following equation:

$$\eta(t) = \frac{\left(C_{inlet}(t) - C_{outlet}(t)\right) \cdot Q}{C_{inlet}(t) \cdot Q} = \frac{C_{inlet}(t) - C_{outlet}(t)}{C_{inlet}(t)}$$

where Q is the flow rate (l/min). The average value of the stepwise efficiencies gives the overall collection efficiency of the test. Each test has been repeated 10 times. Besides, two different flow rates have been tested on the two mini-cyclones respectively, 50 l/min and 30 l/min for BT-20, as well as 15 l/min and 10 l/min for BT-10. The experimental results on collecting efficiencies of BT-20 and BT-10 are given in the table below. They are all above 50%. All of the four configurations meet the performance requirement given in the specification.

TAB. 1: Experimental results on collection efficiencies of mini-cyclones BT-20 and BT-10

	Air flowrate (l/min)	Efficiency (%)
BT-20	50	84
	30	60
BT-10	15	70
	10	56

BT-20 has also been tested in the laboratory of ENS. In FIG.4, the experimental results have been compared to the simulation results obtained from Dietz and Plucinski models. It shows that the collection efficiencies of BT-20 have been underestimated by both models, meaning the mini cyclone BT-20 has higher performance than conventional industrial cyclones. This confirms the successful design of the mini cyclone for WHIFF project.

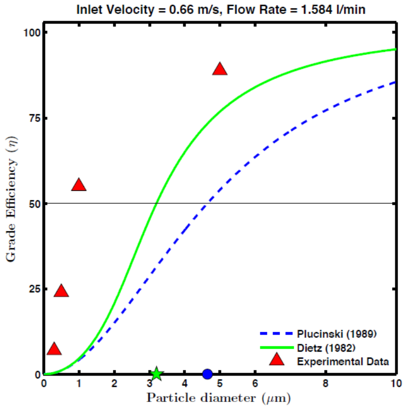

FIG. 4: Comparison of experimental and simulation data

4. Modeling of electro-cyclones

Cyclone performance decreases with particle diameter. It has been demonstrated that particle collection efficiency could be enhanced if electrical forces are employed to supplement the inertial forces. In an electro-cyclone, as shown in FIG.5, apart from the centrifugal force and the drag force, there is an additional force, electric force, acting on the particle. The Electric force is proportional to the product of particle charge and the strength of the electrostatic field. The movement of a particle is determined by the balance of the centrifugal force, the drag force and the electric force.

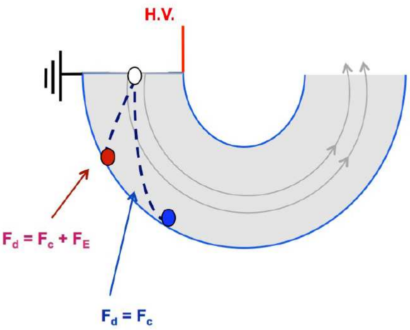

FIG. 5: Governing forces in an electro-cyclone

$$F_{centrifugal} = \frac{m_p V_r^2}{R}$$

$$F_{drag} = 3\pi\mu d_p V_r$$

$$F_{electric} = q_{saturaed} E$$

where

m_p : particle mass
V_r : radial drift velocity
d_p : particle diameter
μ : fluid viscosity
$q_{saturated}$: saturation charge on the particle
E : electric field

The saturation charge is determined by (Flagan 1988)

$$q_{saturated} = \frac{2\Delta V}{D_x \ln\left(\frac{D}{D_x}\right)} \bullet \frac{3\kappa}{(\kappa+2)} \pi\varepsilon_0\varepsilon_1 d_p^2$$

where

ε_0 : Permittivity of vacuum
ε_1 : Relative permittivity of air
κ : Dielectric constant of the particle

The collection efficiency of an electro-cyclone sampler is dependent on operating parameters, e.g. current, voltage, and flow rate; the particle parameters, e.g. particle size, shape, and dielectric properties; and the carrier gas parameters, e.g. humidity, ambient temperature, and composition. It is aided by high charging currents, high voltage gradients and low flow rates.

The modelling of our mini electro-cyclone has been carried out by using 2 models, Dietz (1982) model [9] and Plucinski (1989) model [10], which give the upper and lower limits of collection efficiency prediction, as shown above.

In Dietz (1982) model, the efficiency is give by

$$\eta = 1 - K_0 + \left(K_1^2 + K_2\right)^{\frac{1}{2}} \exp\left(\frac{-2\pi R_c V_{pw} d}{Q_v}\right)$$

with

$$K_0 \equiv \frac{R_c V_{pw} + R_v U_r + R_v V_{pv}}{2 R_v V_{pv}}$$

$$K_1 \equiv \frac{R_v V_{pv} - R_v U_r - R_c V_{pw}}{2 R_v V_{pv}}$$

$$K_2 \equiv \frac{R_c V_{pw}}{R_v V_{pv}}$$

$$V_{pw} = \left(\frac{4\pi \rho_p R_p^2 U_{tw}{}^2}{3 R_c} + q_{saturated} E_w \right) / 6\pi\mu R_p$$

$$V_{pv} = \left(\frac{4\pi \rho_p R_p^2 U_{tv}{}^2}{3 R_c} + q_{saturated} E_v \right) / 6\pi\mu R_p$$

R_p, R_c, R_t and R_v are the radius of particle, cyclone, exit tube and core region. V_{pw} is the radial particle velocity while V_{pv} is the velocity of particles thrown from the core into the annulus. U_r is the radial velocity into the core region. ρ_p is the mass density of the particle, E_w is the electric field at the cyclone wall, E_v is the electric field at the boundary of the vortex. Q_v is axial flow rate.

Plucinski (1989) model is expressed by

$$\eta = 1 - \frac{1}{1+A} \exp\left(- \frac{mA\left(s - \frac{a}{2}\right)}{l} \right)$$

where

$$m = 1 + \frac{\Delta V}{\ln\left(\frac{D}{D_x}\right)} \frac{6}{\pi d_p^3 \rho_p U_0} q_{saturated}$$

$$A = \frac{\pi \rho_p d_p^2 U_0 l}{9 \mu a b}$$

with

a: height of cyclone inlet
b: width of cyclone inlet
s: length of exit tube
l: vortex length
D: cyclone diameter
D_x: diameter of exit tube
U_0: inlet velocity

FIG.6 shows the simulation results of BT-20 collection efficiencies by applying Plucinski model. The presence of electric field enhances significantly the collection efficiency of the mini-cyclone, particularly for small particles even at low gas velocities. The most remarkable improvement is observed at the flow rate of 10 l/min when 5 kV is applied. The electrostatic beneficial effect decreases with the increasing of air flow rate and becomes almost negligible at 50 l/min. It means we should reduce airflow, i.e. air velocity, in the electro-cyclone. Lower air velocity means less pressure drop and less energy consumption. Compared to BT-20 without electrostatic field at 50 l/min, electrostatic enhanced BT-20 can provide a better performance at 10 l/min with 5 kV electrostatic fields.

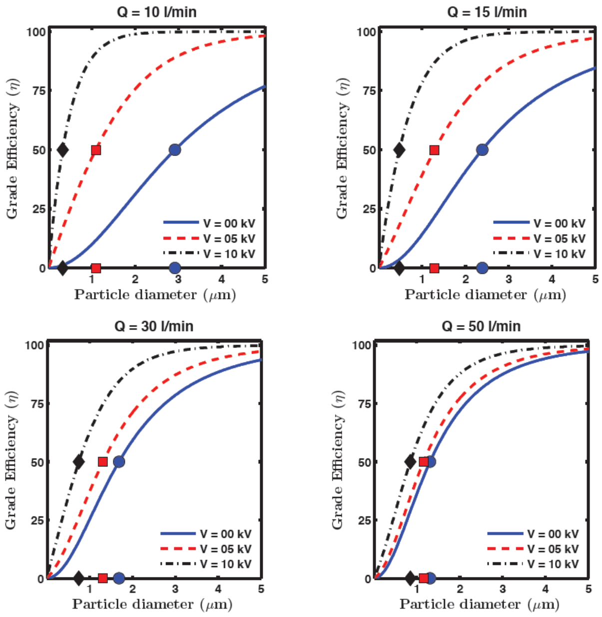

FIG. 6: Simulation results of mini electro-cyclones BT-10 and BT-20

FIG.7 shows the influence of voltage on the cut-off diameter. First of all, we can clearly observe that the cut-off diameter is strongly dependent on the potential gradient in the charging field. Maximum collection efficiency is obtained at the highest voltages. At the voltage of 1 kV, the influence of electrostatic field is too weak to make any notable difference compared to the cyclone without electrostatic (0 kV). It is still the centrifugal force that dominates particle collection so that particle cut-off size decreases with the increasing of flow rate. When the voltage goes up to 5 kV, there is a kind of independence of particle cut-off size of the airflow rate. The collection efficiency is the balance result of centrifugal separation and electrostatic attraction. At lower flow rate, weaker centrifugal force is compensated by electrical force. At higher flow rate, increasing centrifugal force compensates reducing electrostatic enhancement. When the tension increases to 10 kV, a reverse effect of flow rate on cut-off diameter has happened. The cut-off diameter increases with the increasing of flow rate because particle residential time is becoming less and less important and not enough to enable the particles to migrate to cyclone walls. Generally, in our mini electro-cyclone, the collection efficiency is favoured by lower air velocity. The increase of flow rate no longer results in the improvement of its collection efficiency.

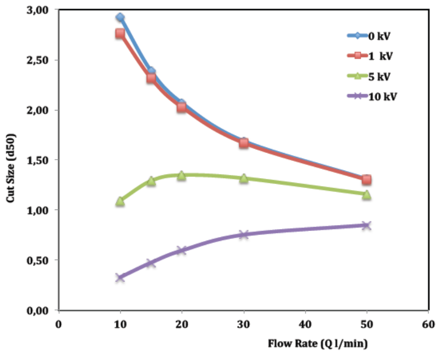

FIG. 7: Dependence of cut-size on applied voltage

5. Conclusions

Firstly, the modeling of pre-dimensioned mini cyclones with 5 models enables the validation of BT-10 and BT-20 designs. The experiments carried out both in Bertin and in ENS on the two mini cyclones, have further confirmed their high collection efficiencies.

Theoretically, by pre-charging the particle and applying a radial electric field within the cyclone, collection efficiency can be improved. The simulation results of BT-20 electro-cyclone have shown that its collection efficiency has been significantly improved by the presence of electrostatic fields. The beneficial electrostatic effect is favored by lower air flow rates in electro-cyclones where electric forces are dominating the separation between of particles from air flux. Lower flow rate means lower pressure drop and lower energy consumption. Therefore, there are good reasons to reduce flow rates in electro-cyclones.

The electrostatic enhancement increases with the strength of electrostatic field. For BT-20 mini electro-cyclone, a potential electrostatic gradient of 5 kV enables us to obtain a higher performance at 10 l/min than at 50 l/min without electrostatic field. The configuration of 10 l/min of flow rate and 5 kV of supply will be chosen for the WHIFF device.

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