Turbulence-particle interactions on surfaces

by

Maxime Inizan

Submitted to the Department of Civil & Environmental Engineering in partial fulfillment of the requirements for the degree of Master of Science in Civil & Environmental Engineering at the

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Abstract

The physics of adhesion and detachment of particles in ventilation ducts is important to understand and control contaminant and pathogen dispersal indoors. This thesis presents an experimental characterization of parameters which affect the resuspension of settled micro-particles and spores in a turbulent airflow channel. We examine, quantify, and analyze the role of relative humidity (RH), air temperature, particle size, and surface properties on particle detachment rate and mode. This is done using a combination of high-speed imaging in a turbulent channel where spores and particles are deposited initially followed by image-processing and particle-tracking. First, we show that ambient moisture hinders particle detachment, however, we also find that this is only true for a relative humidity higher than 60% RH. At lower air saturation, we show that, instead, another effect dominates, leading to a different mode of detachment. Instead of individual particle detachment, it is a collision dynamics leading to cluster formation that dominates the pattern of detachment of particles from surfaces. We find that collisions lead to aggregations of particles on the surface in the form of clusters of self-similar sizes. We find that the larger the cluster (above 5 particles) the more anisotropic its shape, similarly to what was observed in prior literature examining clusters of air-suspended particles in channel flows. We examined and quantified the role of initial particle surface concentration, mean air velocity, and particle surface properties on these results. Our study have implications in the control of pathogen and contaminant dispersal in confined geometries, relevant for a wide range of applications.

Thesis Supervisor: Prof. Lydia Bourouiba
Title: Assistant Professor
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Abbreviations

DMT Derjaguin-Muller-Toporov.

HIT Homogeneous Isotropic Turbulence.

HVAC Heating, Ventilating and Air Conditioning system.

JKR Johnson-Kendall-Roberts.

MFP Mean free path.

OPP Orificed Perforated Plate.

PMMA Poly(methyl methacrylate).

PTV Particle Tracking Velocimetry.

SHPP Straight-Hole perforated plate.
Nomenclature

\( A \) Area of cluster (in \( m^2 \)).

\( C(t) \) Average number of particles inside a cluster at time \( t \).

\( C_0 \) Average particle concentration in the initial image.

\( C_t \) Average particle concentration in the whole image at time \( t \).

\( P \) Perimeter of a cluster (in m).

\( Re \) Reynolds number.

\( T \) Temperature in degree Celsius (°C).

\( U_0 \) Free-stream velocity (in \( m.s^{-1} \)).

\( \lambda_{exp} \) Experimental mean free path (in m).

\( \lambda_{th} \) Theoretical mean free path (in m).

\( \nu \) Kinematic viscosity (in \( kg.s^{-1}.m^{-1} \)).

\( \phi \) Detachment fraction.

\( \rho_f \) Density of the fluid (in \( kg.m^{-3} \)).

\( t_0 \) Time at the onset of motion on the surface (in s) (chapter 6: clustering).

\( t_{50} \) Time to reach half of the absolute difference between the initial particle concentration in a cluster at \( t_0 \) and the final particle concentration in a cluster at \( t_f \) (in s).
$t_f$ Time for which the steady-state is reached (in s) (chapter 6: clustering).

$u_r$ Friction velocity of the fluid defined as $\left(\frac{\tau_w}{\rho_f}\right)^{1/2}$ with $\tau_w$ the wall shear stress (in m.s$^{-1}$).

$u_p$ Particle velocity on wall (in m.s$^{-1}$).
Chapter 1

Introduction

The detachment of micro-particles from surfaces and their entrainment into airflow is an object of study in a wide range of fields. In indoor environments such as in hospitals, this detachment raises questions on the dispersal of dust, bacteria, viruses, or spores, which are important for disease propagation. In a worst case of bio-terrorist release, dispersal of pathogens in ventilation ducts of public buildings represents a serious threat to society [20, 34].

The deposition of particles and their resuspension (also referred to as removal, detachment or re-entrainment in channels or ventilation ducts) have been widely studied. However, key mechanisms of resuspension remain largely unknown [5, 27, 75]. Indeed, these mechanisms are complex and vary depending on the particle size, shape and their chemical and mechanical properties [27]. Resuspension (for which the mechanisms are related to deposition to a certain extent) is typically defined by two types of methods: empirical formulas or equations of particle motion on surfaces. These involve energy or force balance models to define conditions of entrainment for a particle. However, a discrepancy between experiments and theoretical model are large. The number of parameters in these models differs and is inconsistent. Important factors such as the relative humidity remain neglected. Another factor we have observed to be important and largely neglected is collective effects. Particles are typically studied as acting in isolation and the literature on the study of multi-layers or on
preferential particle concentration on detachment of particles from a surface remains limited [11, 27]. However, we observed that this preferential concentration, leading to clustering of micro-particles, can have contrary effects: the collective effect can increase the resuspension rate but also prevent the particles from detaching [chapter 4]. Preferential concentration of micro-particles was mainly analyzed in a 3D system focusing on the vertical plane [51]. We refer to 'aggregate' for agglomerated particles in the air, while we refer to 'cluster' for agglomerated particles on surfaces (2D) [51].

Our goal is to first examine the role of moisture on detachment, and then to elucidate clustering through different parameters (Reynolds number, initial density of particles, types of particles, and relative humidity) and the detachment dynamics, in order to gain insights into the prevention and prediction of risks of biological release or pathogen dispersal.

Within this scope, the present study begins with an overview of biological and physical background in chapter 2. A detailed explanation of the experimental setup is done in chapter 3. The complexity related to the relative humidity is then added in chapter 4 before discussing experimental results on the interaction between airflow and particles in chapter 5. Chapter 6 focuses on the clustering of particles. In chapter 7, we summarize key elements of clustering and highlight possibilities for future study.
Chapter 2

Background

2.1 Biological context

2.1.1 Risk of biological attack

In October 2001, different cases of anthrax infection which has been used as a biological weapon were identified in the United States [20]. After the terrorist attacks on the World Trade Center and the Pentagon, envelopes containing spores that cause anthrax were mailed to news media companies and government officials. Five persons died in eleven inhalation cases. This attack could take many more forms than only being placed in letters. The most likely type of attack would be through the release of anthrax spores into the air, such as in ventilation ducts of public buildings. The study of the dispersal of this pathogen in buildings gives some clues as the risk posed by this threat. Dispersal of a range of other pathogens in buildings also applies to infections in hospitals due to spore-forming bacteria such as Clostridium difficile [12, 55, 72].

It is also important to note that inhalation of airborne particles smaller than 10μm may affect human health (see the Clean Air Act on particulate matter administered by the Environmental Protection Agency [EPA]).
2.1.2 Anthrax and *Bacillus anthracis*

Anthrax is a serious infectious disease caused by gram-positive rod-shaped bacteria known as *Bacillus anthracis*. It can infect all warm-blooded animals, including humans, through cutaneous, inhalation and gastrointestinal pathway. Although contracting anthrax from another person is rare, infection can occur when someone is in contact with contaminated animal products or if spores of the bacteria are inhaled.

The symptoms of anthrax are diverse, depending on the contamination process, and mostly appear within 7 days [19]:

- Cutaneous, the skin exposed itches and soon presents a large boil-like sore which can spread to the lymph nodes and bloodstream if not treated
- Cold or flu-like symptoms that can result in breathing problems, even death
- Fever, abdominal pain, loose/watery bowel movements and blood in vomit.

Anthrax is most common in agricultural regions of South America, Europe, Asia or Africa, but more rare in the United States. If a bioterrorist attack were to happen, *Bacillus anthracis*, which can cause anthrax, would be one of the biological agents most likely to be used because of the ease of procurement (easily found in nature, can be produced in a lab and lasts for a long time in the environment). This weapon can be released quietly without detection (no smell, no taste, and too small to be seen) [19].

*Bacillus anthracis* with lethal toxin can be found in different strains. The spores have a size of a micrometer and a cylindrical shape, low electrostatic charge, and a higher relative hydrophobicity than other bacillus species. In bioterrorist attacks it is most likely to be aerosolized in the form of white powder [20]. For experimentation, similar spores are commonly used. They present no health danger. For instance the *Bacillus thuringiensis* and *Bacillus cereus* are frequently manipulated. A good overview of the properties of *Bacillus thuringiensis* is given in [1].
2.1.3 Sporulation

Spores allow bacteria to survive in extreme conditions, including very dry, acidic, or cold conditions. Spores are thus part of the life cycles of many plants but also other bacterial organisms, corresponding to their unit of reproduction adapted to dispersion and survival for extended periods of time [56]. Biologically, the life cycle of spores is called alternation of generations [56]. Spores are produced by meiosis in the sporophyte (type of cell division that reduces the chromosome number by half). They are usually haploid — containing half of the number of homologous chromosomes in somatic cells— and unicellular cell. Under certain conditions a spore can develop into a new organism using mitotic division, producing a multicellular gametophyte —sexual phase in the life cycle of plants which consists on the development of sex organs—, which eventually goes on to produce gametes. Two gametes fuse to create a new sporophyte —diploid multicellular stage in the life cycle of plant. This process (called sporulation) occurs when there is a depletion of several nutrients in the organism [29]. Sporulation can be divided into several stages (with the densification of DNA, an asymmetric cell division, etc.) [see figure 2-1]. The sporulation involves the production of many new structures, enzymes, and metabolites along with the disappearance of many vegetative cell components. The newly activated genes determine the composition and form of the resulting spores. For instance for Bacillus subtilis, the entire sporulation process takes about 8 hours [48].

2.1.4 From bacteria to spores

Different methods of separation of spores from vegetative cells have been developed. The most commonly adopted is that described by Thomas and Ellar (1983) [63]. The Bacillus parasporal crystal is purified by ultra-centrifugation on a discontinuous sucrose density gradient (67 to 79 % weight per volume [wt/vol] of sucrose). Other methods can be used but in general these separations are time-consuming or require
expensive equipment. A simpler method is explained in [24]. Cells are grown until complete autolysis —destruction of a cell through the action of its own enzymes — which enables release of the spores and toxin crystals in the culture medium. Then purification methods are performed, focusing on the extraction of crystals from the medium, which leaves the spores intact. Different steps are processed, requiring centrifugation and the use of organic solvents, which takes at least a day.

2.2 Airflow turbulence in a channel

An airflow in a ventilation duct might be turbulent for different reasons. For example, the Reynolds number (more detail below) is high and a grid might be present at the entrance of the ventilation, which generates turbulence. As a result, the interaction between particles and the flow might be subject to the flow properties (eddies’ length...
scale, viscous layers, etc.). The following section delves into a general view of the turbulence that can be observed in a ventilation duct.

The Reynolds number \( Re \) represents the ratio of inertial forces to viscous forces within a fluid [57]. It is expressed as \( Re = \frac{LU_0}{\nu} \) with \( L \) the characteristics length, \( U_0 \) the mean flow velocity, and \( \nu \) the kinematic viscosity of the fluid. At low Reynolds number, the flow is dominated by laminar flow (viscous effects are predominant on inertial forces). At high Reynolds number, the flow is turbulent which creates differences in the fluid’s speed and direction, which may sometimes intersect or even move counter to the overall direction of the flow. These currents are called eddy currents (swirling of a fluid). For a turbulent flow, we can define the flow velocity vector as \( \mathbf{u} = U_0 + \mathbf{i} \) with \( U_0 \) the mean velocity vector and \( \mathbf{i} \) the fluctuation vector of velocity and \( |\mathbf{i}| \ll |U_0| \) [57].

### 2.2.1 Ventilation ducts in public buildings

Ventilation ducts are usually the common system to circulate air into large buildings such as hospitals. Indoor air is mixed with outdoor air, thermally conditioned, before returning to the indoor space. The general system of ventilation duct in these large buildings are Heating, Ventilating and Air Conditioning [Heating, Ventilating and Air Conditioning system (HVAC)] systems [61]. The sizing of the ducts depends on the carrying capacity required for a specific space and the ventilation used [14]. Ducts are either round or rectangular in cross section, with different advantages for both forms. For instance rectangular ducts are better for saving room space and to be installed in walls. We will focus on this form for the rest of the study.

Ducts are made of diverse materials (see ASHRAE handbook on duct design). Pressure in the duct is small so materials with a great deal of strength are not needed. The commonly used materials correspond to galvanized sheet steel, aluminum sheet and insulated ducts made from fiberboard. The maximum airflow velocity depends on the selected application. For offices and large building a corresponding maximum velocity would be 1200 – 1500 foot per minute (ft/min) which is equivalent to about
8 meter per second ($m.s^{-1}$). It corresponds to low to medium velocity systems, with a range of Reynolds number between $10^4 - 10^5$ [61]. The size of the duct depends on the airflow velocity required, the air capacity and the noise pollution. For instance in [61] they used a ventilation duct with cross section of 15.2 x 15.2 cm$^2$ at three nominal airflow velocities (in the range of Reynolds number above).

### 2.2.2 Pickup velocity

Determining the critical pickup velocity of particles or spores is intimately related to clustering and particle detachment. This concept can be used to predict whether micro-particles on a channel will be moved and entrained by the gas. Several definitions of pick up velocity were defined in the literature. For instance in [17] the pickup velocity was defined as the gas velocity required to pick up, entrain, re-suspend, blow away or detach particles at rest on the bottom of pipes. The same definition was used in [39] and this is the one we will take in this study. We can summarize it in another way: the pickup velocity is the minimum velocity to put in motion a single particle which was initially at rest on a surface. The motion can correspond to rolling, sliding or even lifting depending on the airflow velocity, intensity and profile. Cabrejos and Klinwing conducted experiments with various materials and developed a theoretical model based on force balance leading to sliding. To conclude this velocity is a combination of different forces such as the shear lift, buoyancy and gravitational forces, drag force and cohesive forces between particles and the surface.

In [58] or in [37], the pickup velocity is defined in relation with the cohesion forces and the minimum force to resuspend the particles (lift or saltation). The velocity obtained is probably higher than the velocity measured with our definition. This definition as some similarities with the threshold velocity $U_{th}$ defined by Ibrahim in his PhD thesis [30]. He described it as the velocity to detach 50\% of the particles on the surface and studied the effect of several factors on it (relative humidity, residence time, mean flow acceleration, initial number density and collisions, final free-stream velocity, final Reynolds number). He observed that the threshold velocity was not showing a de-
dependence on flow acceleration considering the uncertainty of the measurements, with acceleration values from $0.045 \, \text{m.s}^{-2}$ to $0.34 \, \text{m.s}^{-2}$. He distinguished two regimes. The first one is a short term resuspension which lasts during airflow acceleration. Particles are removed most easily. The second regime corresponds to a constant airflow velocity. The particles has a much lower resuspension. One limit of these two regimes I observe in the experiments of this study is the following. When the second regime is reached, the particles have already moved and preferential concentrations already appeared on the surface. The structure is not exactly the same than the homogeneous deposition at the start. Thus it is harder to compare the influence of the mean velocity airflow with no acceleration on a homogeneous distribution of particles.

2.2.3 Turbulence in a channel

Turbulence in channels was mostly studied numerically in prior studies [9, 38, 46]. Here, we give a short review of the results of such studies relevant for our problem of interest.

Internal flow

As developed in Pope - Turbulent Flows, [57] an internal flow is driven by a drop in pressure between the entrance and exit of a channel. In our experiment we can impose the mean velocity which is directly related to the gradient of pressure in our channel. In fully developed regions —large distances from the entry— the flow is assumed to be homogeneous and with a symmetry plane through the middle of the channel. The Reynolds number used to define our flow is $Re = \frac{HU_0}{\nu}$ with $U_0$ the mean flow velocity and $H$ the height of the channel (square section). For Reynolds $Re>1800$, the flow is fully turbulent.

In a turbulent flow the wall shear stress is due to viscous contributions. A zone where viscous forces are dominant appear near the walls because of the no-slip con-
dition at the boundaries [see 2-2]. This region is called a viscous sublayer and the distance associated is \( \delta_v \). We can define a local distance \( y^+ = \frac{y}{\delta_v} \) with this new length \( \delta_v \). The no-slip condition and competition between forces divide the space into different regions such as the viscous wall region for \( y^+ < 50 \) where the shear stress is dominated by viscous effects. For \( y^+ > 50 \) the viscous effects are negligible (outer layer). For \( y^+ < 5 \) the viscous sublayer dominate and turbulence has no effect. For \( 5 < y^+ < 30 \) (buffer layer) there is a competition between the viscous forces and the shear stress forces.

**Grid turbulence**

The use of grids is an easy way to change the turbulence in a channel [41, 73]. Experimentally we found that the pressure loss due to the presence of the grid was
not important leading to a small decrease in mean velocity. As discussed previously the mesh size of the grid changes the Reynolds number considered in the channel by adding new scales of turbulence (smaller eddies). According to the literature (e.g. [53]) an important point when working with grids is flow homogeneity. To get a mean velocity profile homogeneous different conditions should be respected:

- The porosity of the grid (ratio open over total area of the grid structure) should be large enough to prevent coalescing jets and large-scale instability with for instance a porosity greater than 57% [15] (see 2-3)
- Height of the flow must be much larger than the length scale of the energy containing eddies, which is the same order as the mesh size of the grid
- Measurements should be taken downstream (after at least 40 mesh sizes downstream).

However, homogeneous mean velocity does not imply homogeneous fluctuations. When grids are used to create turbulence, the distance to respect to get an isotropic and homogeneous turbulence is about 20 to 40 hole diameters downstream [21]. At this distance the temporal and spatial averages merges. Grid turbulence can be characterized into four regions downstream [64]:

- the initial 'developing' region
- the 'simple' or power-law decay region
- the 'dominating large-scale' region
- the 'final period of decay' region.

The initial developing region correspond to the region where jets are created behind the holes. It is described as a zone of interaction through shear which spawns large turbulent eddies. Most of the energy is centered around a wavelength on the order of the mesh size.

The power-law decay region is a zone of turbulence approximately homogeneous. The particles should be deposed in this region to consider homogeneous isotropic turbulence. To compare different grids, an Orificed Perforated Plate (Orificed Perforated Plate (OPP)) produced roughly 25% higher turbulence intensity than the common
Figure 2-3: Example of a grid. The open area corresponds to circles of diameter $d$ (mesh size). The porosity can be calculated by doing the ratio of open area ($16 \times \pi \left(\frac{d}{2}\right)^2$) on total area ($L^2$).

Straight-Hole perforated plate (Straight-Hole perforated plate (SHPP)). The mean flow almost uniform carries the turbulence through the tunnel. The energy dissipation comes from the Kolmogorov cascade [57]. The OPP has the advantage of producing an extremely clean wind tunnel turbulence in comparison with a SHPP. However, there is a rapid decay of the turbulence as indicated by the fluctuating velocity that rapidly decreases over distance [43, 66].

**Turbulent forces on a rough bed**

Generally on wall flows, the boundaries are taken to be smooth. A more realistic point of view would take into account the roughness of the wall. Roughness on the order of the atomic scale is always present. The literature shows that roughness elements on the order of 0.1μm enhances the resuspension of micro-particles. Several tens of micron of difference on the surface are sufficient to observe an effect. This roughness influences the contact adhesion forces applied on the micro-particles [18].

Another effect of the roughness is observed on the flow. In case of experiments with particles deposed on a horizontal surface, the roughness considered for the flow is modified. A length scale of protrusions or indentations $s$ gives a first approximation
to characterize this variation. The micro-particles create new boundary conditions for the flow. The length scale of indentation $s$ is on the order of magnitude of the particle diameter. In general this new defined roughness has little effect on the laminar regime. The effect appears mainly in turbulent flows and depend on the ratio $\frac{s}{\delta_v}$ with $\delta_v$ the viscous length scale. If the ratio is large enough (roughness scale large compared to the viscous scale $\delta_v$) the Reynolds number of the flow over the roughness element is large ($Re_s = \frac{s}{\delta_v} >> 1$) and the transfer of momentum from the fluid to the wall is accomplished by drag on the roughness elements. For a fully rough case, the friction law is a log-law. This law is similar in the case of a length scale of protusion comparable to $\delta_v$ [See [18] for more details].

**Length scale of the eddies**

Given the channel size $L$, the mesh size of the grids, and the mean velocity, we can derive the Reynolds number associated with the turbulent flow. The largest size of eddies are given by the typical size of the system $L$ (the size of the channel or the grid) and the mean velocity $U_0$. To obtain the smallest eddies scale $\eta$ we can use the following equations obtained using the energy cascade with Kolmogorov hypothesis [57]:

- Local isotropy. At sufficiently high Reynolds number, small-scale turbulent motions $l$ ($l \ll L$) are statistically isotropic.

- First similarity hypothesis. In every turbulent flow at sufficiently high Reynolds number, the statistics of the small-scale motions have a universal form that is uniquely determined by the kinematic viscosity $\nu$ and the rate of dissipation (or energy injection rate) $\epsilon$.

- Second similarity hypothesis. In every turbulent flow at sufficiently high Reynolds number, the statistics of the motion of scale $l$ in the range $\eta \ll l \ll L$ have a universal form that is uniquely determined by $\epsilon$, and is independent of $\nu$.

These hypotheses can be shown to lead to:

$$\frac{\eta}{L} \simeq Re^{-3/4}, \text{ and}$$

(2.1)
\[ \frac{u_n}{U_0} \simeq Re^{-1/4}, \tag{2.2} \]

where \( u_n \) is the velocity at the Kolmogorov scale \([57]\). For example, in case of a mean velocity about \( 6.2 \, m.s^{-1} \) we obtain:

- without grid, a Reynolds number \( Re \simeq 5 \times 10^4 \) and smallest eddies of about \( \eta \simeq 20 \, \mu m \)
- with a mesh size of grid of \( 1.4 \, cm \), a Reynolds number \( Re \simeq 8.6 \times 10^3 \) and smallest eddies of about \( \eta \simeq 15 \, \mu m \)
- with a mesh size of grid of \( 0.6 \, cm \), a Reynolds number \( Re \simeq 3.7 \times 10^3 \) and smallest eddies of about \( \eta \simeq 12 \, \mu m \).

### 2.3 Resuspension

![Sketch of particle resuspension from channel airflow.](image)

Figure 2-4: Sketch of particle resuspension from channel airflow.

Resuspension or reentrainment is the removal of a micro-particle from a surface, where the micro-particle was previously airborne and deposited on this surface (see figure 2-4) \([27, 75]\). More specifically particle resuspension consists of the removal of particles from surfaces after the break-up of the particle-surface bond. In the literature, reentrainment is frequently used for both entrainment and reentrainment.
2.3.1 Overview of the phenomenon

Resuspension is a phenomenon involved in numerous environments and which is applied to different types of particles depending on their size, nature, or other properties. It is usual to find resuspension in different fields such as material physics, interface chemistry, solid mechanics, physics of granular media. With the definition used above we will try to define resuspension despite its complexity by starting with a description of the motion observed in our system.

Experimental studies with high-speed video recordings used to keep track of the motion of particles and the mechanisms of resuspension were performed. It is difficult however, to compare the results due to the range of various conditions considered between experiments, for example particle properties. The properties of the particles (dimensionless particle size \( d_p^* = \frac{d_p \mu}{\nu_f} \)), coupled to the properties of the flow (viscous sublayer length scale \( \delta_u \)), affect resuspension. For instance, with small particles (\( d_p \leq \delta_u \)) the motion is characterized by rolling or sliding motions on the surface. For larger particles the motion is characterized by 'burst-type' resuspension with an important role played by coherent structures [27]. The sweep part of a burst-sweep event plays a role in the detachment process and the dissipative forces and moments were found to be negligible on this effect [30]. During our experiments the rolling or sliding motion was the first to occur. Then, depending on the mean flow intensity we were able to observe a competition between rolling, sliding and lifting (particle detachment characterized by the break-up of the particle-surface contact).

These three motions generate different horizontal layers. For instance the bed load corresponds to particles moving in the bed layer. This motion occurs by rolling, sliding, and, sometimes jumping (saltation). Particle motion is assumed to be dominated by gravity and not by turbulence. In Einstein's publication [23], the bed layer was defined as a flow layer, 2 grain diameters thick, immediately above the surface. The thickness of the bed layer varied with the particle size.

The suspended load is made of particles moving outside the bed layer. The excess
weight of the particles is supported by a random succession of upward impulses imparted by turbulent eddies. In this suspended load we can differentiate the particles in suspension from the particles in saltation. The particles in saltation are re-entrained from a surface but are too large to remain in suspension and thus hit again the surface later on. Upon impacting the surface once again, these particles can lead to the resuspension of other materials present on the surface. They can also be seen as particles bouncing on surfaces. Bouncing particles can be regarded as resuspended since the surface-particle contact was disrupted. However, it can also not be considered as particle resuspension since particles did not adhere first to the surface. Resuspension then just corresponds to the removal of particles already sticking on a surface.

In the following study we will make a difference between aggregate and clusters. An aggregate is a group of particles in suspension forming a larger structure. A cluster is a group of particles deposited on a surface and forming a larger structure on this surface. The term fragmentation will be used to describe the separation of this large structure (aggregate or cluster) into smaller ones.

The detachment of particles can be rationalized using different resuspension models. Two main categories of models emerge: force balance versus energy-accumulation approaches [27]. The former category refers to models where the forces acting on the particles are considered whereas in energy-accumulation approaches, the resuspension is addressed by assessing particle vibrational energy. In Henry’s review [27] a distinction between empirical formulas and equation of particle motion on the surface is made. The latter is divided in static approaches and dynamic approaches whether the study considers only particle equilibrium (and its rupture) or whether it considers both particle equilibrium as well as its detailed dynamics on the surface.

One effect observed by Ibrahim in his PhD thesis [30] was the influence of the residence time on surfaces. Particles deposited for a long time are harder to remove than freshly deposited ones. Our study this residence time is short in comparison with the order of magnitude given in Ibrahim’s thesis [30]. Particles were deposited
five to ten minutes before the onset of detachment in our experimental method. The particle resuspension is generally measured in terms of a particle resuspension rate $k_r$, defined as the ratio between the initial surface concentration of particles and the flux of reentrained particles. This rate has the dimension of a frequency ($s^{-1}$). In the literature, a few experimental studies talked about the repeatability of their detachment/resuspension data. The phenomenology of resuspension for biological or organic particles is similar to solid particles even though the forces involved can be different. Indeed, inter-surface forces can be created due to particle shapes (presence of filaments, non-sphericity, etc.). Experiments with biological and bacterial materials have also shown that detachment is sometimes governed by a balance between hydrodynamic forces and inter-surface forces [27].

2.3.2 Interactions

Granular materials are an ensemble of macroscopic particles which are visible by the naked eye such as glass beads or *Lycopodium clavatum* spores [8, 52]. It means that Brownian motion is irrelevant to characterize their dynamic. Particle-particle interactions are dissipative. Continuous energy input by external forces are necessary in order to keep the particles in motion. As described in [8], the most fundamental microscopic property of granular materials is the irreversible energy dissipation in the course of interaction (collision) between particles.

Particle-fluid Interactions

The detachment of a micro-particle from surfaces is due to the combination of different forces. The micro-particles are initially subjected to gravity ($mg$), a contact adhesion force (interaction between the particle and the surface) $F_s$ and Hertzian forces $F_H$. The presence of the micro-particle in the viscous sublayer causes aerodynamic (viscous) drag $F_d$ and lift $F_L$ forces and moments. Different expressions are found depending on the flow properties and especially the friction Reynolds number.
or Reynolds number of the particle \((Re_p = \frac{d_p u_r}{\nu_f})\) with \(u_r\) the friction velocity [see 2-5]. The friction velocity \(u_r\) is defined by the square root of the wall shear stress \(\tau_w\) on the fluid density \(\rho_f\): \(u_r = \sqrt{\frac{\tau_w}{\rho_f}}\).

![Figure 2-5: Forces applied on a particle in a sheared flow profile.](image)

The distribution of impulse imparted by the flow on a particle is another pertinent parameter to study particle entrainment. The distribution of impulse translates fluctuations of the lift force on the particle. These variations will increase or decrease the effective weight of the particle and thus the critical impulse to lift the particle. The study [2] proposes a method of calculation of the lift force associated with individual impulse events.

The drag force expression we consider in our study is similar to the one described in [32]. The buoyancy, virtual mass and Basset forces —unsteady forces due to acceleration of that body with respect to the fluid— are much less than the drag force because the density of the micro-spheres is much larger than that of air. The mean aerodynamic drag force is modelled as:

\[
F_{drag} = 3\pi f \mu d_p u_r [1 + \frac{3Re_p}{16} + \frac{9Re_p^2 \ln \frac{Re_p}{2}}{80} + 0.0470Re_p^2],
\]  

where the slip correction was neglected because of the relatively large micro-particle diameters. The factor \(f = 1.7\) accounts for the wall effect. The friction Reynolds
number is defined with the diameter of the particle. The lift force is defined from the friction Reynolds number as well. We can find different formulas depending on the assumptions [26, 42, 59], such as:

\[
F_{lift} = (56.9 \pm 1.1)\nu_f \rho_f \left(\frac{Re_p}{2}\right)^{1.87 \pm 0.04} \text{ for } 0.3 < \frac{Re_p}{2} < 2
\]

\[
F_{lift} = (20 \pm 1.57)\nu_f \rho_f \left(\frac{Re_p}{2}\right)^{2.31 \pm 0.02} \text{ for } 1.8 < \frac{Re_p}{2} < 70
\]

Particle-surface Interactions

Surface roughness effect have a great influence on the resuspension of particles [4, 13, 18, 47]. The resuspension shows a dependence on local heterogeneity on the surface such as surface roughness or surface charge heterogeneity. For instance, a surface roughness of only a few angstroms is sufficient to reduce the normal pull-off force to a very small fraction of its smooth-surface value. In [25], a standard deviation of heights of 17Å was shown to reduce the normal pull-off force to about 1% of its smooth surface value. Then resuspension depends on the surface cleanliness [36]. As described in [49] the particles in our experiment were supposed to be in the hydraulically-smooth regime. It means the roughness elements are entirely contained within the viscous sublayer and the velocity profile, as a function of the distance from the virtual wall, practically collapses upon the profile that could be obtained over a smooth wall at the same bulk Reynolds number \(Re_{bh}\) where the characteristic length is equal to the channel height minus the particle diameter.

An interesting point to notice at this stage is the role of capillary forces. The condensation of water leads to an enhanced adhesion force between the surfaces (e.g. relative humidity higher than 60-70%). We can see this modification of the surface roughness as well as an increase on the particle-surface interactions. This part will be detailed in the relative humidity section (chapter 4).

To define the interaction between the particles and the surface, two main theories
were developed:

- **Johnson, Kendall and Roberts** [Johnson-Kendall-Roberts (JKR)] theory [35]. The particles and surfaces are considered to deform elastically upon contact according to the Hertz theory and that an adhesion between the surfaces occurs within the contact area. This theory remains valid for large or highly deformable particles.

- **Derjaguin, Muller and Toporov** [Derjaguin-Muller-Toporov (DMT)] theory [3]. This theory considers the elastic deformation of surfaces (according to the Hertzian theory only) and includes also non-contact forces (Van Der Waals contribution) which act across the gap between the two surfaces. It is valid for a surface stiffness much smaller than unity, i.e. for small or slightly deformable particles.

**Particle-particle interactions**

The number of interactions between particles is closely related to the concentration of particles. These interactions can form agglomerate of particles (collision of pair of particles that can stick together and form a larger structure with a distinct inertia and dynamic) or just change the dynamic of detachment with collisions [27]. These interactions may lead to multi-layers of particles on the surface. More details on this can be found in [28].

**2.4 Preferential concentration**

**2.4.1 Preferential concentration under turbulent flow**

Most studies on preferential concentration under turbulent flow in channel or without any boundary focused on three-dimensional analysis. The forces considered are different depending on the effect analyzed. For instance gravitational forces are taken into account for studies on the preferential aggregation in air. The main goal on this field is to observe the regions of preferential accumulation and understand the dependence with the characteristics of the flow.
Studies on preferential concentration in channel are recent. For instance, [10] studies cluster and underlined that concentrated regions are described with low vorticity and high strain rate. Statistical topography — study of the geometrical properties of the contour lines or surfaces of a statistically isotropic scalar field [10] — fails to predict the distribution of cluster and void sizes in turbulent duct flow. This is likely due to anisotropy and non-homogeneity in the wall-bounded flow, which are absent in Homogeneous Isotropic Turbulence (HIT) and also not accounted for by the statistical topography model.

In [44], micro-particles were released in water and accelerate under the gravitational force at a friction Reynolds number $Re_f = 180 - 360$. Using Voronoi analysis, they determined preferential accumulation regions and underlined statistical characteristics of the streamwise-aligned particles streaks. They observed that the shape, length and temporal persistence of these streaks vary with the grain size, density and turbulence intensity. Also the unevenness of particle distribution and the particle concentration gradient increased with increasing Stokes number. The non-homogeneity of particle distribution was the most distinct under the condition of a Stokes number about unity. For a two-way interaction between solid particles and homogeneous air turbulence [74] found a similar result using an interesting experimental system (cruciform apparatus).

The paper from [68] delves into interface-resolved direct numerical simulations of forced homogeneous isotropic turbulence in a dilute suspension of spherical finite-size particles (5.5 and 11.4 times the Kolmogorov scale $\eta$) in the Taylor micro-scale Reynolds number range $Re_f = 115 - 140$. The study was focused on inertial effects and neglected gravitational effects (by choosing a small density ratio of particle density on fluid density). They quantified the tendency of cluster formation in terms of the standard deviation of Voronoi cells volumes and highlighted a decrease of this tendency with the particles diameter. Contrary to other studies, they not only find no significant statistical correlation between particle locations and the location of intense vertical flow structures (centrifugal effect), but they also showed a small but significant statistical preferential location of particles with respect to specific points.
called "sticky points": points where the fluid acceleration field increases the local particle concentration in one-way coupled point-particles models under Stokes drag. This sweep-stick mechanism for finite-size particles still has to be further understood and completed by more complete models involving force balance analysis. On a previous paper [69] the authors also determined the residence time of particles in a cluster thanks to Voronoï tessellation.

2.4.2 Method of analysis

Numerically, different methods can be used to analyze the resuspension of particles on images. These methods are described in [51] such as the pair correlation, the correlation dimension, and the clustering index (see table 2.1). We will focus on two main methods: the box counting method, for its use in our experiment analysis, and the Voronoï analysis. The box counting method corresponds to a computational domain discretized into a large number of cells with equal sizes. This solution is simple and straightforward, but can show low computational efficiency. Also, this method uses an artificial length scale which introduces uncertainty between numerical results (different size of cells can be used). The Voronoï analysis described in [50, 54] corresponds to a decomposition of space into independent cells associated to each particle. These cells are defined using a collection of points that are closer to a particle than to any other. The computational domain is then divided into non-overlapping Voronoï cells and each of them is attached to an individual particle. This method is computationally efficient and free of scale sensitivity which guarantees the objectivity of the results. The area of each individual cell \( A_i \) is inversely proportional to the local particle concentration. The ratio between the streamwise and spanwise lengths of the Voronoï cells can be used to measure the alignment of the particles [68]. Also, the streamwise direction \( L_{x,\nu} \) and the spanwise direction \( L_{z,\nu} \) are used to measure the anisotropy of streamwise-aligned streaky structures.
Table 2.1: Semi-quantitative evaluation of different methods regarding most relevant indicators. Taken from [51].

<table>
<thead>
<tr>
<th>Visualizations</th>
<th>Clustering index</th>
<th>Box counting</th>
<th>Correlation dimension</th>
<th>Pair correlation</th>
<th>Divergence</th>
<th>Voronoi</th>
<th>Minkowski</th>
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<tbody>
<tr>
<td>Computation efficiency</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
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<td>Concentration map</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>PC quantification</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Intrinsic resolution</td>
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<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Lagrangian tracking</td>
<td>No</td>
<td>No</td>
<td>Difficult</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Clusters/holes identification</td>
<td>Yes</td>
<td>No</td>
<td>Difficult</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Clusters/holes characterization</td>
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<td>No</td>
<td>Difficult</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Chapter 3

Experimental setup

3.1 Experimental system

A schematic of the experimental setup is shown in figures 3-1. The ventilation duct is composed of an airflow extractor fan of entrance diameter of 15 cm and a maximum flow rate of 200 L.s$^{-1}$, connected to a pipe of square cross section $7.3 \times 7.3$ cm$^2$ and a length of about 57 cm. The fan power is driven by a voltage transformer Triax combined with a programmable controller (Arduino). We were able to control the flow rate into the pipe automatically during an experiment and in real time.

The ventilation duct used is built in poly(methyl methacrylate) (PMMA) of approximate dimensions $9 \times 9 \times 50$ cm$^3$. The channel is embedded in a bigger container of $91 \times 45 \times 42$ cm$^3$. In this container we were able to control the humidity rate with a humidifier and dehumidifier connected to humidity sensors. A direct injection of dry air was used to reach the lowest humidity rate. The relative humidity was fixed during an experiment. We worked with a range of relative humidity rates from 10 to 90%. The temperature $T$ was set in the whole room at a specific level in a range of 15 to 30°C. Heat effects of lights were taken into account during the experiment and led to a variability of 1.5°C. A high-speed camera was used to record the experiment at a frame rate varying between 125 to 4000 frames per second and a resolution of $1280 \times 1024$ pixels. Two types of particles were used: glass beads of diameter 50 μm and *Lycopodium clavatum* spores of diameters 30 and 60 μm.
The particles were deposited homogeneously on acrylic substrates (Poly(methyl methacrylate) (PMMA)). We used an anti-static generator to remove all static electricity from the substrate and the particles. Indeed, particles can have an electric charge or magnetic moment, which increases interactions between particles or between particles and surfaces. Collective effects may depend on the inner electric charges of particles and the competition between collisions and electromagnetic forces. We wanted to focus only on the collisions effect rather than having to incorporate electromagnetic forces.

Between two experiments, the substrate was cleaned with ethanol and air to remove any impurity that would lead to a modification of conditions or roughness effect on the surface. It improved the repeatability of the experiments. When temperature and the relative humidity influence were not tested, all experiments were conducted at a temperature of 24°C and a relative humidity of 40%.
3.2 Micro-particles

3.2.1 *Lycopodium clavatum*

One of the surrogates of *Bacillus anthracis* which is commonly used in laboratory is *Bacillus thuringiensis* (Bt). Developing samples of these surrogates can be quite complicated. Indeed, it is challenging to extract these bacteria in the spore form instead of in a compact form. Also the safety precautions to work with bacteria are important for understandable reasons. Rather than using *Bacillus anthracis* or its surrogates, we chose two other types of particles to study the mechanism of detachment: glass beads and Lycopodium spores [see 3-2].

![Photography of Lycopodium clavatum spores of diameter 30 µm (left) and 60 µm (right).](image)

*Lycopodium clavatum* spores present similar properties than *Bacillus anthracis* spores (hydrophobic properties, filaments). Our spores had a larger diameter of particles: 30µm (referred as LS30) and 60µm (referred as LS60). If we consider the dynamics of spores, the Reynolds number is equivalent, which let us expect a similar interaction with the flow. The Stokes number is equivalent to $St = \frac{r_p}{\tau_\eta}$ with $\tau_p$ the particle response time to surrounding flow and $\tau_\eta$ and $\eta$ respectively the dissipation time scale and length scale of the carrier flow [50]. This number is different by an
order of magnitude. This difference mainly impacts the motion in the air and does not modify the detachment from surfaces since particles are still in the viscous sublayer. The density ratio of the particle density and the fluid density is similar between *Lycopodium clavatum* spores and anthrax spores. One other asset of this choice was a better compromise between the size of particles, the size of our observational window and the resolution of our camera. In the end studying *Lycopodium clavatum* spores with a size about 30µm and 60µm enables us to observe the effects of relative humidity, temperature, and collisions on biological micro-particles. For instance, the smaller spores display filaments on their surface, which led to a different collective effect. These filaments were also observed on different strains of anthrax [62].

### 3.2.2 Glass beads

We used spherical glass beads of mean diameter 53µm (with standard deviation of 13µm) and density 2.5 g.cm⁻³ (see figure 3-3). They were relatively mono-dispersed in size, easily deposited on the surface as singlets and monolayer, and also completely contained on the viscous sublayer. We made a comparison between glass beads and *Lycopodium clavatum* spores LS60 which both had a spherical shape, a similar Stokes and Reynolds numbers but a different density ratio, \( \frac{\rho_p}{\rho_f} \), and hydrophilic surface properties.

![Photography of glass beads of diameter 53µm](image)

Figure 3-3: Photography of glass beads of diameter 53µm
3.3 Experimental method

The particles are deposited on the surface via a shaking system and a sieve to get an homogeneous distribution. Static electricity is removed on the substrate and between particles before and after deposition.

The mean velocity flow is fixed during an experiment. We use the following method to control the airflow in the channel. The fan is set to reach a steady-rotation. At this stage the airflow does not interact with particles deposited beforehand. A trapdoor prevents any contact between the flow and the particles. When the fan reached its constant velocity, the trapdoor is pulled up, which creates a fast ramp-up of the flow in the channel. In about one second, the flow reaches its mean velocity. The high-speed camera starts recording the detachment of particles after the motion of the trapdoor. The video is stopped when particles do not detach anymore (see figure 3-1).

3.3.1 Image processing

The videos are analyzed by image processing. A Particle Tracking Velocimetry (PTV) code gives us the path of each particle on the surface. This code is built by incorporating different hypotheses. The sense of the flow on images is specified. A specific particle is followed thanks to its area and assumed position in the next images. The tracking of this particle stops when it collides with another particle or disappears from the window of study. This code is adapted from that developed in [71]. More detail is given below. Images are also analyzed to determine the position of each cluster.

For more precision on the tracking code, the determination of particles’ paths is realized by finding the closest neighbor in a circular diameter from an estimated position. This estimated position is found with a previously calculated velocity. Then the closest neighbour is found by minimization of a function related to the distance between particles and their estimated positions. This method requires to specify a maximum displacement to link a particle between the two first images. The back-
ground of each image is subtracted to determine the particles' motion in each image. This method reduces the error caused by the presence of clusters of particles. Only the particles that are moving between two frames are kept in order to limit error during tracking.

During the association of a path (determination of the path of a particle between more than two frames), it was possible to commit an error because of the first displacement assumption. We indicate a certain velocity and expect to observe a particle around an estimated position. If there is a cluster in the middle of a path or two particles really close, the confusion was high. To palliate this problem, once a particle is identified in the frame \( n \) which seems to correspond to the one we had on the frame \( n-1 \), we automatically analyze the current image to determine if there are clusters or static particles along the path. If so, we stop the tracking of this particle because a collision might occur.

An angular criteria was also added. We observed that the trajectory of a particle can have a high radius of curvature. The variation of trajectory direction between two frames was not higher than a specific angle value however. We specify this relative angle to be about \( \pi/8 \). A change of trajectory with a relative angle beyond this value implied the particle was either impacted by another particle or the path created was an error from the tracking algorithm. The problem with this method comes from the definition of the first particle motion. This initial angle formed with the horizontal axis is the reference for the rest of the tracking. An error at this point will lead to a wrong path. We thus specify that this angle should be under a certain value \( \theta = \pi/8 \) which corresponds to the maximum angle observed during experiments.

### 3.4 Summary

We define the Bulk Reynolds number (ratio of inertial forces to viscous forces) in the following way:

\[
Re_{bh} = \frac{\rho_f h U_0}{\mu_f},
\]  

(3.1)
Figure 3-4: Tracking of particles in four consecutive images. Interval of time: 1/500 s. Re=35 x10³.

<table>
<thead>
<tr>
<th>Particles</th>
<th>Surface</th>
<th>Density (g.cm⁻³)</th>
<th>Reynolds number $Re_{bh}$</th>
<th>Stokes number</th>
<th>Experimental temperature (°C)</th>
<th>Experimental Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beads (50µm)</td>
<td>PMMA</td>
<td>2.5</td>
<td>10³-10⁵</td>
<td>1-70</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>Lycopodium clavatum spores (30µm and 60µm)</td>
<td>PMMA</td>
<td>0.323 and 0.659</td>
<td>15 - 24 - 27 - 30</td>
<td>10 to 90</td>
<td>15 - 22 - 24 - 27 - 32</td>
<td>10 to 80</td>
</tr>
</tbody>
</table>

Table 3.1: Experimental parameters. The Reynolds number is $Re_{bh} = \frac{\rho_f h U_0}{\mu_f}$, where $\rho_f$ is the air density, $h$ a characteristic length (channel height H or mesh size of the grid), $U_0$ the mean airflow velocity, $\mu_f$ the dynamic viscosity of air. The channel height $H = 7.3$ cm. The mesh size of grids is between 0.5 - 1.3 cm.

where $\rho_f$ is the air density, $h$ a characteristic length (channel height H or mesh size of the grid), $U_0$ the mean airflow velocity, $\mu_f$ the dynamic viscosity of air. With a mean velocity airflow from 2 to 13 m.s⁻¹ the bulk Reynolds number varies from $10^4$ to $10^5$. This Reynolds number is high enough to maintain a turbulent flow in the duct [45].

Grids were added to modulate turbulence inside the channel. We modify the Reynolds number definition above to incorporate turbulence effects created by the grid mesh size. Changing the length L by the mesh size used (in the order of millimeter) makes the Reynolds number $Re_{bh}$ vary in a range from $1 \times 10^3$ to $10^5$.

The Stokes number represents the particle capacity to follow fluid streamlines.
For a Stokes number much less than unity, micro-particles follow almost perfectly streamlines. The Stokes number should be on the order of unity to see a competition between the relaxation time of particles and the air-fluctuation time. Even though particles are embedded in the viscous sublayer (effect of viscosity dominates on turbulence effects), we can expect an influence of turbulence effects with the role of collisions. Indeed the particles in saltation create collisions which are an important part of the clustering dynamics. In order to observe this effect, a Stokes number similar or higher than unity is necessary to obtain particles in saltation.

The Stokes number is expressed in our case as:

\[
St = \left( \frac{d_p}{\rho_p / \rho_f} \right)^2 \frac{1 + 2 \frac{\rho_p}{\rho_f}}{36},
\]  

(3.2)

with \(d_p\) the particle diameter and \(\rho_p / \rho_f\) the density ratio between particle and fluid. The Stokes number ranges from 1 to 70. This means that a competition between two phenomena occurs: particles following perfectly the streamlines versus those not detaching from the surface [see table 3.1].
Chapter 4

Role of relative humidity on detachment

Most papers studying the detachment rate of particles in channel do not specify the relative humidity they use in their experiments or simulations [32, 52]. However as described in [18, 30], relative humidity can modify the force required to lift a particle. Most studies on granular media focused on dry granular materials for which effects of interstitial fluids on particle dynamics are negligible [see in [52] with more details and examples such as [22, 33, 67]]. Dominant interactions are not only inelastic collisions and friction (short-range and non-cohesive interactions) but also cohesive interactions due to surface tension. Ambient humidity has then a huge impact because it can lead to tiny liquid bridges which increase cohesion forces. If the system is over-wet, interactions induce a change of the lubrication of solid-solid friction, a velocity-dependent behaviour on the liquid velocity and additional dissipation. The time scale of the dynamics is also affected [52].

Surface tension and capillary effects of the liquid are at the origin of the cohesion in wet granular media. The pressure difference $\Delta P$ between liquid and air is given by the Young-Laplace equation $\Delta P = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$, with $R_1$ and $R_2$ the meniscus curvature radii as shown in figure 4-1. Presence of liquid mainly results in suction and cohesive forces due to the minimization of surface area. An attracting force between two particles is induced by liquid bridges and corresponds to the sum of
surface tension and suction effects. These capillary bridges are described in [16] with a force expressed as:

\[ F_{\text{bridge}} = 2\pi R_2 \gamma + \pi R_2^2 \Delta P \]  \hspace{1cm} (4.1)

The role of relative humidity in ventilation duct is similar. For instance, above a certain threshold, water vapour is adsorbed on particle-surface interfaces. Corn in [18] showed that there is almost no change in adhesion forces with a relative humidity up to 30%. Above this value a rapid increase happens. Results shown in [7] highlight an increase in the threshold detachment velocity with relative humidity increase. These results were corroborated by other authors [30]. Physically, the pull-off force could increase with relative humidity.

Another study on relative humidity was done with different types of micro-particles, including bacterial spore (Bacillus thuringiensis as an anthrax simulant), and different diameters in the range 1 – 20 \( \mu m \) [60]. The flow was laminar (\( Re \sim 10^3 - 10^4 \)). Except for dust mite particles, relative humidity effects were not significant enough over 10 – 80% (within the measurement error range). However, resuspension of bacterial spores from a duct surface was affected by air swirl velocity and particle size.
Also, duct vibrations did not increase particle resuspension. The role of particle diameter was also analyzed. Increasing particle size from $10\mu m$ to $50\mu m$ makes resuspension rate decrease. This trend is reversed with sub-micron particle ($d_p < 10 \mu m$). Nonetheless, only two different relative humidity were used during this study (10% and 80%). It does not describe completely the effect of moisture, especially within this range.

A recent study [40] delves into the effect of relative humidity, surface and particles properties on aerodynamically induced resuspension. They used hydrophilic glass sphere and hydrophobic polyethylene spheres about 20 \( \mu \)m in size and observed that hydrophilic surfaces affect more the detachment than hydrophobic surfaces. Also a relative humidity threshold value was identified below which resuspension rates were essentially constant and in good agreement with a dimensionless model of resuspension. Between $\approx 55\%$ and $\approx 70\%$, the resuspension rate of glass particles decreased by three orders of magnitude. It highlights the impact of the humidity rate on resuspension. However no clear relative humidity impact on biological particles were demonstrated. Ibrahim in his PhD thesis [30] also showed evidence of the effect of residence time at high relative humidity (deposition on the surface for a couple of minutes to 24 hours), which increases adhesion forces. In our study, particles remain no longer than 10 minutes on substrate before starting an experiment so that we can neglect this impact.

4.1 Experimental method

In this section we focus on the detachment of biological particles, *Lycopodium clavatum* spores as described in section 3.2.1, under channel airflow with an emphasis on temperature and relative humidity effects. The deposition method of this experimentation section is similar to the one described in Chapter 3. Apart from the change in ambient conditions, we ramp-up the mean airflow velocity in the channel. A low flow of $1.7 \text{ m.s}^{-1}$ or $2 \text{ m.s}^{-1}$ was running during two minutes to start the fan rotation and
to make relative humidity and temperature homogeneous. We chose these velocity values to be small enough compared to the pickup velocity to prevent detachment. The airflow was then linearly accelerated during 135 s to respectively reach a maximum velocity of 9.8 m.s$^{-1}$ and 12 m.s$^{-1}$. The initial distribution was photographed after deposition. Several pictures were captured at a specific time after the fan acceleration change (see figure 4-2 where $C_0$ is the initial concentration on image). We recorded different set of experiments. Each set corresponds to approximately fifteen experiments of different initial concentrations at a specific temperature, relative humidity, and spores size. Overall we obtained a sample of 1000 distinct experiments.

Figure 4-2: Example of an experiment: images captured at different velocities for the spores 60 $\mu$m. $T=32^\circ$, RH=60%, $C_0=65\%$.

The concentration of particle $C$ is measured on each frame by the ratio of dark
pixels—particles—over the total pixels number (figure 4-4). The image background was removed to limit noise. The initial concentration $C_0$ is then defined as the concentration on the first frame, before onset of airflow. From that, we calculate a detachment fraction $\phi$ as the ratio of initial particles that have detached over the total initial number of particles: $\phi = 1 - C/C_0$. The detachment fraction is equal to 1 if there are no particles left on the observation window. This detachment rate represents the evolution of occupied surface area with time, and thus with the mean airflow velocity. The concentration can be measured 'globally', by considering the full frame, or 'locally', by dividing the full image on a window of $4.7 \times 4.7$ mm$^2$, or in segments of width 4.7 mm (figure 4-3). The latter method furnishes more measuring points for a single image. These 'local' measurements have been used in figure 4-8 that presents the final detachment fraction as a function of the initial concentration.

In this section, we focus on the effects of initial particles concentration, relative humidity, temperature, and particles size [see Table 4.1]. Figure 4-4 shows different type of particles distribution on the surface.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean airflow velocity</td>
<td>1.7 to 12 m.s$^{-1}$</td>
</tr>
<tr>
<td>Relative humidity (RH)</td>
<td>10 to 90%</td>
</tr>
<tr>
<td>Temperature T</td>
<td>18 to 32°C</td>
</tr>
<tr>
<td>Initial concentration C</td>
<td>$10^{-4}$ to 1</td>
</tr>
<tr>
<td>Particles diameter $d_p$</td>
<td>$30 \pm 2 \mu m$ and $60 \pm 6 \mu m$</td>
</tr>
<tr>
<td>Bulk Reynolds number $Re_B$</td>
<td>$10^4 - 10^5$</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of characteristic parameters used on relative humidity and temperature study.

4.2 Experimental results

4.2.1 Relative humidity and temperature effects

Figure 4-5 represents the detachment fraction as a function of mean airflow velocity, for different relative humidity. Experimental results are an average on all initial
concentrations constituting a set of experiments. As expected these results underline an increase of the detachment fraction with the mean airflow velocity regardless of ambient conditions. Besides, the slope of the detachment fraction, function of the airflow velocity, decreases with a relative humidity growth.

Figure 4-6 gives a more quantitative vision. It highlights the final global detachment fraction as a function of the relative humidity, for different temperatures and particle
Figure 4-4: Example of initial distribution of spores 60 μm. (a) $C_0=1.4\%$, (b) $C_0=5.4\%$, (c) $C_0=23.9\%$, (d) $C_0=62.7\%$. Scale bar: 1 cm

sizes. The final 'global' detachment fraction is calculated by considering the concentration on the last image of an experiment. Previous results are systematically confirmed.

This behavior is qualitatively similar to the behavior observed by Ibrahim et al. [31] with steel beads and glass substrate. A change of relative humidity affects the interactions between particles and substrate. Condensation on surface leads to the formation of liquid bridges, which increase capillary adhesion forces. This phenomenon described previously was observed above 30% in [31]. Here, the relative humidity effect only appears around RH=60%. This difference can be explained by the surface of L. clavatum spores, also called exosporium, which presents hydrophobic properties. These spore properties prevent the condensation of water droplets on its surface. For comparison, certain strains of anthrax, such as Bacillus anthracis, demonstrate a similar surface even though the exosporium properties are very variable.
Figure 4-5: Global detachment fraction as a function of the mean airflow velocity, for different relative humidity conditions. $T=32^\circ C$, $d=60\mu m$. Average over all the initial concentrations of an experimental set.

Figure 4-6: Final global detachment fraction as a function of relative humidity, for different temperatures and a velocity $v=9\, m.s^{-1}$: (a) $d=30\, \mu m$, (b) $d=60\, \mu m$

Figure 4-6 does not highlight any significant temperature effect. However, the definition of relative humidity takes into account ambient temperature. Indeed, the relative humidity is the ratio between water vapor pressure in air and the saturated vapor
pressure defined at a specific temperature. Besides, this definition can be related to the probability of forming liquid bridges. Then it is not surprising that the formation of liquid bridges (figure 4-1) relies only on relative humidity and is independent of temperature.

### 4.2.2 Initial concentration effects

![Graph showing the evolution of global detachment fraction as a function of mean airflow velocity, for different initial particle concentrations. T=22°C, RH=10%, d=60µm](image)

Figure 4-7: Global detachment fraction as a function of mean airflow velocity, for different initial particle concentration. T=22°C, RH=10%, d=60µm

In this section, we focus on the role of the initial concentration. Figure 4-7 describes the evolution of global detachment fraction as a function of the mean airflow velocity, for different initial concentrations, at a specific temperature, relative humidity, and spore diameter. The higher the concentration per unit area, the smaller the pickup velocity needed to detach particles, leading to higher detachment fraction for a given velocity.

This effect is confirmed for low relative humidity and low temperature on figure 4-8. It presents the final local detachment fraction for different temperatures, rela-
Figure 4-8: Final local detachment fraction of particles as a function of the initial concentration, for different relative humidity. (a) T=18°C and d=30 μm, (b) T=22°C and d=60 μm, (c) T=32°C and d=60 μm.

...concentrative humidities and spore diameters. First the relative humidity effect is once more confirmed. Moreover, the final detachment fraction appears to grow with the initial concentration for low relative humidity. However, this effect disappears for high relative humidity. The presence of collisions between particles can explained the results at low humidity, as suggested in Ibrahim et al. [31]. For high particle concentration on surfaces, collisions between particles that has detached and downstream particles happen more often, which lead to a higher detachment fraction.

For high relative humidity, the energy transmitted during a collision is small in comparison with the energy of adhesion forces between the substrate and particles and between particles. Then, collision effects are weaker which would explain the lack of...
effects of the initial concentration of particles.

Our experiments shows that initial concentration effects were predominant when initial particles distribution wasn't homogeneous, and the anti-static generator not used. This case corresponds to figure 4-8.b. Further experiments are needed to elucidate further this phenomenon.

4.2.3 Collision effects

![Figure 4-9: Detachment fraction as a function of the mean airflow velocity, calculated for different segments of the frame (see Fig. 4-3). RH=60 %, T=32°C, d=60 μm](image)

To complete our observations of collective effects, we turned to high-speed imaging. Instead of dividing each frame in small windows, we looked at distinct segments of the observation window, perpendicular to the airflow direction (figure 4-3.b). We observe and quantify the evolution of the detachment fraction in each segment as a function of the mean airflow velocity as shown in figure 4-9 for 60 μm spores and relative humidity of 60%. The different curves underline that the detachment fraction is different depending on the distance from the front-line (boundary between the upstream region with no particles and the region with particles). Considering error bars and the
Figure 4-10: Detachment fraction as a function of the mean airflow velocity, calculated for different segments of the frame. RH=80% ; T=32°C ; d=60 μm.

Figure 4-11: Detachment fraction as a function of the mean airflow velocity, calculated for different segments of the frame. RH=60% ; T=32°C ; d=30 μm.
difference between each curve, it is clear that downstream particles (segment 1) detach faster than upstream particles (segment 8). It endorses the hypothesis that collisions from detached upstream particles leads to higher detachment downstream. At high relative humidity this effect disappears (figure 4-10). Thus collisions are a small effect in comparison with adhesion forces at high RH.

For smaller spores of diameter 30 μm this effect differs. The pattern of detachment is quite uniform with regions of void and regions of clusters. Even though this effect is weak, it was regularly observed in our set of data. An explanation for this phenomenon can be the exosporium development on smaller spores. Longer filaments are clearly visible compared to the larger spores (visible in figure 3-2). This difference in surface shape can lead to a new collective effect: instead of increasing the detachment fraction, particles gather and form clusters during collisions.

These results are supported by figure 4-12. We make a comparison between the particles distribution at the beginning and end of experiment. For the *L. clavatum* spores of 60%, we notice a higher detachment downstream (on the right of the image), than upstream (on the left). However, the detachment fraction is sensibly uniform over the image for the 30 μm particles and we observe some clusters in different locations. The exosporium fosters the cohesion effect between particles.

### 4.3 Conclusion

To summarize, we observed a decrease of detachment fraction above a certain threshold of relative humidity (60%). This phenomenon is explained by the evolution of adhesion forces between the particles and the surface. No temperature effects were found other than the relative humidity dependence with temperature, that also characterizes the probability to create liquid bridges.

For low humidity the detachment fraction grows as a function of the particles initial concentration on the substrate. This effect was negligible for high humidity rate. In the end, collective effects (especially based on collisions) give clues to understand this phenomenon by increasing the detachment downstream, or creating aggregates
Figure 4-12: Comparison between different types of particle distribution observed after low airflow, $v=1.7 \text{ m.s}^{-1}$, (right) compared to initial deposition (left). Above: $d=60 \mu\text{m}$, $T=35^\circ\text{C}$, RH=15%, $C_0=27.7\%$. Below: $d=30 \mu\text{m}$, $T=25^\circ\text{C}$, RH=20%, $C_0=25.6\%$. Scale bar: 1 cm.

of particles depending on the spores surface properties.
Chapter 5

Experimental results

In the following section, we focus our study on the particle-velocity profile and the average distance travelled by a particle between two collisions. For this part, we do not define a typical minimum size of clusters (or minimum number of particles to qualify a group of particles as a cluster).

5.1 Flow-particle interaction

The mean flow was measured with an anemometer (Reed Instruments LM-8000). The air velocity resolution is 0.1 m/s and the velocity range is between 0.2 to 30.0 m/s. It was not possible to measure fluctuations with this instrument. We determined the mean airflow velocity in the ventilation duct after having reached steady-state. Then, we tracked particles in a vertical plan, parallel to the mean flow direction and passing through the center of the channel (see experimental setup in figure 5-2), and a horizontal plane focused on the first layer of particles. Their paths were analyzed via image processing (determination of velocity, direction, position).

5.1.1 Vertical velocity

After deposition in the channel, particles are located in the viscous sublayer. As shown in chapter 2 and in the figures 2-2 and 5-1, the viscous sublayer is a region
Figure 5-1: Characterization of different regions of the surface in the ventilation duct from the wall to a length $\delta_v = \frac{u}{u_r}$, with $u_r = \sqrt{\frac{2\tau_w}{\rho}}$ the friction velocity of the fluid defined with $\tau_w$ the wall shear stress. $\delta_v$ has the same order of magnitude as the particle diameter, for the Reynolds numbers we consider (between $10^3$ to $10^5$) [57]. For higher Reynolds number, micro-particles are located between the viscous sublayer and the buffer layer. The dynamics of detachment is then different because of the competition between turbulence and viscous forces. During an experiment, particles detach from the surface and may be airborne in other layers, leading to new interactions with the airflow. In order to understand these interactions between particles and flow, we determined the horizontal velocity of particles in a vertical plan using the system in figure 5-2.

Closer to the surface, the airflow follows a logarithmic law [57]. For our experimental setup, it corresponds to a region approximately between 0.3 mm and 9 mm. We assumed the flow profile in the surface boundary layer to match with the logarithmic law of the wall described by Von Kármán (1930) for nearly aerodynamically smooth surfaces:

$$u^+ = \frac{1}{\kappa} \ln y^+ + B$$  \hspace{1cm} (5.1)

with $\kappa = 0.41$ the Von Kármán constant, $B = 5.2$, $u^+ = \frac{\bar{u}}{u_r}$ with $\bar{u}$ the mean particle velocity and $u_r$ the friction velocity, $y^+ = \frac{y \nu}{\tau_w}$ with $y$ the vertical position and $\nu$ the kinematic viscosity.
Figure 5-2: Sketch of the experimental setup to determine the horizontal velocity of particles in a vertical plane.

Figure 5-3: Tracking of particles in a vertical plane parallel to the mean flow direction and passing through the center of the channel, at a Reynolds number $Re_{bh} = 5 \times 10^4$. We used particle tracking velocimetry (PTV) to follow particles moving in the same direction than the airflow.

We made the hypothesis that the horizontal particle velocity behaves as the flow velocity at a vertical position. By tracking particles in a vertical plane (see figure 5-3), we determine the equation (5.2) relating the horizontal particle velocity and the
Figure 5-4: Detachment of particles for $Re_{bh} = 7 \times 10^4$

$Re_{bh} = 3 \times 10^4$  $Re_{bh} = 5 \times 10^4$  $Re_{bh} = 7 \times 10^4$

Figure 5-5: Detachment of particles for different Reynolds numbers. These Reynolds numbers are obtained by changing the mean flow velocity.

The mean airflow velocity, as shown in the figures 5-6 and 5-7. Each curve represents an average on three different experiments for the same Reynolds number, with more than 500 particles tracked per experiment. Figure 5-4 presents a view of the particles motion from the side view. We visually observe that the maximum vertical position of particles increases with the mean flow velocity, as it can be seen in figure 5-5.

\[
\frac{u}{U_0} = \alpha \ln \frac{y}{H} + \beta
\]  \hspace{1cm} (5.2)

with $\alpha$ and $\beta$ two coefficients. They are almost constant in a certain range of Reynolds number (30 to $50 \times 10^3$) and equal to $\alpha \approx 0.11$ and $\beta \approx 0.7$. These coefficients change with the grid at the entrance. The grids were used to reach a Reynolds number $Re_{bh}$ on the order of $Re_{bh} \sim 10^5$. We consider the mesh size of the grid or the channel height to calculate the Reynolds number $Re_{bh}$. Reynolds number $Re_{bh}$ on the order of $10^4$ are reached without any grid at the entrance of the channel. For instance, the Reynolds number $Re_{bh} = 2 \times 10^3$ with a grid would correspond to the Reynolds number $Re_{bh} = 32 \times 10^3$ without a grid. The mean flow velocity is similar. Only the
length considered in the calculation of the Reynolds number changes. We observe from our results that adding a grid impacts significantly the two coefficients of the equation (5.2) in comparison of their values without grid.

![Graph showing vertical velocity measurements for different experiments.](image1)

**Figure 5-6:** Vertical velocity measurements for different experiments. The smallest Reynolds number is reached with a grid using the same mean airflow velocity as the one considered for $Re_{bh} = 32850$.

![Graph showing vertical velocity measurements for different Reynolds numbers $Re_{bh}$.](image2)

**Figure 5-7:** Vertical velocity measurements for different Reynolds numbers $Re_{bh}$. The smallest Reynolds number is reached with a grid using the same mean airflow velocity than for $Re_{bh} = 32850$. The lines represent a fit of experimental results in the form: $\frac{U}{U_0} = \alpha \ln \frac{Y}{H} + \beta$

From our measurements of the vertical velocity profile, we have determined Saffman
lift force (5.3):

\[ F_{\text{lift}} \propto \rho_f \nu \frac{d^2 \nu}{d y^2} \left( \frac{\partial u}{\partial y} \right)^{0.5} \]

valid for small Reynolds numbers but also for turbulent flow conditions in which the lift force is mainly caused by shear [70].

We were also interested by the wall shear stress \( \tau_w = \rho_f \nu \left( \frac{d<U>}{dy} \right)_{y=0} \) with \(<U>\) the mean flow velocity at vertical position \( y \). We respectively have plotted in the figures 5-8 and 5-9 the lift force at the wall and the wall shear stress as a function of the Reynolds number. We are currently trying to model the behavior of these two parameters, and respectively explain increase and decrease with Reynolds number.

\[ y = 4.2 \times 10^{-11} x + 2.8 \times 10^{-7} \]

Figure 5-8: Saffman Lift force as a function of the Reynolds number.

### 5.1.2 Surface motion

After the study on the vertical velocity profile of micro-particles, we determine their velocity closed to the surface \( u_p \). This velocity is assessed by recording an experiment from the top of the ventilation duct. The side view does not give us enough information because of the number of particles moving in the bed (see figure 5-4) and creating errors of tracking. The measurements from the top view of the surface are done at the center of the channel. Particles are initially located upstream the region of observation. Then this region is empty at the beginning to limit the effect
of collisions or initial concentration. Particles enter in the region of observation with a steady velocity. Errors of measurement may come from particles in saltation, have a higher velocity than the friction velocity. We try to limit these errors through our tracking code.

We wanted to verify how the velocity of particles on the surface $u_p$ evolves with the mean flow velocity. Our set of data shows no significant linear relation between the particle velocity on the wall and the mean flow velocity. We will analyze another relationship between the particle velocity and the wall shear stress to determine if we can predict the increase of particle velocity on the surface with time in future work.

5.2 Mean free path

Tackling the problem of aggregation of particles is complex when particles are coming into the zone of observation. To make a comparison between the clustering patterns obtained for different airflow velocities and initial concentrations, we have chosen to observe a region at 25 cm from the entrance with no particle coming from upstream. This choice was made to improve the repeatability of the experiments and to gain insights into the dynamics of clustering, without saltation that would require us to
have a homogeneous concentration upstream an "infinite" region. Indeed, we visually observed a difference in the detachment with versus without particles upstream. Considering the size of our channel and the turbulence, it was not experimentally conceivable to get an homogeneous concentration all over the surface with the same condition of turbulence and collective effects. Thus, we chose to work with no particles upstream. Almost no particle enters the region, taking into account the errors made from the deposition in the window of study. Only the particles inside the window of study participate to collisions with other particles. The effect of particles in saltation will not be studied here. These particles are lifted and might go settle back onto the surface at a larger distance than the size of the observation region.

5.2.1 Analogy

In a gas flow, we can define the mean free path [Mean free path (MFP)] \( \lambda \) as the average distance travelled by a particle between two collisions. In a 3D isotropic and homogeneously distributed gas flow, the mean free path can be defined as 

\[
\lambda = \frac{1}{\sigma n}
\]

with \( \sigma \) the cross section of a cylinder of radius \( d_p \) (particle diameter) and \( n \) the particle density (see figure 5-11). With a similar reasoning on a plane, we can define the mean free path as 

\[
\lambda = \frac{1}{d_p n}.
\]

This length is similar to the so-called chord-length in two-phase random media [65]. As described in this paper, 'chords are distributions
of length between intersections of lines with the two-phase interface* (see figure 5-12). Considering the clustering on surface, we can divide each image in two types of regions: regions with cluster and regions with void. The mean free path corresponds to the average chord-length in the void region. This length characterizes the average distance between clusters. From now on, we will refer to average of chord-lengths or mean free path to refer to the average distance travelled by a particle between two collisions. This model is rough and will be improved. For instance, it does not take into account particles in saltation, static particles, and the different probability of motion in a specific direction.

![Simple model to determine the mean free path in an isotropic and homogeneous gas flow.](image)

Figure 5-11: Simple model to determine the mean free path in an isotropic and homogeneous gas flow. [image credits to Dr. Christian Brunel]

From our experimental setup we tried to determine this chord-length in two different ways:
- with the particle concentration on the surface area, in regard to previous definition of MFP.
- by tracking particles on surfaces between two collisions.
As a first hypothesis, we assumed that these two definitions would have given us the same result.
5.2.2 Particle density

Depending on the mean flow velocity, the detachment can be partial or complete. For small velocities — around $5 - 6 \text{ m.s}^{-1}$ ($Re = 3 - 5 \times 10^4$) — the detachment is partial and clusters form on the surface. These clusters change the dynamic of detachment. Particles are aggregated in a certain configuration and stay in that pattern even if the flow continues in the channel (see figure 5-13). For higher velocities the detachment may be complete. In both cases the initial concentration is modified. The mean free path calculated by the particle concentration is called $\lambda_{th}$ from now on. The concentration of particles on surfaces evolve during an experiment. Thus, $\lambda_{th}$ characterizes the fluctuation of concentration.

As we can expect, at a given velocity, the initial concentration impacts the final detachment fraction ($\phi = 1 - \frac{C}{C_0}$). In the figure 5-14 we can observe an important detachment for low concentration. For higher concentration, particles agglomerate and the detachment fraction is less important. This effect was observed for other Reynolds number such as in figure 5-15. The Reynolds number dependence is different. For a
given concentration, a higher mean flow velocity, and then higher Reynolds number, will lead to an increase of detachment. The figures 5-16, 5-17 and 5-18 shows three evolution of respective concentrations 25 particles per mm$^2$, 55 particles per mm$^2$, and 100 particles per mm$^2$.

Figure 5-14: Time evolution of the concentration ratio for $Re = 35 \times 10^3$. 

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Figure 5-15: Time evolution of the concentration ratio for $Re = 41 \times 10^3$.

Figure 5-16: Time evolution of the concentration ratio for $C_0 \simeq 25$ particles/mm$^2$.

5.2.3 Mean free path and tracking

The experimental mean free path measured by tracking of particles is noted $\lambda_{exp}$ in the rest of the study. Our tracking code enables us to follow a particle between two collisions. This collision can happen when a particle hit a cluster or another particle on the surface or in saltation. As previously explained, we can expect a decrease of this distance when the concentration increases. The role of the Reynolds number is more complicated to predict. The mean flow increases the velocity of the particle. However at a given concentration, homogeneously distributed, the particle velocity is not as important as the distance between two particles. This distance might not
change for a higher velocity. However, with this assumption the time of flight between two collisions change as a function of this new particle velocity. In other words, a higher mean flow velocity increases the detachment fraction and then the probability of particle to detach at time $t$. Then, the distance between two particles changes as a function of this new probability of detachment. We aim to determine these different aspects with our particle tracking velocimetry code. At the moment, the code we use is not accurate enough to follow precisely particles between two collisions. Slow particles are easy to follow on surfaces, and figure 5-19 presents the evolution with time of the average particle velocity, at the Reynolds number $Re = 35 \times 10^3$. The
signal trend is not clear. We will continue our work on this experimental analysis in the future.

Having a deeper understanding of the mean free path is essential to get more clues on the comprehension of clustering and final detachment of particles. These elements are key to apprehend the propagation of diseases in indoor environments.

Figure 5-19: Velocity of particles on the surface at $Re=35\times10^3$. This velocity is obtained by tracking particles on the surface.
This chapter focuses on the clustering of micro-particles on a surface under a turbulent channel airflow. We pay specific attention to the effects of initial concentration and Reynolds number in order to understand their role on the clustering and the detachment of particles. For a given size and type of particles, we assume that the clustering effect previously pinpointed in prior chapters is mainly controlled by these two parameters. Increasing the initial concentration has an impact on collision and aggregation effects. We hypothesize that the pickup velocity of a single particle aggregated in a group of particles is higher than the pickup velocity for an individual particle. The clustering of particles on surfaces then changes the final detachment at a specific velocity. The concentration of particles inside a cluster $C(t)$ will be studied in relation with the average particle concentration in the whole image at time $t$, $C_t$ (average number of particles per image divided by the area of the whole visualization domain), and the average particles concentration in the initial image, $C_0$. For the following experiments, the temperature is 24°C and relative humidity 40%. We have experimentally studied the change of clustering pattern with the initial concentration of particles and the mean flow on parameters such as the number of clusters, the detachment fraction, and the shape of the clusters.
6.1 Shape of the clusters

In this first section, we focus on the shape of these groups of particles by underlining the relationship between their perimeter $P$ and area $A$.

6.1.1 Perimeter vs. area

This relationship was studied in prior work such as [6, 50] for a turbulent ventilation channel. Both of these studies analyzed the relationship between the perimeter $P$ and area $A$ of clusters of particles viewed in a vertical plane perpendicular to the mean airflow. In our study we look at a horizontal plane parallel to the surface of the ventilation duct and find similar results. We identify each group of particles on the window of observation and determine their perimeter and area. Figure 6-1 represents the perimeter of these regions as a function of the square root of their area.

Figure 6-1 describes the deviation of clusters from roundness. For small clusters we find a quasi-circular form; this changes when we reach more than five particles in a cluster. Thus two different behaviors can be observed on the figure 6-1. For small group of particles (less than five particles), $P$ and $A^{1/2}$ are related by an equation $P \propto (A^{1/2})^{1.2}$ which is similar to the variation observed in [50]. Small and compact group of particles have a variation almost linear between $P$ and $A^{1/2}$. However, for larger clusters our results highlight the fractal nature reported in Aliseda et al. [6] with a new relationship $P \propto (A^{1/2})^{1.6}$. Figure 6-1.c shows evidence that this effect does not depend on the concentration and the mean airflow velocity. In the end, only one of these parameters is sufficient to describe the dimension of the clusters. The same relationship was observed with another type of particles, the Lycopodium clavatum spores (figure 6-2). It is important to notice that five particles leads to a difference in shape of the group of particles. For the section on the inter-cluster distance, and future studies, we will use this number to characterize a cluster: a cluster will be a group of particles on surfaces composed of at least five particles.

Another point to pinpoint from [6, 50] is the decrease at the power $-2$ of the di-
Figure 6-1: Perimeter $P$ vs. square root of the area $A$ of glass bead clusters. The value $A^{1/2} \approx 10^{-1}$ corresponds to five particles aggregated in a cluster. (a) Concentration of particles of 50 particles per mm$^2$, (b) Reynolds number $Re=35 \times 10^3$, (c) For all Reynolds numbers and concentrations
Figure 6-2: Perimeter $P$ vs. square root of the area $A$ of clusters of *Lycopodium clavatum* spores. The value $A^{1/2} \approx 10^{-1}$ corresponds to five particles aggregated in a cluster. (a) $C_0 = 35$ particles per mm$^2$, (b) $Re = 41 \times 10^3$, (c) For all Reynolds numbers and concentrations.
Figure 6-3: Probability density function of cluster area for $Re = 35 \times 10^3$ (a) non-normalized, (b) normalized by the mean cluster area.

mension of clusters as the concentration level increases. At different airflow velocity and different initial concentration we find the same exponential decrease with a coefficient -2 (see figures 6-3,6-4). In figure 6-3 the concentration does not seem to affect the physical mechanisms behind the decrease. The curves collapse when we divide the cluster area by the average cluster area for different concentrations. Moreover, the same trend is observed for other Reynolds numbers (figure 6-4.a). We present on the same figure 6-4.b all the experiments with glass beads (with different Reynolds numbers and initial concentrations) we observe the robustness of this decrease at a power $-2$. The gradient of color indicates an increase in particle concentration.
Figure 6-4: Probability density function of the ratio of number of particles per cluster divided by the average of this number at steady state. (a) $Re = 45 \times 10^3$, (b) All Reynolds number and concentration taken together. The gradient of color evolves from blue to red with increasing concentration.
6.2 Number of particles per cluster

From our first observations we assumed that the average number of particles per cluster should vary with the initial concentration (see figure 6-5). At a constant airflow velocity, a change in the initial concentration seems to change the collisions and/or aggregation of particles, which impact the final detachment of these particles on the surface. For instance, figure 6-6 describes the average number of particles per cluster at steady-state as a function of initial concentration. At a given velocity, the number of particles per cluster increases with the concentration. At a given concentration, the average number of particles decreases with the mean flow velocity, or Reynolds number here. If there are more particles initially on the surface, there will be more particles inside a cluster. Indeed, when the initial concentration increases, the mean distance between two particles is smaller. If a particle is picked up by the mean flow, it will have less kinetic energy when it impacts another particle, or this impact will be softened by the particles surrounding the collisions. The energy of impact will also be transferred to neighbouring particles through additional collisions.

Figure 6-7 represents the evolution of the average number of particles per cluster divided by the total number of particles on the whole image at Reynolds number $Re = 35 \times 10^3$. It defines the averaged normalized concentration within clusters for each
experiment and measures the average relative overloading of particles inside clusters. At a specific mean flow velocity, this overloading increases with the concentration. The time scale $t_{50}$ defined in this figure represents the time to reach half of the total variation of the average number of particles per cluster. In other words, $t_{50}$ is the time for which we verify:

$$< N(t_{50}) > = < N(t_0) > \pm 0.5 \times |(< N(t_f) > - < N(t_0) >)|,$$  \hspace{1cm} (6.1)

with $N$ the number of particles per cluster at time $t$. The sign depends on the evolution of the average number of particles per cluster. If the final image presents less particles per cluster on average, the sign is negative. We will come back on the use of this time scale later. For the moment, $t_{50}$ is used to re-scale the evolution and compare the effect of initial concentration and mean flow velocity.

Figure 6-6: Average number of particles per cluster at $t_f$ (steady-state) as a function of the initial concentration $C_0$ for different airflow velocities. The Reynolds numbers are calculated by changing the mean flow velocity in the expression $Re = \frac{UdH}{\nu}$.

Figure 6-8 shows the aggregation effect due to the mean airflow. The initial distribution is made as homogeneous as possible in an experiment. However, 3D aggregation during the settling of particles by gravity occurs. Also during impact on surfaces, particles may aggregate and form groups of two or three particles (see images 6-5 and 6-10). These images highlight the difference in clustering at the steady-state, and the
Figure 6-7: The evolution with time of the number of particles per cluster divided by the total number of particles on the whole image at $Re = 35 \times 10^3$.

Figure 6-8: Number of particles per cluster at time $t$ divided by initial number of particles per cluster as a function of the concentration.

dependence on the initial concentration. It also underscores the difference between the final clusters observed and the initial clusters due to the distribution of particles. It gives a hint on the influence of the Reynolds number to get a partial detachment of particles, with clustering pattern on surface. For instance, for a Reynolds number below $41 \times 10^3$ the probability to get clustering is higher. For higher Reynolds number the detachment is almost complete.

As shown in figure 6-9, an increase in the initial concentration leads to a higher
number of particles in a cluster. The evolution of the average number of particles per cluster divided by the initial average number of particles per cluster should be a trade-off between the number of particles on a surface and the distance between each particle. If we increase the concentration, the distance between each particle decreases which limits the collision effects. Conversely, if the concentration decreases, collective effects are diminished. In figure 6-9, the concentration of 33 particles/mm$^2$ shows an almost constant average number of particles per cluster. If we look at the experiment in 6-5, it seems larger groups of particles are created. The average number of particles per cluster stays almost constant. This can be explained by the calculation of this number, that takes into account every type of group of particles, and even single particle. Figure 6-10 shows the detachment of glass beads at a concentration of 109 particles/mm$^2$, from the onset of experiment to the steady-state, at a velocity $v = 4.8$ m.s$^{-1}$.

### 6.2.1 Influence of the type of particles

To better understand previous experiments on relative humidity (chapter 4), we make a comparison between clustering with glass beads and with *Lycopodium clavatum*
Figure 6-10: Detachment of glass beads deposed on a surface at \( Re = 35 \times 10^3 \) and \( C_0 = 119 \) particles/mm\(^2\) (a) \( t_0 \), (b) \( t_f \).

Spores. Their respective diameters are similar: 53\( \mu \)m and 60\( \mu \)m. The main difference in physical properties is their density and roughness. The spores are spherical with almost no filaments but a rough surface (see figure 3-2) whereas the glass beads have a smooth surface. Figure 6-11a highlights an observation made during the experiments: the pickup velocity for spores is different than the pickup velocity for glass beads. At \( v = 4.8m.s^{-1} \), the detachment has started for glass beads and is on the contrary almost non existent for spores. For instance, in figures 6-12 and 6-13 we can observe for low concentration of particles a reorganization of the number of particles per cluster. For high concentration of particles, particles do not detach. Relating that to the density, this example shows that the smaller the density the larger the pickup velocity is. Given the number of airflow velocities on these figures, we cannot make any conclusion on the influence of this parameter on the number of particles per cluster. Indeed, at a higher velocity, particles gather and form clusters (as seen for \( v = 6.2m.s^{-1} \)). Nonetheless, our range of Reynolds number is not large enough to conclude on its role on the overload of spores in a cluster.
Figure 6-11: Evolution of the number of spores per cluster over the total number of particles at different concentration. (a) $C_0 = 30 \text{ particles/mm}^2$; (b) $C_0 = 208 \text{ particles/mm}^2$.

### 6.2.2 Turbulence effect

In this part, we focus on the influence of turbulence on detachment. The Reynolds number in figure 6-14 is defined by the mesh size of the grid or, in the absence of grid, by the width of channel. The mean flow velocity and initial concentration are constant. Adding a grid at the entrance changes the turbulence in the channel, especially by changing the eddies size [57]. With less turbulence (smaller mesh size), the average number of particles per cluster divided by the total number of particles remains constant (figure 6-14). Then, with less turbulence the average number of particles per cluster remains constant even if there are changes in cluster location,
Figure 6-12: Detachment of spores deposed on a surface at $Re = 35 \times 10^3$ and $C_0 = 31$ particles/mm$^2$ (a) $t_0$, (b) $t_f$.

Figure 6-13: Detachment of spores deposed on a surface at $Re = 35 \times 10^3$ and $C_0 = 247$ particles/mm$^2$ (a) $t_0$, (b) $t_f$.

or particles do not detach as it can be seen by the comparison between figure 6-15 and figure 6-16. If we study first the figure 6-17 we can notice an increase in
the final ratio, average number of particles per cluster divided by the number of particles, with turbulence. The slopes are also interesting because we clearly see for low Reynolds number the decrease in detachment described before. Nonetheless, figure 6-18 underscores a different trend. First if we compare both figures which have the same concentration, we notice that the final ratio, average number of particles per cluster divided by the number of particles, increases with the airflow velocity. Besides, an effect of the turbulence is hard to demonstrate for \( v = 8 \text{ m.s}^{-1} \). In figure 6-18 the highest ratios are obtained for low Reynolds number \( Re_{bh} \) and the lowest ratios for high Reynolds number. The different experiments underline the need for detailed fluctuation measurements of the turbulent flow. We will pursue this study for a larger range of mean flow velocity in order to further understand the influence of turbulence on the load of particles in clusters.

![Graph](image)

Figure 6-14: Average number of particles per cluster divided by the total number of particles at time \( t \). The Reynolds number in figure 6-14 is defined by the mesh size of the grid or, in the absence of grid, by the width of channel. The mean flow velocity is fixed at \( v = 4.8 \text{ m.s}^{-1} \) and the initial concentration fixed at \( C_0 = 102 \text{ particles/mm}^2 \).

### 6.2.3 Time scale \( t_{50} \)

We defined previously the time scale \( t_{50} \) to compare the different results at different concentration or velocity. Figure 6-19 presents the different \( t_{50} \) found for the experiments with glass beads. We noticed a possible dependence of this time in \( Re^{-2} \).
Figure 6-15: Detachment of glass beads deposed on a surface at $Re=1560$ and $C_0=100$ particles/mm$^2$. The mean flow velocity is $v=4.8m.s^{-1}$ and this experiment includes a grid at the entrance. (a) $t_0$, (b) $t_f$.

Figure 6-16: Detachment of glass beads from a surface at $Re = 35 \times 10^3$ and $C_0=119$ particles/mm$^2$. The mean flow velocity is $v=4.8m.s^{-1}$ and this experiment includes no grid at the entrance. (a) $t_0$, (b) $t_f$. 

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Figure 6-17: Turbulence effect on the average number of particles per cluster for glass beads. The mean airflow velocity is fixed at $v = 4.5 \text{ m.s}^{-1}$ and the initial concentration at $C_0 = 45 \text{ particles/mm}^2$. The Reynolds number is calculated by taking the mesh size of the grid, or without grid at the entrance, the width of the channel $H = 7.3 \text{ cm}$ (highest Reynolds number).

Figure 6-18: Turbulence effect on the average number of particles per cluster. The mean airflow velocity is fixed at $v = 8.1 \text{ m.s}^{-1}$ and the initial concentration about $C_0 = 50 \text{ particles/mm}^2$. The Reynolds number is calculated by taking the mesh size of the grid, or without grid at the entrance, the width of the channel $H = 7.3 \text{ cm}$ (highest Reynolds number).

This dependence can be explained by the following scaling law. We consider the flow acceleration $a$ constant in the ventilation duct and equal to $a = \gamma$. We observe the flow at a distance $L$ from the entrance. This acceleration comes from the ramp-up of airflow velocity when the trapdoor has just closed. At $t_{50}$ and $t_f$ we verify the
equation $\gamma \sim \frac{u_{50}}{t_{50}} \sim \frac{u_f}{t_f}$. The flow reaches its maximum velocity $u_f$ in the region of observation at $t_f = \frac{L}{u_f}$. It gives that $\gamma \sim \frac{u_f^2}{L} \sim \frac{u_{50}}{t_{50}}$ and so $t_{50} \sim \frac{u_{50}L}{u_f^2}$, with $u_{50}$ determined by the mean flow velocity $u_f$ which is the only variable here. Thus, $t(u) \sim \frac{1}{u_f^2}$, or in other words $t(u) \sim Re^{-2}$. We are working on the experimental verification of this argument.

![Figure 6-19: Variation of the time scale $t_{50}$ as a function of $Re^{-2}$.](image)

### 6.3 Inter-cluster distance

In this section, we are interested in the distance between clusters and try to understand if the formation of a cluster in a certain location leads to clustering in another location. At the same time, the distance between clusters may vary with the initial concentration, mean flow velocity and turbulence. To first investigate these different assumptions, we looked at the distance between two closest clusters. Considering each cluster, we determined the smallest distance from the center of the cluster to another center of cluster. The images 6-20 show the group of particles identified by the function `regionprops` of Matlab. On the images, these groups of particles are represented by ellipses. From that, we look at the distance of the closest cluster for a given group of particles. In this section, we consider a cluster as a group of at least five particles, in reference to the section Perimeter vs. Area and the change in
coefficient. In this first analysis we take the average of all the smallest distance between clusters without considering any projection on a specific axis. The figure 6-21 presents the inter-cluster distance results for different concentrations and mean flow velocities. These experiments were realized without grid at the entrance of the ventilation duct. Figure 6-21 shows the results of inter-cluster distance for glass beads. The gradient of color evolves from blue to red with the increase of initial concentration. Crosses represent the absence of cluster on the surface. We notice the increase of inter-cluster distance with the initial concentration at a given velocity (Reynolds number). A raise in mean flow velocity at a given concentration diminishes the inter-cluster distance as we can observe from the comparison between $Re = 3.5 \times 10^4$ and $Re = 4.5 \times 10^4$. Figure 6-22 presents the inter-cluster distance for concentrations of spores. At a given velocity and initial concentration, for instance for $Re = 35 \times 10^4$, this distance is greater for spores than for glass beads. We should also remember that for this velocity, the detachment fraction was much less important for spores. In order to go on this comparison, we will complete our set of data and describe the results in future studies. In particular, the distance between two clusters on the same axis, parallel to the carrier flow, will be evaluated in order to further understand the physical mechanisms of detachment, and complete the related-study on the mean free path.
Figure 6-20: Detachment of glass beads from a surface at $Re = 35 \times 10^3$ and $C_0 = 32$ particles/mm$^2$. Clusters are visualized by ellipse. (a) $t_0$, (b) $t_f$.

Figure 6-21: Inter-cluster distance for different concentrations of glass beads and mean flow velocities. Crosses on the figure indicate the absence of clusters at the steady-state. We identify as a cluster a group of at least five particles. The gradient of color evolves from blue to red as the initial concentration increases.
Figure 6-22: Inter-cluster distance for different concentrations of spores and mean flow velocities. Crosses on the figure indicate the absence of clusters at the steady-state. We identify as a cluster a group of at least five particles. The gradient of color evolves from blue to red as the initial concentration increases.
Chapter 7

Conclusion

7.1 Summary

Understanding the detachment of micro-particles from surfaces and their entrainment in ventilation ducts of indoor environment is essential for the prevention of bio-terrorist releases or disease propagation. In this study we mainly focus on the resuspension of particles, the different factors which influence their final detachment at a given airflow velocity, moisture and temperature. Our work emphasizes the important effect of initial concentration, mean flow velocity, relative humidity and turbulence, to describe the physics of detachment of micro-particles.

Experiments were done in a ventilation duct built on poly(methyl methacrylate). High-speed imaging was used to record the detachment of the micro-particles at different fan velocities. The images were then treated by image processing and particle tracking velocimetry algorithms were developed and used to analyze the removal, motion and aggregation of particles.

The detachment fraction of particles or spores increases with the mean airflow velocity. For the effect of relative humidity, we have studied the detachment of Lycopodium clavatum spores from a turbulent airflow. We have noted that, above a threshold of RH=60%, an increase of the moisture leads to a decrease in detachment.
The formation of liquid bridges between particles and the surface, and between particles, leading to increase of the capillary adhesion forces, can explain this phenomenon. The effect of temperature was not significant. Nonetheless, this parameter is embedded in the calculation of the relative humidity, which qualifies the probability of liquid bridges to form between particles.

The role of initial particle/spore concentration was demonstrated for low moisture with an increase of removal for higher initial concentration. Collisions between particles are predominant and confirmed by the non-homogeneity of detachment. Microparticles located upstream detach and impact particles downstream. Collisions at high Reynolds number (greater than $5 \times 10^4$) increases the detachment downstream. This effect does not appear for high relative humidity, collisions leading to weaker forces than adhesion forces. Besides, the surface of the particles was also considered. In particular, the presence of filaments on the spores surface (exosporium) facilitates the aggregation of particles.

To better understand collective effects induced by collision and aggregation we oriented our study on the clustering of micro-particles on surfaces. We have proceeded to analyze the vertical velocity of particles and determined a logarithmic dependence of the velocity profile with the vertical position $y$ away from the wall. The coefficients are modified by the turbulence of the flow and an increase in Reynolds number. The detachment of particles from surfaces is dependent on the initial particle concentration as it has been observed in our moisture experiments. An increase of initial concentration diminishes the detachment fraction because of the formation of groups of particles. These clusters change the dynamics of detachment. Moreover, adding grids reduces the detachment of particles suggesting the need for more refined measurement of flow fluctuations.

We then analyze the average distance travelled by a particle between two collisions called mean free path in our study. The role of particle density was underlined to characterize this length. Further development is necessary to validate theoretical results with experimental results.
For different types of particles, initial concentrations and mean flow velocities, we noticed the same relationship between the perimeter and the square root of the area of clusters. For small clusters (less than five particles), the perimeter varies almost linearly with the square root of area as would be expected for a circular geometry. For larger clusters the relationships is modified. The perimeter evolves as an exponent 1.6 of the square root of the area, which is consistent with the scaling reported in Aliseda et al. [6] although their study focused on clusters in the air in 3D, while we focus on clusters on surfaces in 2D.

We found that the number of particles per clusters increases slightly with the initial concentration and varies with the Reynolds number. Indeed, the number of particles per clusters drops with an increase of the mean flow velocity. The inter-cluster distance, spatial measure of the distance between two closest clusters, still needs to be further investigated.

### 7.2 Impact on the propagation of diseases

The role of relative humidity is interesting to pinpoint regarding the transmission of diseases due to the removal of dust, bacteria or other type of particles in indoor environments. For instance, in order to clean a ventilation channel, low moisture airflow would be better to improve the removal efficacy. Collective effects are also important to take into account however. We can imagine a process where particles are added to the system during a cleaning so that collisions increase the detachment of previously settled particles. On the contrary, to prevent any detachment of particles, a high moisture is recommended (beyond 60%) in the regions of interest. Since ventilation channels are not only straight and corners are regions of accumulation, the development of an engineering method controlling the moisture to increase aggregation of particles in certain regions, and/or circulate air at a lower velocity than the pickup velocity for these agglomerated particles are interesting implications of our work.
7.3 Next steps

To go further in the understanding of the clustering, a thorough analysis of the collective effects would be necessary, with for example, numerical and experimental models to describe the collisions between particles and its impact on local concentration field along particle trajectories. The typical residence time of particles inside a cluster may give precious insight to improve the model of mean free path. The respective role of volume and mass loading in a cluster is important to clarify. In particular, this study focuses on static cluster. However, we notice the ephemeral formation of dynamic clusters — agglomeration of particles and motion of the group of particles—at high Reynolds number. This phenomenon of agglomeration is not well understood. Another point which is highlighted in the literature is the effect of multi-layer. When doing experiments with spores, the presence of multi-layers of particles was frequent and make the physics of detachment more complex. A deeper analysis of this parameter will permit to better reproduce a real case of biological release, represented by a stack of particles with typically more than a monolayer.

In spite of this work interest on indoor environment, particle resuspension raises question at the intersection of different fields (biology, physics, chemistry, engineering, etc.). Finally, the results in this thesis extend beyond flow in ventilation and have important implications for modeling of particle deposition on surfaces in confined domains in general, including in airway and respiratory systems, and for evaluation of risk and containment of chemical or biological attacks indoors, but also outdoors in dense urban environments.
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