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ABSTRACT

Many biologically active materials are transported as bioaerosols 1-10 µm in diameter. These particles can deposit on cooling and heating coils and lead to serious indoor air quality problems. This paper investigates several of the mechanisms that lead to aerosol deposition on fin and tube heat exchangers. A model has been developed that incorporates the effects of several deposition mechanisms, including impaction, Brownian and turbulent diffusion, turbophoresis, thermophoresis, diffusiophoresis, and gravitational settling. The model is applied to a typical range of air velocities that are found in commercial and residential HVAC systems 1 - 6 m/s (200 - 1200 ft/min), particle diameters from 1 - 8 µm, and fin spacings from 3.2 - 7.9 fins/cm (8 - 16 fins/inch or FPI). The results from the model are compared to results from an experimental apparatus that directly measures deposition on a 4.7 fins/cm (12 FPI) coil. The model agrees reasonably well with this measured data and suggests that cooling coils are an important sink for biological aerosols and consequently a potential source of indoor air quality problems.

INTRODUCTION

Bioaerosols, particles consisting of or containing biological material, are common in indoor environments. Although often benign to humans, some have been linked to allergies, morbidity, and mortality. There are many sources and sinks of these materials in indoor environments, but one particular area of interest in buildings is the heating, ventilating, and air conditioning (HVAC) system. There is potential for biological pollutants to deposit and grow on heat exchangers, in ducts, air handler units, and splitter boxes where they are out of sight of building occupants. Once a colony has established itself, it can spread or release harmful or odorous byproducts throughout a building.

One neglected area of study is the fouling of HVAC heat exchangers. Much of the engineering research and anecdotal information on fouling of coils focuses on the energy and performance impacts of coil fouling (Krafthefter and Bonne 1986; Krafthefter et al. 1987; Anonymous 1987; Neal 1992). The energy impacts are significant, and worthy of further study, but less is known about bioaerosol deposition and contamination of HVAC heat exchangers. The problem has received some attention by manufacturers of products to clean and protect cooling coils: several companies offer cleansers, antimicrobial coatings, or other systems as an attempt to limit biological growth.

Although there is extensive engineering and microbiological literature on bioaerosols, there is relatively little information on biological contamination on HVAC coils. Muyshondt et al. (1998) discuss the HVAC system as both a source and sink of biological and other contaminants and conducted CFD simulations to determine the likelihood and amount of 1 - 100 µm aerosol deposition on typical air conditioner evaporator coils. Their conclusions are that a typical cooling coil "will collect significant amounts of aerosol in the particle size range of 5 – 100 µm AD [Aerodynamic Diameter]." They also suggest that the dark, moist areas around evaporator coils represent ideal growing conditions for biological material and that the significant deposition of aerosols provide the nutrients that can lead to biological growth. Morey (1988) suggests similarly ideal growing conditions for fungus in the HVAC system in a commercial building; "The presence of adequate nutrients (debris inherent on heat exchanger surfaces) and moisture provide an ideal site for fungal amplification." Hugenholtz and Fuerst (1992) describe measurements of bacteria concentrations in a large commercial air handling system and found significant quantities of bacteria on the cooling coil on other surfaces in the system. Other work, such as that of Batterman and Burge (1995), further describes the implications of biological growth in HVAC systems.

This previous work represents a good start to this important problem. There are still some obvious gaps in literature: there is no experimental particle size resolved data of deposition on HVAC heat exchangers; there is limited understanding of the mechanisms that lead to particle deposition in these

systems; and there is an incomplete understanding of how bioaerosols in indoor air can develop into biological growth on heat exchangers. This paper addresses these concerns by answering the following three questions:

1. What are the biological contaminants in indoor spaces that are of concern for heat exchanger deposition?
2. With what likelihood do biological aerosols deposit on typical cooling coils?
3. Is it possible, or even likely, that that the biological material in these aerosols remains viable once deposited?

The experimental and analytical research in this paper focusses on answering the second question. The first and third questions are discussed by applying the findings of other researchers.

Before answering these questions, it is important to describe the system being studied. In this study we are concentrating on the fin and tube heat exchangers (often referred to as coils) commonly found in commercial and residential HVAC systems. Typical coils consist of horizontal refrigerant tubes connected by thin vertical fins to increase heat transfer. A typical residential heat exchanger has two staggered sets of 0.95 cm (3/8 inch) copper refrigerant tubes that run horizontally through vertical aluminum fins. Commercial and industrial systems can have much larger tubes. Fin spacings range from 2.4 to 7.9 fins/cm (6 - 20 fins/inch or FPI), with typical systems having 4.7 fins/cm (12 FPI). The fins are typically around 100 µm thick and are often corrugated to increase surface area for heat transfer. Heat exchanger depth can vary, but typical residential and small industrial and commercial heat exchangers are about 5 cm (2 inch) thick (in the direction of air flow). In order to achieve higher capacities, coils are sometimes arranged in series, so that the air exiting the first coil enters the second coil directly, and so on. Bulk air velocities typically range from 1 to 6 m/s (200 – 1200 ft/min) in the coils in these systems. These velocities correspond to Reynolds numbers of 100 - 2000 in the fin channels of the heat exchanger core, and 2 to 3 orders of magnitude higher in the ducts upstream and downstream of the coils where the characteristic dimension is the duct diameter.

These coils can be operated in a variety of modes. Most coils of concern are used for air-conditioning. When cooling, typical surface temperatures range from 5 to 16 °C (41–61 °F) and often condense water from the air stream. Typical systems have relatively high air velocities of 1-6 m/s (200-1200 ft/min). The same coils, or similar coils, can also be used for heating either with a condensing refrigerant, as in a heat pump, or with hot water. Surface temperatures for heat pumps are about 27 – 35 °C (81–95 °F) and are typically much hotter for hot water systems. These values can vary significantly over short spans of times as systems cycle. The moisture and thermal conditions on a coil can have a dramatic effect on viability of deposited biological material, this will be discussed later.

BIOLOGICAL AEROSOLS IN INDOOR ENVIRONMENTS

There are a wide range of bioaerosols that have been identified in indoor environments. They come in many different forms and are often attached to inert particles or contained in water droplets. For deposition on cooling coils we are largely interested in two types of organisms: fungi and bacteria. There are other biological agents present in indoor air that also present health concerns, such as viruses, dust mites, algae, and pollen. These particles are either relatively rare (viruses), large and not particularly biological active in HVAC systems (dust mites, pollen), or commonly associated with standing water (algae) that is not common on cooling coils (although standing water in drain pans of air conditioners can present an environment suitable for algae growth, we are focussing on the cooling coil itself in this study).

Fungi are common in indoor environments and are often referred to as mold. Fungi are often allergenic or toxic themselves, although we are often more concerned with their spores that can also be allergenic and toxic. Additionally, as fungi grow, they can produce mycotoxins, metabolic byproducts that can be harmful to humans (Foarde et al., 1994; Miller, 1992). Fungi can also be associated with odors and related to occupant complaints in buildings. There are many species of fungi, and even limiting the range of interest to those species commonly found in indoor environments, spore sizes span a very large range both between and with fungal species. Foarde et al. (1994) lists the size ranges of spores from 12 common indoor mold species and they range from 2 - 50 µm and Gravesen et al. (1994) suggest a smaller range from 2 - 20 µm. They often have irregular shapes that can significantly affect their transport and deposition behavior.

Indoor fungi concentrations also span very large ranges. In a review of studies in 21 large and small commercial buildings, Morey (1988) reported ranges of fungal concentrations spanning six orders of magnitude from 10 to 13×10^7 colony forming units or CFU/m^3 ($0.3 - 4 \times 10^5$ CFU/ft^3). Significantly, the highest reading in the study came from a sampling location 3 - 6 ft downstream of a coiling coil that had "considerable moist organic debris on it." Foarde et al. (1994) summarized the work of six researchers studying fungal concentration in 383 residences and 4 office buildings with no occupant mold complaints. A similarly wide range of airborne fungal concentrations was reported with a 0 - 10^4 CFU/m^3 (0 -300 CFU/ft^3) range in the residential sites, and a 1 – 900 CFU/m^3 (0 - 30 CFU/ft^3) range in the commercial sites. The same study also summarized research on fungal concentrations in buildings with occupant complaints and found a similar range, but typically with elevated concentrations over the non-complaint buildings, and with differing dominant fungal species.

In addition to fungi, bacteria can also be allergens and cause disease and sickness. Legionella, the bacterium associated with Legionnaires disease, is one of the more infamous bacterium in indoor environments, although it is much more commonly associated with drain pans and condensate systems than directly with cooling coils. Bacteria common in the indoor environment range in size from 0.1 – 6 µm, with many of them being submicron particles. The study of these bacteria is complicated by the fact that they often are attached to larger particles. Even though bacteria can be spherical, rod-like, or ellipsoidal in shape, the larger particles that they attach themselves to tend to have a large surface area and are typically highly irregular particles (Foarde et al., 1994). Although there is not widely available data on indoor bacteria concentrations, Pelikka et al. (1995) report bacteria concentrations of 80-120 CFU/m^3 (2.3 – 3.4 CFU/ft^3) in a study of 4 homes and 5 - 50 CFU/m^3 (0.14 – 1.4 CFU/ft^3) in 3 office buildings. Hugenholtz and Fuerst (1992) studied bacteria concentrations on a "well-maintained" supply air cooling coil. They found concentrations of various *Blastobacter* species that ranged from 10^5 – 10^7 CFU/m^2 (10^4 – 10^6 CFU/ft^2) on the heat exchanger fins and downstream air concentrations that ranged from 160-1600 CFU/m^3 (4.5 – 45 CFU/ft^3). Despite individual buildings with high levels of bacteria and fungal spores, it is important to put these numbers in perspective. Pelikka et al. (1985) report that in typical indoor environments, only 1 in 10^3 particles are a fungal spore, 1 in 10^6 small (sub-micron) particles that dominate indoor air concentrations are associated with bacteria, and 1 in 10^3 larger particles are associated with bacteria. Despite these seemingly low numbers, biological contamination of coils can still be a problem because the volume of air that passes over coils is high. Five times the volume of the air in a residential building per hour is a rule of thumb for an operating cooling system. These high flows can therefore transport substantial amounts of material to the coil. Some of the particles, particularly larger particles, in this air stream are likely to be filtered, depending on the efficacy of the filter installed. Other researchers have investigated microbial deposition and growth on HVAC filters (Kemp et al., 1995; Foarde and Hanley, 2001). However, in typical systems there is often unintentional filter bypass because of poor filter installation practices and duct leakage on the return (negative pressure) side of the system which can lead to some or all of the air not being filtered.

MODEL OUTLINE FOR PARTICLE DEPOSITION ON COOLING COILS

To investigate how bioaerosols deposit on cooling coils, we have performed detailed laboratory experiments to quantify deposition on a typical cooling coil. We also developed a theoretical model to predict the deposition rates, and compared the model predictions to the measured laboratory results.

The model was developed to use input information that is relatively easy to obtain. It requires air velocity in a duct, particle diameter, and fin spacing as its major inputs. It focuses on deposition associated with the particle inertia (such as impaction and interception on fin edges and refrigerant tubes), gravitational settling of large particles and Brownian diffusion of small particles in the heat exchanger core. Additional deposition, caused by turbophoresis, the motion of large particles down a turbulence intensity gradient, in the entry region of the fins is also included. If the heat exchanger is in heating or cooling mode, there can be a change in deposition from thermal effects (thermophoresis) and humidity concentration gradients (diffusiophoresis), although these effects are typically small compared to other deposition mechanisms. Thermal effects are incorporated in the model, but, for comparison to the isothermal coil experimental results, are not used in this analysis.

Despite the complex geometry and airflow in a typical fin and tube heat exchanger, the model takes a relatively simple approach to the system being studied. The model is described in more complete detail in Siegel and Carey (2001). The basic approach is to divide the deposition mechanisms into two distinct types: those that cause deposition at a particular point in the heat exchanger, such as impaction on the

leading edge; and those mechanisms that cause deposition throughout the heat exchanger core, such as gravitational settling on the fin corrugations. The first type of deposition is calculated directly, the second by comparing the characteristic time for a particle to move through the evaporator to the characteristic time for the particle to deposit by a deposition mechanism. The ratio of these two quantities gives a prediction of whether a particle will deposit.

This approach has the advantage of being relatively simple to implement and computationally trivial. However, it also has a high level of uncertainty associated with it because it omits many details of fluid behavior. Additionally, like almost all particle deposition models, it considers only spherical particles. As has been pointed out earlier, many bioaerosols are non-spherical. Despite these limitations, the model gives a first order approximation of particle deposition in a heat exchanger

There are two additional limitations to the modeling. The first is that the modeled deposition on the refrigerant tubes is likely an upper bound on the actual deposition. This is because the air streamlines around each tube are smoother and more rounded than those modeled. A more detailed analysis is being developed using experimental relationships from Israel and Rosener (1983) and Wang (1986). However, these results will likely predict a lower bound on the actual deposition because they assume fully developed laminar flow. The second limitation is that there is an important deposition effect that is not included in the model. This mechanism is a result of inlet turbulence which leads to particle impaction on the walls from the initially turbulent flow just inside the coil. Even though the Reynolds number suggests that the flows in the heat exchanger core would be laminar, surface roughness, geometric non-uniformities, and residual turbulence from the bulk flow can all lead to turbulence at low Reynolds numbers, particularly in the entry region of the heat exchanger core. These mechanisms are important in certain types of particle sampling, but are not well understood or described in the literature for a relevant geometry. Current experimental work is being done to estimate the magnitude of these mechanisms.

MODELING RESULTS

Modeling results for coils with fin spacings from 3.1 – 4.7 fins/cm (8-12 FPI) and velocities from 1 – 5 m/s suggests the following broad general conclusions:

- Aerosols in size range of 0.1 – 1 µm are unlikely to deposit.
- Particles in the range of 1 – 10 µm, are likely to deposit on the leading edge of the evaporator by impaction, with minor contributions to deposition from gravitational settling on fin corrugations and turbophoresis near the leading edge. Over the range of fin spacings and air velocities of interest, deposition fractions of 1 – 20 % are common in this particle size range. This is the particle size range of greatest interest for many common bioaersols.
- Very large particles, 10 – 100 µm such as those found in indoor dusts and large fungal spores, are very likely to deposit by turbophoresis and by gravitational settling in the corrugated channels of the fins, and by impaction on the leading edge of the fins and on refrigerant tubes in the core of the heat exchanger. Although such large particles are likely to be filtered, filter bypass because of poor installation or duct leakage after the filter on the return (negative pressure) part of the HVAC system, is a common phenomenon.

Figure 1 shows the results of the modeling for 3 different fin spacings and an air velocity of 2 m/s (394 ft/min). The model predicts that particles are more likely to deposit for smaller fin spacings. Particles between 0.1 and 1 µm, although very common in indoor environments, are unlikely to deposit. For particle diameters in the range of 10 – 50 µm, deposition in the core of the heat exchanger is largely caused by impaction on the refrigerant tubes and is essentially fin spacing independent for a given velocity. There are two kinks in the deposition curves in Figure 1. The first occurs at 3 - 5 µm and is because impaction on the leading edge of the fins becomes perfectly effective at removing particles from the air directly in front of each fin. Even though the particle impaction increases geometrically with increasing particle diameter, the maximum deposition that can result from impaction is reached when the air in front of each fin edge is completely swept of particles. The kink at 30 – 50 µm is caused by the same limit of impaction deposition on the horizontal refrigerant tubes that run through the heat exchanger.

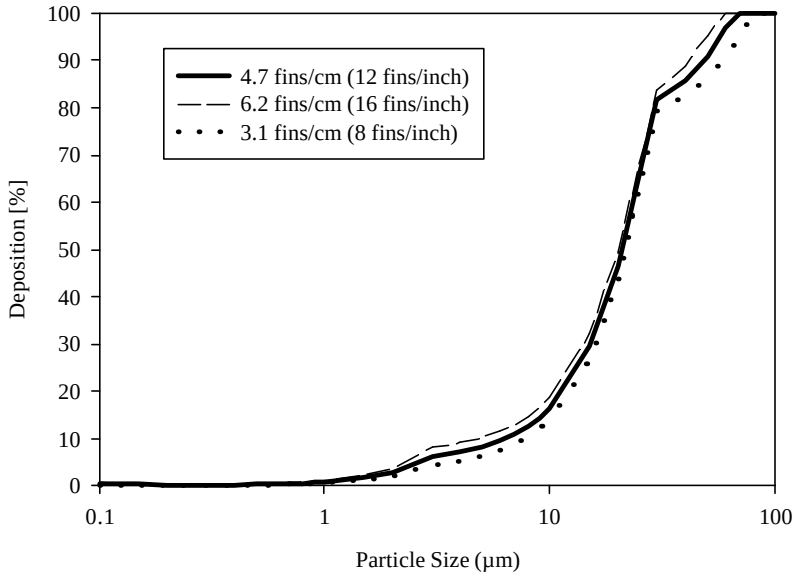

Figure 1:Modeled Deposition as a Function of Fin Spacing for a Bulk Air Velocity of 2 m/s.

Figure 2 shows three deposition curves at different velocities for a 4.7 fin/cm (12 FPI) coil. The results are similar to those described above in Figure 1. The results for 5 m/s (984 ft/min) suggest that inertial effects, particularly impaction, are especially important for deposition for 1 – 20 µm particles. Impaction on refrigerant tubes is completely exhausted by 20 µm particles. Deposition for 30 µm and greater particles at high velocity is considerably lower than for these particles at lower velocities. This is because gravitational settling becomes important for very large particles and residence time in the evaporator coil decreases as the air velocity increases. Thus, gravitational settling is less likely to cause deposition at high air velocity.

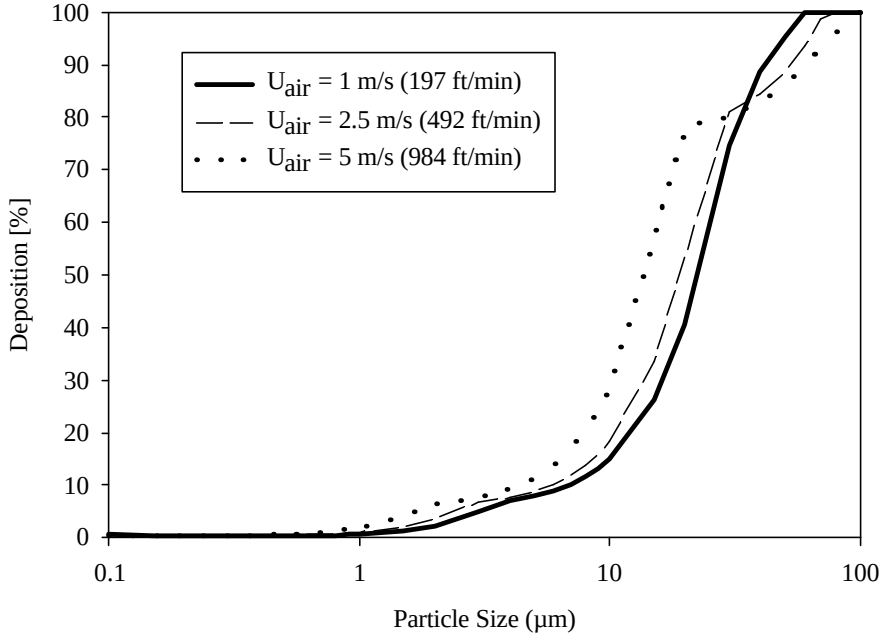

Figure 2: Modeled Deposition as a Function of Bulk Air Velocity on 4.7 fin/cm (12 FPI) Heat Exchanger.

The results presented in Figures 1 and 2 are roughly consistent with the published results from computational fluid dynamic simulations of Muyshondt et al. (1998). The current results suggest slightly more deposition than was predicted by Muyshondt et al. (1998), particularly at the upper end of the particle size range. This discrepancy is likely caused by the fact that the corrugation of fins was not modeled in Muyshondt et al. (1998) and thus no gravitational settling on vertical fins was included. Muyshondt et al. (1998) also suggest more differentiation in deposition amounts for different fin spacings. This discrepancy might be caused by limitations of CFD code to accurately simulate turbulent boundary layers on the fin surfaces. The precise nature of the boundary layers are crucial to modeling particle deposition to surfaces when using a CFD scheme. Despite some minor differences, this modeling work agrees with the conclusions of earlier work that suggests common bioaerosols (<20 μm) deposit on heat exchangers with low deposition fractions, typically less than 20%.

EXPERIMENTAL METHODOLOGY

Although the modeling described above is a useful predictor of important deposition mechanisms, many models tend to underpredict the deposition associated with real particles. Some researchers have suggested that this is due to the effects of deposition surface roughness, or non-homogeneities associated with air turbulence. In order to answer some of these questions, this study included an experiment to measure particle deposition associated with fin and tube heat exchangers.

The apparatus used for this experiment is illustrated in Figure 3. Monodisperse (single size) spherical particles, tagged with fluorescein, are generated with a vibrating orifice aerosol generator (TSI model 3450) and then charge neutralized. The particles are mixed with a HEPA filtered air stream designed to eliminate ambient particles, and sent into 24 m (80 ft) of straight 15 cm (6 inch) square duct. The duct air velocity can be varied continuously over the 1-6 m/s (200-1200 ft/min) range of interest. These velocities correspond to Reynolds numbers of 10000 to 61000 based on characteristic length of the duct, and Reynolds numbers of 150 to 900 in the fin spacing based on the velocity in the core of the coil and the space between fins. The coil is constructed in the same way as residential and small commercial applications. Several honeycomb flow straighteners are used upstream of the coil to promote fully developed turbulent flow with a uniform concentration of test particles. The particle-laden air then passes through the cooling coil, which consists of a 4.7 fin/cm (12 FPI) coil that entirely fills the duct. The coil and the duct are grounded to minimize electrophoretic effects. The coil was not cooled or heated for this work. This will be investigated in future experiments, and should have a significant impact on the viability of deposited biological material.

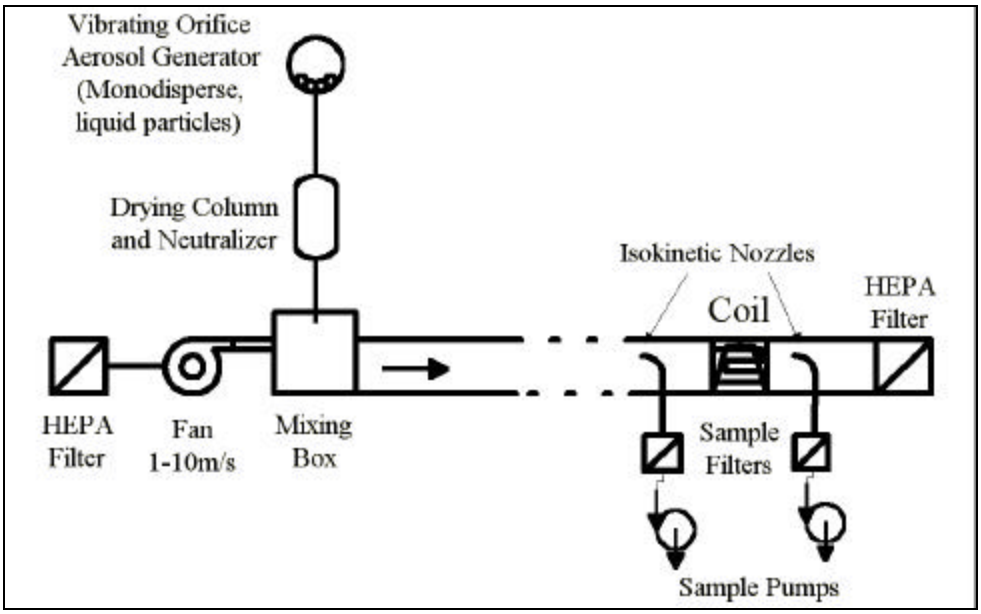

Figure 3: Evaporator Coil Deposition Apparatus

Particles are sized with an aerodynamic particle sizer (TSI Model 3320). Particle air concentrations are measured up and down stream of the duct by isokinetically sampling the air onto filter paper, which are later extracted with a chemical buffer. The fluorescence of the resulting solution is measured in fluorometer (Turner Designs Model TD700) in order to determine particle concentration. Because of non-uniformities associated with mixing downstream of the coil, three different samples are taken along the vertical centerline of the duct and averaged. The deposition fraction is defined as:

$$D = 1 - \frac{C_{down}}{C_{up}} \tag{1}$$

where:

D	=	*Deposition fraction [-]*
C_{down}	=	*Average downstream concentration [mg/m^3 (lb/ft^3)]*
C_{up}	=	*Upstream concentration [mg/m^3 (lb/ft^3)]*

The results of the isokinetic sampling are checked by removing the test coil from the duct and extracting the deposited particles and using the same fluorometric techniques to determine the deposited mass. The deposition calculated by this technique is:

$$D = \frac{M_{coil}}{C_{up} \cdot U_{bulk} \cdot A_{duct} \cdot t} \tag{2}$$

where:

D	=	*Deposition fraction [-]*
M_{coil}	=	*Mass deposited on coil [mg (lb)]*
C_{up}	=	*Upstream Concentration [mg/m^3 (lb/ ft^3)]*
U_{bulk}	=	*Bulk Air Velocity [m/s (ft/min)]*
A_{duct}	=	*Cross sectional duct area [m^2 (ft^2)]*
t	=	*Experimental Time [s]*

Additionally, in order to better understand the deposition mechanisms that lead to the accumulated material on the coil, the extraction of the coil was done in such a way as to allow the separation of the material on the leading edge from deposited material in the core of the coil.

The deposition described by Equation 1 is typically slightly higher than that calculated by Equation 2, because it also includes deposition on the duct before and after the coil. For high velocities and large particles, this discrepancy can be quite large. For this reason, all of the experimental data presented was calculated using Equation 2.

EXPERIMENTAL RESULTS

Deposition as a function of particle size is shown in Figures 4-6 for three air velocities and several particle sizes. The plots also include the results from the modeling analysis for each experimental air velocity for comaprison.. An uncertainty analysis was also conducted on the experimental results. This analysis yielded a 1 - 10% relative error range on the results, with typical values of about 2%. Error bars are indicated on the plots, but their small size often makes them difficult to see, particularly for the smaller velocities shown in Figures 4 and 5. Three repetitions of the experiment were completed at each of two data points, 3 µm particles at 1.5 m/s (295 ft/fin) and 5.5 µm particles at 5.2 m/s (1024 ft/min), to confirm the validity of the uncertainty analysis.

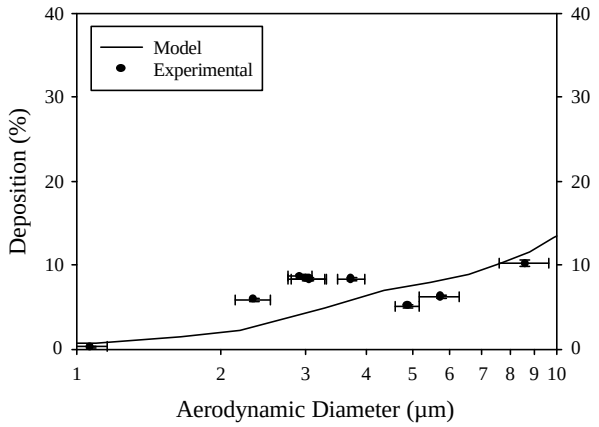

Figure 4: Experimental and Modeled Deposition for 1.5 m/s (295 ft/min), Reynolds number in the duct of 15000, Reynolds number in core of 230. Horizontal error bars indicate one standard deviation in particle aerodynamic diameter.

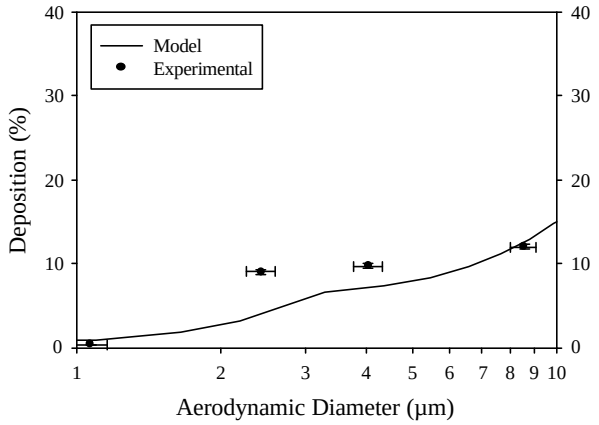

Figure 5: Experimental and Modeled Deposition for 2.5 m/s (413 ft/min), Reynolds number in the duct of 25000, Reynolds number in core of 370. Horizontal error bars indicate one standard deviation in particle aerodynamic diameter.

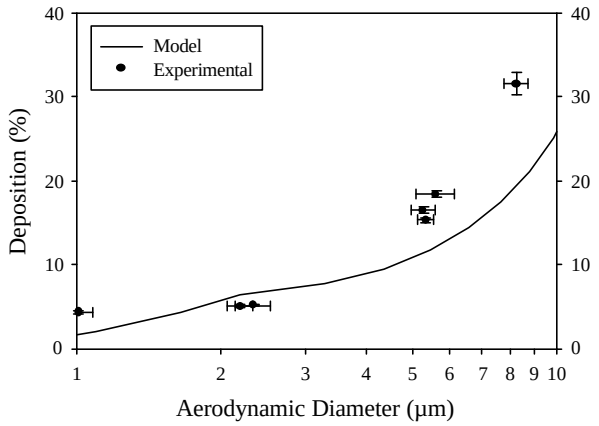

Figure 6: Experimental and Modeled Deposition for 5.2 m/s (1024 ft/min) , Reynolds number in the duct of 53000, Reynolds number in core of 770. Horizontal error bars indicate one standard deviation in particle aerodynamic diameter.

DISCUSSION OF EXPERIMENTAL RESULTS

The model predictions, although outside of the range of the uncertainty for the experimental data, are typically quite close to the experimental results. The disagreement of the results seems to get worse with increasing velocity. Given the importance of impaction on fin edges for the particle size range of interest, this suggests a problem with the modeling of impaction. The impaction model is currently quite crude and work is underway to improve this part of the model. Another possible reason for the discrepancy between modeled and measured results is related to the fact that increasing the velocity leads to larger air turbulence in the duct. This turbulence might be associated with resuspension of particles from duct surfaces and fan blades. The experimental repetitions for 3 µm particles at 1.5 m/s (300 ft/min) on Figure 4 suggest that the uncertainty analysis is valid for this velocity. However, the repetitions for 5.5 µm particles at 5.2 m/s (1000 ft/min) on Figure 6 do not overlap and thus the actual uncertainty in the measured results is larger than predicted for higher velocities. A blank run at 5.2 m/s with no particles was done to test the resuspension hypothesis and the measured amount of resuspended material is currently being integrated into an improved (and slightly larger) uncertainty analysis for the high velocity experiments.

There is also some indication in the plots that the model might underpredict deposition, particularly for high air velocities and larger particle sizes. Data collection is currently underway for 20 µm particles to test this hypothesis. The inclusion of inlet turbulence deposition, discussed above in the modeling section, will also likely improve the agreement between modeled and measured results.

Another suggestion of why this underprediction might be occurring is that typical evaporators, including the test coil, often have discontinuities in the fins in the core of the heat exchanger. These discontinuities are part of the manufacturing process and would lead to increased deposition from impaction of particles at the resulting additional edges. Preliminary analysis from experiments where the leading edge of the fins, defined as the first 5 mm, was extracted separately from the core suggest that 15 - 35 % of the of the total deposited material deposits on the leading edge. This is a smaller amount than would be predicted with the model, which suggests increased deposition in the core and supports the fin discontinuity impaction theory.

Before discussing the results further, there are two caveats in using these experimental results to predict biological aerosol deposition on heat exchanger coils in general.

- The first is that the source of particles used in the experiment generates spherical particles. Many biological aerosols are not spherical, and this can affect their transport and deposition behavior. Hinds (1982) and Wileke and Baron (1993) summarize the work of several researchers to develop methodology to relate non-spherical particles to an equivalent spherical diameter. The net result of much of this work is that unless a particle is very different from a sphere, such as a fiber, is that the difference in behavior will not be large. In the context of this experiment, this added uncertainty is not particularly large, but care should be taken when applying these results to very non-spherical particles.
- The second caveat is that although the experimental technique allows for some determination of the separation of particle deposition on different parts of the evaporator, it doesn't allow for precise distribution information. This information would be very useful for determining the viability of deposited biological material. If a fungal spore deposits at the leading edge of the evaporator, the local humidity, temperature, and nutrient availability will be very different than if it had deposited on a refrigerant tube. This is discussed in more detail below.

Despite these caveats, this experiment provides particle size resolved data of deposition on an air conditioner, which is an important first step. For biological aerosols, these results suggest that as an aerosol gets larger it has a greater probability of depositing. However, there is still a remaining important question: even if microbiological material deposits on an evaporator, what is the likelihood that it will be viable or cause problems for building occupants? It is very difficult to make broad predictions because of the inherent complexity of biological systems. For example, seemingly identical conditions might lead to growth of a certain fungal species in one situation, but not in another. Furthermore, each species and individual does not deposit in isolation: the wide range of biological contaminants in the indoor environment will compete and coexist in complex ways. However, without making explicit predictions for specific species and conditions, it is possible to estimate the likelihood of deposited particles being viable.

Fungi and bacteria have certain requirements for growth including water, nutrients, suitable pH, temperature, and local airflow. The availability of nutrients and the pH of condensed water are largely determined by the amount and constituents of previous deposition. Other researchers have established that

these quantities can be sufficient to sustain microbiological growth (Morey, 1988; Muyshondt et al., 1998). Temperature and moisture availability on a cooling coils are complicated, because they can vary significantly over a short span of time as the HVAC system cycles. Furthermore, they can vary dramatically over a short span of space within the coil itself. The leading edge of an evaporator fin is typically quite close to the ambient air temperature, whereas the area of a fin near a refrigerant tube is much closer to the refrigerant temperature. Similarly moisture is likely to condense on the part of a coil that is coldest. Condensation is also determined by the humidity content of the air, and the presence of an existing water film. In addition to contributing to the viability of deposited microorganisms, the additional layer of condensate on heat exchanger fins will lead to increased deposition and retention of aerosols.

Typical coil surface temperatures, air relative humidities, and likliehood of condensed moisture indicate that there are a number of fungal species that could be supported in the microenvironments of a cooling coil, although many fungal species prefer slightly warmer indoor temperatures (Gravesen et al. 1994; Foarde et al. 1994). A complication is cycling behavior because the coil can warm up and dry out between cooling cycles. However, there are a substantial number of coils that run for very long periods of time (in larger commercial systems), as well as coils with inadequate drainage or sufficient surface roughness or deposited hygroscopic material that they retain moisture for long periods of time. Furthermore, some species of interest can tolerate fluctuations in temperature, and many fungal spores can remain in dormant state in periods of relatively low humidity (Gravesen et al. 1994). Hugenholtz and Fuerst (1992) measured bacteria and fungi concentrations on cooling coils and found that fungi were likely to be found on relatively dry surfaces, such as (non-condensing) reheat coils and other HVAC surfaces. Bacteria were found at high concentrations on all cooling coils in the studied system. Bacteria tend to prefer warmer conditions, although there are several species that can survive at these lower temperatures. The temperatures associated with heat exchangers in heating mode, and also for fan operation but heat exchanger off mode, are ideal for a wide range of fungi and bacteria. Although bulk moisture is a preferable water source for many microorganisms, sufficiently moist air is enough to support bacteria on heating or fan only coils, particularly if a moist enough microenvironment on the heat exchanger surface is available. The possibility exists for viable conditions on heat exchangers in all modes of operation, although cooling coils seem like the most likely growth area.

There are several problems that might result for deposition of bioaerosols on a viable heat exchanger surface. The first is that these organisms can create metabolic byproducts, such as mycotoxins, which can cause irritation, allergies, odors, and in extreme cases, occupant sickness. Furthermore, fungal spores can easily be entrained in air flows typical in HVAC systems (Foarde et al., 1994) and can have affects on the occupants as well as lead to growth in other parts of the building. The microorganisms themselves can also cause various reactions in people, although to get to indoor air, they have to be re-entrained in the air flow. Relatively little work has been done in this area, but Macher et al. (1995) have looked the transfer of bacteria to air in contaminated evaporative air coolers (EACs). Even with an artificially high level of contamination of bacteria in their study, there was relatively little bacteria to air transfer in these systems. Furthermore, an EAC represents a more likely source of air contamination than a heat exchanger, because EACs have hygroscopic materials and direct contact between a water pool and an air stream. Hugenholtz and Fuerst (1992) found relatively low air concentrations of bacteria downstream of an air-conditioning coul fouled with bacteria and they further found an order of magnitude variation between different days Lastly, even if not linked to odor or health problems, deposition and growth of biological material on heat exchangers can lead to a variety of energy and air conditioner performance impacts (Krafthefter and Bonne, 1986; Krafthefter et al., 1987; Siegel and Carey, 2001)

So far this paper has looked at bioaerosols deposition on heat exchangers as a potential source of indoor environment contamination. Muyshondt et al. (1998), among others, has mentioned the possibility of HVAC system components being a sink for contaminants. Although a cooling coil may not be the best place to store biological material, cooling coils do serve to remove some bioaerosols from the air stream. In the case of dust mites, pollen and other material that are unlikely to be viable on a cooling coil surface, deposition is a trade off between diminished air conditioner performance and energy use and removing these items from indoor air. Given the inaccessibility of most coiling coils for regular cleaning purposes, they are far from ideal filters. An additional concern is that cooling coils are sometimes cleaned as part of HVAC service and maintenance operations, which can re-release potentially allergenic and otherwise harmful material. A preferable solution would be properly designed, and maintained, filtration and elimination of all filter bypass.

CONCLUSIONS

The modeling and experimental results presented here show that there is a clear potential for common indoor bioaerosols to deposit and be viable on HVAC heat exchangers. Experimental and modeling results show that larger bioaerosols will deposit with greater efficiency than smaller bioaerosols. Deposition fractions ranged from less than 1% for 1.1 µm particles at low velocities to over 30% for 8 µm particles at 5.2 m/s (1024 ft/min). Impaction on fin leading edges and tubes is a significant contributor to deposition for particles greater than 1 µm and gravitional settling and turbophoresis are important mechanisms for deposition of particles greater than 10 µm. The model does an adequate job of predicting trends and general magnitudes, although it is outside the range of uncertainty for the experimental data.

This research is a first step and there are still important questions to be answered. Although there is evidence that many air condtioing coils present viable environments for bacterial and fungal growth, further research on microorganism viability on heat exchangers would be useful. Further research on resuspension of deposited biological material would also be important to close the knowledge gap between deposition and occupant problems. And, perhaps most importantly, field studies that measure how much and what types of biological growth exist on HVAC coils in typical buildings would add greatly to this topic. Further research on coil cleaning and other prevention techniques would also help building operators look toward solutions to biological fouling of HVAC heat exchangers.

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