Atmospheric Environment 144 (2016) 257–265

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Bioaerosol deposition on an air-conditioning cooling coil

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HIGHLIGHTS

- Deposition behavior to cooling coil is similar for bacterial and fungal bioaerosol.
- Bioaerosol deposition is enhanced by the presence of water condensation.
- Deposition of DNA to coil is approximately balanced by removal from water drainage.
- Viable microbes appear to reproduce on coil surface during periods of inoperation.

ARTICLE INFO

Article history:
Received 11 January 2016
Received in revised form
31 August 2016
Accepted 2 September 2016
Available online 4 September 2016

Keywords:
Bioaerosols
DNA
Deposition
Cooling coil
Condensate water

ABSTRACT

This study is concerned with the role of a fin-and-tube heat exchanger in modifying microbial indoor air quality. Specifically, depositional losses of ambient bioaerosols and particles onto dry (not cooled) and wet (cool) coil surfaces were measured for different airspeeds passing through the test coil. Total, bacterial and fungal DNA concentrations in condensate water produced by a wet coil were also quantified by means of fluorescent dsDNA-binding dye and qPCR assays. Results revealed that the deposition of bioaerosols and total particles is substantial on coil surfaces, especially when wet and cool. The average deposition fraction was 0.14 for total DNA, 0.18 for bacterial DNA and 0.22 for fungal DNA on the dry coil, increasing to 0.51 for total DNA, 0.50 for bacterial DNA and 0.68 for fungal DNA on the wet coil. Overall, as expected, deposition fractions increased with increasing particle size and increasing airspeed. Deposited DNA was removed from the cooling coil surfaces through the flow of condensing water at a rate comparable to the rate of direct deposition from air. A downward trend of bacterial and fungal DNA measured in condensate water over time provides suggestive evidence of biological growth on heat exchangers during nonoperational times of a ventilation system. This investigation provides new information about bioaerosol deposition onto a conventional fin-and-tube cooling coil, a potentially important factor influencing indoor exposure to microbial aerosols in air-conditioned buildings.

1. Introduction

The fin-and-tube heat exchanger is a ubiquitous component of air-conditioning systems in mechanically ventilated buildings, employed to condition the temperature and humidity of air delivered to indoor environments (Pongsoi et al., 2014; Tang et al., 2016). In warm seasons for temperate and subtropical climates, and during the whole year for tropical climates, the heat exchanger (commonly referred to as a cooling coil) is utilized to cool and dehumidify the air (Chen et al., 2016). The aggregate energy transfer at this location across all air-conditioned buildings accounts for much of the total energy demand and also peak energy demand during warm conditions in cities worldwide (Siegel and Carey, 2001).

The air supplied to mechanically ventilated buildings inevitably passes over heat-exchanger surfaces and the interaction between

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http://dx.doi.org/10.1016/j.atmosenv.2016.09.004
1352-2310/

the air and the cooling coil surfaces can modify air quality, both for the flow path from outdoors to indoors and for recirculating airflows. Modeling and experimental studies reveal that some particles in the airstream could deposit onto the heat exchanger surfaces (Siegel and Nazaroff, 2003; Waring and Siegel, 2008; Gröhn et al., 2009; Grigonyte et al., 2014). Some studies also have suggested that previously deposited particles on coil surfaces could become reentrained in the airflow and constitute a secondary source of indoor particles (Siegel and Carey, 2001; Siegel, 2002).

Important knowledge gaps remain concerning how heat-exchanger surfaces in air-conditioning and mechanical ventilation (ACMV) systems influence indoor air quality. With regard to microbial air quality, it is important to note that heat exchanger surfaces are regularly wet in air-conditioning seasons in areas with moderate or elevated humidity. Observational studies have documented that the use of cooling coils could increase bioaerosol levels in indoor environments, suggesting a potential role of cooling coils as a source of indoor bioaerosols (Hugenholtz and Fuerst, 1992; Abe, 1998; Bluyssen et al., 2003; Jo and Lee, 2008). In addition to the potential release of biological materials, another process on cooling coil surfaces might also be important. Biological aerosol particles may deposit on cooling coil surfaces and be removed from air. Some fraction of the deposited particles may be transferred to the condensate water and be removed from the indoor environment through the drainage process. However, only one prior study has discussed the possibility of such bioaerosol deposition on cooling coil surfaces (Siegel and Walker, 2001). To the best of our knowledge, no work has yet been published that experimentally investigates bioaerosol deposition processes onto an air-conditioning cooling coil.

The objective of this research is to provide a systematic experimental investigation of bioaerosol transformations across a typical fin-and-tube heat exchanger in a model vapor-compression ACMV system similar to those used in modern air-conditioned buildings in tropical environments. In brief, the deposition fractions of ambient bioaerosols that include bacterial and fungal aerosol particles, size-resolved total particles, as well as monodisperse polystyrene latex (PSL) particles were measured for dry (not cooled) and wet (cooled) coils. Total, bacterial and fungal DNA concentrations in condensate water draining from a wet coil were also analyzed using a Qubit fluorometer and a quantitative PCR system. This study contributes to a better understanding of bioaerosol transformation processes as pertinent influences of indoor microbial air quality in air-conditioned buildings.

2. Materials and methods

2.1. Experimental apparatus and test procedure

This work was conducted using a laboratory apparatus (see Fig. 1) in which a fin-and-tube cooling coil system was situated between connecting upstream and downstream ducts. The cooling coil was of conventional design, comprising four rows of cylindrical copper refrigerant tubes, which were oriented horizontally and to which were attached vertical aluminum fins. The apparatus had a fin pitch of 3.1 fins/cm (within the common range of 2.4–7.1 fins/cm) and a center-to-center tube spacing of 7.6 cm. The corrugated fins were 0.1 mm thick and 44 mm deep in the direction of air flow. The copper tubes, which were inserted into aluminum vertical fins with full fin collars, had an outer diameter of 1.59 cm and a 0.09 cm thick wall.

The test apparatus was sited in a laboratory that was open to ambient air during working hours. A variable speed fan, installed at the inlet of the test coil system, pushed air through 3.6 m of straight 42 cm × 42 cm square upstream duct. The air then passed through

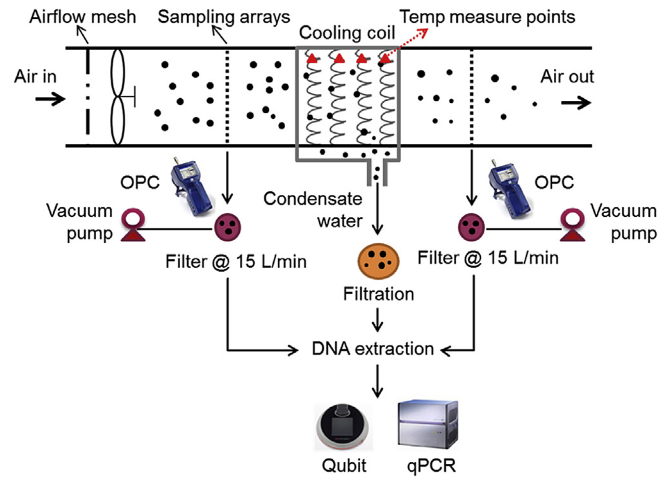

Fig. 1. Schematic diagram of system for studying particle and bioaerosol deposition onto an air-conditioning cooling coil.

the fin-and-tube heat exchanger which has the same area as the upstream duct (42 cm × 42 cm), followed by another 3.6 m section of straight 42 cm × 42 cm square duct downstream. Air speeds inside air-handling unit cooling coil systems commonly range from 1 to 4 m/s (Siegel and Nazaroff, 2003; Siegel and Carey, 2001). In this work, we used the variable speed fan to test three air speeds for the open sections of the ducts: 1.0, 1.5 and 2 m/s. If not otherwise specified, the results presented here are for an air speed of 1.5 m/s, which converts to a mass flow rate of 1030 kg/h of dry air passing through the coil surfaces (Rim et al., 2015).

This work was conducted in Singapore, where the ambient dew point temperature is consistently high. Dry-bulb temperatures typically range from 25 to 32 °C and the ambient relative humidity (RH) was always above 75% during these experiments. Continuous measurements were made of air temperatures, RH and air speeds using air velocity meters (VELOCICALC Air Velocity Meter Model 9545, TSI Inc., Shoreview, MN, USA) at two cross-sections that were positioned 0.5 m upstream and 0.5 m downstream of the cooling coil. We utilized nine measurement locations defining a uniform grid through each of the two cross-sections of the duct. Airflow parameter values are reported in Fig. S1 in the supporting information. When the cooling coil was operated, surface temperatures were also continually measured using digital thermometers (Fluke 54 II B Dual Input Digital Thermometer, Fluke Corporation, WA, USA). The measurement points were located on the top of the side face for each of the four rows of copper refrigerant tubes (as marked by red triangles in Fig. 1). Results are shown in Fig. S2.

In this work we studied two operational conditions: cooling coil off ("dry coil," which refers to a coil that is not being cooled and that is also not wet) and cooling coil on ("wet coil," which refers to a cooled coil onto which condensation occurs continuously). For the dry coil, the fan was on and the compressor was off for all experimental time. The entire system was dry and nominally isothermal. Conversely, for the wet coil, the fan and the compressor were on at all times. Cooling was achieved, and condensate water was produced, by sending the coolant R-134a through the cooling coil system. Both modes of operation were tested in steady state with regard to thermal conditions. In our experiments, the surface temperatures of the wet coil (16–6 °C from Row 1 to Row 4, see Fig. S2) were much lower than those of dry coil (room temperature, ~26 °C). For all experiments, the cooling system as well as the fan were operated from 8 a.m. to 7 p.m., Monday through Friday, and were off for other times to simulate one type of typical operation in