INDOOR POLLUTANT MEASUREMENT AND MODELING COMPARING IMPACT OF SURFACE CHARACTERISTICS

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ABSTRACT

It is estimated that Americans spend 90 percent of their time indoors and there has been an epidemic increase in asthma and allergy worldwide. These observations have driven debate on the role of carpeting and its impact on indoor air quality and health. This paper reviews studies, employing computational fluid dynamics modeling, to elucidate the interaction of dust mite antigen (modeled as spherical particles) with soft vs. hard flooring surfaces and their ability to allow resuspension into the breathing zone. We have found, contrary to conventional wisdom, carpet can play an important positive role in the health of an indoor space. Quantitative results indicate carpet can function in a filter-like capacity by trapping and holding particulate matter out of the breathing zone. When used in combination with proper maintenance and cleaning equipment, carpeting may function to maintain and improve a healthy indoor air environment.

INDEX TERMS

IAQ, Allergens, Asthma, Carpet, Computational Fluid Dynamics, Health Effects

INTRODUCTION

Over the last 25 years, a considerable amount of effort has been focused on the study of indoor air contaminants. The early days of research focused primarily on chemical exposures, however, the last few years have seen a subtle shift in attention toward airborne particles. This change in focus has been driven by research, which associates small particles ($PM_{2.5}$) with increased mortality (Creason, 2001), and observations of a dramatic increase in reported asthma in the last 30 years (Lang, 2001). The latter was coincident with work and lifestyle changes, which have resulted in most Americans spending about 90% of their time indoors. In addition to health and quality of life implications, the economic impact of asthma and allergy is significant. The direct cost of asthma morbidity and mortality in 1998 in the United States alone was estimated at $12.7 billion (Weiss, 2001).

Although the etiology of asthma is viewed as intricate, many of the triggers are believed to be airborne allergens. The development of an understanding of the exposures and associated risks has been difficult due to the complex behavior of particles indoors. Factors such as settling rates, multiple primary sources, resuspension rates, effects of turbulence, and affinities for interior surfaces make it a challenge to accurately quantify exposures. However, it is generally recognized that 2-10 micrograms of dust mite antigen per gram of dust are threshold values for the onset of asthma symptoms and sensitization, especially in children (Platts-Mills, 1988).

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Predictive models have been a cornerstone in science and industry. One particularly useful tool has been computational fluid dynamics (CFD), which has seen widespread application in the aerospace, automotive, and chemical industries (Proceedings, 2001). The result has been the development of a high degree of confidence in the theory and application of CFD to air flows.

Limited clinical studies by The Ohio State University Medical School have shown that initially high levels of dust mite antigen (Der p 1) in carpeting can be readily reduced to less than 2 microgram per gram of dust. However, despite this dramatic reduction in Der p 1 levels, no clinical improvements were observed (Payton, 2000). These results suggest that it is not the absolute quantity of antigen present in carpet but rather their inhalation availability that is critical.

The intent of this work was to explore CFD as a new tool and technique to improve our understanding of the basic fluid and particle mechanics that determine the motion of particles within a dwelling and the interaction of allergen particles with various interior surfaces. Once established we then examine how these interactions impact the availability of such particles to be resuspended into the breathing zone. To the best of our knowledge this is the first time CFD has been applied to this complex problem.

METHODS

Computational fluid dynamics calculations were performed with CFX4 from AEA Technology Engineering Software [www.aeat.com/cfx], a three-dimensional finite volume code running on a Silicone Graphics Origin 2000 super computer utilizing eight parallel processors. A given model typically required 24 hours of CPU time to when running on four processors.

In general, a fluid-borne particle dynamics problem is a multiphase flow problem. However, since the particle concentration is very low and the particle size range is small, <40 microns for typical airborne allergens, the problem can be solved as a single-phase problem using the so-called algebraic slip model (AEA Technology, 2001). Since the particle concentration is dilute (ca. 50 $\mu g/m^3$), the particles neither interact with one another nor significantly impact the flow field. Since the particles are so small, they accelerate up to the local fluid velocity over time scales at least two times smaller than the characteristic convective time scales operating within the room. Thus, to a high degree of accuracy the particle velocity is equal to the local fluid velocity plus the particle settling (slip) velocity. Model details will appear elsewhere (Cicciarelli, et al. 2002).

Carpet is modeled as a porous medium. This is a physically appropriate means of representing the detailed fibrous structure of a carpet, providing the physical properties of the porous medium, void fraction and resistance tensor, are obtained from a sensible physical analysis of the fibrous structure/fluid interaction. Void fraction is readily obtained from carpet construction, and is typically in the neighborhood of 0.9. The resistance tensor can be computed by treating the carpet as a regular array of cylinders and applying known drag relationships, as discussed elsewhere (Batchlelor, 1977). In this case one can show that

$$|R| = \frac{\eta \mathrm{Re}}{4r} C_D(\mathrm{Re}) < \frac{A}{V} > \qquad (1)$$

where |R| represents the magnitude of the resistance, η the air viscosity, r the filament radius, Re the filament Reynolds number ($2\rho Ur/\eta$), C_D the drag coefficient, <A/V> the filament surface area per unit of occupied volume, ρ the air density and U the free stream air speed. For flow normal to the cylinder axis and Re less than 1,

$$C_D = \frac{8\pi}{\mathrm{Re}\ln(7.4/\mathrm{Re})} \tag{2}$$

It turns out that the product $\mathrm{Re}C_D$ changes by only about a factor of two as Re changes by two orders of magnitude, from 1.0 to 0.01, hence this expression for the resistivity is not only physically sensible but it is insensitive to local variation in the air velocity field. It also leads to predictions for the resistance comparable to known correlations for fibrous porous media (Dullien, 1992). Enhancement of drag due to non-circular filament shape (i.e., trilobal) and finite separation distance is also accounted for and is discussed in detail elsewhere (Cicciarelli, et al 2002). Presently our model ignores electrostatic and van der Waals interactions between carpet fibers and allergen particles. We believe this is a conservative approach (Hedge, 2001).

RESULTS

Model studies to date have shown that under circumstances typical of residential dwellings, the airborne particle concentration in the room is reduced by the presence of carpet, even in the absence of attractive electrostatic or van der Waals forces. By virtue of the fluid mechanics alone, carpet acts very much like a filter. Airborne particles settle into the carpet, due to the pull of gravity on the particles, and are not easily removed from the carpet by air currents within the room or through the action of walking. Hard surfaces, on the other hand, offer no additional resistance to air motion and consequently particles on or near the hard surface are more readily resuspended into the air, the result being the potential for higher exposure of airborne particles in the breathing zone.

This is illustrated by Figure 1, which represents instantaneous airborne particle concentrations at child height (about 3 ft above the floor, averaged over the room) and adult height (about 6 ft above the floor, averaged over the room) in a single 12x12x 8 foot room with a single air inlet in the ceiling, a single return in one wall, no open doors or windows, and an 11 minute HVAC cycle (off for 10 minutes, on for 1 minute, etc.) over ca. two hours. The room was initially uniformly filled with 5 micron diameter, 2000 kg/m^3 density particles at 50 μg/m^3. In the lower figure, the inlet air was perfectly filtered, so no additional particles entered the room. In the upper figure, the inlet air was unfiltered and of a constant particle loading of 50 μg/m^3. No virtual objects were moving in the room during the simulation. The corresponding particle settling velocity is 0.148 cm/s and the relaxation time is 7.56x10^{-5} s.

In both cases it is clear that the concentration of particles in the sample zone over a hard surface eventually becomes significantly larger than that over the carpeted surface. This difference increases with each HVAC cycle and is manifest by the increasing delta between the hard and carpeted surface curves (solid vs. dashed lines) as a function of time. The lower values for the carpeted case are the result of physical particle entrapment within the carpet. The cumulative exposure to occupants who spend significant time within the dwelling is proportional to the running time average of these instantaneous curves, which is not shown, but clearly the difference in running time averages also grows with time. In the case of allergens, for which short term exposure is sufficient to initiate an allergic response, the

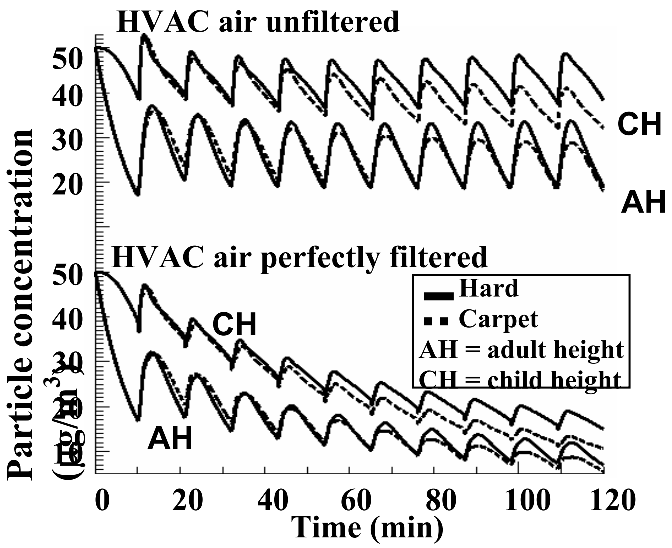

Figure 1. Instantaneous time dependent concentration of 5 micron diameter particles in adult and child breathing zones over multiple HVAC cycles; hard vs. carpeted surfaces.

instantaneous concentration is of interest. In either case, the model indicates that the presence of carpet reduces exposure potential compared to an identical system without carpet.

Examination of Figure 1 reveals that as time progresses the amount of particulate matter available for resuspension by the HVAC system decreases. The model results are consistent with a settling process (gravity) whereby once a particle comes in contact with the filter like medium of a three-dimensional soft floor covering fabric, it becomes mechanically trapped. Once trapped the carpeted surface is treated just like a filter element where resuspension is based on dislodgement from the filter like face fiber structure. Consistent with literature observations (Wille, 1974), this airflow mediated dislodgement process is much more difficult for a carpeted surface vs. that which takes place over a hard surface flooring material. Wille observed it requires approximately ten times the air velocity to resuspend a settled particle from a carpeted surface vs. a hard surface. This result is also consistent with Nishioka, et. al., who observed that approximately 1% of the bulk dust resides on the carpet surface and would thus be more difficult (i.e., less available) for resuspendsion (Nishioka, 1999). It is important to reiterate that these calculations completely neglect particle-fiber interactions, specifically those interactions that are typically present in filters that retain particles by virtue of electrostatic, van der Waals or geometric factors. If such factors are included, the computed differences between hard and carpeted surfaces would be expected to increase. We plan to incorporate these factors into future model studies.

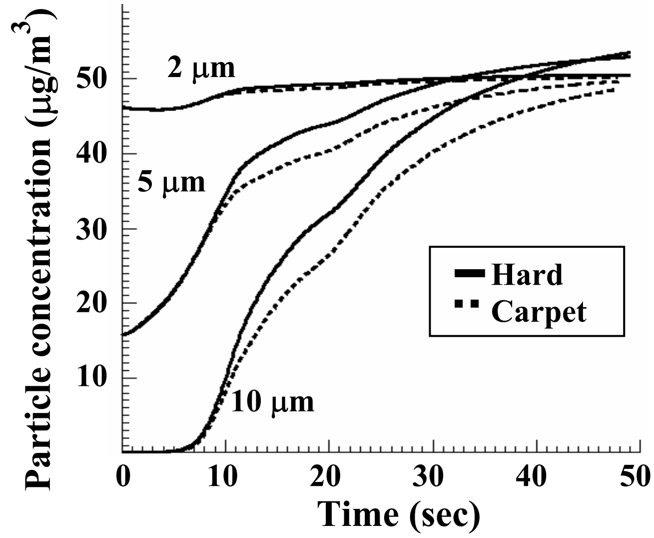

Figure 2. Instantaneous time dependent concentration of 2, 5 and 10 micron diameter particles in adult breathing zone during 40 second walk period after 10 minute initial settling period; hard and carpeted surface.

Figure 2 illustrates 2, 5 and 10 micron diameter airborne particle concentrations in the adult breathing zone for the case in which particles are initially uniformly concentrated within the room, settle for 10 minutes, and then a virtual adult walks in a 6 ft diameter circle at 4 ft/s for 50 seconds, all in the absence of HVAC. The CFD simulation faithfully accounts for the details of walking by imparting the appropriate velocity field at the appropriate locations. Details will be discussed elsewhere (Cicciarelli, 2002). It is intuitively expected, and supported by the model studies, that human motion stirs up particles that have settled on the floor. The impact of this motion is seen to be greater for a hard surface than a carpet surface and is consistent with the same reasoning cited in the case for HVAC induced particle motion.

DISCUSSION

The primary driver of our model studies is to bring a disciplined, scientific modeling approach to an element of this problem, which thus far has not been explored. Namely, it is well know that carpeted surfaces contain (or retain) higher levels of dust and antigens. What has never been examined in detail is the ease or difficulty with which such trapped particles can be resuspended into the breathing zone. In other words, just because these particles are present in the flooring substrate, there is no evidence that they are available for inhalation and thus irritation. An extensive review of the scientific and medical literature indicates properly maintained carpet has no adverse impact on indoor environments or human health (Berry, 2001). Dr. Alan Hedge of Cornell University has stated, “concerns that carpeting in schools is contributing to an increase in respiratory problems, allergies and asthma in schools are unfounded,” (Hedge, 2001). Model results reported here are consistent with these conclusions and we believe shed additional light on the mechanisms involved.

These results are also consistent with an interesting observation reported by Jaakkola, et al, who studied 251 healthy infants and toddlers compared to 251 diagnosed with asthma (Jaakkola, 1999). He found that children with PVC flooring in nurseries, bedrooms and other rooms had an 80% higher risk of asthma than those in PVC free homes. While there was no cause and effect established, it is known in the medical literature that sensitization occurs when exposure to high loadings of allergens can occur (Sporik, 1990). Our quantitative modeling results suggest that such exposures may be higher over hard surfaces since these surfaces have been shown to more easily release particles, which are then resuspended into the breathing zone. Hard surfaces are also generally considered more difficult to clean since sweeping and mopping tend to push materials around and resuspend them as opposed to vacuuming or extracting carpets where containment, with the proper equipment, is much easier. In fact, one could conclude that if a building has a moisture ingress problem resulting in mold growth, ripping out carpeting may actually exacerbate the problem but, certainly will not solve it.

The work reported here is based on model studies which have yet to be experimentally validated. However, the tools employed are well established and their application to such problems is reasonably straightforward. More work remains to be done since a relatively small number of cases have been examined vs. the large number of possibilities. Clearly, one of our objectives is to facilitate a discussion of the application and results of these tools. In addition, preliminary experimental results are consistent with model predictions.

CONCLUSION AND IMPLICATIONS

The model results reported here clearly indicate that established conventional wisdom regarding the adverse role of carpet on indoor air quality is simply wrong. Our results support the concept that, when properly maintained using the right tools and equipment, carpeting has the potential to actively contribute to maintaining or improved indoor air quality and thus the overall indoor environment. This function is accomplished when the three dimensional fiber networks themselves (e.g., carpet) function in a “filter-like” fashion to trap and hold dust, dirt, and allergen particles resulting in minimal resuspension into the breathing zone.

Many view the concept of carpet functioning as a "sink" to be a negative attribute. The authors believe this is in fact a favorable function. If it were not for the filter-like property of the carpet face fibers, much of the outside dirt, pesticides, heavy metals, allergens and dust that are routinely tracked in on shoes would be free to be dispersed through the home or office and readily suspended into the breathing zone. By contrast, when carpet acts in this filter-like capacity, these materials appear to be held securely until one desires to remove them with vigorous extraction and containment techniques. As our computational studies have shown, resuspended particles are at a significantly lower concentration over a carpeted surface vs. a hard surface.

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