

IMPORTANCE OF HUMIDITY ON THE PERFORMANCE OF GAS PHASE FILTRATION MEDIA

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Biography

Matthew C. Middlebrooks is the Senior Research Engineer at AQF Technologies (a part of BBA Filtration), where he has been employed for over three years developing custom products and exploring product fundamentals for the molecular contamination filtration industry. He has worked in Research and Development for 17 years in the fields of filtration, specialty products, and melt-spun fibers. Mr. Middlebrooks earned BS and MS degrees in Chemical Engineering from Clemson University. He has been married 19 years and has a 15-year-old daughter.

Abstract

Automotive cabin-air filters are increasingly being used to remove odors and other gaseous contaminants from the outside air. Testing standards have already been established for comparing the performance of these filters. These standards specify a relative humidity of 50% \pm 2% because it is accepted in the industry that the humidity level will impact the adsorption performance of activated carbon, the current adsorbent of choice. In actual application, however, these filters will be exposed to unconditioned, ambient air with humidities ranging from perhaps 10-100%. This paper will provide the results of lab studies on the impact of relative humidity on the adsorption performance of gas phase filtration media. The study has examined the impact of humidity on physical and chemical adsorption using plain and impregnated activated carbons.

Keywords: Airborne Molecular Contamination, Air Filtration, Adsorption, Chemisorption, Impregnation, Breakthrough, Relative Humidity, Capacity.

Introduction

Increasing emphasis is being focused on gas-phase contaminants and their impact on the health, safety, and comfort of people and on the performance of various production processes. Applications range from yield improvement in microelectronic cleanrooms to relief of sick-building-syndrome symptoms to filtration of pollutants and odors in automotive cabin-air systems. And yet, effective technology for controlling so-called 'molecular contaminants' in an air stream is still early in its development. Users are trying to learn how best to employ gas-phase systems at the same time that they are determining what contaminants they are trying to control.

A variety of filtration technologies are available to choose from, but most commercially available systems operate on the principle of adsorption of the contaminants onto extended

surface area materials. Activated carbon is the most common of these sorbent materials, but activated alumina and zeolite are also used for certain applications. These sorbents can be used as virgin materials to remove the contaminants by physical adsorption onto the surface (physi-sorption) or they can be impregnated with chemicals designed to react with targeted contaminants (chemi-sorption). In this second case, the sorbent acts mainly as a carrier for the chemical reactant and repository for the byproducts. In limited cases the sorbent may actually act as a catalyst, as in the case of activated carbon catalyzing the conversion of ozone to oxygen.

In addition, the characteristics of the air stream must be considered when trying to achieve a certain level of performance. Changes in the flow rate, temperature, and humidity of the air stream can all affect ability of the adsorbent to do its job. The following study will begin to define the impact of humidity changes on the performance of gas-phase adsorbent media.

Relative Humidity as a Contaminant

Physical adsorption is accomplished through weak molecular forces, such as van der Waals forces, between the adsorbent and the adsorbate or contaminant. All compounds will exhibit this effect to some extent so that equilibrium is established on the adsorbent surface based on the relative affinities of the various components of a gas mixture for the adsorbent and their respective concentrations in the air stream. Since physical adsorption is a related process to condensation, the affinities are somewhat related to the boiling point (higher boiling point usually gives greater adsorption) and the heat of condensation (though the heat of adsorption is up to 2-3 times higher). Oxygen and nitrogen, the major components of air are very weakly adsorbed, but water is sufficiently adsorbed that we must consider it as another contaminant competing for space on the surface of the adsorbent. This water in the air stream, represented by the humidity, is often present at much higher concentrations than the contaminant we are interested in removing, as shown in the following illustration.

Relative humidity is defined as the percentage ratio of the partial pressure of water in the air stream to the saturated pressure, or vapor pressure, of water at the given temperature. For example, at 72°F the vapor pressure of water is 20.07 mm Hg¹ (at this temperature 1 atmosphere = 763 mm Hg). Thus, at a relative humidity of 50% the partial pressure of water is 10.035 mm Hg out of 763 mm Hg, or 1.319%. This is equivalent to a concentration of 13,190 ppm. Most test standards for testing gas phase filtration performance are conducted at contaminant concentrations of 100 ppm or less, while actual application contaminant concentrations are typically 0.1 ppm or less.

We would expect that the physical adsorption of any contaminant with a lower affinity for carbon than water would be strongly affected by the humidity level. However, a contaminant with a higher affinity for carbon should be relatively immune to the presence or absence of humidity. With a chemi-sorption process water would not generally be an effective competitor for the chemical reaction that is taking place. In fact, most reactions will proceed quicker in a solution, so that the presence of some water might actually enhance the adsorption of the contaminant.

Testing Program

For this study, dynamic adsorption testing was conducted on several carbon-loaded nonwoven media under controlled conditions. The temperature of the test air was controlled at $72^{\circ}\text{F} \pm 1^{\circ}\text{F}$ for all of the tests. Each of the media samples was tested as a flat sheet at a media velocity of 20 feet per minute. This media velocity is within the range of the conditions for a well-designed, pleated filter. All of the media were commercial AQF Technologies products loaded with 500 grams per square meter activated carbon within a 20x50 mesh size range. Three different types of carbon were used: a virgin high activity coconut shell carbon and two impregnated carbons targeted at sulfur dioxide and ammonia respectively. Tests were performed using N-butane, toluene, sulfur dioxide, and ammonia at levels consistent with standard test methods for the cabin-air market (80 ppm, 80 ppm, 30 ppm, and 50 ppm respectively). As such, these tests would be considered “accelerated” conditions; i.e. concentrations were elevated to produce results within a practical and economic timeframe. Each test was replicated to limit the impact of random noise on the conclusions.

Each combination of media and contaminant gas was evaluated at 35% and $75\% \pm 2\%$ relative humidity. These levels were chosen based on the capability of the test equipment to get as wide a spread in humidity as possible. From the above calculations these humidities correspond to concentrations of 9,205 ppm and 19,725 ppm of water respectively.

Results

N-butane is removed purely by physical adsorption so that a virgin activated carbon would work best by maximizing the available surface area. However, N-butane’s boiling point is very low, 25°F , and its affinity for carbon is also low. We see in Figure 1 that this is reflected in the breakthrough curves for low and high humidity. The breakthrough at 5 minutes is more than doubled, from 9% to 27% when the relative humidity is raised from 35% to 75%. Another way of looking at it is that the time it takes to reach 50% breakthrough at high relative humidity is less than half the time at low relative humidity. The higher water concentration present at high relative humidity shifts the equilibrium on the adsorbent to more water and less N-butane, causing the N-butane to break through quicker.

By contrast, toluene, also removed through physical adsorption on the activated carbon, shows no impact from the change in relative humidity. In Figure 2 the breakthrough curves for 35% and 75% relative humidity are almost identical. This is because toluene has a much higher affinity for carbon than water (boiling point of toluene = 230°F). Due to toluene’s strong adsorption on the carbon surface the equilibrium is not significantly affected by changes in the water concentration. Also note how much longer it takes for the toluene to reach 50% breakthrough than N-butane. This also reflects its much higher affinity for the carbon and translates to higher capacities for toluene than N-butane.

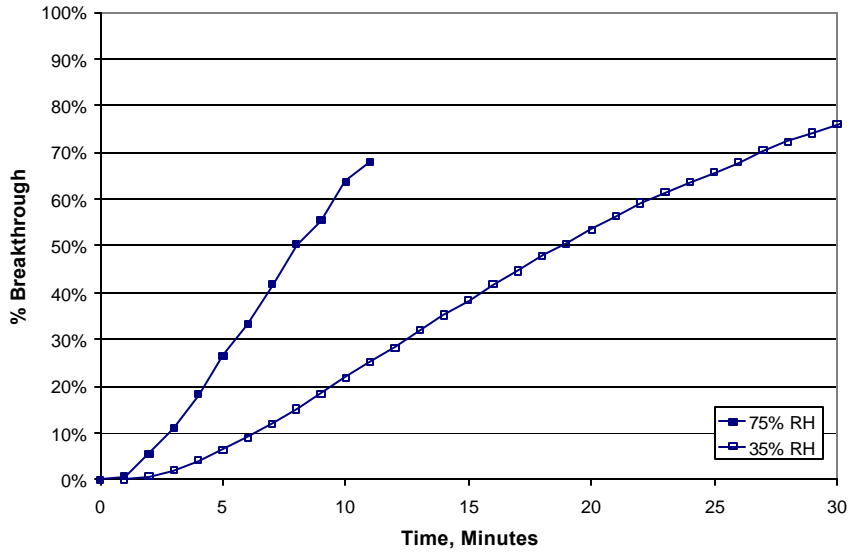


Figure 1. N-butane Breakthrough vs. Relative Humidity.

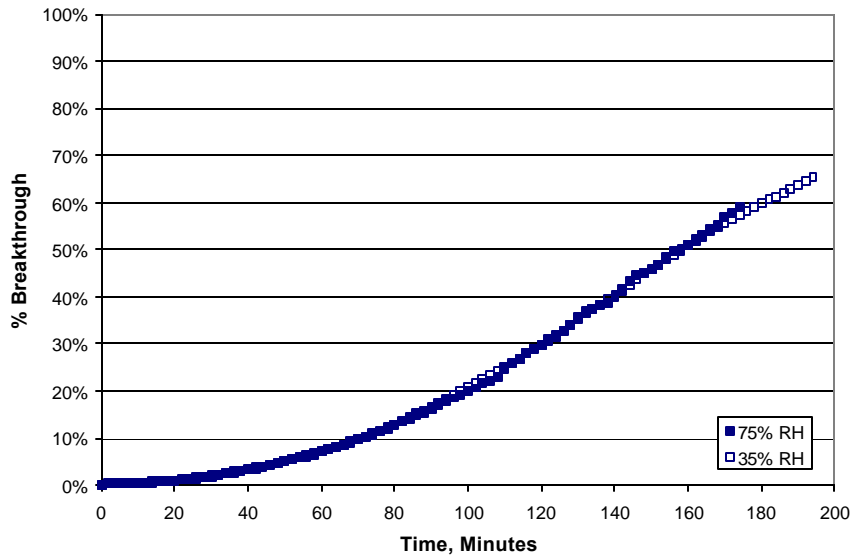


Figure 2. Toluene Breakthrough vs. Relative Humidity.

An impregnation is usually used to enhance the capture of sulfur dioxide, but even virgin carbons show some effectiveness. It is not clear whether this is from physical adsorption or chemical reaction with impurities on the activated carbon surface. Figure 3 shows the impact of relative humidity on the adsorption of sulfur dioxide using both a virgin and an impregnated carbon. Comparison of the breakthrough curves for the virgin activated carbon supports the chemisorption hypothesis since the removal is enhanced with higher humidity. Interestingly, the impregnated carbon shows virtually no affect with the change in relative humidity. Most likely there is some moisture present with the impregnation on the activated carbon even at low humidity, which is enough to facilitate the reaction. Additional moisture from higher relative humidity neither interferes with nor increases the removal above this base level. We have noted in our labs that impregnated carbons very quickly regain moisture after being dried, even when the relative humidity is low.

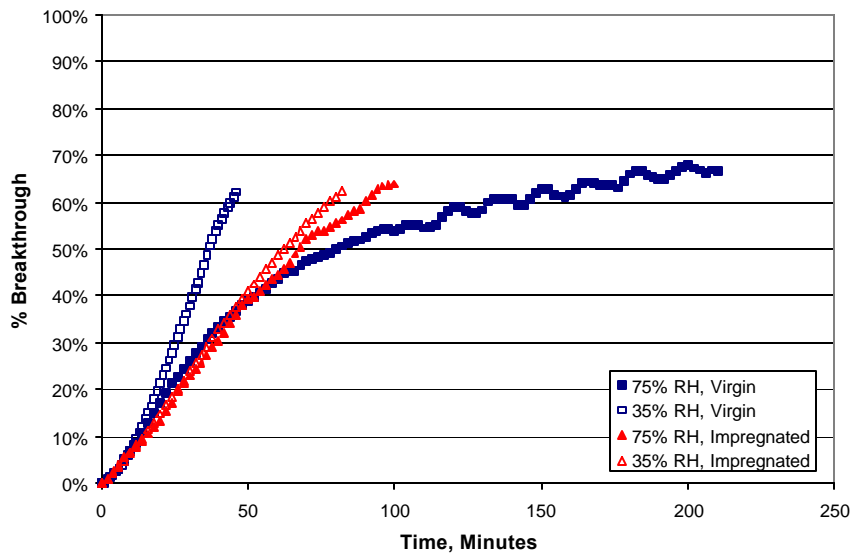


Figure 3. Sulfur Dioxide Breakthrough vs. Relative Humidity, Virgin and Impregnated Carbons.

Virgin activated carbons show no effectiveness against ammonia, through physical or chemical adsorption, and impregnations are necessary to remove this contaminant. Figure 4 shows the breakthrough curves at 35% and 75% relative humidity using an activated carbon impregnated to target ammonia. Just as in the impregnation for sulfur dioxide we see very little impact of the relative humidity level on the performance of the filtration media. In fact, the difference shown is not statistically significant compared to the variation between the replicate tests. Again, we theorize that some low level of moisture is present on the conditioned samples that enhances the reaction while further changes due to relative humidity have little impact.

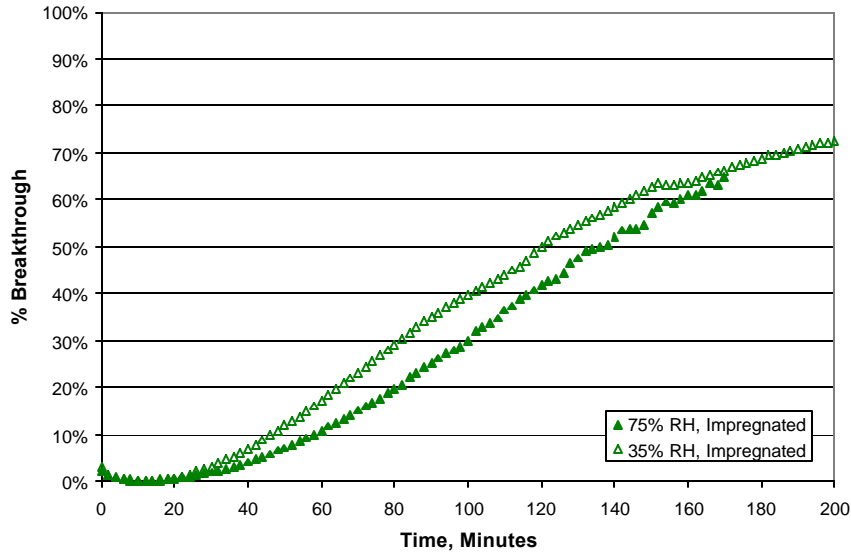


Figure 4. Ammonia Breakthrough vs. Relative Humidity, Impregnated Carbon.

Implications for Cabin Air Filtration Applications

This is by no means an exhaustive study of the influence of relative humidity on gas phase filter performance. We have not examined the interaction of relative humidity and temperature, the impact of carbon activity, the use of alternative functional particles, or the interaction of relative humidity and impregnation on physical adsorption. However, we can already see the need for controlling relative humidity during testing to achieve repeatable data. We can also begin to see the implications of these results on the performance of these types of filters in actual application.

Typically, cabin-air filters are placed in the air conditioning system not only to protect the occupant from allergens and odors, but also to protect the cooling coils from dust buildup. They are usually located upstream of the cooling system and are subjected to ambient air with its normal variation in temperature and relative humidity. From the results shown above, the same gas phase filter based on a virgin activated carbon would have radically different removal performance in different areas of the country such as the dry Southwest versus the wet Southeast. In one area the performance against volatile organics represented by N-butane would be better while in the other the removal of weak acids like sulfur dioxide would be enhanced. Impregnated carbons could be used to stabilize the performance of chemi-sorbed contaminants, but these are generally more expensive and sacrifice some performance against physically adsorbed compounds.

Moreover, we can also imagine changes in performance within the same area due to changes in relative humidity throughout the day. This could be especially troublesome for physisorbed species since they can desorb from the filter media depending on the equilibrium conditions. For instance, butane or other similar compounds with poor affinities for activated carbon could be adsorbed while the humidity was low, say 50% or less. If a storm front moves in, raising the relative humidity to near 100% at the same general temperature, the butane would be forced off of the activated carbon by the water being adsorbed. Depending on how heavily loaded the filter was at the time of the humidity change, the concentration downstream of the filter could easily be higher than the concentration in the ambient air. This is not likely in the case of chemisorption since the chemical bonds that are created are much stronger and less sensitive to the equilibrium effect.

These potential impacts illustrate the importance of properly designing the entire filtration system to achieve the performance desired or at least being aware of the potential changes in performance within the span of normal operating conditions. The proper design could involve a filter designed for the worst possible conditions, or an adsorbent particle that is less sensitive to humidity effects, or a system that places the filter in more controlled conditions. Different combinations of performance requirements, physical limitations, and economics will lead to a variety of answers to these design issues.

Conclusions

1. Control of relative humidity during breakthrough testing is critical to achieve repeatable results.
2. Low relative humidity favors the removal of physically adsorbed contaminants with low affinities for the adsorbent.
3. Relative humidity has negligible impact on the removal of physically adsorbed contaminants with high affinities for the adsorbent.
4. Higher relative humidity favors the removal of chemically adsorbed contaminants on virgin carbon. Impregnated carbons appear to have sufficient moisture present that relative humidity is not a factor.

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References

- ¹ "Section 3: Physical and Chemical Data", Chemical Engineer's Handbook 5th Edition, 1973.