Optimization of fibrous air filter on the basis of particle condensational growth during the air cooling and dehumidification process using mathematical modeling

Zhuangbo Feng¹, She-Jie Cao¹,∗

¹ School of Civil Engineering, Guangzhou University, Guangzhou 510006, China
∗shijie.cao@gzhu.edu.cn

Abstract. Indoor ultra-fine particles have significantly adverse effects on human health. Under the condition of high concentration, the widely used HEPA (High-Efficiency Particulate Air) requires expensive operation cost. Previous study indicated that air cooling and dehumidification system could greatly increase particle size (from dozens of nanometers to several micrometers) due to the condensation effect during the process of air conditioning in hot and humid regions. Because of the condensational growth of particles, low-grade air filters can be used to achieve high efficiency and lower cost. This study developed mathematical model to predict particle size variation in cooling and dehumidification process and investigate its effect on fibrous filter performance. The steps are as follows: 1) Based on the state-space model, distributions of supersaturation ratio in condensational dehumidification process were simulated; 2) The modified Lagrangian method and SSR-based model were used to simulate particle trajectory and size increase; 3) Based on the prediction of condensational growth of particles, the air filter performance model were adopted to investigate the condensation effect on fibrous filter performance. The results shows that condensational dehumidification improve the filtration efficiency of middle-efficiency fibrous from 72% to 92%, quality factor from 0.016 to 0.031. Utilization of condensational dehumidification could decrease energy consumption of fibrous filtration system by 53%. This study is of great significance to improve the effectiveness and economy through the coordinated control for indoor pollutants, temperature and humidity control in humid and hot climate region.

1. Introduction
The public health impact of particulate matter (such as ultra-fine particles or PM$_{2.5}$) in ambient air has been of great concern [1]. To remove particle pollutant efficiently, most air purifiers on the market have been equipped with a high efficiency particulate air (HEPA) filter [2]. Utilization of HEPA causes many negative impacts: high pressure drop and electric energy consumption, expensive replacement cost and ventilation fan noise. Therefore, economic and relatively high efficiency air filtration technology draws more and more attention [3].

In hot and humid regions, condensational dehumidification is an effective and widely-used method to ensure indoor relative humidity level. Simultaneously, condensational dehumidification could change particle size distribution and enhance performance of air filtration system, as described by figure 1. Humid air can be supersaturated upon cooling by any means. Under the supersaturation condition, particles begin to grow in size by water vapor condensation [4]. Once ultrafine particles have grown to a few micrometers in diameter, the grown particles are relatively easy to remove, e.g. with simple impactors, because of their increased inertia [3]. Previous study selected water vapor condensation and inertia impactor for ultrafine particle filtration as an alternative method without a HEPA filter [3]. The
results indicated that it enabled the growth of any type of ultrafine particle in the form of a water droplet within ~0.1 s. The filtration performance of impactor was not comparable to fibrous filter, and it is mainly used in industry environment. Coupling of condensational dehumidification and fibrous filter will lead to better filtration performance, which is suitable in residential environment control. Otherwise, the available researches only focused on experiments. The mathematical models are very necessary in engineering design and optimization.

In the current study, mathematical modeling was developed to simulate particle condensational growth and fibrous filter performance. The influences of condensational dehumidification on filtration efficiency and quality factor were analyzed based on the proposed model.

2. Methodology

2.1 Mathematical Model

The mathematical model adopted in the current study consists of two parts: predictions of particle condensational growth and fibrous filter filtration. Equation (1), the so-called “SSR-based model”, was used to simulate particle size variation in condensational dehumidification process [3]. Equation (1) was based on Lagrangian trajectory concept.

\[
\frac{d(d^*)}{dt} = \frac{4MD}{Rd}\left(\frac{P}{Ps} - 1\right)
\]

Where \( t \) is time (s), \( d^* \) is particle size (m), \( M \) is molecular weight of water, \( \rho_p \) is density of the water droplet (kg/m\(^3\)), \( T \) is temperature (K), \( D \) is diffusion coefficient of the water vapor (m\(^2\)/s), \( P \) is partial pressure of the condensing water vapor (Pa), \( Ps \) is saturation water vapor pressure (Pa), \( SSR \) is the so-called supersaturation ratio \((P/P_s)\). The distribution of SSR in heat exchanger is an essential factor in particle size prediction. The widely used state-space model was adopted in the current study to determine relative humidity and SSR value in water vapor condensation process [5].

The numerical model from literature was utilized to simulate air flow and particle filtration in pleated fibrous air filter [6]. The pleat structure was treated as an ideal rectangle because of the high pleat density in actual filters. The filter medium was modeled as porous zone. The constant porous permeability was assigned in each cell located in porous filter medium. The Lagrangian method was used to model particle motion in pleated filter. In order to simulate particle removal and filtration, the single-fiber filtration efficiency model was coupled into Lagrangian method. Detailed information could be found in literature [6].

2.2 Case Description

This part describes the information about condenser (heat exchanger) and pleated air filter. In the present modeling, a type of cross-flow flat-plate heat exchanger was used as condenser. It consisted of nineteen thin aluminum flat plates (30-cm high and 24-cm long). These plates were stacked vertically (not on top
of each other) in a rigid rack, and aligned parallel to each other at equal intervals of 1.5 cm. Hot and humid air (30°C, 90%) and tap water (15°C) flowed through the channels formed by the plates. The condensational dehumidification occurred in air side, resulting in a supersaturation state. The state-space model was used to simulate the water vapor condensation process. The middle-efficient pleated air filter was adopted. The average fiber size was 5 μm, solidity ratio was 0.1, filtration velocity was 0.1 m/s, filter thickness was 2 mm. Filtration velocity was defined as the ratio of air flow rate to total area of pleated air filter. The fiber distribution was assumed as isotropic. The initial particle size distribution was from previous research [3]. The median particle size was 0.21 μm.

3. Results and Discussion
Figure 2 compares particle size distributions before and after the cross flow flat-plate heat exchanger. The initial distribution of particle size was based on atmospheric dust, which was different from that in literature [3]. The mathematical model in “methodology part” was adopted to determine particle sizes after condensational growth. Water vapor condensation increased particle size remarkably. After condensational air dehumidification process, the median particle size increased from 0.21 μm to 0.91 μm. For the widely used fibrous filter, the value of MPPS (Most Penetration Particle Size) was 0.2-0.4 μm [7]. Water vapor condensation changed particle sizes to those values larger than MPPS, which was beneficial for filtration performance improvement. Similarly, the particle size range varied due to particle condensational growth. Before dehumidification, particle size range was narrow (0-0.6 μm). Water vapor condensation enlarged particle size range to (0-1.7 μm). Obvious particle condensational growth could be utilized in particle filtration. In the current study, the particle diameter increase ratio was less than that in previous literature, due to different air parameters before dehumidification [3].

Figure 2. Modeled results of condensational growth of ultrafine particles

Figure 3 shows the modeled particle filtration efficiency curve of pleated fibrous air filter (AM10) utilized in the current study. The effects of particle size on filtration efficiency was considered. The mathematical model from literature was used to determine the particle filtration efficiency curve. It was observed that the filtration efficiency for very small (such as < 100 nm) or large particles (such as > 1000 nm) was higher. The diffusion and impaction effect caused this phenomenon. The smaller particles had higher diffusion induced single-fiber efficiency, and lower impaction induced single-fiber efficiency. The filtration efficiency of MPPS (0.25 μm) was 65%. This filter type was middle-efficient with pressure drop of 80 Pa. This pressure drop value was determined by formulas from previous research [6]. Particle condensational growth will influence particle size distributions, resulting in change of fibrous filter performance.
Figure 3. Fractional filtration efficiency of pleated fibrous air filter (AM10)

Figure 4 describes the modeled particle size distributions before/after pleated air filter with and without water vapor condensation. Figure 4(a) shows that fibrous filter could remove most of the incoming particles. Water vapor condensation increased particle sizes and changed particle size distributions. The number of particles located in range of most penetration size (0.2-0.4 μm) were reduced largely. The variation of particle size distribution improved filtration performance of fibrous filter obviously. Figure 4(b) shows that two curves of particle size distributions had similar shape if ultra-fine particles did not flow through heat exchanger. After air filtration process, particle number concentration was higher than that with condensational dehumidification. The reason was that most of incoming particles located in most penetration size range. Besides, the filtration efficiency curves of two conditions in figure 4 (a-b) were the same to that shown in figure 3. The reason was that filtration efficiency was determined by fibrous filter characteristics, not the incoming particles.

Figure 4. Particle size distributions before and after pleated air filter (a) with water vapor condensation (b) without water vapor condensation

Figure 5 shows pleated filter efficiency for total particle number (0-2.5 μm) with and without condensational dehumidification. The filtration efficiency in figure 3 and figure 5 were quite different, representing fractional efficiency and total number efficiency respectively. The particle fractional efficiency was not analyzed in the current study due to that particle size distribution varied due to condensation growth. For original ultra-fine particles, filtration efficiency was only 72%. Condensational growth could increase filter efficiency to 92% without adding the pressure drop and energy consumption. Figure 6 shows the influences of water vapor condensation on quality factor of air filter. Quality factor was an widely used index, which considered filtration efficiency and pressure drop simultaneously. In the current study, filtration efficiency for total particle number was utilized in quality factor calculation.
Detailed description of quality factor could be found in literature [7]. The results indicated that water vapor condensation improved quality factor of fibrous filter by about 50%, from 0.016 to 0.031.

![Figure 5. Filtration counting efficiency for total particle number](image)

![Figure 6. Quality factor of air filter with and without condensational dehumidification](image)

We also tried to used the condensational dehumidification assisted air filter with less pressure drop to achieve approximately the same filtration efficiency for air filter without considering dehumidification. Compared with original filter medium described above, solidity ratio of the new air filter was reduced (0.065 vs. 0.1). The pressure drop and energy consumption were reduced up to 53%. Utilization of condensational dehumidification could decrease energy consumption of fibrous filtration system by above 50%.

The current study utilized mathematical model to simulate particle condensational growth and investigate its influences on filter performance. Some previous researches conducted related experiments on particle condensational growth. The current study did not utilize the experimental data in model validation due to the incomplete description of heat exchanger in experimental. In future study, the accurate experiments will be conducted to validate mathematical model.

4. Conclusions

In the current study, mathematical modeling was adopted to simulate particle condensational growth and investigate its influences on filter performance. In hot and humid regions (30°C, 90%), condensational dehumidification could increase particle size obviously (> 4 times), resulting in improve fibrous filter efficiency and quality factor. Coupling air dehumidification and filtration processes is an effective way to improve indoor air quality and reduce energy consumption simultaneously. In cold climate regions, this method could be used in industry buildings with load of extra heat and moisture.

The most important limitation of the current research was lack of experimental validation. Accurate measurements will be conducted to compare with numerical results. The current study did not consider
the filtration behaviors towards liquid droplets in humid environment, and future work will extend to this complex physical phenomenon.

Acknowledgements
The authors would like to acknowledge the coordinated support from Natural Science Foundation of China (Grant No.51808138; Grant No. 51778385)

References
[1] E. Lee, Y. Zhu, 2014. Application of a high-efficiency cabin air filter for simultaneous mitigation of ultrafine particle and carbon dioxide exposures inside passenger vehicles. Environmental Science & Technology. 48: p. 2328-2335.
[2] J. Liu, T. Hsiao, K. Lee, et al., 2018. Association of ultrafine particles with cardiopulmonary health among adult subjects in the urban areas of northern Taiwan. Science of the Total Environment. 627: p. 211-215.
[3] J. Pyo, Y. Ock, D. Jeong, et al., 2017. Development of filter-free particle filtration unit utilizing condensational growth: With special emphasis on high-concentration of ultrafine particles. Building and Environment. 112: p.200-208.
[4] P. Demokritou, T. Gupta, P. Koutrakis, 2002. A high volume apparatus for the condensational growth of ultrafine particles for inhalation toxicological studies. Aerosol Science and Technology. 36: p.1061-1072.
[5] Y. Yao, M. Huang, J. Mo, et al., 2013. State-space model for transient behavior of water-to-air surface heat exchanger. International Journal of Heat and Mass Transfer. 64: p.173-192.
[6] Z. Feng, Z. Long, 2016. Modeling unsteady filtration performance of pleated filter. Aerosol Science and Technology. 50: p.626-637.
[7] J. Cai, 2002. Air Filtration ABC. China Construction Industry Publishing House, Beijing, China.