Fluffy-Like Glass Fiber Filters Made of 3D Hierarchical Silicone Nanofilaments

（三维多级结构硅纳米丝构建的绒毛状玻璃纤维滤纸）

Zhiqiang Zhou[12], Tianle You[1], Yun Liang[1], Min Tang[1]（周志强[12]，游天乐[1]，梁云[1]，唐敏[1]）

[1]School of Light Industry and Engineering, South China University of Technology, Guangzhou, China

（华南理工大学，轻工科学与工程学院，广州）

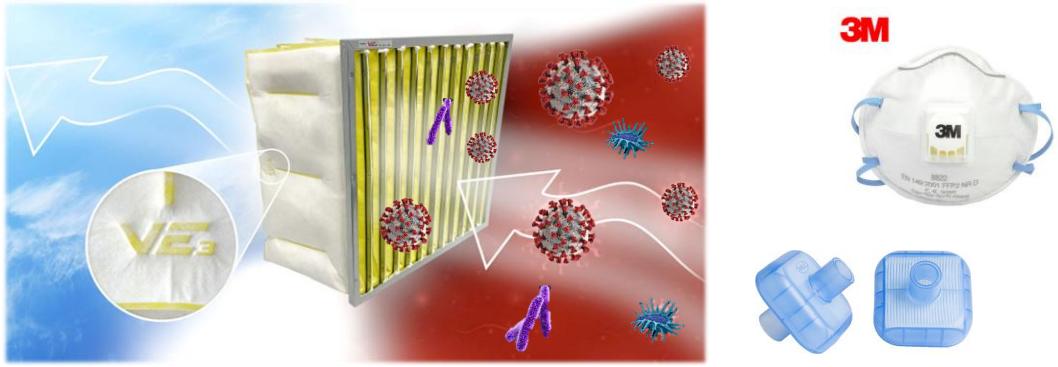
[2]College of Textile Science and Engineering, Zhejiang Sci-Tech University, Hangzhou, China

（浙江理工大学，纺织科学与工程学院，杭州）

Contents

1.Challenges in the development of air filters（空气过滤面临的挑战）

Air filters play a key role in meeting the air cleaning needs of various sectors.
（空气过滤材料/过滤器在满足各个领域的空气洁净度需求都发挥着重要作用）

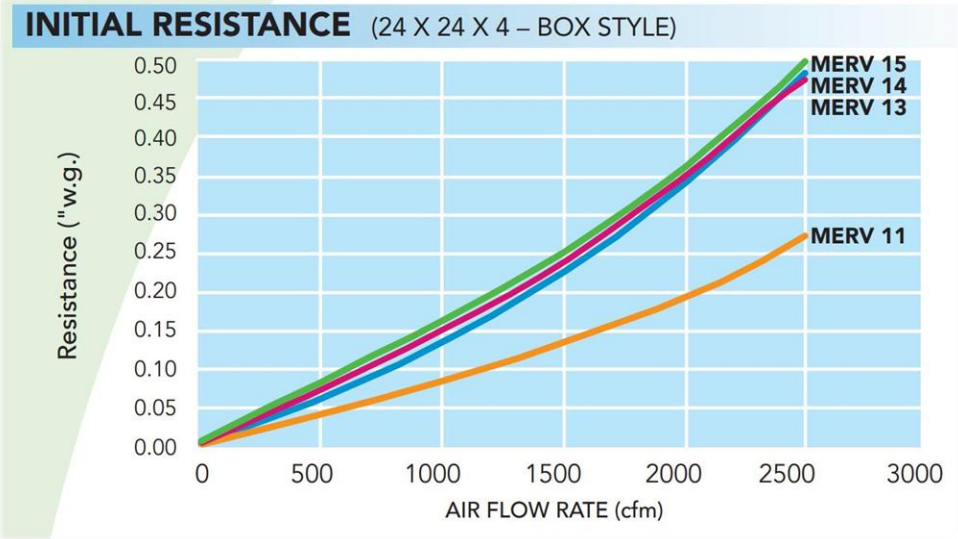


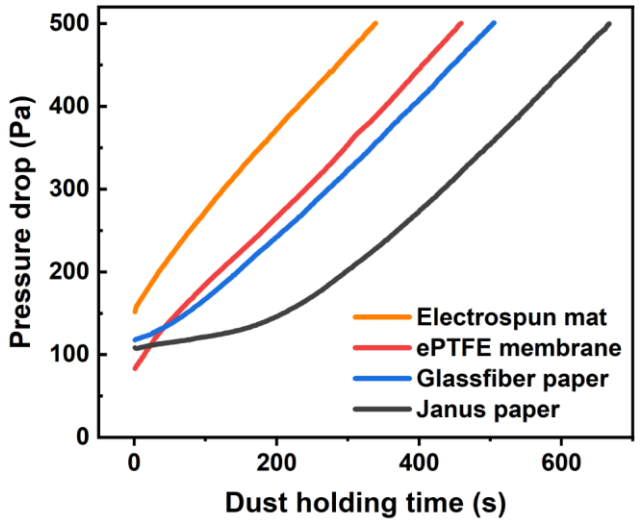
Air filter media and filters（空气过滤材料/过滤器）

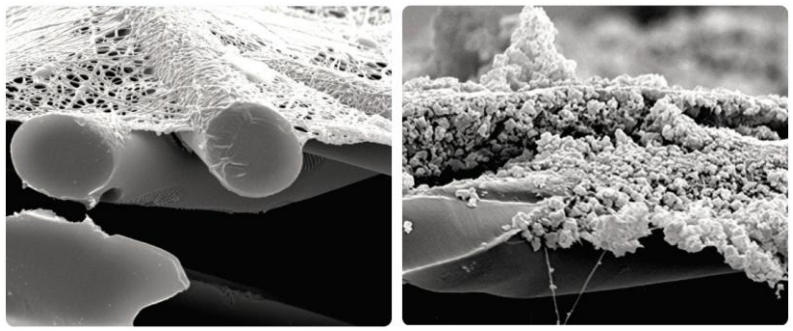
Personal protection（个人防护）

semiconductor fabrication（半导体制造）

The issues of air filters: filtration efficiency-resistence trade off; short life time.
（空气过滤材料存在的两大问题：过滤效率和阻力的矛盾；使用寿命短）





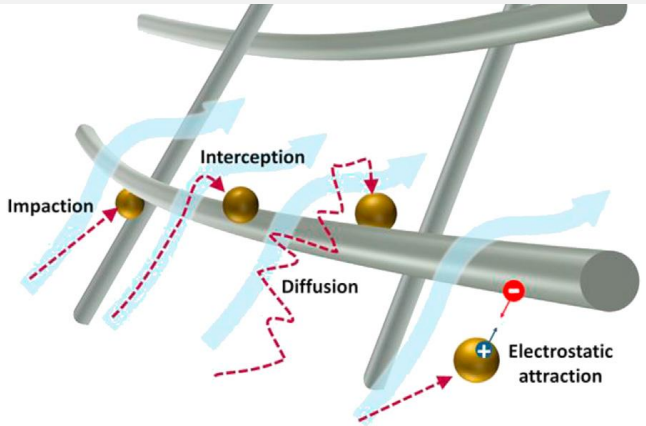


The changes after dust loading
（颗粒加载前后变化）

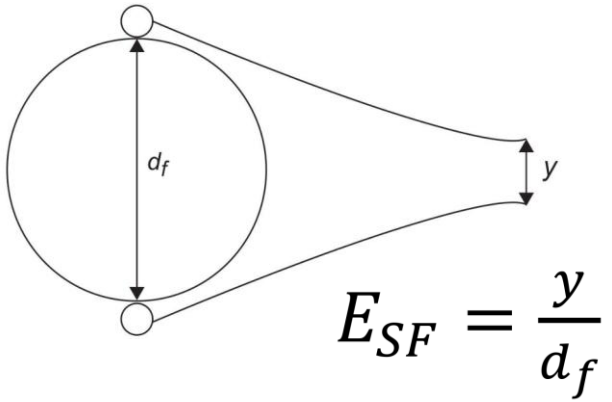
1.Challenges in the development of air filters（空气过滤面临的挑战）

Single fiber theory: filtration efficiency increases as the fiber diameter decreases.
（单纤维过滤效率理论：纤维直径越小，过滤效率越高）

Aerosols captured by the fibers
（细纤维捕获颗粒污染物）

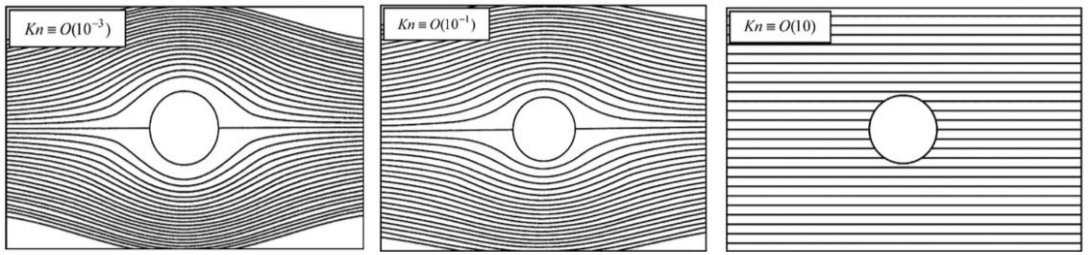


single-fiber capture mechanisms
（单纤维捕获机制）



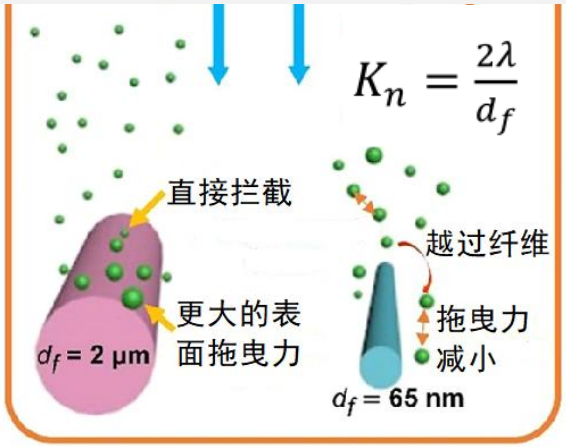
Single fiber efficiency model
（单纤维效率模型）

Flow field around a single fiber: the fiber drag force on airflow reduces as the fiber diameter decreases.（纤维周围的流场理论：纤维直径越小，对气流的曳力越小）



continue flow　slip flow　free molecular flow

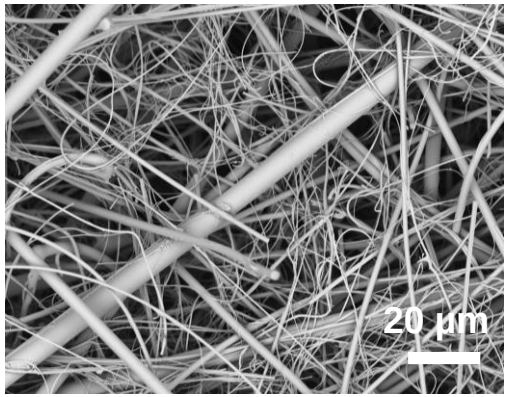
P. Li, C. Wang, Y. Zhang, F. Wei, Small ***2014****, 10, 4543.*



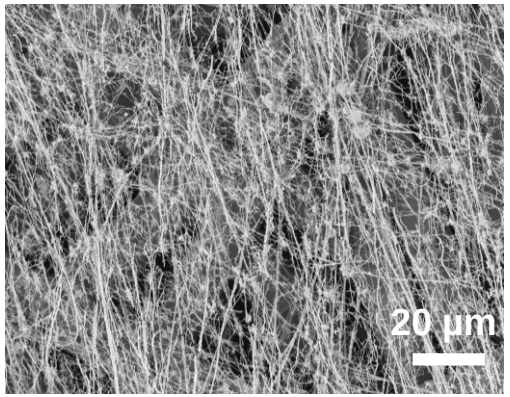
When the fiber diameter is about the mean free path of the air molecules (~66 nm), the gas velocity is non-zero at the fiber surface because “slip” occurs.（“滑移效应”使纤维对气流的曳力显著减小）

1.Challenges in the development of air filters（空气过滤面临的挑战）

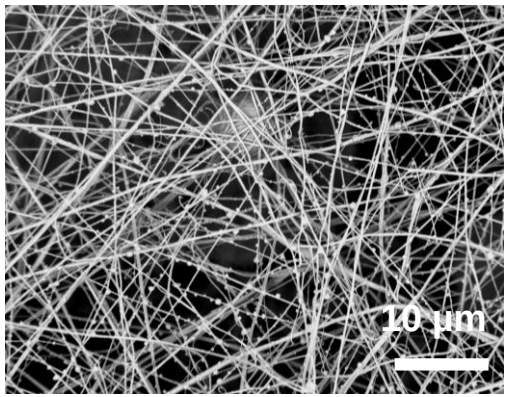
Micro/nano fibrous air filter media: Glass fiber paper, ePTFE membrane, and electrospun mat.
（微纳米纤维空气过滤材料：玻璃纤维过滤纸、ePTFE膜、静电纺丝纳米纤维膜等）



Glass fiber filter media

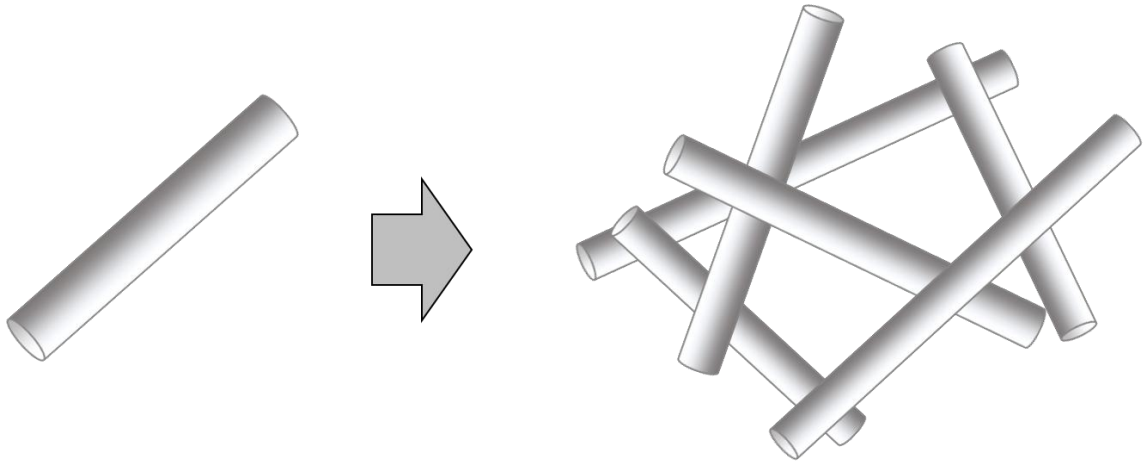


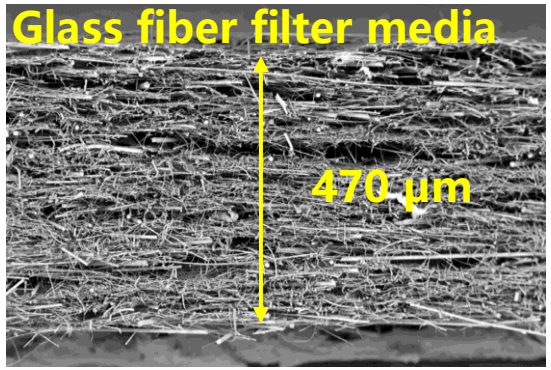
ePTFE membrane

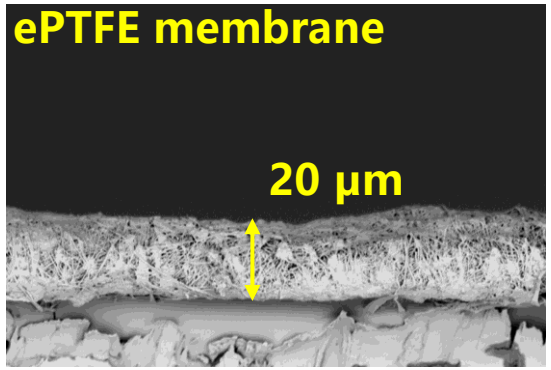


Electrospun mat

Fiber Assembly into Filter Media: fine fibers aggregate easily, forming a dense two-dimensional layered structure. This compact arrangement can limit the functionality of fine fibers.（单纤维向滤材（纤维集合体）的转变：细纤维易聚集，以及二维层状结构致密，限制细纤维发挥作用。）



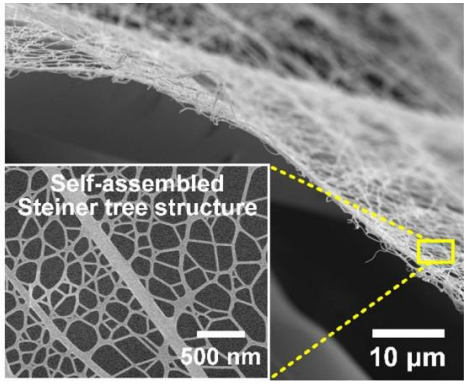




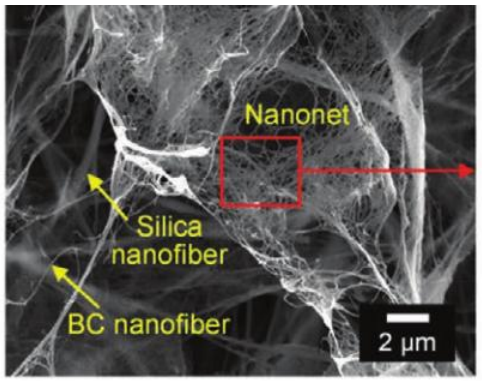
E11-class filter media

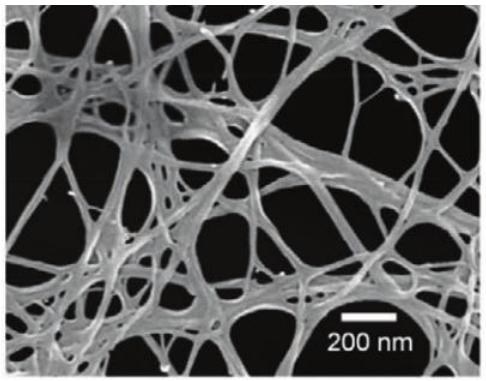
1.Challenges in the development of air filters（空气过滤面临的挑战）

Hierarchical structure design: maximizes the benefits of fine fibers, reduces resistance; Increases the porosity, and enhance dust holding capacity.（多级结构设计：能够更好的发挥细纤维的作用，降低阻力；增加孔隙率，提高容尘性能）

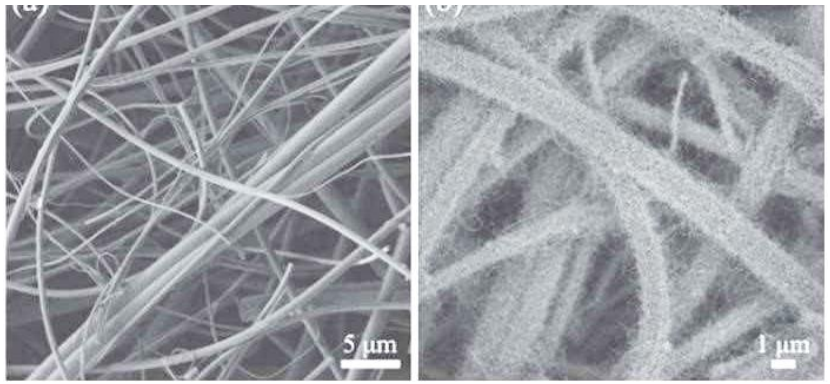


Nano-net (electrospinning)
纳米蛛网

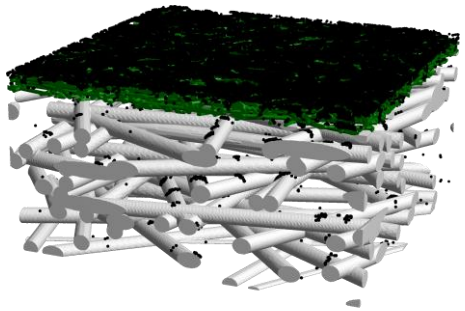




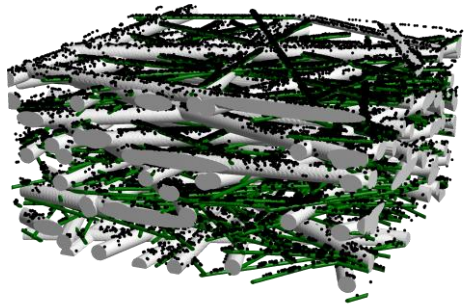
Aerogel (freeze-drying)
气凝胶



In situ forming carbon fiber
(high-temperature CVD)
原位生长的碳纤维



Surface filtration（表面过滤）



Deep filtration （深层过滤）

Existing Challenges: complex preparation processes and limited capability of fiber structure design（存在的问题：回顾现有的研究工作，大多制备工艺复杂，细纤维结构难以有效调控）

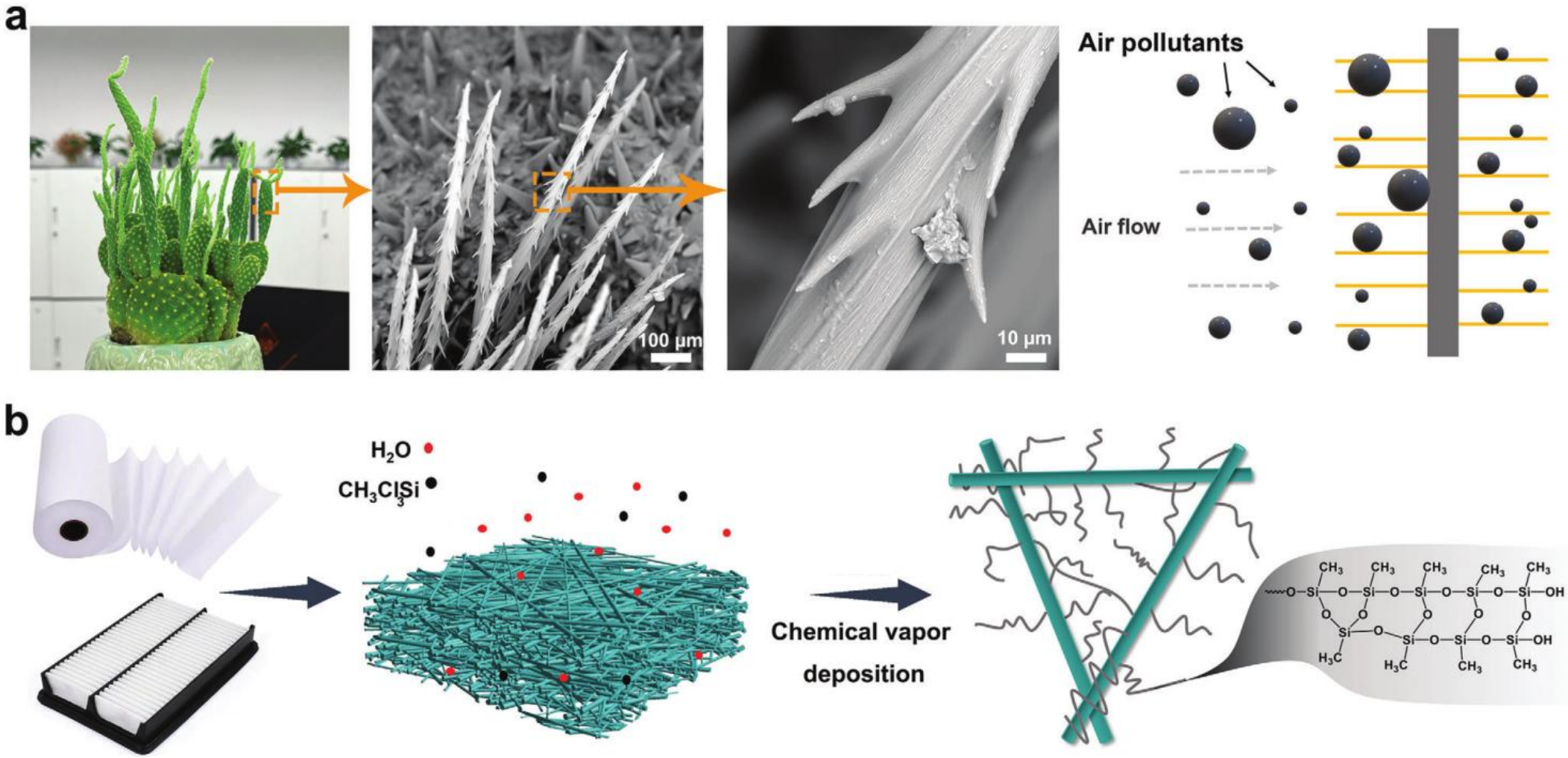
Contents

2. Bionics design of the fluffy-like air filter（绒毛状玻璃纤维滤纸的仿生构建）

Object: **To assemble nano-sized fibers into macroscopic filters.**

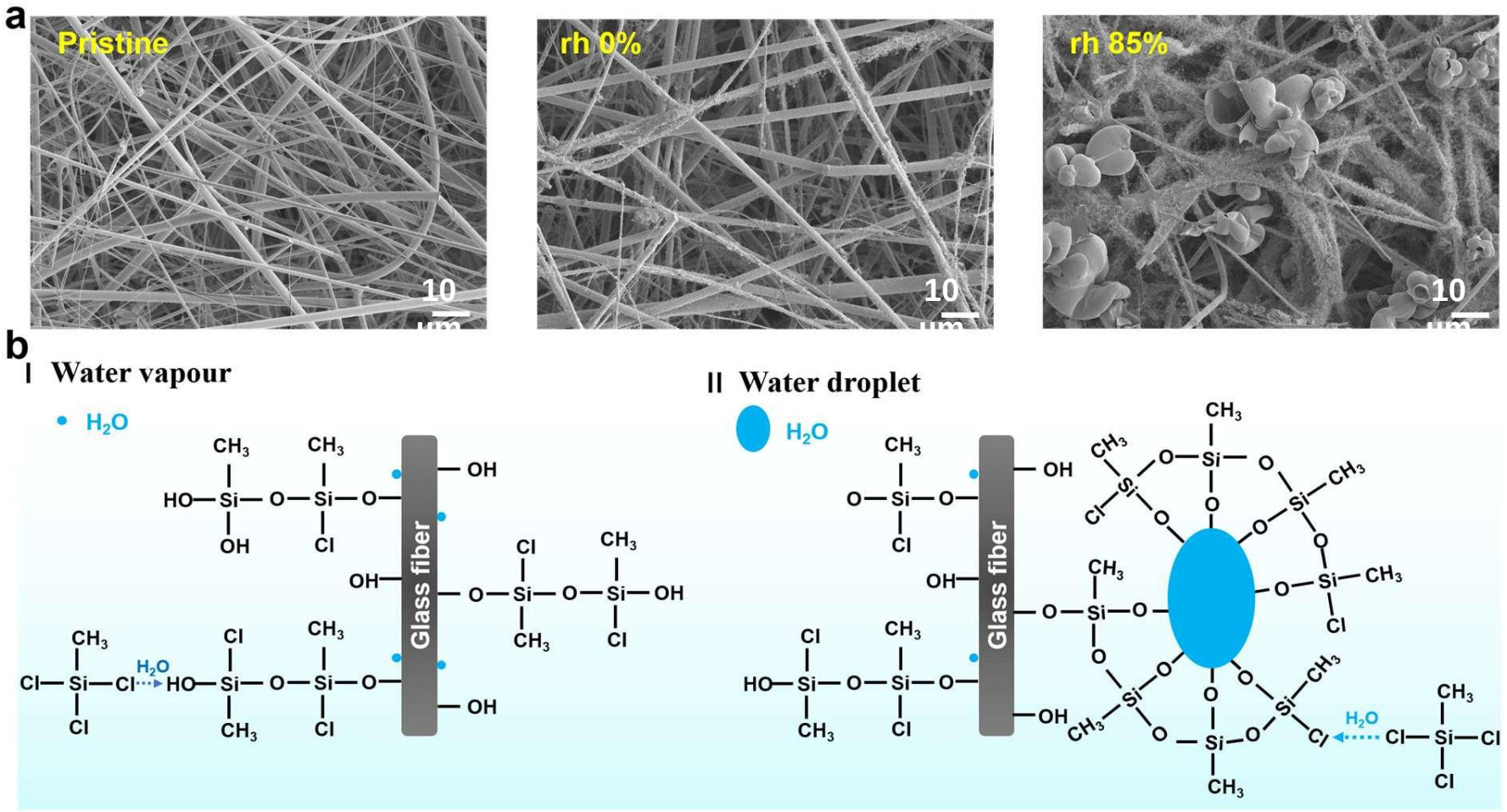
To explore the potential of the slip effect in enhancing the filter performance.

（制备三维多级结构的纳米纤维过滤材料，使其具备高均匀度、高孔隙率，从而充分发挥纳米纤维的滑移作用）



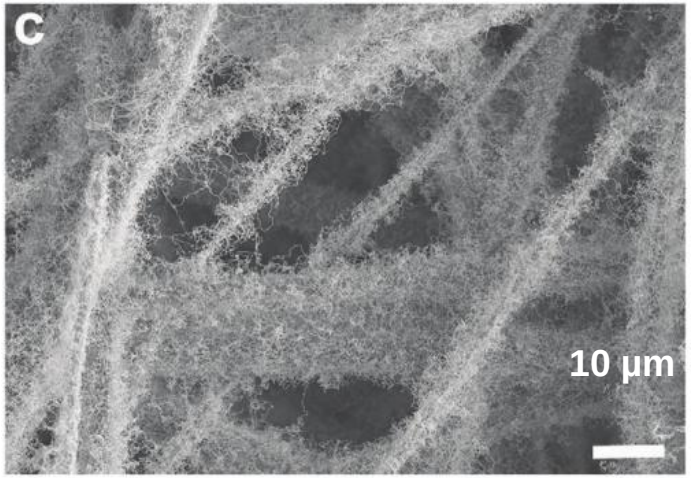
2.Bionics design of the fluffy-like air filter（绒毛状玻璃纤维滤纸的仿生构建）

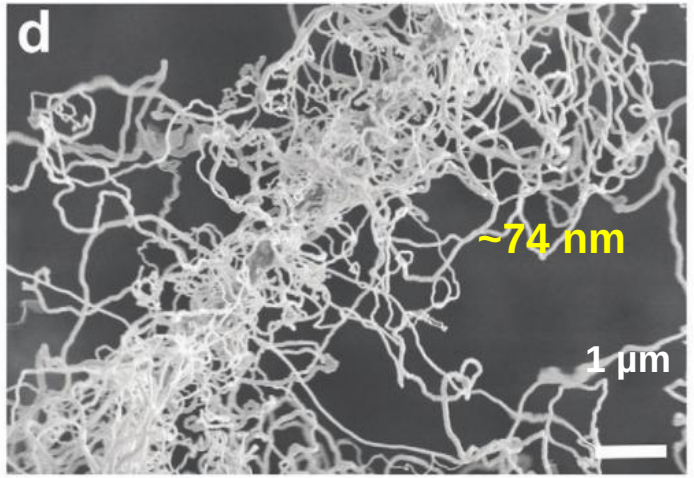
TCMS, containing hydrolyzable chlorine groups, reacts with water to form silicone nanofilaments on the surface of glass fibers under varying ambient humidity conditions.（通过控制甲基三氯硅烷（CH_3Cl_3Si）与玻璃纤维表面的羟基（-OH）反应时的湿度，优化玻璃纤维表面硅纳米丝的生长形态）

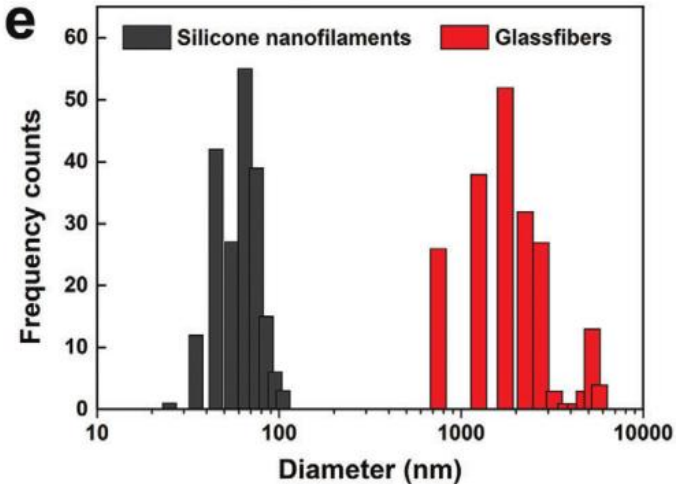


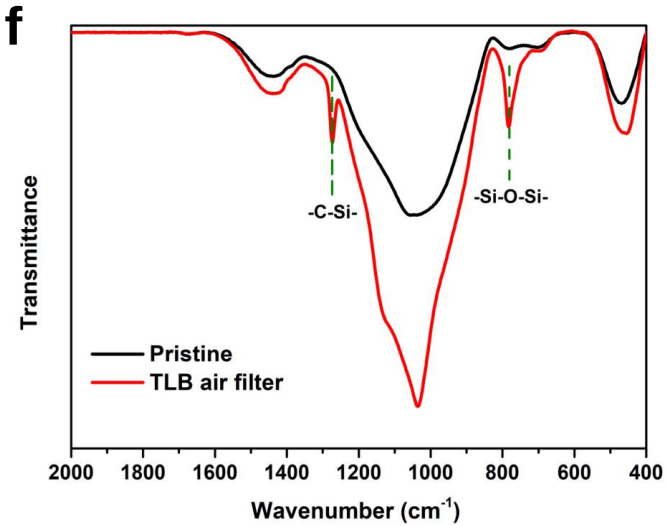
2.Bionics design of the fluffy-like air filter（绒毛状玻璃纤维滤纸的仿生构建）

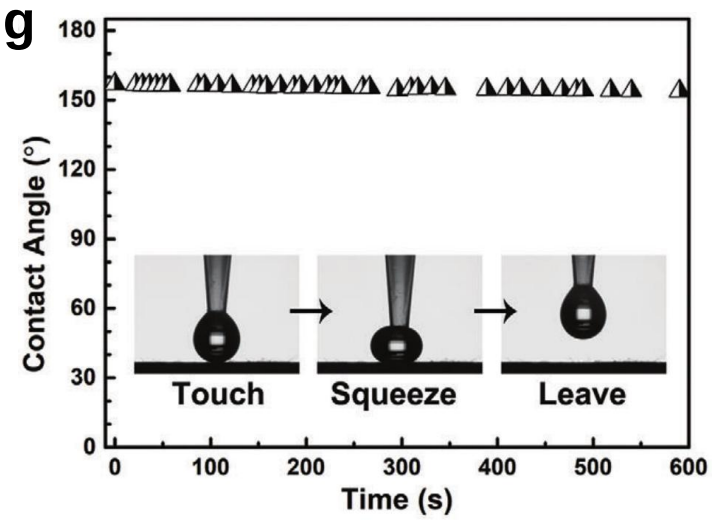
Under 50% relative humidity (RH), the 3D-templated silicone nanofilaments, with an average diameter of approximately 74 nm and a length exceeding 10 μm, are oriented perpendicular to the glass fiber.
（在50%湿度条件下反应时，玻璃纤维表面的硅纳米丝呈现三维结构形态，平均纤维直径约为74 nm，长度超过10 μm）





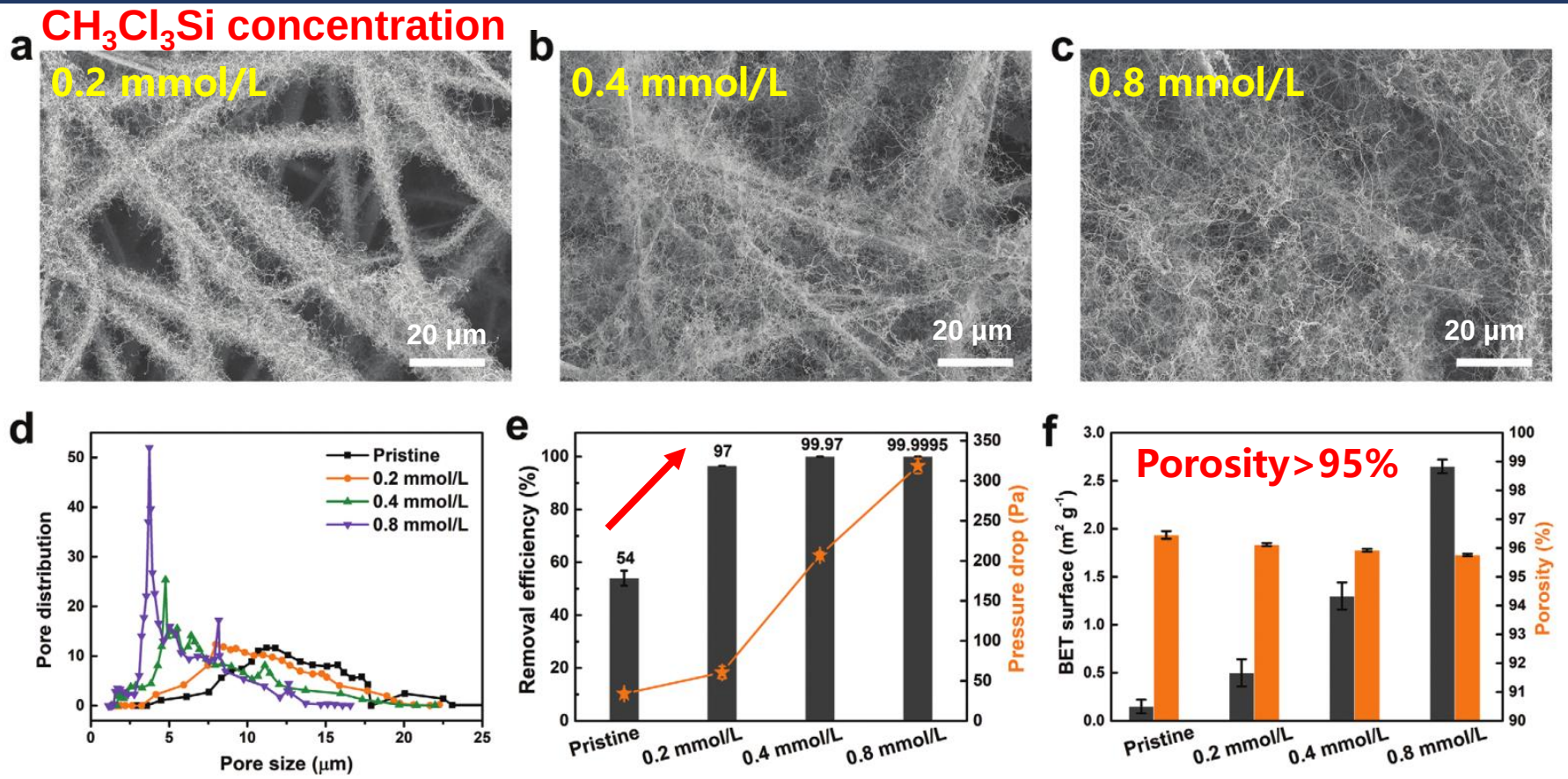






Contents

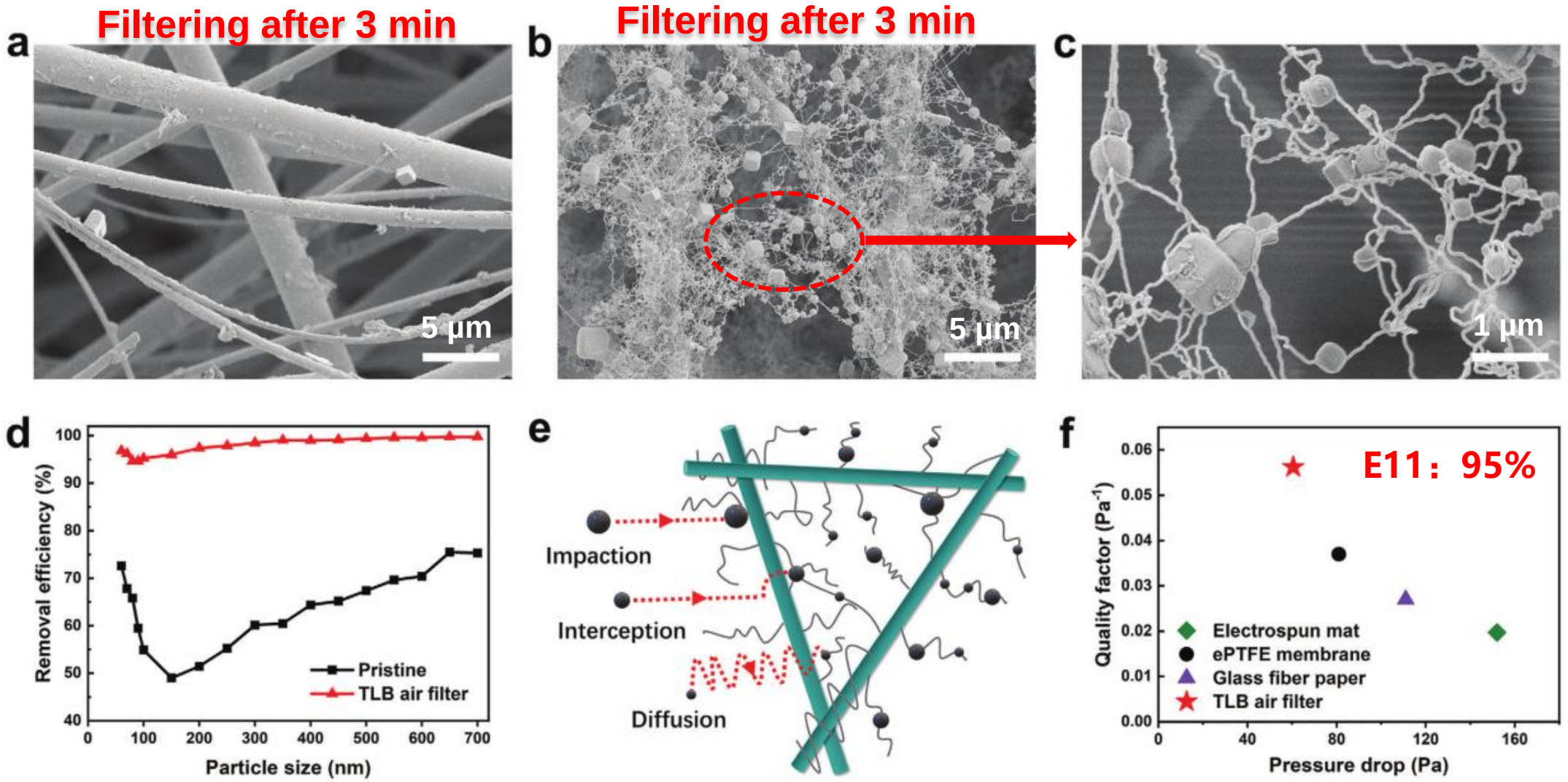
3. Tunable filtration class enabled by flexible structures（结构调控及其过滤性能）



Filter class	TLB air filters /Pa	Commercial I- Fibrway /Pa
	reduced by 45%	
E11 (≥ 95%)	61 ± 8	110 ± 7
E12 (≥ 99.5%)	114 ± 6	203 ± 8
H13 (≥ 99.95%)	207 ± 4	260 ± 7
H14 (≥ 99.995%)	252 ± 8	341 ± 9
U15 (≥ 99.9995%)	319 ± 9	402 ± 9

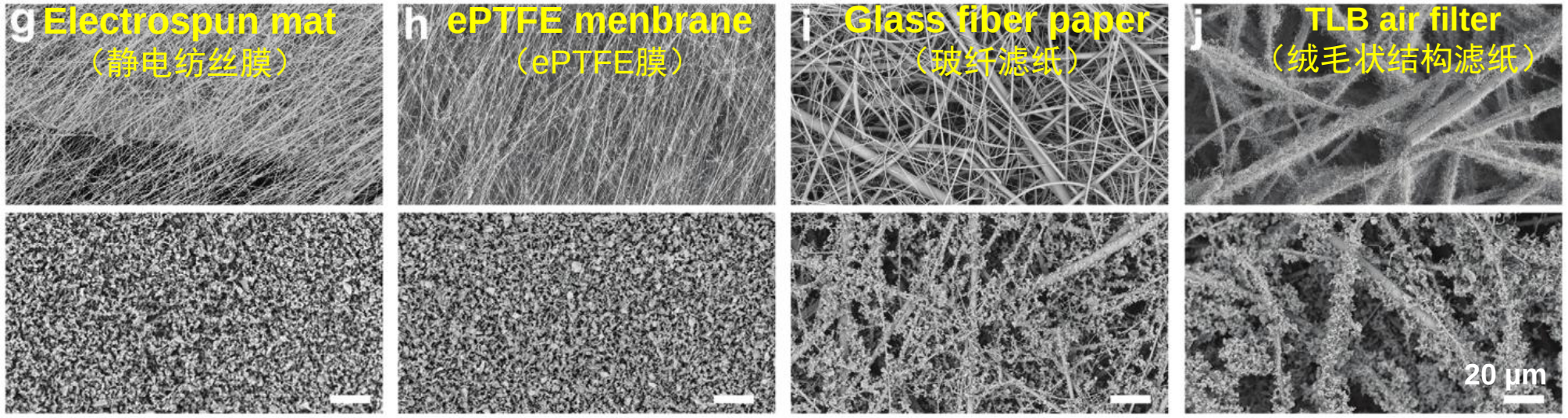
The selectable filter classes (F7 ~ U15) achieved through controlled silicone-nanofilament assembly enable TLB air filters to meet diverse requirements, with their filtration performance surpassing that of standard commercial air filters.（E11-U15级滤纸的过滤阻力均远低于商用玻纤滤纸）

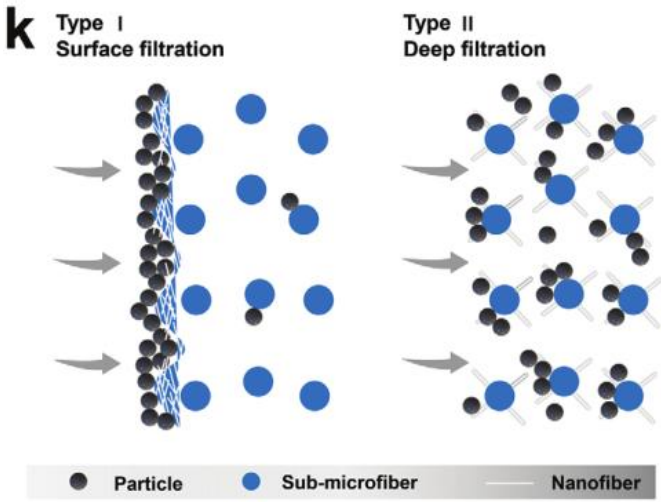
3. Tunable filtration class enabled by flexible structures（结构调控及其过滤性能）

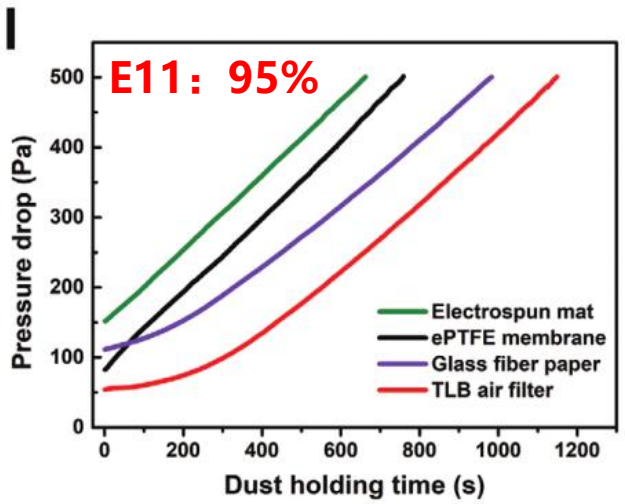


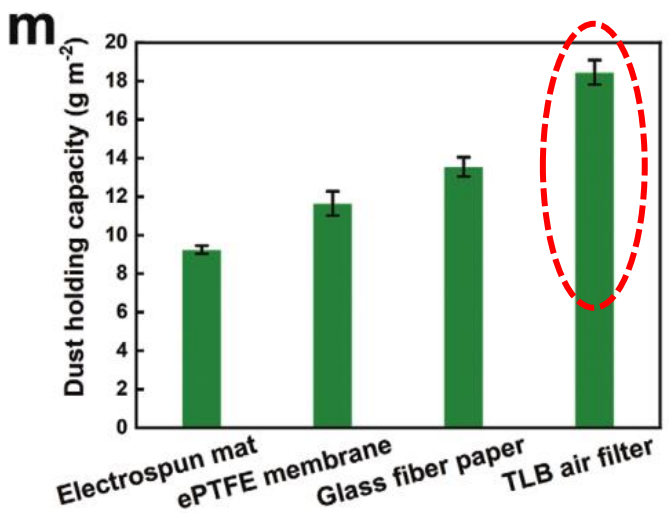
The structurally innovative design of the TLB air filters, achieved by assembling 3D hierarchical nanostructures on templated substrates, leverages the significant advantages of the nanofibers to passively capture air pollutants.（微米级玻璃纤维上生长硅纳米丝极大的提高了滤纸对颗粒的捕获能力，使其过滤效率提高）

3. Tunable filtration class enabled by flexible structures（结构调控及其过滤性能）









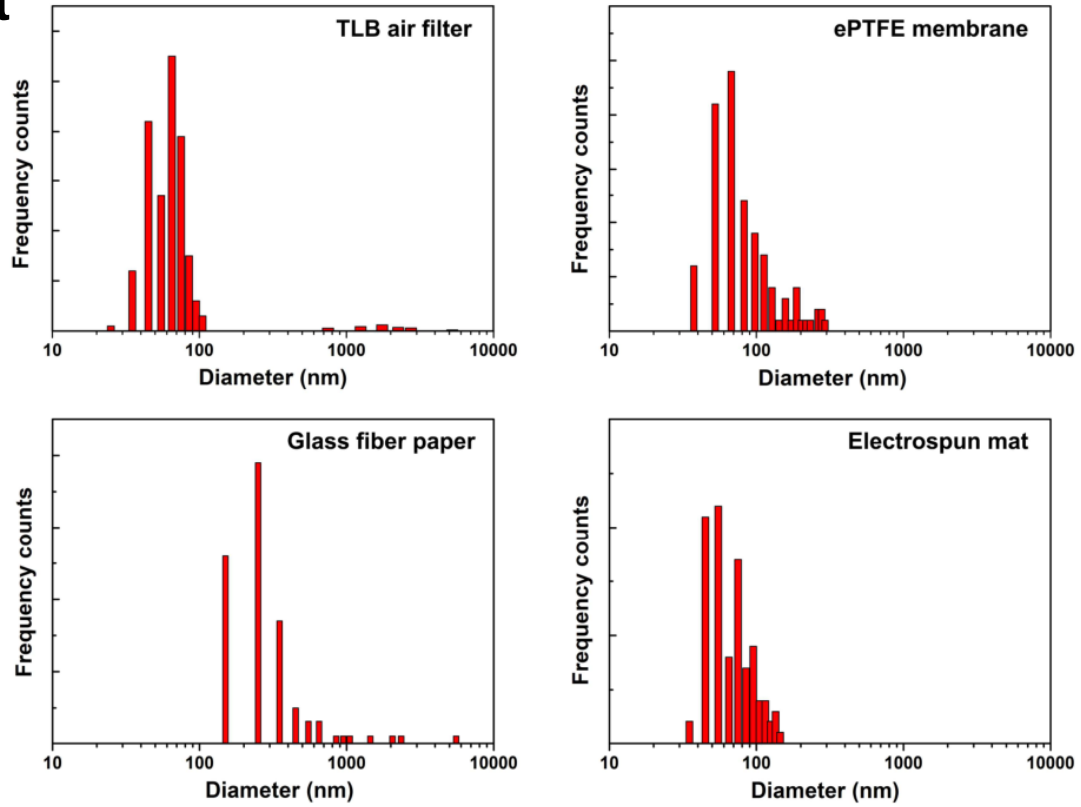
Their dust holding capacity (18.5 g/m^2) surpasses that of commodity air filters, including electrospun mat (9.2 g/m^2), ePTFE membrane (11.7 g/m^2), glass fiber paper (13.6 g/m^2).（E11级绒毛状结构滤纸容尘量为18.5 g/m^2，高于静电纺丝膜（9.2 g/m^2）、ePTFE膜（11.7 g/m^2）和玻纤滤纸（13.6 g/m^2），具备更长的使用寿命）

Contents

4. 3D filter geometry and flow field analysis (模型构建及流场分析)

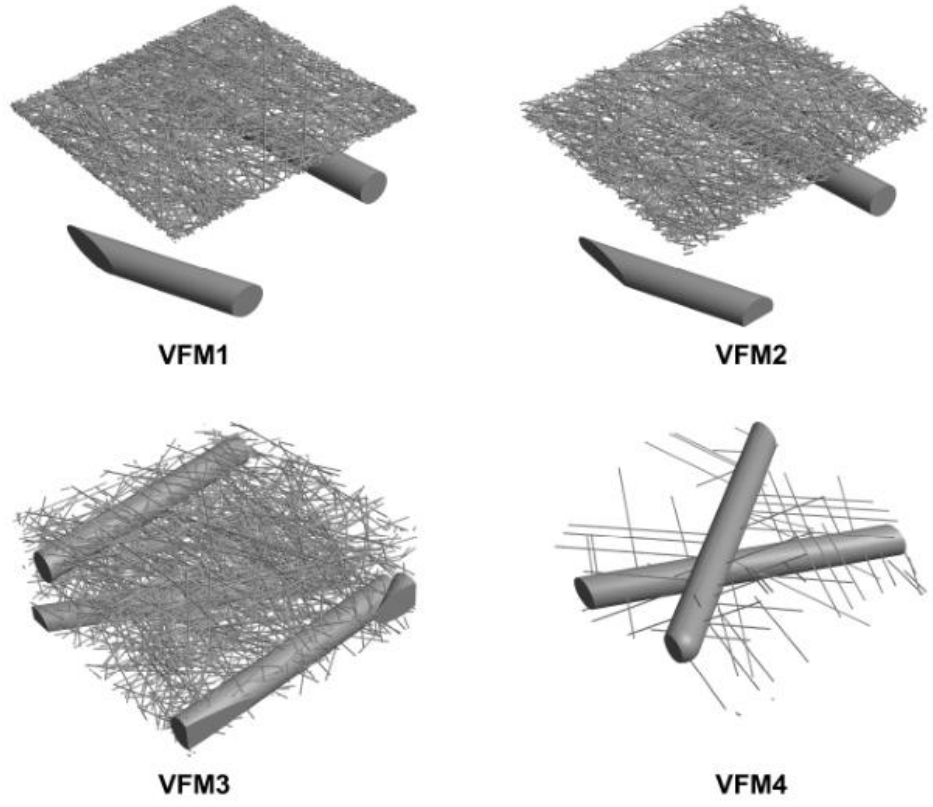
Four types of virtual filter media (VFMs), with structural features similar to those of the considered filters, were constructed using the PaperGeo and GrainGeo modules of the voxel-based numerical simulator GeoDict.（利用GeoDict构建静电纺丝膜、ePTFE膜、玻璃纤维纸、绒毛状玻璃纤维纸的等效模型）

a



The fiber diameter distribution of TLB air filter, ePTFE membrane, glass fiber paper, and electrospun mat.
（绒毛状玻璃纤维纸、 ePTFE膜、玻璃纤维纸、静电纺丝膜的纤维直径分布）

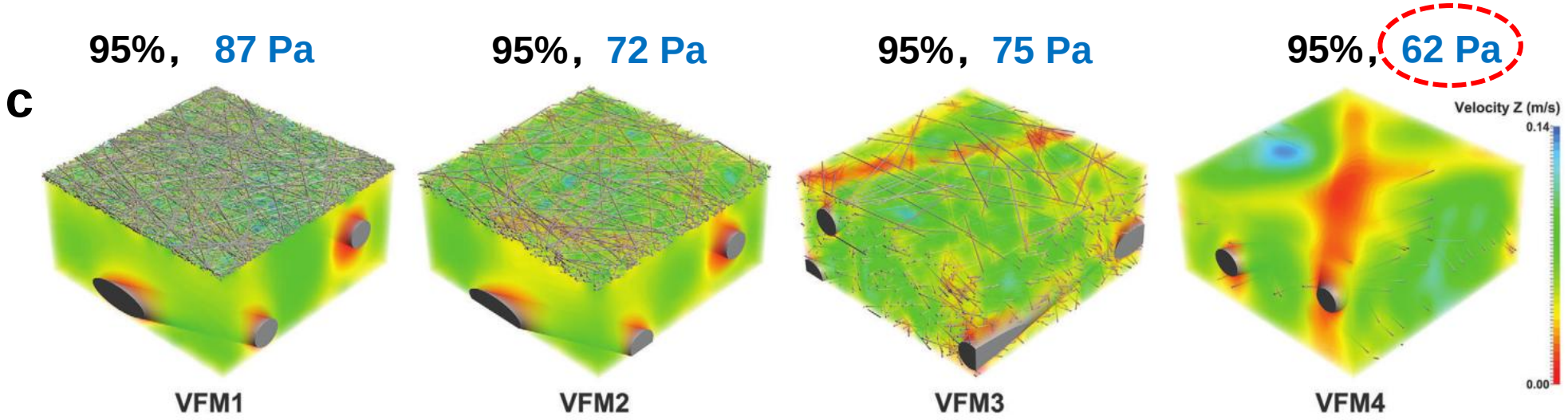
b

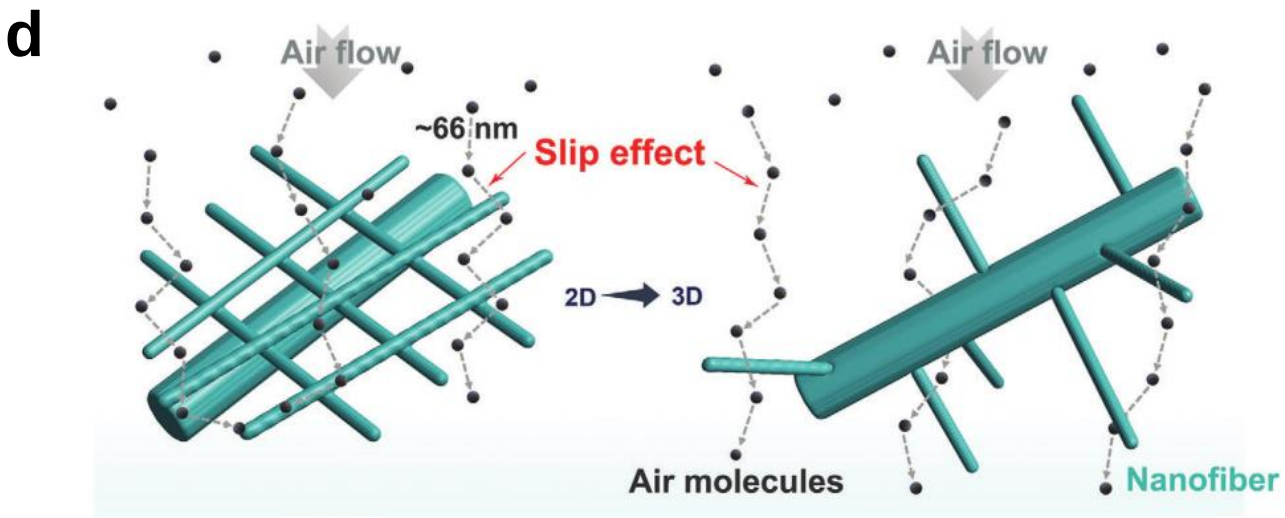


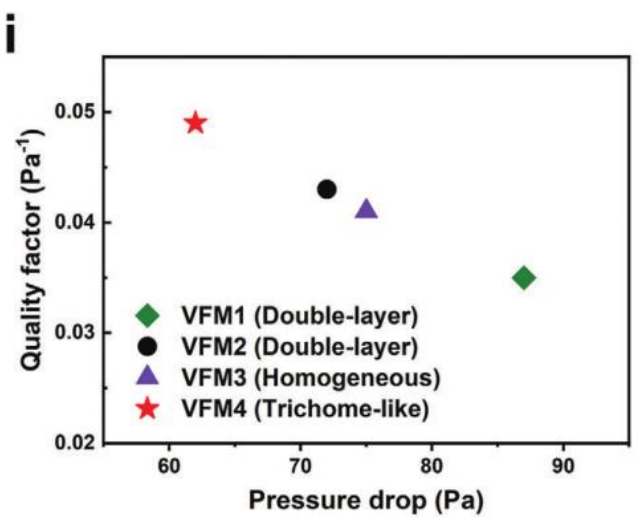
Four types of virtual models
（利用GeoDict构建的四种等效模型）

4. 3D filter geometry and flow field analysis (模型构建及流场分析)

The 3D hierarchical nanostructures on templated substrates offer a significant advantage by maximizing the slip effect's utilization, effectively overcoming the efficiency-resistance tradeoff in air filter systems.（模拟的流场分布表明：纳米纤维多级结构可以最大程度的发挥纳米纤维表面的滑流效应，克服效率和阻力之间的矛盾）



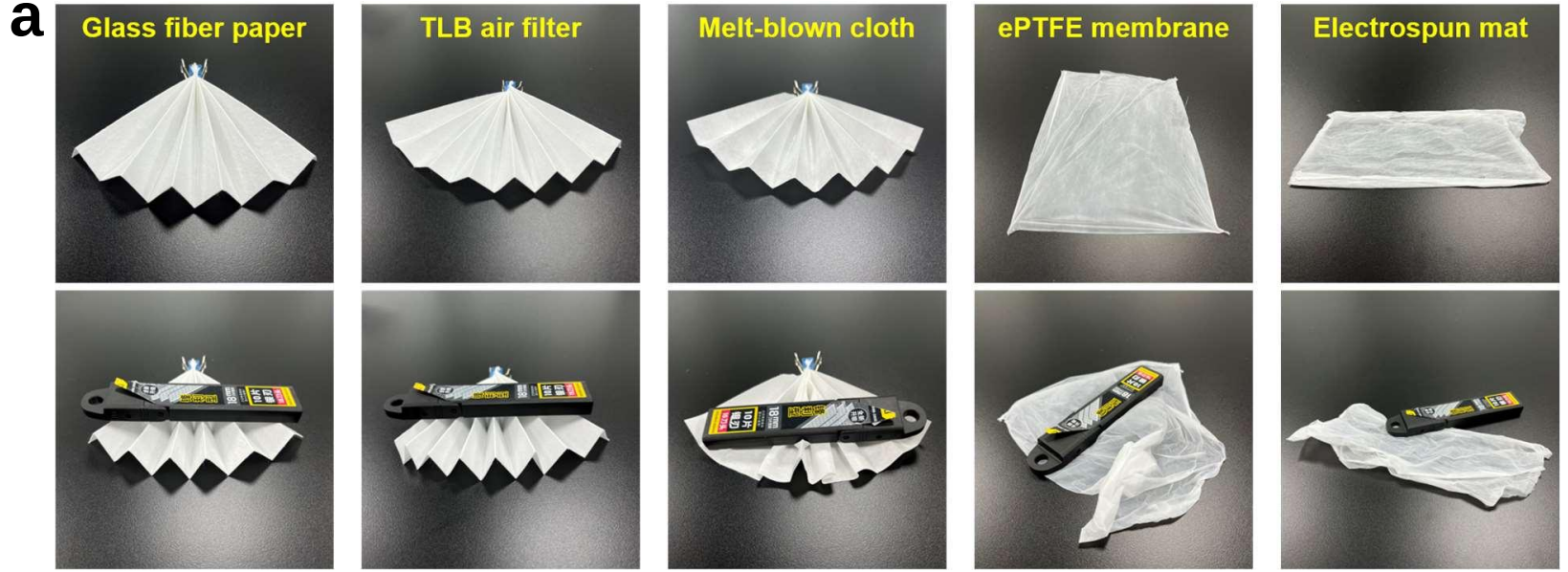




Contents

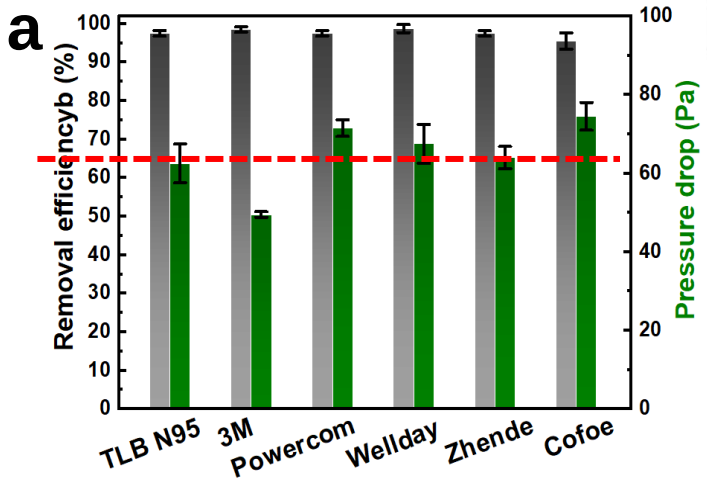
5. Performance evaluation and applications（性能评价及应用）

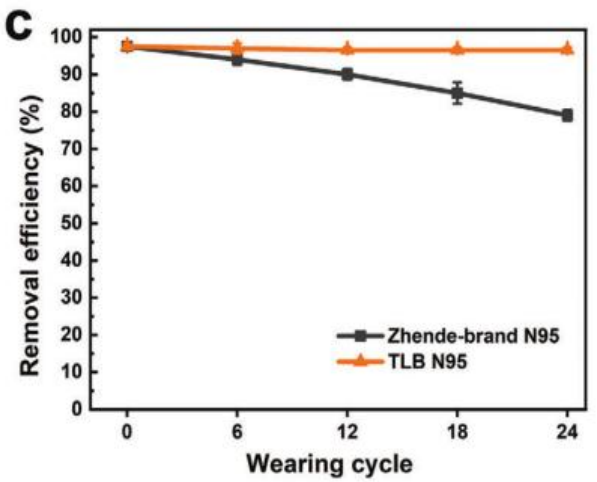
Their integral filtration performance surpasses nearly all types of air filter media, including electrospun mats, ePTFE membranes, glass fiber paper, and melt-blown non-woven.（其整体过滤性能（如过滤效率、阻力、机械强度和容尘量）超过静电纺丝膜、ePTFE膜、玻璃纤维纸和熔喷布）



5. Performance evaluation and applications（性能评价及应用）

Resistance
（阻力）





TLB N95's removal efficiency and respiratory resistance were comparable to those of commercial N95 respirators, exhibiting a stable removal efficiency after a 24-cycle wearable mask test.（与商用的N95口罩阻力相当，但具备更好的过滤稳定性，提供持续稳定的防护效果）

Contents

6. Conclusion and future perspectives（结论及展望）

- TLB air filters with 3D-templated silicone nanofilaments (average diameter of ≈ 74 nm) were developed using a simple and scalable in situ CVD method.

（基于简单的原位 CVD 方法开发具有三维结构硅纳米丝（平均直径为 ≈ 74 nm）的绒毛状玻纤滤纸，可以使用一步法直接转化制备商业过滤介质和过滤器）

- Theoretical modeling and experimental results demonstrated that the structurally innovative design of the TLB air filters, achieved by assembling 3D hierarchical nanostructures on templated substrates, leverages the slip effect to passively capture air pollutants, overcoming the tradeoff between pressure drop and filtration efficiency.

（理论建模和实验结果表明，通过在玻纤滤纸上组装 3D 多级纳米纤维结构的创新设计发挥了纳米纤维表面产生滑移效应的显着优势，极大地克服了压降和过滤效率之间的矛盾）

- The selectable filter class of TLB air filters (up to U15, ≈99.9995%) meets the needs of various applications. Their overall filtration performance—encompassing removal efficiency, pressure drop, stability, and dust holding capacity (DHC)—surpasses that of widely used commercial air filter media, including electrospun mats, ePTFE membranes, glass fiber paper, and melt-blown non-woven.

（可调控的过滤等级（高达U15，≈99.9995%）满足各种应用的需求，其整体过滤性能（如过滤效率、阻力、稳定性和 容尘量）超过了广泛使用的商用空气过滤介质，包括静电纺丝膜、ePTFE 膜、玻璃纤维纸和熔喷布）

谢　谢！

华南理工大学
South China University of Technology

过滤分离材料研制概况

依托平台

先进纸基材料技术国防科技工业创新中心（国家级-2023）

先进纸基材料关键核心技术集成攻关大平台（部级-2022）

造纸与污染控制国家工程研究中心（国家级-1996）

制浆造纸工程国家重点实验室（国家级-1989）

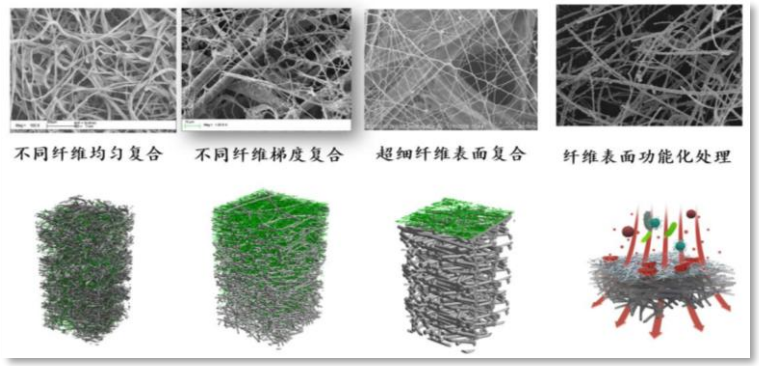
广州市黄埔区华工纸基材料创新研究院

广州市黄埔区中新知识城，规划面积**33000**m^2

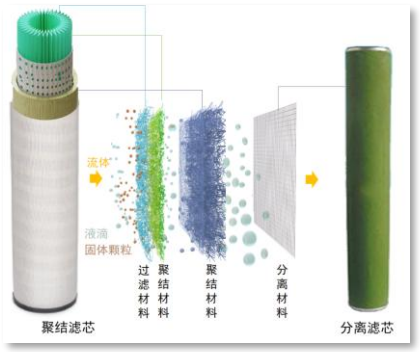
场地集中：办公、科研、工程验证实验场地统筹布局

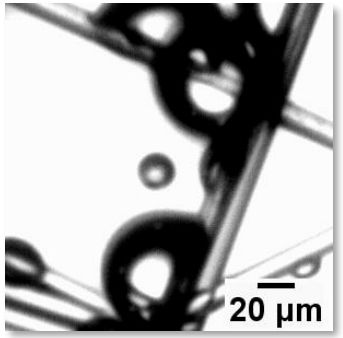
主要研究方向

空气过滤

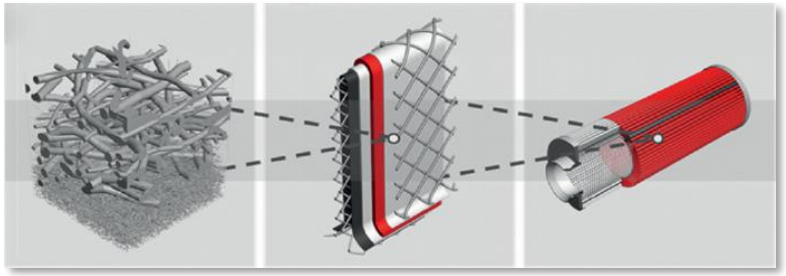


聚结分离

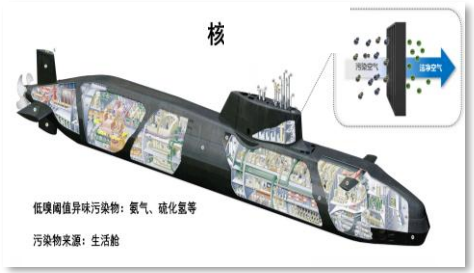


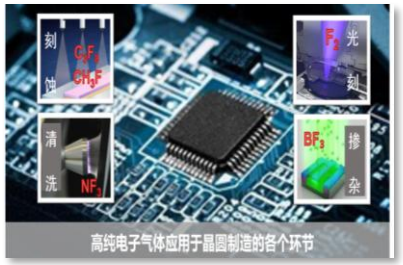


液体过滤

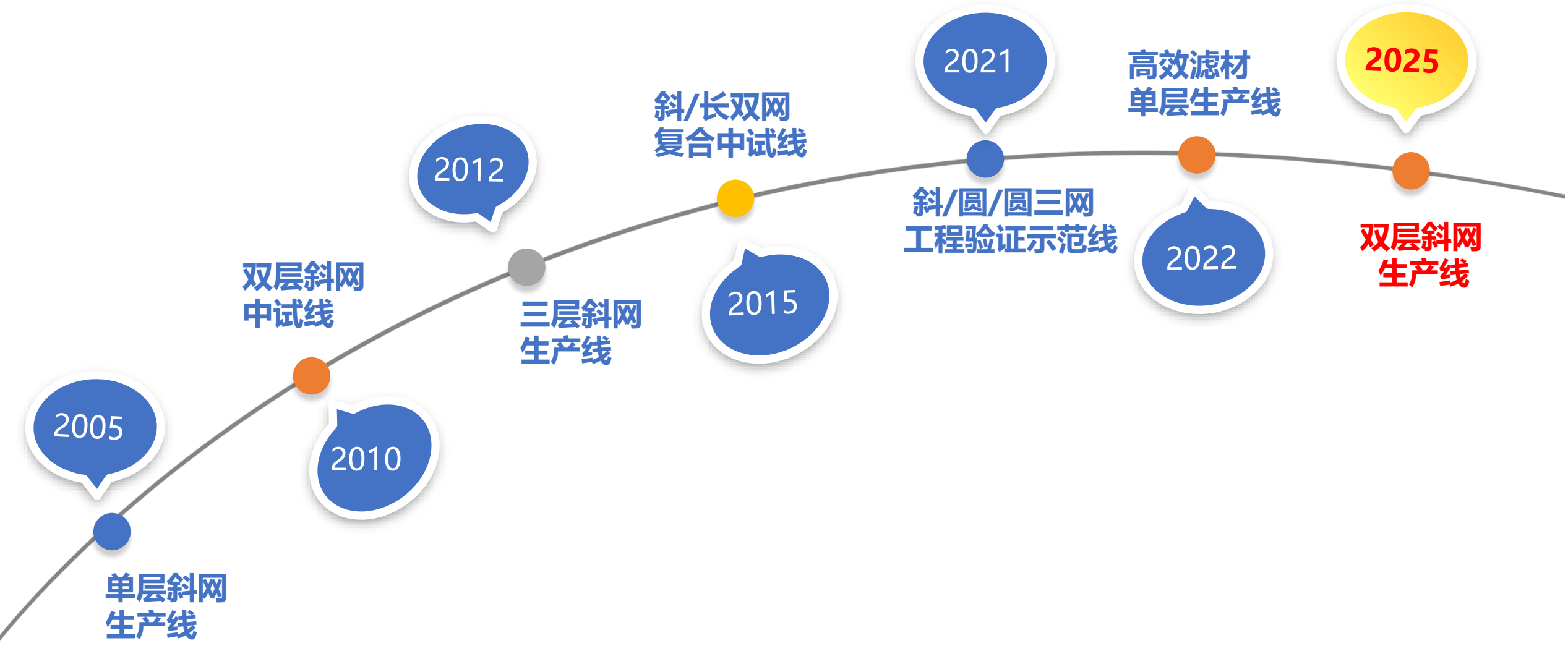


吸附分离





科研成果转化


2005
单层斜网
生产线
2010
双层斜网
中试线
2012
三层斜网
生产线
2015
斜/长双网
复合中试线
2021
斜/圆/圆三网
工程验证示范线
2022
高效滤材
单层生产线
2025
双层斜网
生产线

科研成果转化

主流车企OEM应用

中国重汽 SINOTRUK

中国陕汽

潍柴动力 WEICHAI POWER

SANY

北汽集团 BAIC Group

玉柴集团 YUCHAI GROUP

NISSAN

Ford

GEELY

HAVAL SUV领导者

BYD

长安汽车

SAIC 上汽集团 SAIC MOTOR

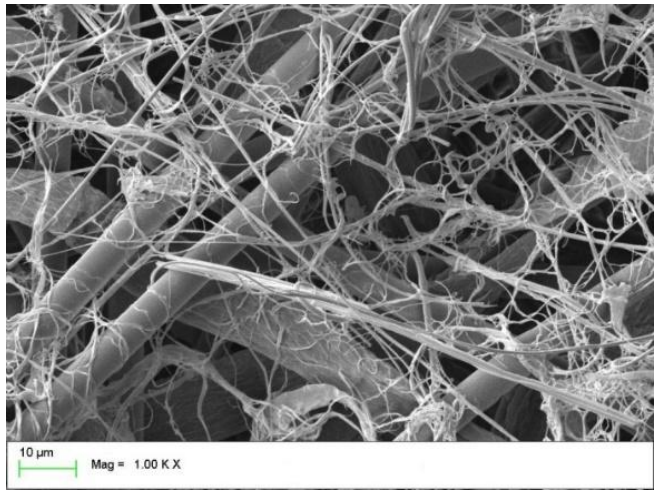
广汽传祺

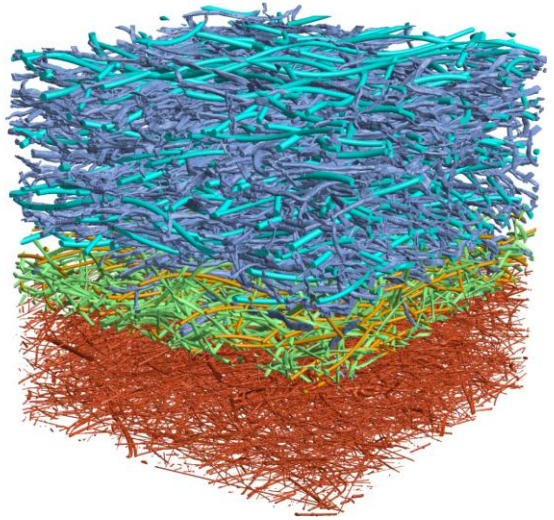
神龙汽车

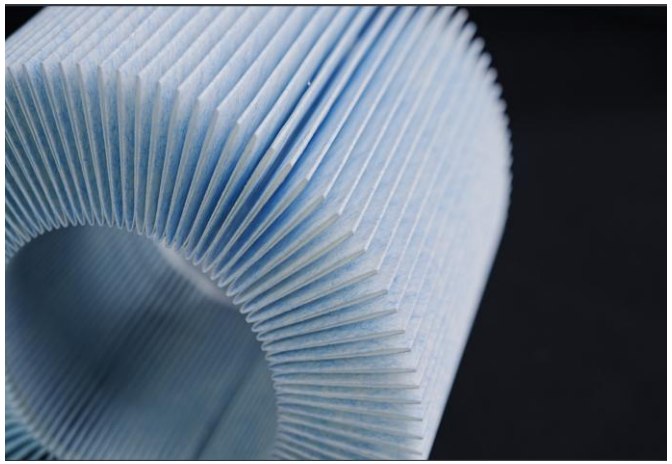
奇瑞汽车 CHERY AUTOMOBILE

主要科研条件

- **纤维**尺度研究平台
- **滤材**尺度研究平台
- **滤芯**尺度研究平台







“原始性创新、工程化验证、应用技术”完整的科学技术链条

主要科研条件

TOPAS AFC-131
过滤材料反吹性能实验台

PALAS MFP3000
单张滤料过滤性能测试台

TSI 8130A
高效空气滤材过滤性能试验台

TOPAS MBP116
超高效空气滤材过滤性能试验台

GMN FWSETB-900-10
在线燃油水分离效率试验台

GMN MPTB-600-30
液体过滤多次通过试验台

TOPAS PAF112
舱室气体吸附试验台

PALAS DFP3000
压缩空气过滤器及滤材过滤测试台

为推动中国过滤分离行业技术进步而努力！