微流体科创

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微流体科创加密文档

机动车排放 PM2.5 的惯性冲击收集器

项目概述

近几年空气中的可吸入颗粒物污染显著，其影响不仅使得空气能见度降低，更重要的是严重影响了居民的身体健康。专家称，大气污染是呼吸系统疾病发病的重要原因。例如北京十年来肺癌增加了 60%，这是非常惊人的数字，空气污染是一个非常重要的原因。据介绍，专家曾做过研究，PM2.5 每立方米增加 10 个微克，呼吸系统疾病住院率可以增加到 3.1%。要是灰霾从 25 个微克增加到 200 微克，日均病死率可增加到 11%。灰霾不仅对呼吸系统有影响，而且对心血管、脑血管、神经系统都有影响。在大气污染的现状面前，个人生活方式的改变“杯水车薪”，原因在于大气污染跟整个外环境、内环境息息相关，比非典可怕得多。非典可以考虑隔离，或采取各种办法,但是大气污染、室内污染是任何人跑不掉的。所以治理 PM2.5 不仅是个商机，更是对改进公共健康的巨大贡献。

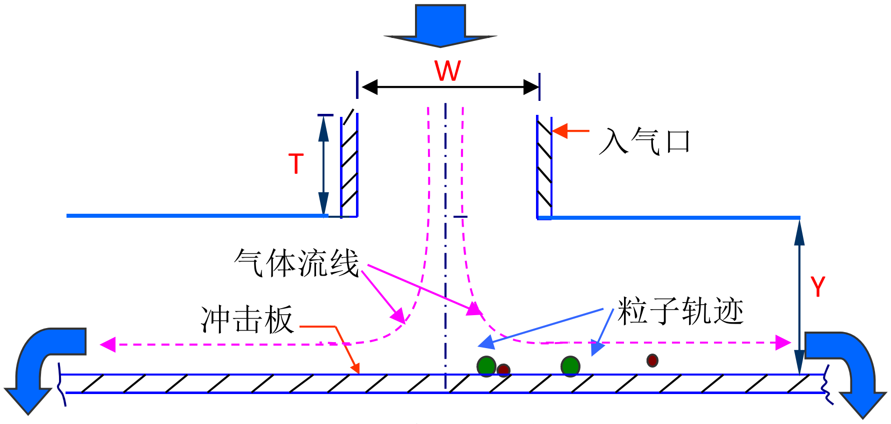

图1：惯性冲击原理图

机动车排放是 PM2.5 的一个重要来源，例如北京市环保局采用的机动车排放对 PM2.5 的贡献率是 23%，假如直接在第一时间就防止这部分 PM2.5 排入大气，对治理 PM2.5 的意义是不言而喻的。微流体科创计划商业化用于在线实时过滤收集机动车排放的 PM2.5 的惯性冲击收集器，彻底防止机动车排放的 PM2.5 进入大气。惯性冲击通过粒子的惯性将粒子和携带粒子的气体进行分离并进而将其收集。如图 1 所示，当携带粒子的气流突然改变流动方向时，由于惯性，粒子将继续沿着原来方向运动，这样粒子就和携带它的气流分开来了。

PM2.5 是指大气中小于 2.5 微米的粒子，要把机动车排放中这么小的粒子过滤下来，采用传统的滤纸滤网方法的话，过滤孔径将会要求达到亚微米或纳米大小，从而阻塞排放，而且滤纸滤网收集的粒子会积累在其表面，即使可以用来过滤，其使用寿命也会很短。而微流体科创的惯性冲击收集器将克服以上缺点，使防止机动车排放的 PM2.5 进入大气成为可能。如图 2 所示，和传统过滤相比，惯性冲击收集 PM2.5 具有以下优点，

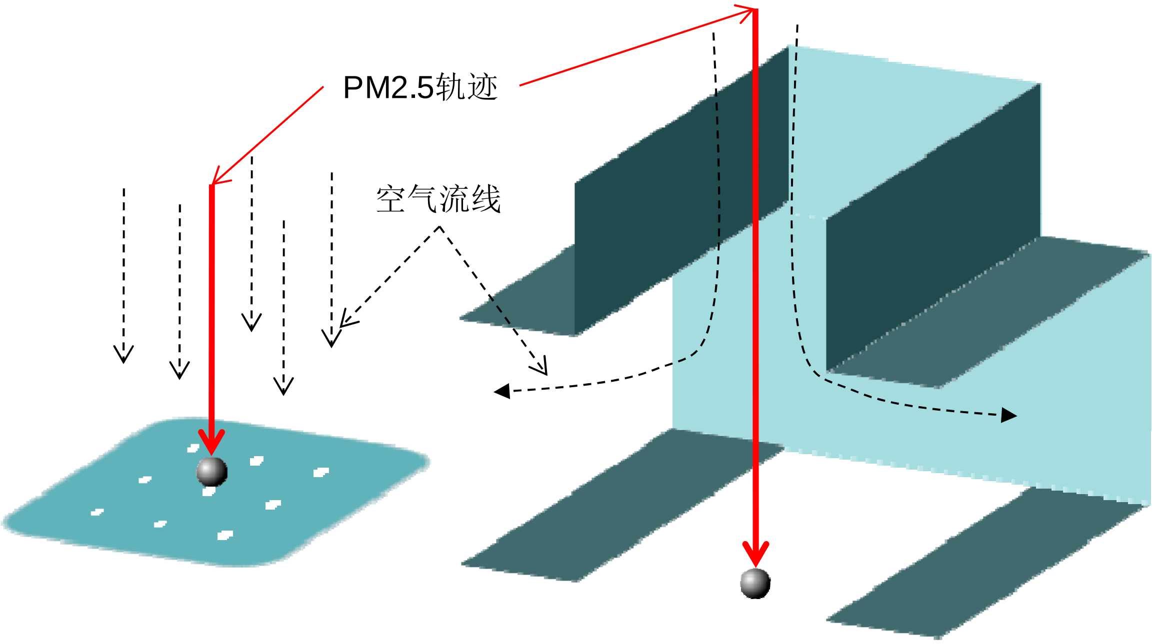

图2：传统滤纸过滤PM2.5（左）和惯性冲击收集PM2.5（右）的比较。

1. 惯性冲击收集器的通气管道尺寸要比滤纸滤网要求的尺寸大 1000 倍左右，根据流体力学理论，对应的流动阻力就会小 1 亿倍左右，不会影响机动车的尾气排放；
2. PM2.5 将会和排气分离而被收集在专门的收集器里，不会因为粒子的累积而阻塞尾气排放；
3. 惯性冲击收集器将由半导体工艺材料生产，耐高温腐蚀等，可在机动车尾气中长期工作，而且可以大规模廉价生产。

商业化策略

微流体科创的机动车排放 PM2.5 惯性冲击收集器如图 3 示，将包括两个主要部件，一个是永久性的置入尾气排放通道的惯性冲击器，另一个是可置换的 PM2.5 收集袋。冲击

器把尾气中的 PM2.5 分离并排入收集袋中，收集袋中装满粒子后，需要换装新收集袋。我们将通过和汽车制造商的合作来加快我们的市场进入和占有率，也将寻求政府的政策支持来推广产品的应用。我们最初将锁定两个收入来源：1）做汽车制造商的原始设备制造商；2）直接销售机动车排放 PM2.5 的收集器及其耗件。这些都是可并行实现的，我们打算保持我们灵活的商业模式以应对客户需求和市场条件。我们已经在学术和工业领域与一些潜在的客户和战略合作伙伴建立了联系，并合作申请政府支持和引导测试我们的产品。

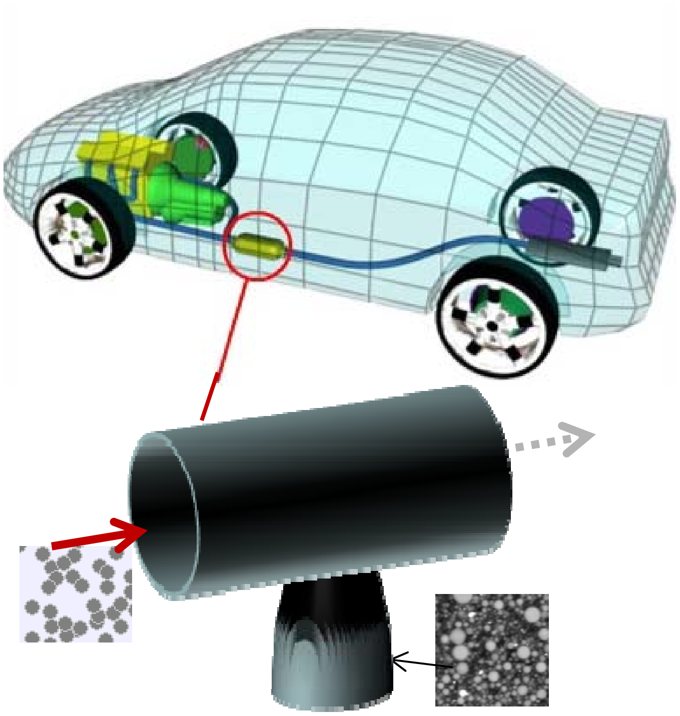

图3：PM2.5惯性冲击收集器将包括一个永久的通尾气的惯性冲击器和一个可置换的PM2.5收集袋。

1. 汽车制造商的原始设备制造商——我们将作为 PM2.5 惯性冲击收集器技术开发公司向汽车材制造商销售 PM2.5 收集配件，通过这些汽车制造业的渠道伙伴将 PM2.5 收集器集成到车上。这种策略的优点是能够采用很少的资本快速利用现有的销售渠道。缺点是，我们将在我们的价值链中匀一定比例的利润给我们的渠道合作伙伴。当来自我们的 PM2.5 收集技术的重要的附加值与这些渠道合作伙伴融合，汽车生产商将有足够动力将我们的产品集成到他们的产品上。

当我们的初始试点示范和商业模式被成功证实，该模式将是一个非常有吸引力的以高资本效率快速增进市场渗透的选择。

2. 机动车排放 PM2.5 收集器——我们将成为 PM2.5 收集器制造商，拥有核心技术与销售队伍，通过销售代表直接将产品销售给终端用户。半导体芯片的制造，PM2.5 收集器的组装和包装仍将采用外包形式。详细的产品设计和开发工作由我们自己规划、采购和施工总承包(EPC)。我们将负责产品开发、销售、客户关系、合同以及网络接口管理。

这条路线使得我们能控制项目的执行，收集客户对我们的产品的直接反馈信息，同时避免了在创业阶段产品组装所需的项目融资的提高。这让我们的资金要求适度，并使我们未来能灵活地过渡到其他商业模式。缺点是我们自己团队的销售能力和项目的有效实施将成为市场渗透的瓶颈。我们将无法利用现有的销售渠道而需要建立我们自己的销售队伍和项目执行团队。然而我们相信，在前 5 年的项目初始阶段，产品开发人员每年低于 30 人时，我们这个模式可以取得成功地运营并实现强劲增长。

投资机会和退出策略

微流体科创(www.MicrofluidicFoundry.com)由 CEO 易明强博士和 CTO 孟晓凡博士于 2011 年在美国加州创建，主要研究开发微/纳米技术、微流体、微机电系统技术和其应用产品，有超过 40 年的业界经验。微流体科创计划建立一个能完成生产半导体芯片关键工艺的自有设施。这些关键工艺不需要非常昂贵的半导体设备但却非常依赖于加工经验。对尤为需要依赖昂贵设备加工工艺的标准半导体,我们将采用外包形式。这种策略会带给我们以最小的资本投资获得可靠的芯片生产线。

拥有很好的获得政府的资金资助的机会，相对于我们的市场规模和预计销售，我们只需低资本投入，微流体科创是一个非常有吸引力的种子投资机会。我们已经与几个品牌风险资本投资公司进行了交流，正在寻求“最适合”的增值投资者。

微流体科创正在以兑换券或股权的形式寻求 20 万美元的种子资金，用于我们第一年的活动。我们计划最起码 4 至 5 年后被收购或首次公开上市 (IPO) 。

技术详述

在惯性冲击收集器中，PM2.5 的运动轨迹和携带它的尾气流线分离开来，从而实现 PM2.5 收入收集袋而净化后的尾气才能排入大气，背后的理论基础如下。

机动车尾气 PM2.5 的惯性撞击收集器内设一如图 1 所示 T 形管，扁形喷嘴入口，入口宽度 w 远小于其长度 L，从而可以忽略一个维度方向的速度，将流体的流动简化为二维流动。尾气流动遵循斯托克斯方程和连续性方程，在采用特征长度 W，特征速度 U（入口平均速度），和特征压力 $\frac{\rho_f \nu U}{W}$（ρ_f 是尾气密度，ν是尾气粘度）无量纲化的形式是，

$$\begin{aligned}\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}&=\mathrm{Re}\frac{\partial p}{\partial x}\\ \frac{\partial^2 \mathrm{v}}{\partial x^2}+\frac{\partial^2 \mathrm{v}}{\partial y^2}&=\mathrm{Re}\frac{\partial p}{\partial y}\\ \frac{\partial u}{\partial x}+\frac{\partial \mathrm{v}}{\partial y}&=0\end{aligned} \qquad (1)$$

在方程 1 中，u 是尾气 x 方向的速度分量，v 是尾气 y 方向的速度分量，p 是压力场。而 Re 是雷诺数，$\mathrm{Re}=\frac{\mathrm{UW}}{\nu}$，衡量流场中惯性力对粘性力的比例。

PM2.5 粒子的运动则由牛顿第二定律确定，在采用特征长度 W，特征速度 U，特征时间 $\frac{\mathrm{W}}{\mathrm{U}}$ 无量纲化的形式是，

$$\begin{aligned}\frac{Stk}{2}\frac{d^2x}{dt^2}&=\mathrm{u}-\frac{dx}{dt}\\ \frac{Stk}{2}\frac{d^2y}{dt^2}&=\mathrm{v}-\frac{dy}{dt}\end{aligned} \qquad (2)$$

在方程 2 中，（x，y）是 PM2.5 粒子的位置坐标，t 是时间变量。而 Stk 是斯托克斯数，$Stk=\frac{\mathrm{Re}}{9}\left(\frac{\rho_\mathrm{p}}{\rho_\mathrm{f}}+\frac{1}{2}\right)\left(\frac{d_p}{W}\right)^2$，衡量粒子在静止气体中的滞止距离和入口宽度的比例（ρ_p 是粒子密度，$\mathrm{d_p}$是粒子直径）。

通过求解上述方程，我们可以得出收集 PM2.5 所需的惯性冲击器尺寸大小和工作参数等，图 4 是两组样本数据。

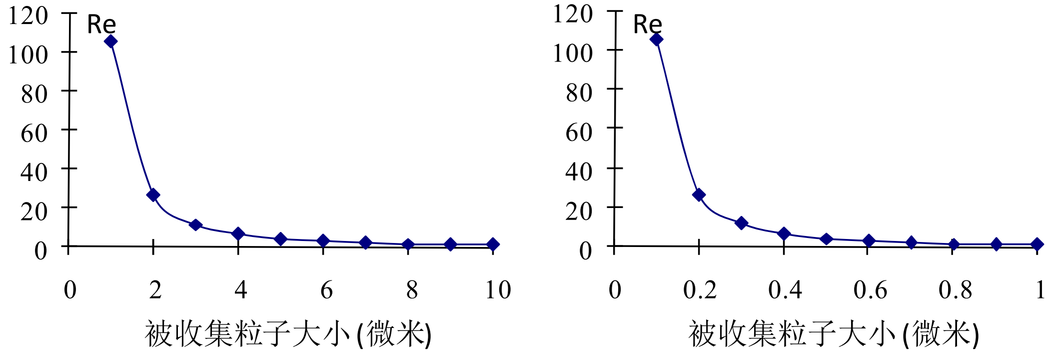

图4：雷诺数和被收集的粒子大小的关系。左边是入口宽100微米是的数据，右边是入口宽10微米时的数据。

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(54) Title: MINUTE DEVICES AND INTEGRATED SYSTEMS FOR PARTICLE SIZE DETECTION, SEPARATION AND COLLECTION BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY

(57) Abstract: Disclosed are minute inertial impactor devices which are comprised of ceramic tape. These devices can be standalone or incorporated into a unitary fluidic and mechanical component system containing various other elements, also preferably produced from ceramic tape. The impactor comprises a plurality of ceramic layers and an impaction surface. The impaction surface can be fabricated in a planar, concave or wedge-shaped geometry, or surface treated to enhance collection efficiency. The devices of the present invention can be assembled in a series or parallel configuration.

MINUTE DEVICES AND INTEGRATED SYSTEMS FOR PARTICLE SIZE DETECTION, SEPARATION AND COLLECTION BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY

Cross-Reference to Related Application

This application claims the benefit of U.S. Provisional Patent Application No. 60/165,225, filed November 12, 1999, the entire disclosure of which is incorporated by reference in the present application as though set forth herein in full.

Field of the Invention

This invention relates to minute devices for particle separation and collection, such as inertial impactors, that are fabricated from ceramic tape. The present invention also includes a minute, unitary system for particle separation, collection and, optionally, detection, which is fabricated utilizing ceramic tape technology.

Background of the Invention

The development of microchip devices and systems, commonly referred to as "lab-on-a-chip" technology, enables the integration of chemistry with mechanics, electronics and optics, as well as the integration of multiple analytical systems into a very small area within a unitary structure.

Such systems may be used, among other things, for the detection of air-borne pathogens and contaminants. Ambient air often contains dust particles that must be removed prior to introducing the air into an analytical device. Occasionally, it may be desirable to separate particles of certain sizes (i.e., compatible with the size of bacteria) for further analysis. The functions of separation and isolation of particles in various size ranges can be efficiently and inexpensively accomplished through the use of an inertial impactor, a device that separates particles from a gas stream according to their mass by suddenly changing the direction of the particle-laden stream. The heavier and/or larger particles continue along a relatively straight trajectory towards an impaction surface, whereas the lighter particles follow the gas stream and exit the impactor. The impaction surface can be either solid of liquid, and it can be removable from the device. Morever, by making the impaction surface from an active material, such as a piezoelectric, the mass of the accumulating particles can be determined.

Inertial impactors have previously been used, among other things, for air quality monitoring, gravimetric, biological and chemical analysis; and stack sampling. Using experiments and numerical simulations, Marple and co-workers studied in detail the performance of macroscopic impactors. Marple, V.A., Liu, B. U. H., et. al. "Fluid Mechanics of the Laminar Flow Aerosol Impactor", *Aerosol Science*, Vol. 5, 1-16, 1974, Marple, V.A., Liu, B. U. H., et. al. "Fluid Flow and Aerosol Impaction in Inertial Impactors", *J. Colloid and Interface Science*, Vol. 53, 31-34, 1975, Marple, V.A., Liu, B. U. H., et. al. "Characteristics of Laminar Jet Impactors", *Environ. Science Technology*, Vol. 53, 31-34, 1975, Marple, V.A.. and Rubow, K. L., "Theory and Design Guidelines" in Cascade Impactor: Sampling and Data Analysis (1986), Marple, V.A., Rubow, K. L., et. al. "Low Flow Rate Sharp Cut Impactors for Indoor Air Sampling: Design and Calibration", *J. Air Pollution Control Association*, Vol. 37, 1303-1307, 1988 and Marple, V.A., Rubow, K. L., et. al.

"Microorfice Uniform Deposit Impactor (MOUDI): Deposition, Calibration, and Use", *Aerosol Science Technology*, Vol. 14, 434-446, 1991, which are incorporated herein by reference. Marple's group obtained design charts and efficiency curves as functions of the impactors' geometry and Reynolds numbers.

A need exists for small scale or minute particle separation and collection devices which are adaptable for integration in microchip devices and systems.

Summary of the Invention

It is an object of the present invention to provide small scale, relatively inexpensive devices, the dimensions of which are measured in hundreds of microns, and which are capable of sampling and separation of micron-sized particles from a particle-laden gas stream according to particle mass. It is a further object of the invention to provide a particle collection system comprising an array of the minute inertial impactors of the invention arranged in series or in parallel to collect particles of varying sizes entrained in a gas stream thus effectively functioning as a "particle spectrometer".

These objects are accomplished by the device described herein, which is effective for separating and collecting particles from a particle-laden gas stream according to particle mass, and which is constructed as a unitary structure from a plurality of ceramic layers bonded together. The plural ceramic layers include (i) at least one layer defining an entrance passage for introducing the gas stream into the device in a flow path having a given direction; (ii) at least one layer defining an elongated cavity which has a length that is transverse to the flow path of the incoming gas stream and which receives the gas stream from the entrance passage and directs it through the device; (iii) at least one layer providing an impaction area disposed in alignment with the direction of the gas flow path for receiving a first fraction of the particles in the gas stream and for causing at least a part of the gas stream to be diverted longitudinally of the cavity away from the direction of the flow path, and a dispersion area for receiving the diverted part of the gas stream, which entrains a second fraction of the particles in the gas stream; and (iv) at least one layer defining at least one exhaust port for discharging the diverted part of the gas stream from the device.

The particle separation and collection device of the invention can be embodied in a system which incorporates a cascade arrangement of inertial impactors disposed in series or in parallel to collect particles of various sizes from an incoming particle-laden gas stream. A preferred embodiment of such a system further includes another ceramic layer that defines a second elongated cavity which is in fluid communication with the exhaust port of the above-described device, and receives the diverted gas stream from the exhaust port. This second cavity has a second impaction area aligned with the gas stream discharged from the exhaust port to cause at least a part of the diverted gas stream to be rediverted longitudinally of the second cavity away from alignment with the exhaust port. The rediverted gas stream carries another part of the second fraction away from the second impaction area. This system preferably includes still other ceramic layers, one of which defines a second exhaust port connected to the second elongated cavity, and another of which defines a third cavity connected to the second exhaust port. The third cavity receives the rediverted gas stream from the second exhaust port. The third cavity contains a third impaction area aligned with the connection to the second exhaust port to cause at least a part of the rediverted gas stream to be again diverted longitudinally of the third cavity away from alignment with said second exhaust port. The again-diverted gas stream carries a part of the second fraction away from said second impaction area. Additional ceramic layers and ports may be provided, depending on the degree of separation desired.

Additional elements may be combined with the devices and systems of the invention for a variety of detection and analytical applications. One application for the devices and system of the invention is for the sampling of air or other gaseous fluid for the presence of air-borne pathogens or other particles which can be subsequently detected.

Unlike the impactors of the prior art, inertial impactors composed of ceramic tape in accordance with the present invention are smaller scale, typically having dimensions in the hundreds of microns. Their smaller size allows these detectors to sample micron-size particles in a efficient and effective manner.

Brief Description of the Drawings

The foregoing summary, as well as the following detailed description of the preferred embodiments, is better understood when read in conjunction with the accompanying drawings in which:

Figure 1a is an enlarged, isometric view of individual layers of ceramic tape prior to stacking, lamination and sintering;

Figure 1b is an enlarged, cross-sectional view of the assembled and post-fired ceramic tape structure taken at line A-A depicted in Figure 1a;

Figure 2 is an enlarged, cross-sectional view of a minute impactor assembled from seven layers of ceramic tape;

Figure 3a is an enlarged, plan view of the inlet nozzle of the minute impactor depicted in Figure 2;

Figure 3b is an enlarged, inverted plan view of the exit ports of the minute impactor depicted in Figure 2;

Figures 4a, 4b and 4c are enlarged fragmentary, cross-sectional views showing several examples of solid impaction surface geometrics, which can be custom designed in accordance with the flow profile to improve collection efficiency;

Figure 5 shows the fraction of collected particles (E) as a function of the square root of the Stokes Number, for a theoretical study of the characteristics of impactors in accordance with this invention;

Figure 6 is an enlarged fragmentary view of a system incorporating multiple ceramic-based inertial impactors arranged in cascade format;

Figure 7 is a diagrammatic illustration of the experimental setup used to determine the collection efficiency of a stand alone impactor of the present invention;

Figure 8 illustrates the particle size distribution of a particle-laden stream in the presence or absence of an impactor; and

Figure 9 shows the fraction of collected particles (E) as a function of the square root of the Stokes number, for an experimental study of the characteristics of impactors in accordance with this invention.

Detailed Description of Preferred Embodiments

The present invention is directed to small scale devices for particle separation, collection and, optionally detection, as well as integrated systems that incorporate such devices, which are assembled from or utilize components which are fabricated from ceramic tape. This fabrication technique allows the creation of complex or three dimensional, yet minute, devices without the need for expensive tooling or facilities.

Inertial impactors are typically used in the measurement of aerosol size distribution and collection of samples for further chemical analysis. The particle-laden incoming stream can be either a solid or liquid aerosol. The heavier and/or larger-sized particles continue along a relatively straight trajectory or minor flow stream towards an impaction surface where they are deposited, and the lighter and smaller particles follow the major flow stream and exit the impactor. Both the larger and smaller particles can be collected for any desired method of analysis such as direct-reading, continuous instrumentation, or be sent to a subsequent stage or stages for further work up.

The removal of particles (liquids, solids, mixtures thereof) from a gas stream requires deposition and attachment to an impaction surface. The impaction surface within the device can be either a solid or a liquid, embodied in various sizes and shapes. The impaction surface may be surface treated, e.g. with an adhesive coating, to prevent "particle bounce" or rebounding of the larger particles back into the major flow stream. Depending upon the application, the device may include means for measuring the mass of the accumulating particles. For example, the impaction surface can be made from an active material, such as a piezoelectric material, e.g. quartz, lead zirconate titanate ("PZT"), lithium niobate, polyvinylidene fluoride ("PVDF"), or from a thin membrane which may be subjected to either normal vibrations or vibrations in the form of traveling waves, which allow the mass of the accumulating particles to be measured. Impaction surfaces made from active materials may exhibit a shift in the natural frequency in response to an accumulation of particles, whereby the frequency shift is correlated to the weight of the accumulated particles.

After particles are deposited upon a surface, they can be removed at regular intervals to prevent reentrainment into the gas stream. This can be accomplished, for example, by providing a collection medium in the impaction area in the form of a liquid drop, which can be manipulated for removal from the device.

Two parameters which may be used to characterize the performance of an inertial impactor are separation or collection efficiency and wall loss. An effective inertial impactor is one that exhibits good efficiency and low wall loss.

Efficiency can be affected by the medium in which the particles are suspended. When the suspended particles are in a liquid aerosol, the efficiency of the impactor approaches the theoretical efficiency. However, when the suspended particles are in a solid aerosol, the efficiency is much lower than the theoretical efficiency, due to particle bounce and particle reentrainment. These problems can cause larger particles in minor flow stream to be admixed within the smaller particles in the major flow stream, and vice versa. Wall loss also contributes to lowering the efficiency of inertial impactors. Thus, when the larger particles accumulate on the impaction surface to a certain thickness, these particles may be swept back into the major flow stream.

Green ceramic tape is a versatile material that enables the combination of various electronic, mechanical, fluid transport and electronic elements into an integrated system within a monolithic structure, without the need for using external hydraulic interconnections. The term "minute" as used herein in reference to channels, passageways, conduits, vias, interconnections, cavities, chambers or other void spaces of the devices and systems described herein, is intended to signify at least one cross-section dimension of width or depth on the order of $10\mu m$ to 1cm, preferably on the order of $20\mu m$ to $500\mu m$, and more preferably $50\mu m$ to $300\mu m$. For many applications, channels of 200μm width will be useful. Cavities in the structures may have somewhat larger dimensions (e.g. 60μm to 1cm). The term "minute" and "meso-scale" are sometimes used interchangeably in describing the present invention.

In fabricating the devices of the invention, ceramic tape layers are sized to meet the external dimensions of the intended device with the tape in its green or unfired state. Next, minute flow conduits, channels and/or portals are formed in the individual layers of tape. These flow conduits, channels or portals can be created in a variety of ways that include, but are not limited to, mechanical machining, e.g., computer numerically controlled (CNC) milling and punching, chemical etching, laser machining, binder extraction, photo-forming or related techniques known in the art. A variety of shapes of flow conduits, including without limitation straight, T-shaped, U-shaped, L-shaped, spirals or curves, can be incorporated into one or more of these layers. Flow conduits in various layers can be interconnected through the use of hollow vias. These layers are aligned, stacked, and then laminated and bonded together by sintering under temperature and pressure conditions sufficient to yield a hardened, monolithic body, with complex internal interconnections. Tape composition may vary from layer to layer depending upon the desired properties and applications of a particular device or system.

One of the difficulties encountered in applying ceramic tape technology is the occurrence of dimensional changes, such as shrinkage, bowing and other related deformations, that occur during the lamination and sintering process. Deformation usually occurs in the direction perpendicular to the tape's x-y plane and the degree of shrinkage can be up to 15% of the tape's original dimensions. The degree of shrinkage on the external dimensions can be corrected by accounting for the shrinkage in the design process. It is more difficult, however, to correct the dimensional changes such as shrinkage and bowing for the internal cavities or flow conduits. To remedy this, the internal cavities or flow conduits of the device are filled with sacrificial material, such as graphite and an organic binder mixture, prior to the lamination and sintering process. The sacrificial material then burns out during the sintering process and a hardened, monolithic device with a reduced amount of shrinkage on the internal conduits or cavities is produced.

In the fired state, small structures can be subsequently machined using diamond tools and lasers. Diamond points are used to create intricate features with small dimensions, and diamond slurry can be used to define symmetrical shapes. Both CO_2 and eximer lasers may be utilized to machine alumina and other ceramics with high precision.

Interconnects to an external flow supply can be added to the ceramic device through applying an adhesive, such as epoxy, to affix glass or metal fittings to the surface of the ceramic. If desired, glass fittings such as Kimble's Borosilicate Glass (KIMAX Brand N-51A) can be directly bonded to the ceramic by heating the glass above its transition temperature because the thermal expansion coefficient closely matches that of ceramic tape. Furthermore, metallic fittings can be bonded by metallizing the surface of the ceramic device and brazing the fittings to the ceramic surface.

The devices disclosed herein and the flow passage within them are adaptable to a variety of design requirements depending upon the application. Design adaptations will include, for example, the formation of conduits of various shapes and dimensions, making the impaction surface of an active material, forming the impaction surface in different geometrical configurations, surface modifications, and the like. An example of a surface modification may be the application of an impervious coating to the internal cavities to reduce surface roughness and ease the passage of fluid through these cavities.

Because of their versatility, the ceramic structures of the present invention can be readily adapted to create minute particle separation and collection devices or systems comprising an array of such devices which effect particle collection in cascade fashion. The flexibility of the manufacturing method allows devices of other materials, such as silicon or metal windows, to be incorporated or embedded into the ceramic structure.

In preferred embodiments, the individual layers of the minute impactors comprise DuPont® 951 series Green Tape™. This tape is a low temperature co-fire ceramic ("LTCC") tape which consists primarily of alumina particles, glass frit, and organic binder. The tape is characterized by high strength, low coefficient of thermal expansion, refire stability, and is compatible with co-fired materials (such as conducting paste that is screen-printed to the green ceramic tape) and via fill compositions, if the application requires said features. The thickness of the tape used for the devices can vary anywhere from about 100μm to about 250μm. As those skilled in the art will appreciate, however, other ceramic tapes can be utilized in practicing this invention.

The shrinkage of DuPont® 951 Green Tape™ is on the order of 12.27%±0.3% in the x, y direction and 15%±0.5% in the z direction, according to the DuPont® Design Parameters and Considerations for Green Tape™, which are incorporated herein by reference. Shrinkage can be affected further by the number and size of cavities within the individual layers or the degree of metallization on each layer.

Figure 1a depicts 3 layers of green ceramic tape designated 1, 2, and 3. Layer 3 has two openings, 4 and 5, that are formed by CNC milling or punching. Layer 2 has an L-shaped conduit or flow channel 6 therein. Holes 4 and 5 and flow channel 6 are formed by placing layer 1 and layer 2, respectively, onto the platform of a CNC milling machine. The green layers are held in place by a vacuum chuck or similar means. The CNC milling machine cuts openings 4 and 5 or flow channel 6 in accordance with a computer generated design for each individual layer of the device. Openings 4 and 5 and flow channel 6 are filled with a mixture of graphite and organic binder to maintain dimensional integrity of these internal cavities during the lamination and sintering steps. The graphite and organic binder mixture burns out during the sintering process.

Lamination and sintering can occur in a variety of ways and at different time, temperature, and pressure settings depending upon the ceramic tape used for the device, the number of layers, and any devices or pastes that may be applied to the individual layers pre-firing. The aligned and stacked layers are subjected to temperature and pressure parameters sufficient to bond the layers together into a unitary structure. Uniaxial lamination takes place in a hydraulic press with heated platens. The aligned, layer stack is pressed at about 70°C and 3000 psi for about 10 minutes to form a laminate. DuPont, the manufacturer of the 951 series tape, recommends that the laminate be typically rotated 180° after the first five (5) minutes.

Alternatively, isostatic lamination occurs in a specially designed press which uses heated water or other fluid. Time and temperature are usually the same as uniaxial pressing but rotation of the laminate is not required. The laminate is vacuum sealed within a plastic bag to prevent water from attacking the ceramic tape layers.

After lamination is complete, the laminate is then fired on a setter tile within a kiln or furnace. The graphite and organic mixture and other organics within the laminate burnout at temperatures which range from about 200°C to about 500°C. The laminate is usually "soaked" within this temperature range to ensure full decomposition of the organics. The temperature is then gradually increased to the sintering temperature. Typical sintering temperatures for ceramic tape devices are between about 850°C to about 875°C. The device may be further subjected to additional firing steps if thick film resistors, dielectric, conductors, or other devices are applied in a post-fire operation.

Layers 1, 2, and 3 are aligned and stacked together and bonded to form a monolithic structure or device, 7 as shown in Figure 1b. Each layer is placed into a precision lamination fixture and positioned over tooling pins until all layers of the device 7 are assembled. Figure 1b is a cross-sectional view of the ceramic tape structure after stacking, lamination and sintering taken at line A-A depicted in Figure 1a. Opening 4 can be used as an inlet port of the device 7 and flow channel 6 can be used as a capillary or fluid sample holder depending upon the desired application of device 7. Fittings can be affixed to opening 4 to facilitate introduction of fluid into flow channel 6. Opening 5 (not shown in Figure 1b) can be used as an outlet port of device 7 and can also have a fitting attached to it to facilitate fluid removal from the device.

The device 7 may be subjected to post-firing machining depending upon the desired application and design parameters. Machining methods vary depending upon considerations of cost, edge control, tolerances, and shape. A dicing saw may be used to form rectangular sharped devices with tight outside dimensional tolerances and high quality edges. Another machining method, ultrasonic cutting, allows tight tolerances and exceptional edge quality of unusually shaped parts. The drawback to ultrasonic cutting is that it is expensive and slow in comparison with other cutting methods. Yet another machining method, laser cutting, allows for tight tolerances at a lower price than comparable methods. However, the quality of the edges produced by laser cutting is poor. In comparison with post-firing laser cutting, pre-firing laser cutting of green ceramic tape will produce quality edges. Unfortunately, the outside edge tolerances of pre-fired laser machine parts are poor due to dimensional changes resulting from firing.

A basic form of a minute, inertial impactor in accordance with the present invention is shown in cross-section in Figure 2. The impactor 10, comprises multiple layers of 250μm LTCC tape. Each layer is about 230mm thick after firing. Three (3) layers define the inlet nozzle 8. The adjacent three (3) layers define the cavity section, 11, of impactor 10. The other layer serves as the bottom of cavity section 11 and provides a flat impaction area 12 for the collection of larger diameter particles. Impaction area 12 may be surface-treated, e.g. with an adhesive coating, to enhance collection efficiency. Depending upon the application, the impaction surface may also made from an active material such as a piezoelectric or an actuated flexible member in order to measure the mass of the accumulating particles. In this embodiment, the layer that functions as the impaction surface also contains exhaust ports 9a and 9b for the major flow stream containing the smaller sized or finer particles.

Figures 3a and 3b show plan and inverted plan views, respectively, of inertial impactor 10. Figure 3a shows the top layer, with the opening of inlet nozzle 8. Typical dimensions of nozzle 8 in an inertial impactor constructed of 250μm green ceramic tape are about 500μm in width and about 5mm in length. Figure 3b shows the bottom layer of impactor 10, with exit ports

9a and 9b, which have approximately the same dimensions as nozzle 8.

The device shown in Figures 2, 3a and 3b is fabricated according to the same general procedure described above, with reference to Figures 1a and 1b.

In use, particles may be introduced into impactor 10 via an aerosol-laden air stream. The stream is drawn through nozzle 8, by inducing a vacuum downstream of the device, and is accelerated so that the particles in the stream have a greater inertia. As the air stream passes into cavity section 11, the particles with sufficient inertia, i.e. the relatively larger sized, on heavier mass particles, deviate from the major flow stream and impinge upon impaction surface 12. The smaller sized, lower mass particles pass through the exhaust ports 9. Whether impaction occurs depends on the particle's size, its position when entering the impactor, the impactor's geometry, the inlet velocity profile, and the Reynolds number. The collection efficiency of larger particles may be lower than expected based on theoretical considerations. This may be due to the occurrence of particle rebound off the impaction area 12 and reintroduction into the major flow stream. Furthermore, after the larger particles collect on the impaction surface 12, the particles may be "blown away" and reintroduced into the major flow stream.

Instead of a flat impaction surface as shown in Figure 2, it is contemplated that the impaction surface can have a variety of different geometries depending upon the requirements of the system. By custom designing the impaction surface in accordance with the flow profile, the collection efficiency of the device can be improved. For example, the impaction surface can be cup-shaped 41, concave 43, or wedge-shaped 45 as shown in Figures 4a, 4b and 4c. It should be understood that the particular geometries just mentioned are merely representative of the various geometries of impactor surfaces that can be employed.

A theoretical study of the characteristics of two minute impactor designs, one with and one without a recess in the impaction area, has been conducted. M. Yi et al., "Theoretical and Experimental Study of Mesoscopic Impactors", Micro-Electro-Mechanical Systems (MEMS) - Symposium ASME-Publications - MEMS, Vol. 1, 517-22 (1999). The entire disclosure of this paper is incorporated by reference herein.

The theoretical study consisted of a numerical solution of the Navier-Stokes equations for the fluid's flow field and a solution of Newton's equation of motion for the particles. The particle cut-off sizes and the impactor's efficiency curves were computed as functions of the jet-to-plate distance, nozzle size, recess size, and the jet's Reynolds number ($Re<100$).

The computations were carried out for the two limiting cases of uniform and parabolic inlet velocity profiles. Marple's computations (cited above) were reproduced for an inlet velocity profile which was between the parabolic and uniform distributions. Figure 5 is a graphical representation of the fraction of collected particles (E) as a function of the square root of the Stokes number for the case in which $RE=100$, $T/W=Y/W=1$, and $\rho=10^3$, T being the inlet nozzle's length, Y being the distance from the nozzle exit to the impaction surface and W being the nozzle opening width. The squares and triangles correspond, respectively, to uniform and parabolic inlet velocity profiles. The diamonds, which lie between the results for the two limiting cases, represent Marple's computational results for an intermediate velocity profile.

As shown in Figure 6, the ceramic impactors of the invention can be fabricated in a cascade-type system 100. By this is meant that in addition to the basic impactor 110 fabricated from ceramic layers defining inlet passage 118, elongated cavity 121, impaction area 122 and exhaust ports 119a and 119b, another ceramic layer 130 is included to form a system which further comprises a second stage of elongated cavities 131a and 131b in fluid communication with exhaust ports 119a and 119b, respectively. Each second stage elongated cavity has an impaction area 132a and 132b, which are in alignment with the gas stream discharge from exhaust ports 119a and 119b, respectively. The cascade structure may be extended by including yet additional ceramic layers, one of which 135 defines second stage exhaust ports 139a 139b, 139c and 139d from the second stage cavities 131a and 131b, and another of which 140 defines a third stage of elongated cavities 141a, 141b, 141c and 141d in fluid communication with the second stage exhaust ports. Each of the third stage cavities has an impaction area 142a, 142b, 142c and 142d, respectively, which are aligned with the gas streams from the second stage exhaust ports.

In operation, a particle-laden gas stream introduced through inlet passage 118 is received by cavity 121. A fraction of the heavy particles, comprising the minor flow stream, impinges upon impaction area 122, where those particles remain and the major flow stream, comprising the lighter particles is diverted longitudinally of cavity 121 away from the direction of travel of the incoming gas stream and discharged through exit ports 119a and 119b. The discharged minor flow stream is received by cavities 131a and 131b and is again separated into major and minor flow streams, with collection of the heavier particles of the newly-separated minor flow stream occurring at impaction areas 132a and 132b. The separation process is multiplied and repeated in the same manner by means of impaction areas 142a, 142b, 142c and 142d in the third stage cavity. The gas stream is discharged through exhaust ports 149a, 149b, 149c and 149d.

For optimum separation efficiency, the distance between the exit of the inlet passage or of the exit ports, as the case may be, and the impaction areas of each stage should be reduced as the gas flows downstream.

As previously noted, hybrid devices can be fashioned from LTCC tapes in conjunction with various other structural materials. Hybrid structures for high temperature applications may incorporate glass compositions, silicon or metals, so long as the thermal expansion coefficient of the selected material is compatible with the ceramic material. Once the ceramic is fired, a wide variety of plastic materials may be included in the resulting monolithic structure.

The fabrication methods described herein enable rapid prototyping, layered manufacturing with its attendant advantages and economical production of various minute, inertial impactor devices and systems comprising such devices.

The following example is provided to describe the invention in further detail. This example is provided for illustrative purposes only, and should in no way be construed as limiting the invention.

EXAMPLE 1: COLLECTION EFFICIENCY TESTING

The experimental setup used to determine actual collection efficiency is depicted in Figure 7. Oil-based aerosol particles ranging in diameter from 1μm to 6μm were generated by a Model 3450 Vibrating Orifice Aerosol Generator (VOAG), 16. The VOAG 16 created monodisperse particles with a narrow particle size distribution. The particles were generated by mixing specified amounts of olive oil and 2-propanol (isopropyl alcohol). The particles were dispersed and mixed in an air stream that flowed upward through an Aerosol Neutralizer, 17, and a flexible connecting tube 18 and fed into impactor 20. A fraction of the particles was collected inside the impactor, 20. The air stream was then drawn into a Model 3320 Aerodynamic Particle Spectrometer (APS), 21. APS, 21, counted the number of particles in the major flow stream as a function of their size for a period of 20 seconds and was operated at the constant flow rate of 5 liters per minute with a sample flow rate of 1 liter per minute.

In order to test the effects of the flow rate on the impactor's performance, a by-pass branch 22, consisting of a filter 23, flow meter 24 and valve assembly 25, was added upstream of APS 21 as shown in Figure 6. By adjusting the by-pass valve 25, the flow rate through the impactor could be varied from 0.3 to 1 liter per minute. The by-pass flow rate was monitored with a flow meter 24.

Due to concern about the potential loss of particles during the induction phase, and in order to minimize such losses, a special entry adapter was designed and constructed using a rapid prototyping machine (FDM 1650) to provide a gradual transition from the circular cross-section of the feed tube (3.2mm diameter) to the rectangular (5mm long x 0.6-0.9mm wide) nozzle opening of the impactor.

In each set of experiments, the distribution of the collected particles in the absence of the adapter and impactor, in the presence of the adapter alone, and in the presence of both the adapter and impactor was measured. The difference between the number of particles detected by the APS in the presence and absence of the impactor was used to determine the collection efficiency of the impactor. A similar method was used to determine the particle loss in the adapter. A typical particle size spectrum obtained in the presence of the adapter with and without the impactor is depicted in Figure 8. In Figure 8, the squares represent the presence of an impactor whereas the diamonds represent the absence of an impactor. Finally, the volume occupied by the accumulating, collected particles was estimated. The effect of the collected particles on the impactor's geometry was found to be insignificant.

Figure 9 graphically depicts the fraction of collected particles (E) as a function of the Stokes number for this experiment. The parameters of the inertial impactor used in this experiment was as follows: W=930μm; T=700μm; Y=700μm; T/W=0.75; and Y/W=0.75. Re=216. The carrier fluid for the incoming stream was air and the "particles" were droplets of olive oil. The triangles, squares, and diamonds correspond, respectively, to theoretical predictions for a parabolic inlet velocity profile, theoretical predictions for a uniform inlet velocity, profile, and to experimental observations. Despite the discrepancies between the experimental results and the theoretical predictions, the two were in qualitative agreement.

Inertial impactors of the present device may be incorporated into an integrated ceramic tape-based, minute, fluidic and mechanical component system. It is anticipated that these systems will act as portable field devices for detection and analysis of particles in a gaseous or air medium at a significantly reduced cost due to the lower cost of fabrication.

While certain embodiments of the present invention have been described and/or exemplified above, various other embodiments will be apparent to those skilled in the art from the foregoing disclosure. The present invention is, therefore, not limited to the particular embodiments described and/or exemplified, but is capable of considerable variation and modification without departure from the scope of the appended claims.

What is claimed is:

1. A minute device for separating and collecting particles from a particle-laden gas stream according to particle mass, said device comprising a plurality of ceramic layers bonded together:
   a. at least one of said ceramic layers defining an entrance passage for introducing said gas stream into said device in a flow path having a given direction;
   b. at least one of said ceramic layers defining an elongated cavity for receiving the gas stream from said entrance passage and directing said gas stream through said device, said cavity having a length which is transverse to the flow path of said gas stream traversing said entrance passage;
   c. at least one of said ceramic layers providing an impaction area disposed in alignment with the given direction of said flow path for receiving a first fraction of the particles in said gas stream and for causing at least a part of said gas stream to be diverted longitudinally of said cavity away from said given direction; and a dispersion area for receiving the diverted part of the gas stream, said diverted part of the gas stream having a second fraction of the particles in the particle-laden gas stream;
   d. at least one of said ceramic layers defining at least one exhaust port for discharging the second fraction of particles and said diverted part of the gas stream

from said device, said ceramic layers constituting a unitary structure in which said cavity is disposed between said entrance passage and said impaction area.

2. A device according to claim 1, wherein said impaction area comprises a surface transverse to said given direction and having a recess aligned with said given direction to collect said first fraction.

3. A device according to claim 2, wherein said recess is cup-shaped.

4. A device according to claim 2, wherein said surface is flat, and said recess consists of a concavity in said flat surface.

5. A device according to claim 2, wherein said recess is wedge-shaped.

6. A device according to claim 1, wherein said at least one exhaust port is positioned at one end of said cavity, said exhaust port exhausting said diverted part of the stream along with said second fraction.

7. A device according to claim 6, including a second exhaust port at the opposite end of said cavity, said diverted part of the stream and the second fraction being exhausted through both said exhaust ports.

8. A device according to claim 1, wherein at least one of said ceramic layers defines a second elongated cavity connected to said exhaust port, and receiving the diverted gas stream from said exhaust port, said second cavity having a second impaction area aligned with the connection to said exhaust port to cause at least a part of said diverted gas stream to be rediverted longitudinally of said second cavity away from alignment with said exhaust port, said rediverted gas stream carrying a part of said second fraction away from said second impaction area.

9. A device according to claim 8, including means in said impaction area to collect particles of the second fraction which are not carried away from said second impaction area.

10. A device according to claim 1, including means in said impaction area to collect said first fraction of the particles in the particle-laden gas stream which are not carried away from said impaction area by said diverted stream.

11. A device according to claim 1, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

12. A device according to claim 1, wherein said entrance passage has at least one cross-section dimension in the range of 10μm to 1cm.

13. A device according to claim 1, wherein said entrance passage is in a first of said plurality of layers, said cavity is in a second of said plurality of layers, and said exhaust port is in a third of said plurality of layers.

14. A device according to claim 13, wherein said exhaust port and impaction area are in the same layer.

15. A device according to claim 13, wherein a fourth of said plurality of layers defines a second elongated cavity connected to said exhaust port, and receiving the diverted gas stream from said exhaust port, said second cavity having a second impaction area aligned with the connection to said exhaust port to cause at least a part of said diverted gas stream to be rediverted longitudinally of said second cavity away from alignment with said exhaust port, said rediverted gas stream carrying a another part of said second fraction away from said second impaction area.

16. A device according to claim 15, wherein a fifth of said plurality of ceramic layers defines a second exhaust port connected to said second elongated cavity, and a sixth of said plurality of layers defines a third cavity connected to said second exhaust port, and receiving the rediverted

gas stream from said second exhaust port, said third cavity having a third impaction area aligned with the connection to said second exhaust port to cause at least a part of said rediverted gas stream to be again diverted longitudinally of said third cavity away from alignment with said second exhaust port, said again-diverted gas stream carrying a part of said second fraction away from said second impaction area.

17. A device according to claim 1, wherein said impaction area includes means for *in situ* measurement of the mass of accumulating particles.

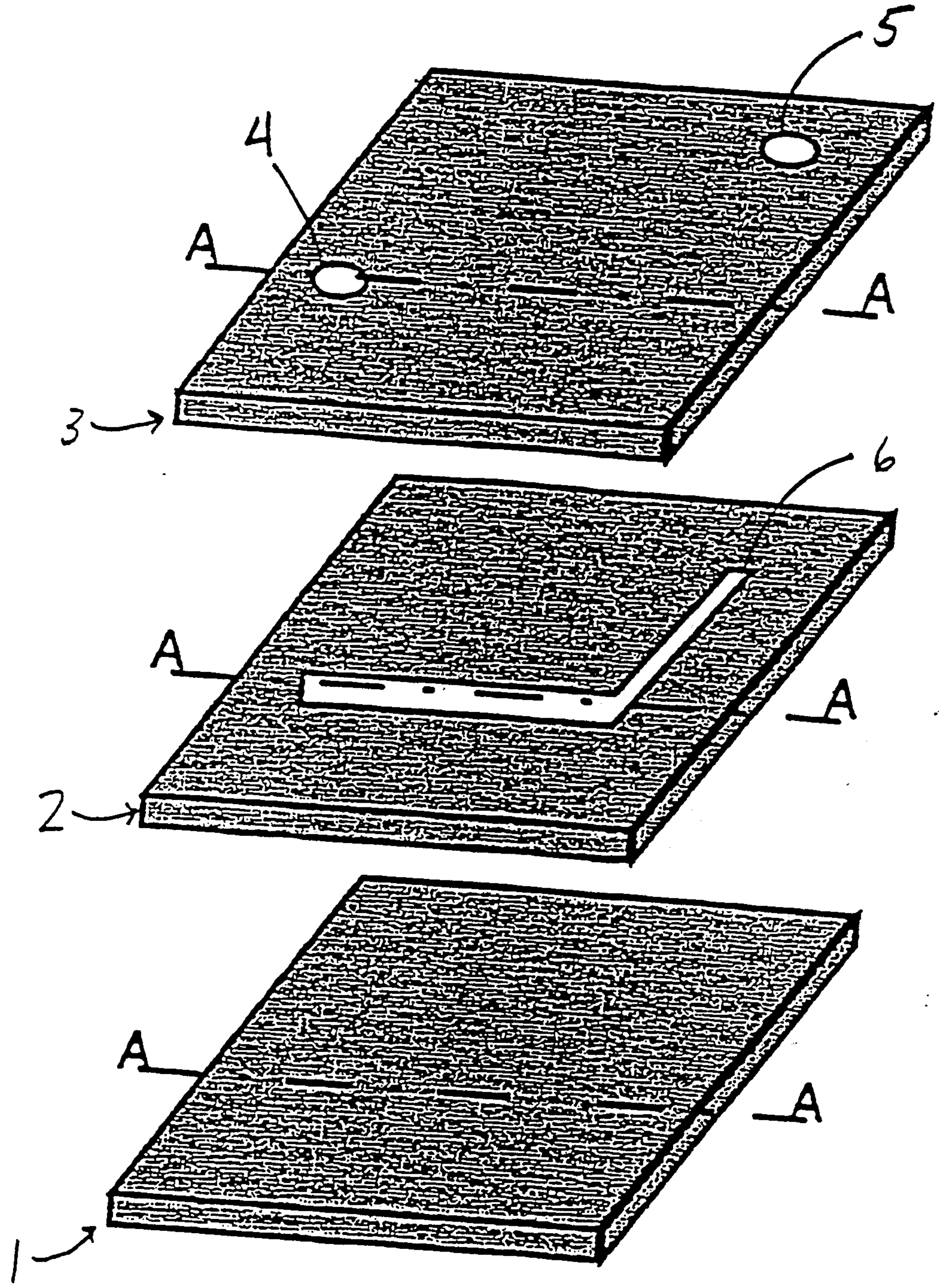


Figure 1a

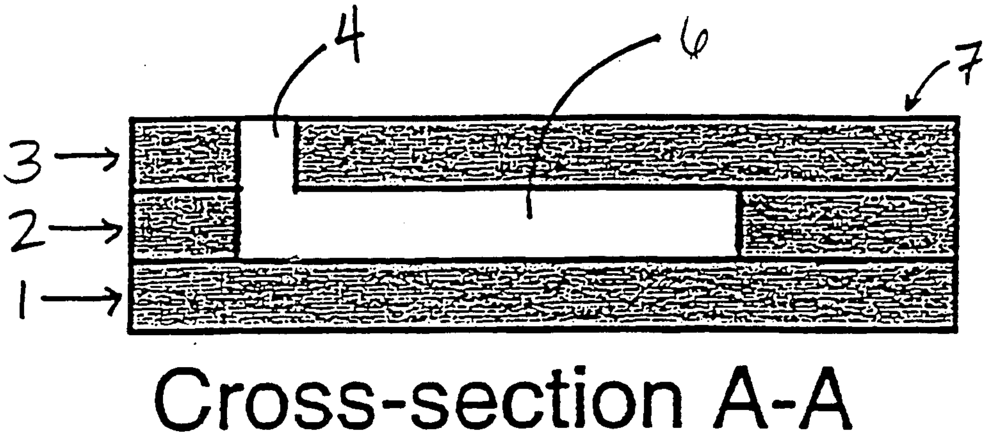


Figure 1b

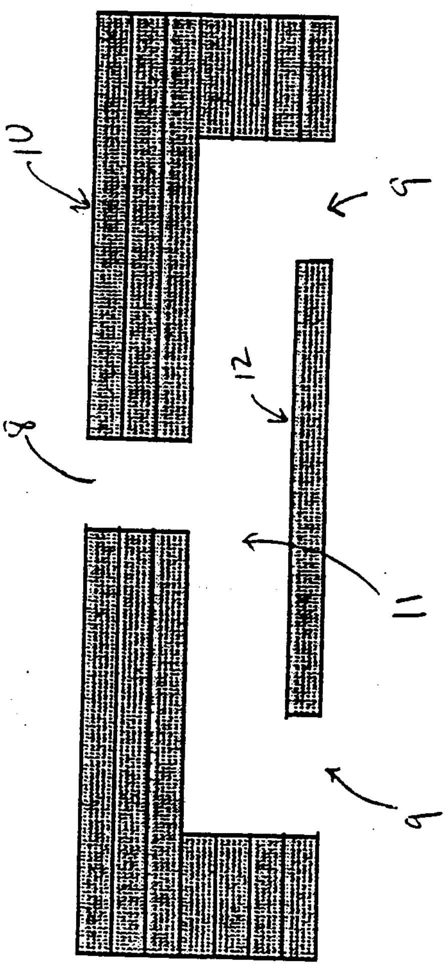


FIG. 2

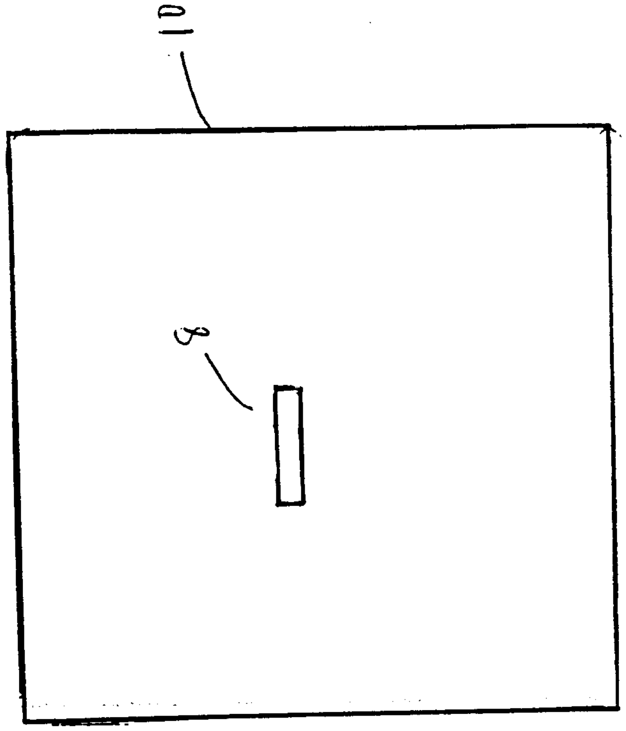


FIG. 3a

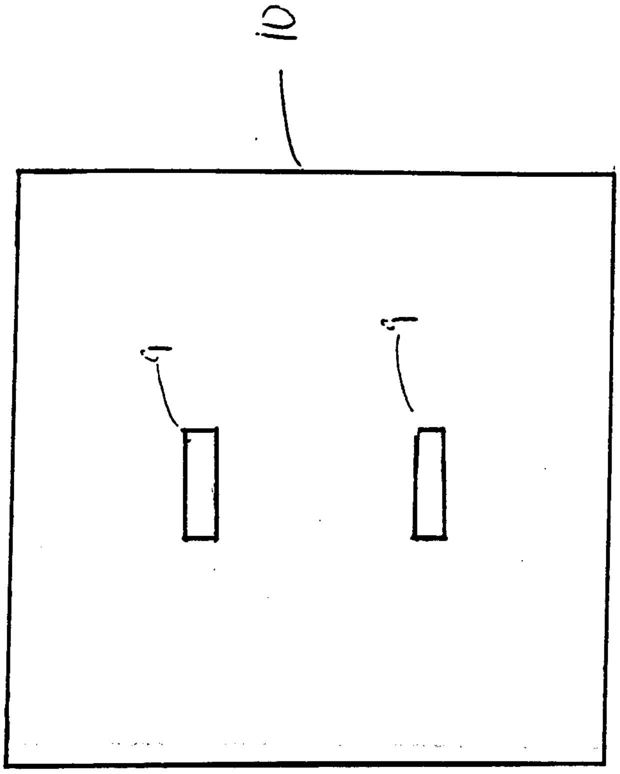


FIG. 3b

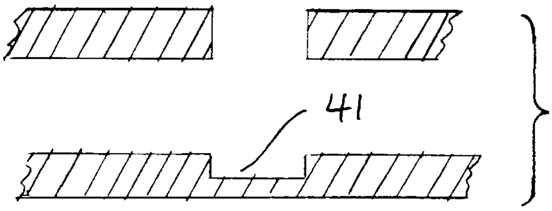


FIG. 4a

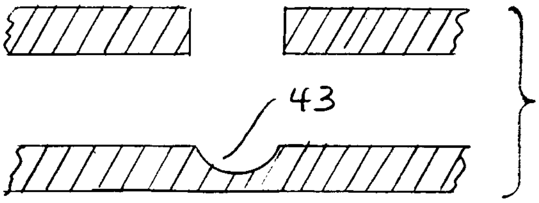


FIG 4b

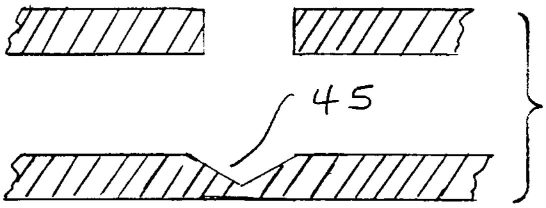
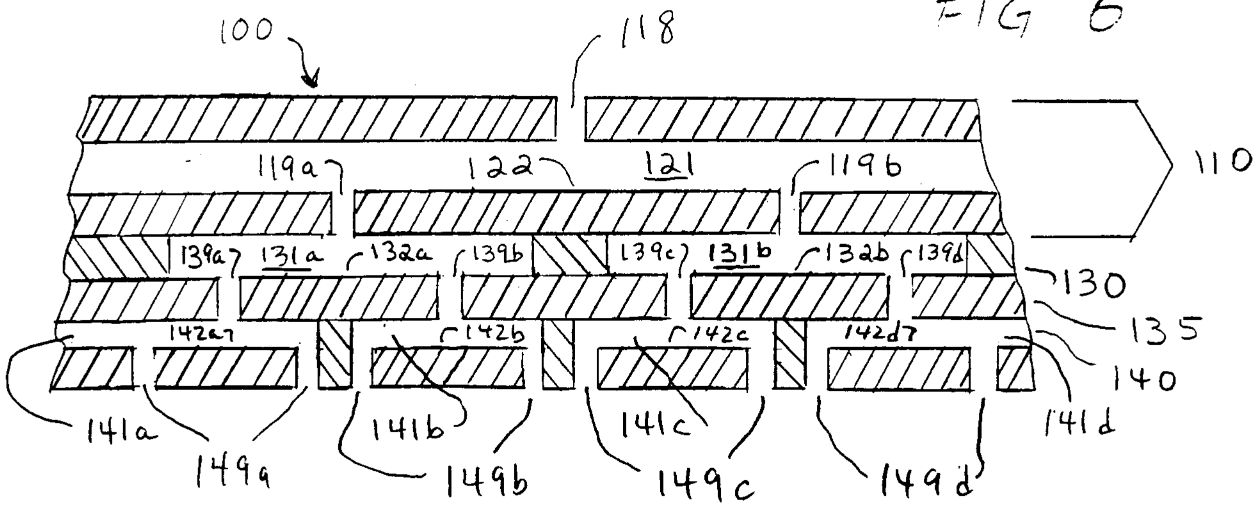


FIG 4c

FIG 6



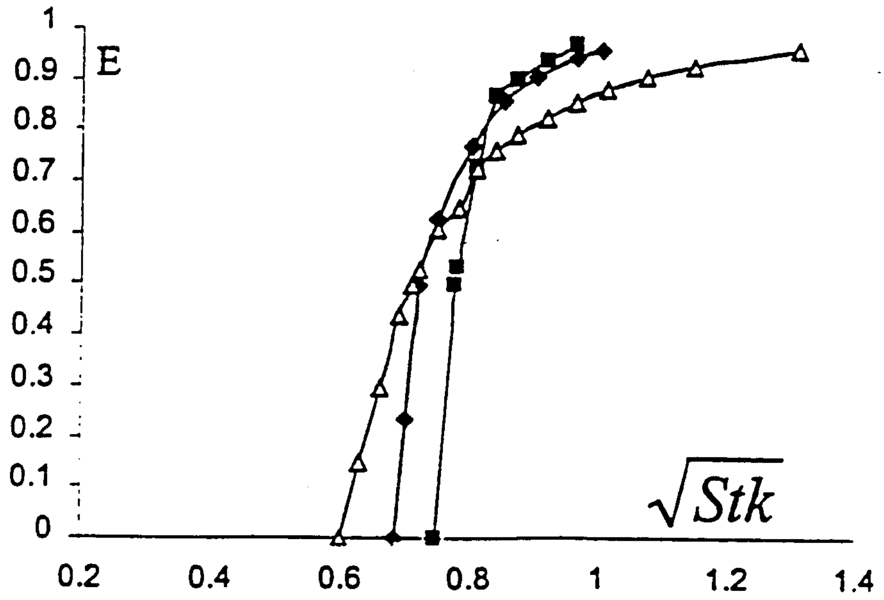


FIG. 5

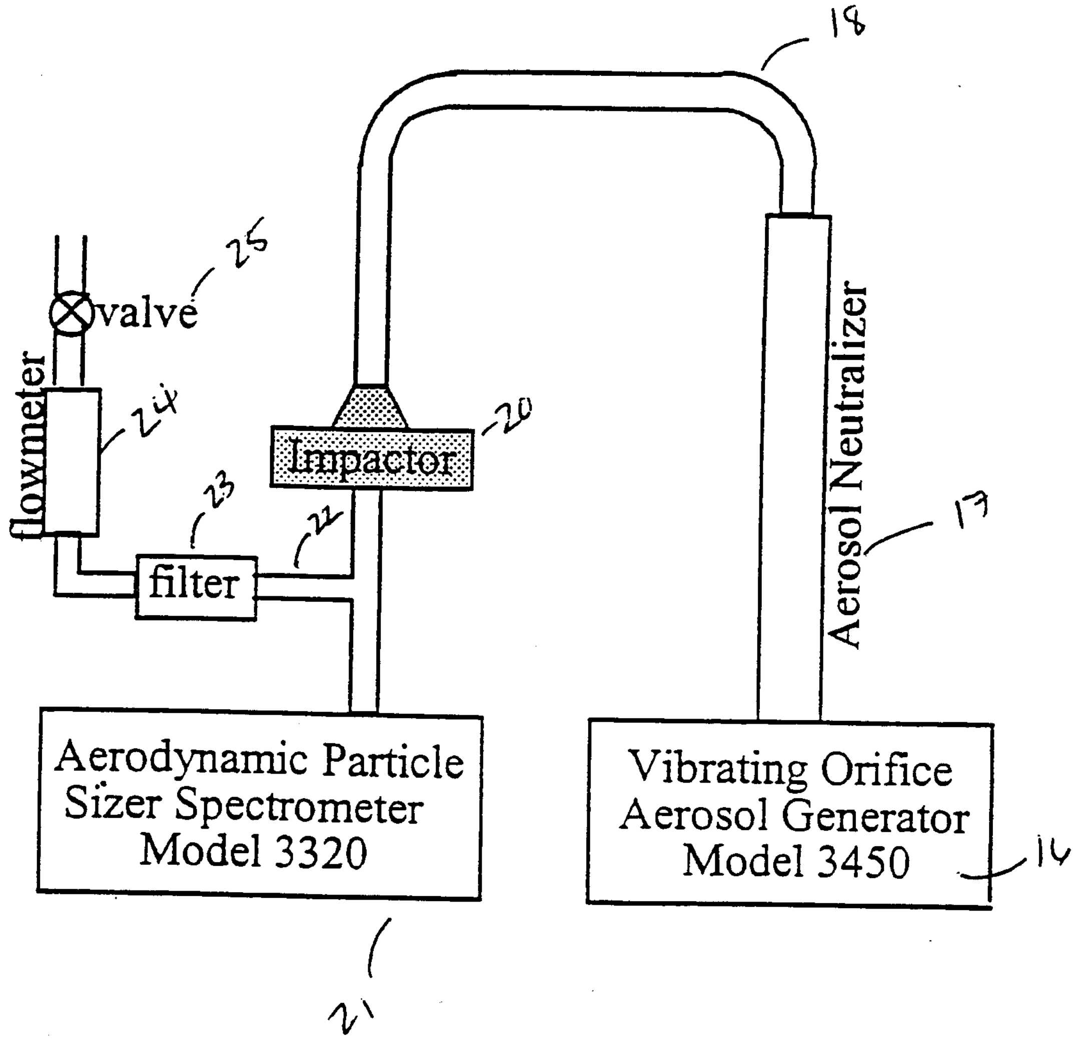

18
25
valve
flowmeter
24
20
Impactor
Aerosol Neutralizer
23
22
filter
17
Aerodynamic Particle Sizer Spectrometer Model 3320
Vibrating Orifice Aerosol Generator Model 3450
16
21

FIG. 7

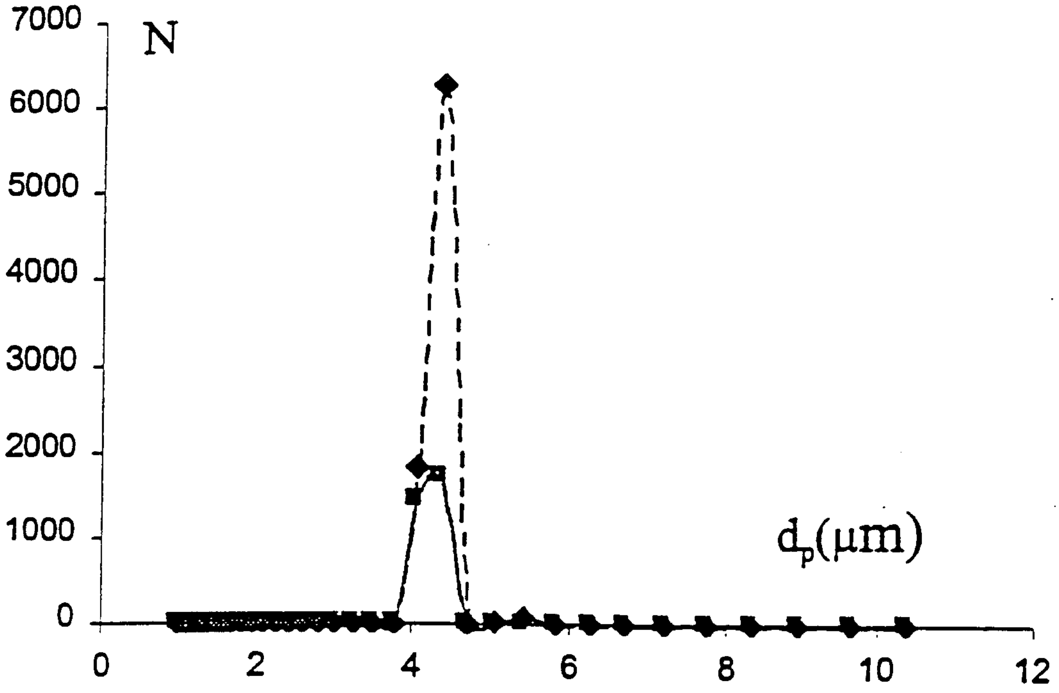


FIG. 8

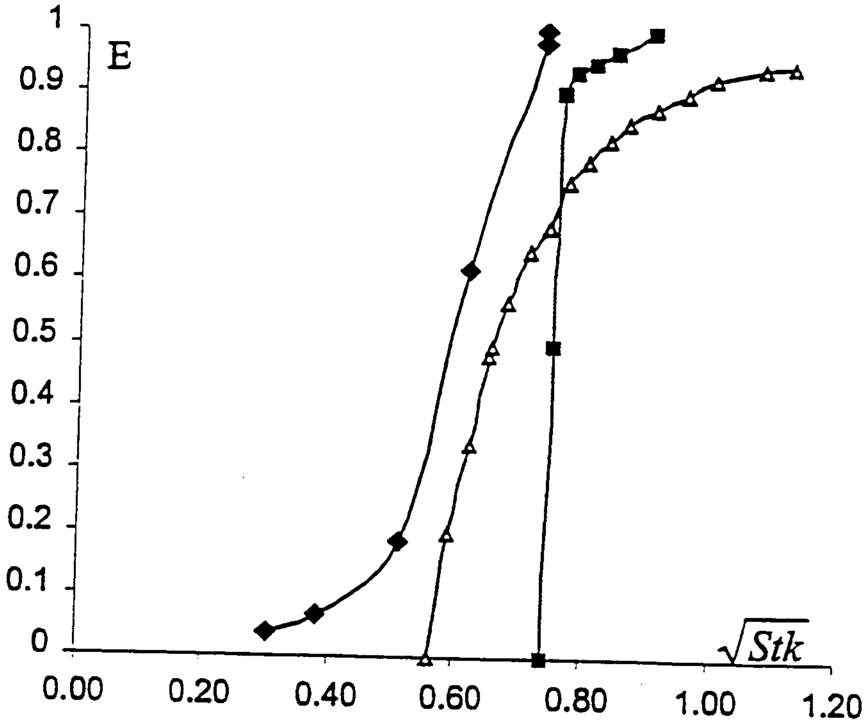


FIG. 9