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Nanofabric nonwoven mat for filtration smoke and nanoparticles

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The process of production of filtration mats of various thickness from PVC and PVDF polymers by the electrospinning method is presented in the paper. Filtration of nanoparticles and submicron particles is an important problem in industry and health protection systems, in particular in air-conditioning and ventilation appliances. This problem can be effectively solved by application of non-woven fibrous filtration mats. The experimental investigations of mechanical properties of nanofibrous filtration mats produced by electrospinning and the measurements of removal efficiency of submicron particles from flowing gas have indicated potential usefulness of these nanomats for gas cleaning of air-conditioning systems and/or ventilation ducts. The experimental results obtained for cigarette smoke of a mass median diameter of about 1 μm, used as test particles, have shown that nonwoven nanofibrous filtration mats produced by electrospinning have a good filtration efficiency for nano- and submicron particles, owing to a pressure drop similar to HEPA filters. Particles of this size are particularly difficult to be removed from the flow by a conventional method, for example, by a cyclone or electrostatic precipitator.

Keywords: nanofibrous mat, filtration, electrospinning.

INTRODUCTION

Filtration of submicron particles, including nanoparticles, is an important problem in industry, environment and health protection systems. In air-conditioning systems removal of submicron particles, including spores, bacteria or viruses, and tar from cigarette smoke remains still an unresolved issue[1]. The submicron particles, which are difficult to remove irrespective of their source, are very dangerous for human health due to their penetration to lower airways. One of the methods which can be used to solve this problem is using nonwoven nanofibrous filtration mats for air filtration. The most effective method of nanofibrous mat production developed in recent years is polymer material electrospinning[2–3]. Mats produced by electrospinning are of uniform density and are built from fibers of nearly the same diameter. Most of the papers published on the subject of electrospinning are intended for production of nanofibers for various nanotechnology applications, with an increasing number of applications in biotechnology[4], nevertheless recently, the problems of fabrication of nanocomposite membranes for gas cleaning applications by Ramakrishna et al.[1], Jaworek et al.[5], Jaworek et al.[6] and Sundarrajan et al.[7] have also been explored.

The physical background of electrospinning lies in the utilization of electrical forces for generating shear stress on the surface of a viscous liquid, usually a polymer solution, flowing from a capillary nozzle. Under this stress, the jet becomes thinner, and finally a thin fiber is formed after solvent evaporation.

In this paper, we demonstrate the electrospinning technology used for the production of nanofibrous filtration mats in the form of non-woven fabric, and present the results of measurements of the efficiency of removal of cigarette smoke particles from gas.

EXPERIMENTAL SET-UP

A photograph of the experimental set-up is shown in Figure 1. A thin metal nozzle made of a hypodermic needle of an outer diameter of 0.45 mm was used for the production of nanofibers. During the process of electrospinning, the polymer jet flowing out from the capillary nozzle was elongated, forming a thin thread, which became thinner due to the solvent evaporation. The electrospun fibers were deposited onto a thin metal grid stretched on a metal frame with the dimensions of 15 mm x 15 mm which was placed on a horizontally rotating grounded plate ("turn-table"). The distance between the nozzle tip and the table was about 120 mm. The nanofiber mats were electrospun from poly(vinyl chloride) (PVC), poly(vinylidene fluoride) (PVDF) polymers. PVC was dissolved in a 1:1 dimethylformamide (DMF) and tetrahydrofuran (THF) mixture by stirring at room temperature to obtain 9% solution. A 15% PVDF solution was obtained by dissolving 0.9 g PVDF in 2.48 g of DMAC (N, N Dimethylacetamide) and 2.84 g of acetone. The electrospinning was carried out at room temperature and a humidity of 45–50%. The flow rate of the polymer solutions was 1 ml/h, and the voltage was 12 kV and 14 kV for PVC and PVDF, respectively.

The morphology of the nanofibrous filtration mat produced by electrospinning was tested under a Zeiss EVO 40 scanning electron microscope and a NIKON Eclipse TS-100F optical microscope. The diameter of

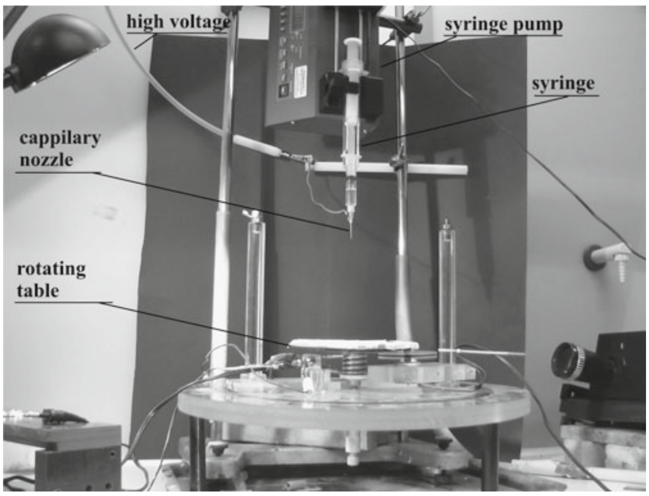


Figure 1. Stand for production of nonwoven filtration mat

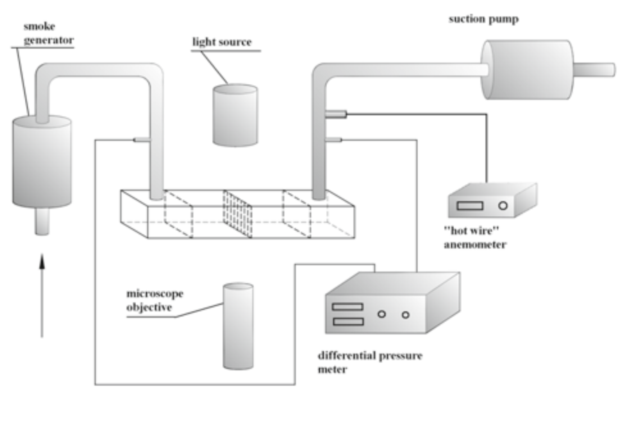


Figure 2. Schematic diagram of experimental stand for filtration process measurement

the produced PVC and PVDF fibers was in the range of 600 to 800 nm and 400 to 600 nm, respectively.

The deposition time of the fibers on the grid substrate was 8, 16, or 24 min in order to produce mats of various thickness. After the electrospinning process had been completed, each electrospun mat was dried in a vacuum chamber.

Photographs of metal grids covered with a nanofibrous layer of different thickness obtained after 8, 12 and 16 min of electrospinning are presented in Figures 3 a, b and c, respectively.

The distribution of the electric field potential and the flow rate of the polymer are the most important parameters of production of a high quality filtration mat. The electric field distribution was calculated by the finite elements method for a real 3D dimension. The numerical simulations of potential distribution between the capillary nozzle electrode and the plate collector electrode are presented in Figure 4. The electric field is the strongest near the capillary tip where the polymer jet is elongated and forms a thin thread. The Laplace equation was solved to calculate the electric field distribution. A high voltage of a magnitude equal to that used in the experiment was imposed to the needle and the plane at the bottom was grounded.

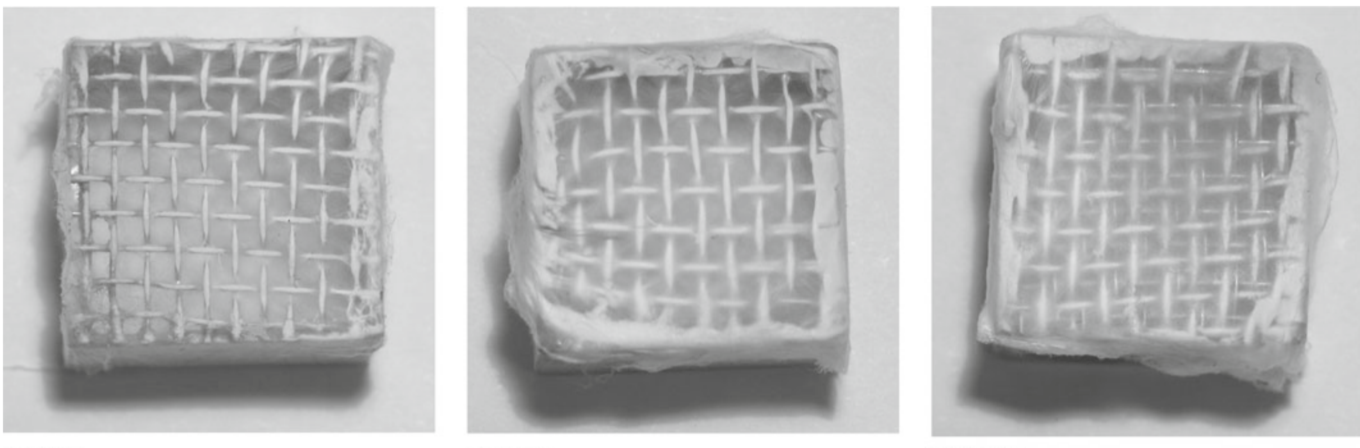
The investigations of the mechanical properties of nanofabrics were carried out by the optical method. A deformation of the nanofibrous mat mounted in a small channel of the cross section of 15 mm x 15 mm under the air flowing throughout the channel was observed by a NIKON Eclipse TS-100F microscope (Fig. 2). The pressure drop on the nanofibrous mat filters of different thickness was measured by various flow rates of air. The face velocity of the air was measured by a TSI 8455 hot--wire anemometer . The mat surface deformation during the experiments by the applied velocities was insignificant.

The effect of the mat thickness on the collection efficiency was measured by the determination of concentration of particles in the channel in front and downstream of the filtration mat by the optical microscope technique. The relative changes in the concentration of particles were determined from light extinction measurements using a NIKON CCD camera DS1 and mounted in the microscope. Cigarette smoke was used to test the efficiency of removal of smoke particles. Before and after the experiment, the filtration mat was tested under a ZEISS EVO 40 scanning electron microscope in order to estimate qualitatively the effect of the deposit particles on the fibrous filter morphology.

RESULTS

SEM micrographs of PVC polymer mats produced by the electrospinning method are shown in Figure 5. Figure 5 (a) presents an image of a clean fibrous filter, and Figure 5 (b) an image of a filter after cigarette smoke deposition. As smoke particles are mainly composed of tar, the fibers are covered with a thin film of tar which wets the fiber material. Some thin membranes which bridge the fibers can also be observed in these micrographs. SEM micrographs of a clear HEPA filter are shown in Figure 5 (c), and a filter covered with cigarette smoke particles in Figure 5 (d). It follows from a comparison of these micrographs that the diameter of HEPA filter fibers is much larger than the diameter of PVC polymer mats. This difference very clearly shows that one of the most important advantages of nanofibrous polymer filtration mats is that the small diameter of the fibers reduces the flow resistance of filters for the same filtration parameters.

Photographs of the same PVC mat taken with a NIKON Eclipse TS-100F optical microscope are shown in Figure 6. Figure 6 (a) presents an image of a clean fibrous filter, and Figure 6 (b) an image of a filter after cigarette smoke deposition. The optical microscope photograph differs from that taken with the SEM. Smoke



a) 8 min b) 12 min c) 16 min

Figure 3. Photographs of grids with nanofibrous nonwoven mats of three different thicknesses, made with different deposition time

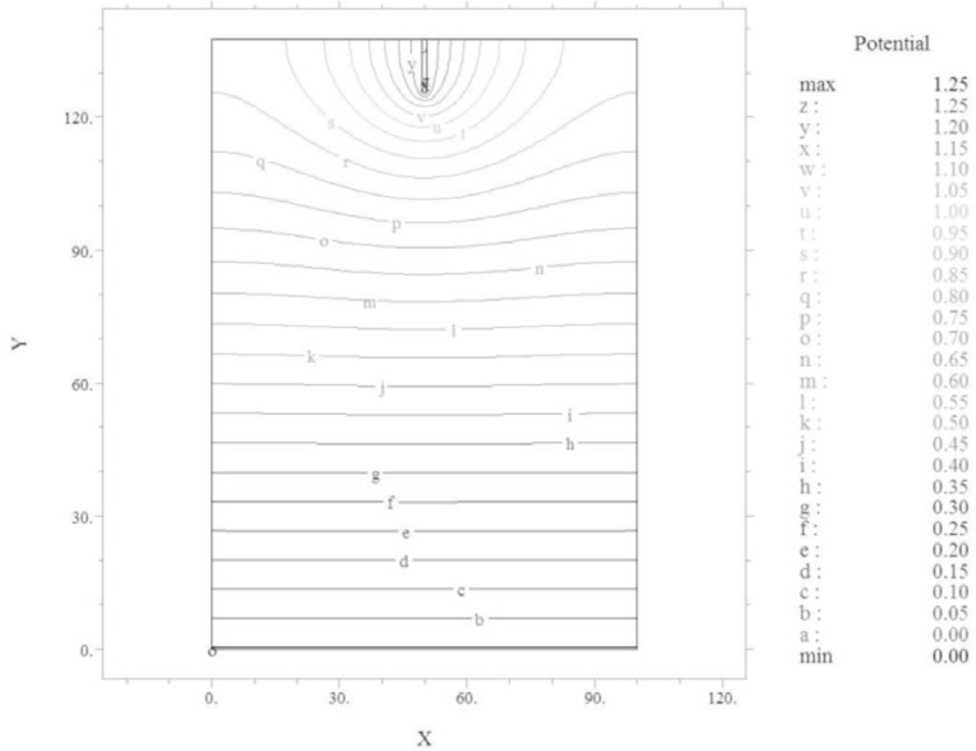


Figure 4. Potential distribution between capillary nozzle and plate collector electrode

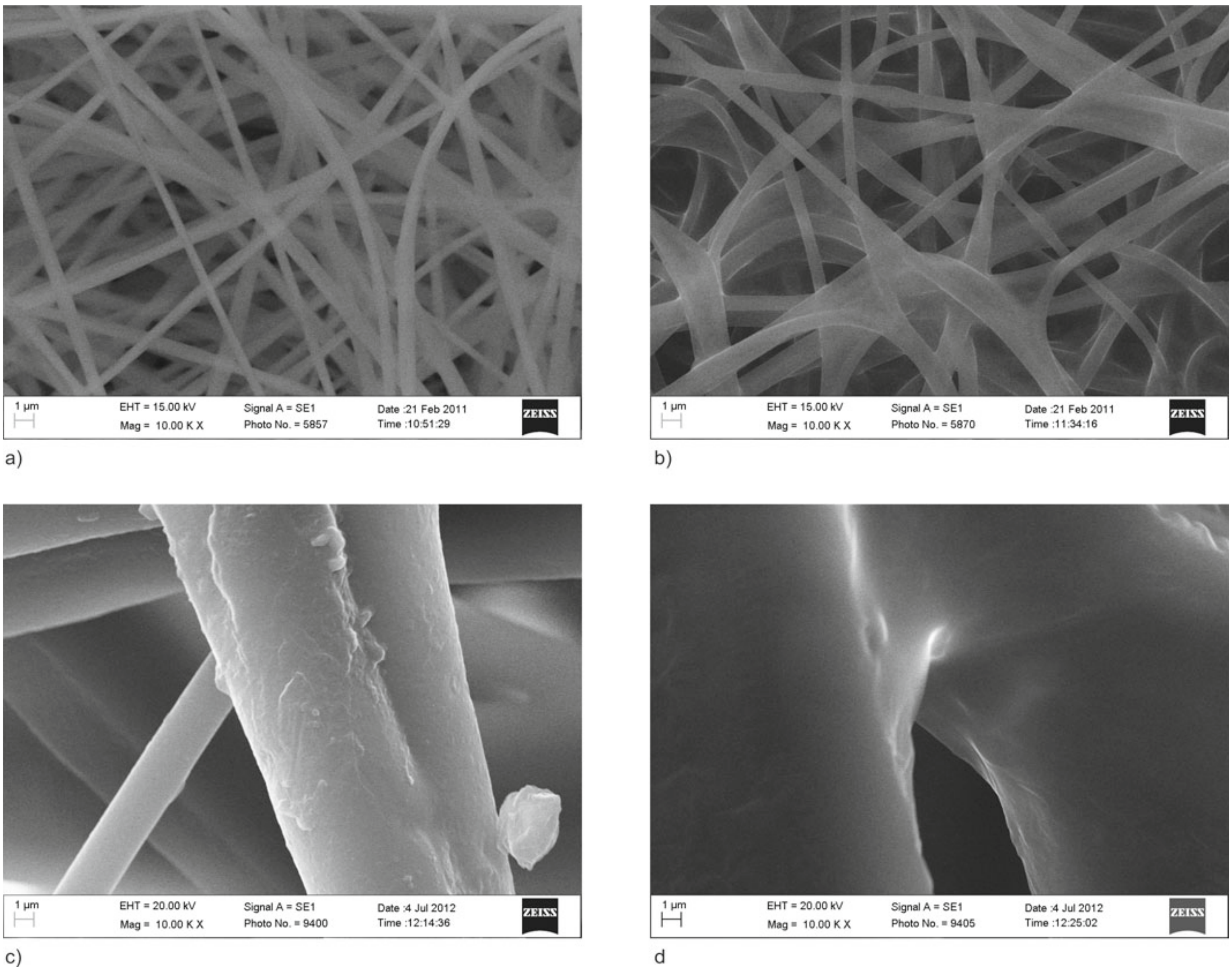


Figure 5. SEM micrographs of PVC nanofibrous polymer mats. (a) Clean filter, (b) Filter covered with cigarette smoke particles, (c) Clean HEPA filter, (d) HEPA filter covered with cigarette smoke particles

densely covers the fibers, and thin threads and beads (possible nicotine) can be noticed between the fibers. The difference between pictures in Fig. 5 b and Fig. 6 b results probably from the evaporation of nicotine after the mat bombardment by an electron beam in vacuum in the SEM.

The pressure drop on the filter is a linear function of gas velocity that indicates the viscous flow of air through the filtration mat. The collection efficiency of the nanofibrous mat filter is higher than for a HEPA filter (Fig. 7 b) by a similar pressure drop that is very important in air conditioning systems. The difference in the collection efficiency between the nanofibrous filter and the HEPA filter increases with the increasing face velocity. The face velocities used in the experiment are typical for slow flows rates in air-condition systems. A traditional cyclone system and few-layer HEPA filters do not give satisfactory results for this velocity. Electrospun nonwoven nanofibrous filtration mats have better operational parameters, for example, a lower pressure drop, than traditional systems used and a higher or similar efficiency of removal of particles with a diameter smaller than 1 μm.

The effect of the nanofibrous mat thickness on the particle removal efficiency is quite difficult to achieve as the structure of the prepared mat is elastic, and the thickness of the mat can change depending on the hydrodynamic force caused by the flowing gas. The mat spinning time was therefore the parameter used to characterize the mat properties.

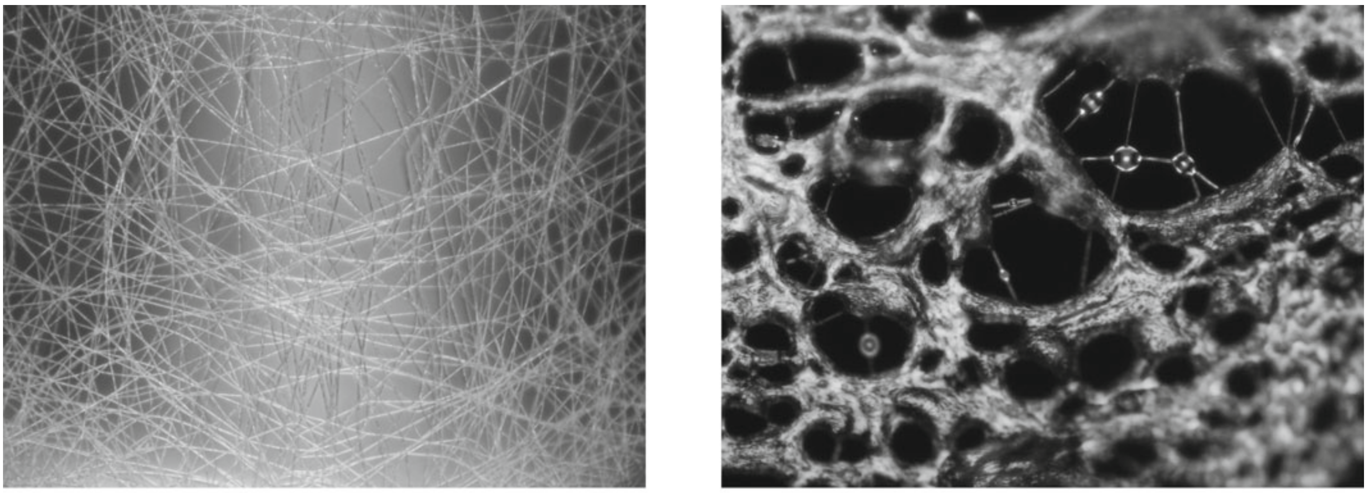
Another aspect which is connected with the problem of measuring the thickness of a nanofibrous mat is its irregular structure.

SUMMARY

The experimental results on the production and filtration properties of a nanofibrous filter mat, including the efficiency of removal of cigarette smoke particles from gas are presented in the paper. The numerical calculation of a potential distribution is presented in the paper as well.

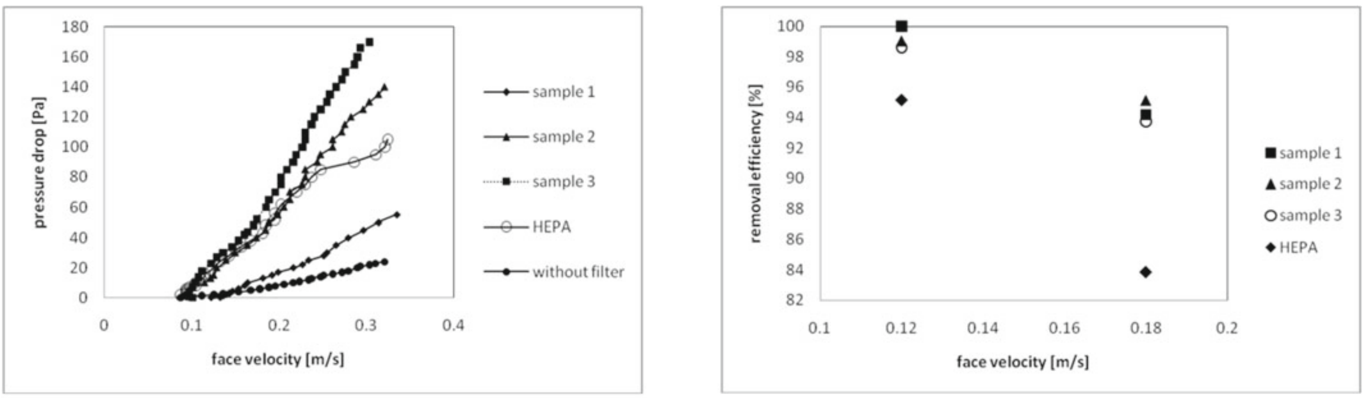
A nanofibrous filtration mat produced by the electrospinning method consists of fibers of a diameter in the range from 400 to 800 nm. The mats produced by electrospinning from PVC and PVDF were of high porosity, uniform density and made of fibers of nearly the same diameter which allowed obtaining a uniform pressure drop distribution over the entire surface of the filter.

The experimental results have shown that nonwoven nanofibrous filtration mats have a good filtration efficiency for nano- and submicron particles, better than HEPA filters. The pressure drop on a nanofibrous filtration mat is similar to HEPA filters.



a) b)

Figure 6. Optical microscope photographs of PVC nanofibrous polymer mats. (a) Clean filter, (b) Filter covered with deposited cigarette smoke



a) b)

Figure 7. Pressure drop (a) and cigarette smoke removal efficiency (b) measured by optical method. PVC nanofibrous polymer mats. Sample 1: 8 min deposition on grid substrate, Sample 2: 16 min, and Sample 3: 24 min

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