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RESEARCH ARTICLE

Facile Preparation of Novel Stainless-steel Mesh for Efficient Separation of FOG (Fat, Oil and Grease) and Water

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ABSTRACT: Large excesses of fat, oil, and grease (FOG) in food waste enter sewer systems on a daily basis, resulting in "fatbergs" that can lead to significant economic loss due to expensive removal. It is therefore vital to prevent the release of FOG into sewer systems. In this report, a low-cost and convenient method was established to coat the durable stainless-steel mesh with nano-needles and hydrogel, rendering the mesh simultaneously superhydrophilic and superoleophobic. The obtained mesh demonstrated superior capability in separating cooking oil from water, thus, showing immense potential for application.
KEYWORDS: wastewater treatment; fat; oil; grease; separation; superhydrophilic; superoleophobic.

Introduction

As one of the most common cooking ingredients, large amounts of oil are consumed every day, producing excess waste fats and grease that accumulate into a mixture of water and FOG (fat, oil, and grease). Currently, most FOG is released into sewer systems through kitchen sinks. When the FOG accumulates in pipelines, solid deposits that block the flow of drainage and sewer movement are formed. Known as "fatbergs",[1] these FOG blockages can pose a difficult problem for urban communities around the world. Every year, there are 10,000-36,000 sanitary sewer overflow events in the US and 25,000 in the UK, half of which are due to FOG.[2] Moreover, it is very expensive to mitigate the problems caused by fatbergs. In London alone, the annual cost to clean FOG-blockages reaches £18 Million[3] while one major fatberg clogging cost the city as much as £400,000.[4] New York City was forced to spend $19 Million on fat-berg removal in 2018 alone.[5]

Superhydrophobic coatings have excellent water repelling capabilities[6] and have been broadly employed for oil-water separation. For example, superhydrophobic sponges prepared using environmentally friendly and low-cost methods can efficiently remove oil submerged in seawater.[7] However, FOG-water mixtures generated in the kitchen contain water as the majority of the mixture, resulting in the need to continuously separate large amounts of water from oil. In this case, a superhydrophobic mesh or sponge is not ideal because water will rapidly block pores, leading to poor oil-water separation. In contrast, if a filter simultaneously demonstrates super-high affinity to water and super-high repulsion to oil when it is immersed in water, it is highly desired for FOG-water separation because water can quickly pass through the system with the oil components rejected.[8] The so-called superhydrophilic and underwater superoleophobic meshes have become increasingly reported in literature for oil-water separation.[9,10] The key to such materials is the existence of a stable water film kept in nanometer-sized structures on the material's surface. Currently there are two primary methods to prepare superhydrophlic and underwater superoleophobic surfaces:

1) nanometer-sized hydrophilic roughness generated using dipping,[11] spraying,[12] etching,[13] mineralization,[14] electrodeposition,[15] or laser-based methods.[16] A good example is the array of $Cu(OH)_2$ nano-needles on Cu surface based on the etching method using aqueous solution of sodium hydroxide and ammonium sulfate.[13]

2) a thin layer of hydrogel saturated with water which is coated onto the material's surface.[17,20] A popular hydrogel for this purpose is calcium alginate, which is produced from natural products like seaweed.[21]

The majority of literature methods for the preparation of superhydrophilic and underwater superolephobic meshes/membranes rely on expensive chemicals and complicated procedures, making it difficult to expand the scope of implementation in the real world. Simultaneously, there are also limitations in the current primary methods for the preparation of such meshes:

a) Because water film kept in the capillaries or pores can easily be drained due to gravity, the hydrophilic nanostructures (nanoparticles, nano-needles, nanowires, or nanotubes, etc.) may not effectively prevent the drainage of the water film during repeated use.

b) The water-saturated hydrogel is soft and can be damaged easily.

Considering the nanostructures, e.g., nano-needles can protect the hydrogel, and the hydrogel can keep a stable water film, it is reasonable to hypothesize that the combination of hydrophilic nano-needle structures and a coating of hydrogel might achieve synergy and lead to better FOG-water separation.

So far, copper meshes 22–24 and stainless-steel meshes 25–27 have been commonly used in literature studies, although cotton 28 and glass 29 meshes are occasionally reported. Copper mesh suffers from weak strength, low chemical stability, and relatively high cost. On the other hand, it is important to considered that a stainless-steel mesh would offer advantages over copper, in terms of lower cost and mechanical strength, providing that the surface properties can be better tailored accordingly to the application.

Therefore, this communication describes results from experiments using surface-modified stainless-steel mesh. It is clearly demonstrated that the synergy of nano-needles and hydrogel leads to significant improvement of oil-water separation performance of the mesh. As a result, strong and durable stainless-steel mesh with excellent oil-water separation capability can be prepared using a very convenient and low-cost method.

■ Methods

Materials:

Copper sulfate pentahydrate (from Alpha Chemicals), sodium hydroxide (from Belle Chemical), ammonium persulfate (from Eisen-Golden Laboratories), sodium alginate (from Modernist Pantry), calcium chloride (from Pure Organic Ingredients) and stainless-steel woven wire 200 mesh (12"× 40", from Yikai Store) were used as received. The DC power supply (model KPS305DF) was manufactured by EVENTEK. Food color, vegetable oil, distilled water, copper pipe and a 2-inch PVC union socket end ("Solvent Union", manufacture by Homeworks Worldwide LLC., IL, USA) were purchased from a local hardware store. Home-made chili oil was used as dye for vegetable oil.

A pocket optical microscope (ioLight Model 1, manufactured by ioLight Limited, U.K.) was used to examine the meshes.

Modification of stainless-steel mesh:

Figure 1 shows the protocol used to modify the surface of the stainless-steel mesh. In the first step, a layer of copper is coated onto stainless steel mesh. In the second step, the fresh copper layer is modified to grow hydrophilic nanoneedles on the copper surface. Finally, a layer of hydrogel is formed on the surface of either the fresh copper layer or the copper layer with $Cu(OH)_2$ nanoneedles.

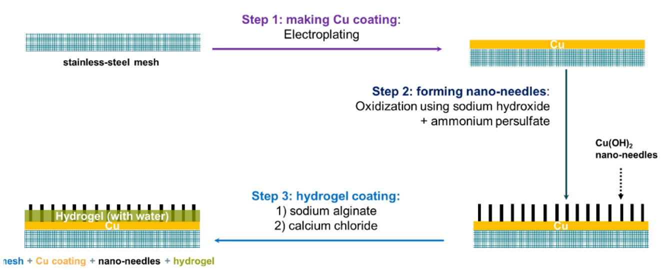

Figure 1: Three steps used for the modification of the stainless-steel mesh. In Step 1, the stainless-steel mesh was coated with a layer of copper using an electroplating method. In Step 2, a layer of copper hydroxide nano-needles was grown on the Cu layer. In Step 3, a layer of calcium alginate hydrogel was deposited on the $Cu(OH)_2$ nano-needles.

All the preparation experiments were conducted at ambient temperature. The details of the procedure are as follows.

Step 1: Coating stainless steel mesh with Copper

First, stainless steel woven wire mesh was cut into an 8-cm (diameter) circle. Then it was rinsed with water. After this cleaning process was repeated three times, the mesh was dried in air. A copper rod was polished with a piece of fine-size sandpaper first. Then, it was washed with water three times and dried in air, too. In the next step, both the stainless-steel mesh and the copper rod were immersed into 500 mL $CuSO_4$ aqueous solution (1 M) in a glass beaker. The distance between the mesh and the copper rod was kept at 5 cm. Then the copper rod was connected to the positive output of DC power supplier using the cord with an alligator lead and the stainless-steel mesh was connected to the negative output of the DC power supplier. After that, the DC power supply was turned on, and the voltage and current values were adjusted to coat a copper layer onto the stainless-steel mesh. The voltage and current used in this experiment are 3 V and 2 A, respectively. The electroplating time was kept at 1 hour for all samples.

Step 2: Growth of Cu(OH)2 needles on Copper layer

This method's details were also described in literature.[13] First, 100 mL aqueous solution containing sodium hydroxide (2.5 M) and ammonium persulfate (0.1 M) was prepared. Then the freshly prepared Cu-coated mesh was meshed with water and immersed into this solution for 1 hour. After the treatment, the copper-coated mesh became dark green. The mesh was then taken out of the solution and washed with water to remove the residual solution.

Step 3: Formation of calcium alginate hydrogel

Details of the procedure can be found in the literature.[21] First, 100 mL aqueous solution of sodium alginate (0.05 wt%) and 100 mL aqueous solution of $CaCl_2$ solution (5 wt%) were prepared, respectively. The mesh obtained after Step 2 was soaked in the sodium alginate solution for 5 minutes. Then it was taken out and washed with water to remove residual sodium alginate solution. After that, it was immersed in the $CaCl_2$ solution for 10 minutes.

Evaluation of the oil-water separation capability of the surface-modified mesh:

The oil-water separation capability of the prepared meshes was evaluated in this experiment. As explained in Figure 2, vegetable oil was doped with chili oil to make a red-colored oil while green food dye was added into water to prepared green-colored water. The colored oil and colored water were mixed in a bottle at 50:50 ratio (v/v) prior to the test. Then a piece of modified mesh was mounted onto in the middle of a Union Socket End ("Solvent Unit") made of PVC (2-inch). After that, the mesh was rinsed with some water. Once the water drained, the solvent union was placed on the top of a cup. The oil-water mixture described above (50 mL oil and 50 mL water) was shaken for 30 seconds, then it was poured into the solvent union. After 10 minutes, the liquid collected in the cup was poured into a volumetric flask. The volume values of the oil layer and the water layer were read after the oil and water had a clear boundary.

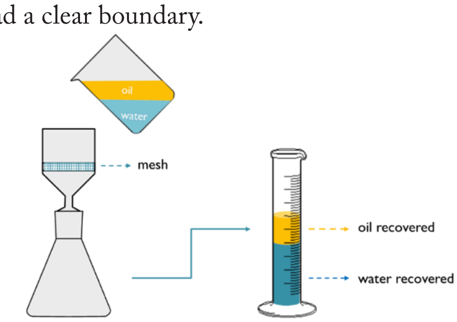

Figure 2: Schematic of the estimation of oil-water separation capability of the mesh.

Two parameters will be calculated to evaluate the performance of the mesh.

$$oil\ rejection\ \% = 1 - \left(\frac{oil\ recoveryed\ by\ tested\ mesh}{oil\ recovered\ by\ steel\ mesh}\right) \times 100 \qquad (1)$$

$$water\ recovery\ \% = \left(\frac{water\ recoveryed\ by\ tested\ mesh}{water\ recovered\ by\ steel\ mesh}\right) \times 100 \qquad (2)$$

Results and Discussion

A series of meshes were prepared using different modification conditions:

1) Stainless-steel mesh with copper coating.
2) Stainless-steel mesh with copper coating and nano-needles.
3) Stainless-steel mesh with copper coating and hydrogel coating.
4) Stainless-steel mesh with copper coating, nano-needles, and hydrogel coating.

For each modification condition, two independent meshes were prepared for performance evaluation. Images of the tested meshes are given in Figure 3. It is evident that electroplating of copper onto stainless-steel mesh reduces the pore size of the mesh (Figure 3). The growth of nanoneedles further lowered this value. Coating of hydrogel onto the mesh slightly decreased the pore size.

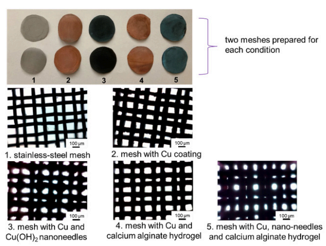

Figure 3: The meshes under evaluation and their microscopic images. The pore size of the mesh was slightly reduced after modification.

A typical result of the recovered water and oil is given in Figure 4.

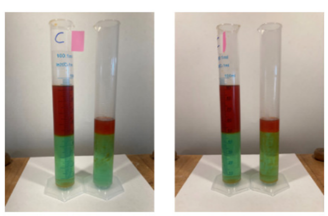

Figure 4: Oil-water separation using stainless-steel mesh (left) or stainless-steel mesh with copper coating (right). The two images represent the results of two independent measurements on individual samples. It is evident that the tests had good repeatability.

The water recovery (%) and oil recovery (%) results are listed in Table 1 and plotted in Figure 5.

Table 1: Water recovery (%) and oil recovery (%) results of the meshes investigated. The synergy of the nano-needle and hydrogel was evident by the complete water recovery as well as full oil rejection.

sample	water recovery, avg. (%)	oil rejection, avg. (%)
base mesh	100.0 ± 0.5	0.0 ± 0.5
base mesh + Cu	100.0 ± 0.5	68.8 ± 3.5
base mesh + Cu + nanoneedles	100.0 ± 0.5	80.0 ± 3.5
base mesh + Cu + hydrogel	100.0 ± 0.5	82.5 ± 5.3
base mesh + Cu + nanoneedles + hydrogel	100.0 ± 0.5	100.0 ± 0.5

The detailed morphology of the original mesh and the modified mesh cannot be examined at sub-micron level, however, the preparation of $Cu(OH)_2$ nano-needle/nanotube using sodium hydroxide-ammonium persulfate has been well documented. Therefore, it is reasonable to assume the desired nano-needle structures were formed on the meshes as reported in literature.

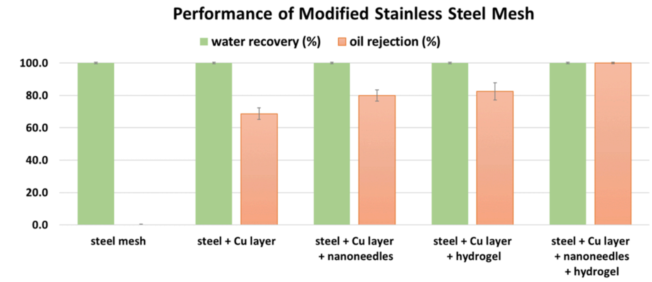

Figure 5: Performance of the original and modified stainless-steel meshes under investigation. Modifying the mesh with nano-needle or hydrogel alone could not lead to full oil rejection. On the other hand, the mesh modified with both nano-needle and hydrogel could completely separate oil and water.

The water recovery results (Table 1, Figure 5) of each tested mesh were all 100%, indicating that all meshes were superhydrophilic. The oil recovery results of these samples, on the other hand, were vastly different. The original stainless-steel mesh did not show any oleophobic properties and all tested oil passed through the mesh. When the stainless-steel mesh was coated with a fresh copper layer via electroplating, only 30% of the oil passed through the mesh, demonstrating certain oleophobic properties. Further modification of the Cu-coated mesh with either nano-needles or hydrogel will enhance the oleophobic properties of the mesh slightly, but none of these methods could completely separate oil from water (Figure 6). When these two treatment methods were combined to get a nano-needle array with a layer of hydrogel, no oil passed through the modified mesh, clearly demonstrating the desired superhydrophilicity and superoleophobicity of the modified mesh (Figure 6).

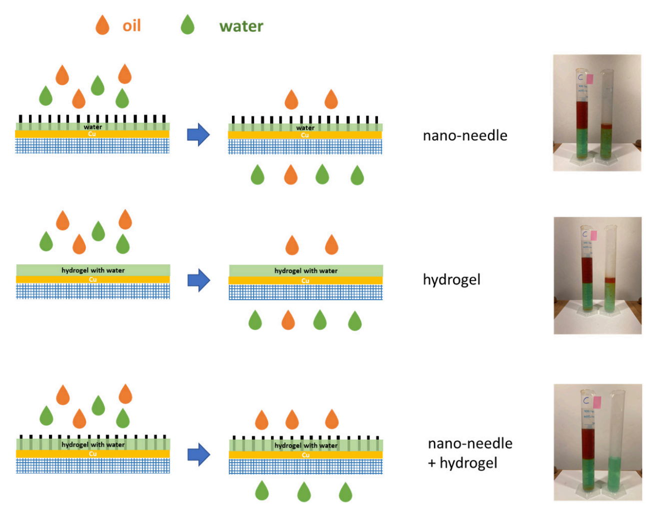

Figure 6: Schematic of the different oil-water separation performance of the meshes with different modification methods. Complete oil-water separation was achieved only when the mesh was modified by nano-needle and hydrogel.

Therefore, the hypothesized synergy of nano-needles and hydrogel regarding oil-water separation capability was demonstrated. Moreover, the meshes with desired performances can be prepared using readily available, low-cost

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materials and a convenient method. Therefore, it is expected that such meshes can be supplied at affordable prices on a large scale. The wide application of these meshes can significantly reduce the amount of FOG released into wastewater system and markedly minimize the economic loss and negative environmental impact caused by FOG clogs.

Through the approach described in this work, it was evident that a facile and cost-effective method has been established to prepare superhydrophilic and underwater superoleophobic meshes. It is envisioned that these meshes can be conveniently manufactured on an industrial scale to separate FOG from water, leading to the effective elimination of environmental and economic issued caused by FOG.

Although the method detailed in this report is extremely simple, its economic benefit could be significant if it can be applied in large scale. All the materials used in this proof-of-concept experiment purchased from local/internet shops were inexpensive. A single piece of unmodified 200 mesh stainless steel mesh (30 × 60 cm) can be purchased at $10 and the price for bulk purchase will be much lower. The cost of chemical for the modification of one piece of the mesh is less than $0.50, so the cost of the modified mesh (30 × 60 cm) can be controlled at less than $5/piece. Since water co-exists with FOG in the pipeline, the modified mesh can be installed in the pipeline for continuous FOG-water separation. In contrast, current cleaning operation of the pipeline clogged by FOG requires shutting down the water flow to remove the FOG blockage which is significantly more expensive because it involves wages for the workers and economic loss due to shut down. If this convenient and low-cost technique can be used extensively in the world, the financial benefit will be even more dramatic.

Conclusion

It has been shown that a state-of-the-art superhydrophilic and superoleophobic mesh with excellent oil-water separation capability can be conveniently prepared using low-cost materials. The key to this success was the combination of nano-needle structures and hydrogel coating on the mesh. The deployment of this novel method can help to significantly minimize the amount of FOG in sewer systems, leading to a dramatically positive economic and environmental impact.

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