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A review on application areas and surface geometry in superhydrophobic materials

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Abstract
Superhydrophobic surfaces offer many advantages beyond just being hydrophobic (water repellent) to the surface. The superhydrophobic property can be achieved by artificially creating geometric structures on the material surface. These geometric structures reduce the contact area between the liquid and the surface. The contact angle between the liquid and the surface gives rise to two conditions: hydrophobic and hydrophilic. If the contact angle between the surface and the liquid is above 90 degrees, a hydrophobic state occurs. If the angle is below 90 degrees, the surface is in a hydrophilic state. One of these two states is determined depending on the need and provides alternative solutions for many problems that currently await engineering interventions. Scientific studies in the field of superhydrophobia are increasing day by day. Interest in superhydrophobia is expected to grow further, as it offers environmentally friendly and economical solutions to ongoing challenges in various sectors. Superhydrophobic materials also offer a method of preventing icing due to their ability to prevent liquid retention on the material surface through their water repellent properties. Since the reduction of the contact area between the liquid and the material surface on superhydrophobic surfaces leads to a decrease in the friction factor, the friction of the flow on the material will also decrease. These properties of superhydrophobic materials generate interest in sectors such as aviation and marine. This study describes the properties of superhydrophobic surfaces created through various methods on materials, focusing on applications such as anti-icing and reduction of friction factor.

1. Introduction

With the widespread use of the internet recently, access to technological and scientific studies and research and development opportunities are increasing. For this reason, the development of computers, which are increasing day by day and almost becoming an indispensable part of our lives, is accelerating. The use of developed microelectronics in every field is the event that triggers the development of computer technology [1].

In the last quarter of the 20th century, the developments in the world of science have realized that material properties at the nanometer (billionth of a meter) level have become quite important. With scanning tunnel microscopes that can directly view atoms and the atomic force microscope derived from this microscope, the first stage of producing artificial materials has been realized, while providing the opportunity to examine atoms one by one and being able to be transported to the desired location in a controlled manner. Since the desired physical and chemical materials can be produced in artificial materials designed in nanometer sizes, more functional, stronger and faster processes can be produced. These new types of materials also open the doors of savings in many areas. Producing materials that consume less energy, take up less space and are smaller will also solve the problems in many sectors [2].

Quantum laws seem to be valid in atomic dimensions. The material can show visible changes depending on the arrangement of the atoms. For example, when an atom is removed from a molecule or an atom is added, the properties may change partially or completely, and many properties of the molecule such as physical, chemical, mechanical and conductivity properties may become different. This changes the feature in nano-structures and creates different opportunities for many technological applications [3].

Micro-electro-mechanical system (MEMS) is a process technology comprising miniaturized mechanical and electro-mechanical parts made using micro-fabrication methods [4-7]. Microfluidics is the science and technology of systems that process or manipulate small amounts of fluidics (10−9 to 10−18L), using channels measuring from tens to hundreds of micrometers [8]. Branson et. al. [9] studied Superhydrophobic Surface Coatings for Microfluidics and MEMs.

Yu et al. [10] presents a controllable superhydrophobic helix capable of directional bubble distribution. In the liquid, the bubble tends to stay above the helical structure and cooperates with the helical rotation. The speed of bubble delivery can be easily adjusted in terms of the spacing length of the helix. Continuous bubble collection and distribution was accomplished by integrating the helix with a gas needle, and the anti-flotation transport of the air bubble was demonstrated using an oblique superhydrophobic helix.

In recent years, scientists have focused on superhydrophobic surfaces for its non-wetting effect, corrosion resistance, friction factor, anti-icing, anti-fogging, anti-bacterial and self-cleaning properties. Superhydrophobic coated materials can be used at marine and aerospace industry areas. A major difference of the properties of a hydrophobic surface and a hydrophilic surface is given in Figure 1 and Figure 2.

Properties	Hydrophobic Surfaces	Hydrophilic Surfaces
Contact angle	High (> 90°)	Low (< 90°)
Adhesiveness to water	Poor	Good
Wettability	Poor	Good
Solid Surface free energy	Low	High

Figure 1. Hydrophilic and hydrophobic surface properties [5].

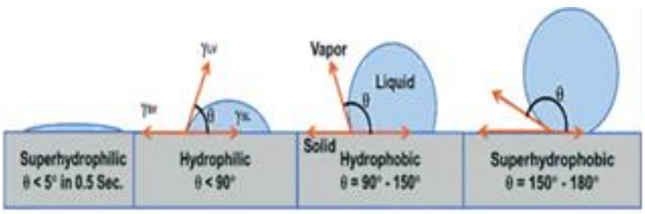

Figure 2. Various conditions according to contact angle of the drop of liquid on the surface [11].

Dou et al. [12] developed a prototype anti-icing coating with cross-linked hygroscopic polymers grafted into photolithographically prepared micropores on a silicon wafer surface. This method greatly reduces the ice bond strength and there are no durability problems as water can be reclaimed from moisture or melted ice. However, this prototype coating is of limited use because it is impractical to prepare micropores and graft cross-linked hygroscopic polymers in micropores on different solid substrates. Therefore, it is more preferable to have a mechanically sound coating with a durable lubricating aqueous layer, and most importantly, the coating can be applied directly over a variety of solid surfaces. Finally, it is crucial for the practical application of anti-icing coatings.

Materials that control ice buildup are important for aircraft efficiency, highway and power line maintenance, and building construction. Most current defrosting systems involve the physical or chemical removal of both energy and resource-intensive ice. A more desirable approach would be to prevent ice buildup rather than to end ice buildup. Recently, much attention has been paid to the freezing of static water droplets resting on supercooled surfaces. However, ice accumulation begins with droplet/substrate impact followed by freezing. Here, the focus is on the behavior of dynamic droplets affecting supercooled nanostructured and microstructured surfaces. Detailed experimental analysis of the temperature-dependent droplet/surface interaction shows that highly ordered superhydrophobic materials can be designed to remain completely ice-free down to approximately -25 to -30°C due to their ability to repel water acting before ice nucleation. Ice accumulated below these temperatures can be easily removed. The factors contributing to droplet retraction, needling, and freezing are combined with the heat transfer and wetting dynamics of classical nucleation theory, laying the foundation for the development of rationally designed anti-icing materials. In particular, the potential of hydrophobic polymeric coatings containing cell and closed cell surface microstructures suitable for enhanced mechanical and pressure stability, easy replication and large-scale fabrication, and opportunities for better tuning of materials and chemical properties are highlighted [11].

Atmospheric icing from supercooled droplets in the atmosphere can have catastrophic consequences for man-made structures built in cold climates and high-altitude regions, resulting in both socioeconomic losses and loss of human life. To reduce the icing problem, active deicing has been developed, which includes chemical, thermal and mechanical techniques to remove the ice that has already accumulated. However, these techniques are sub-optimal as they face problems such as high energy consumption, environmental hazards, high economic costs, and the need for frequent reapplications [11,12].

Most research in the field of superhydrophobicity focuses on surfaces with open cell structures, eg; column-like surfaces and surfaces containing mounds and valleys. Closed-cell surfaces have been reported to have a comparative advantage in that they are better at holding their hydrophobic properties under pressure. Using LAMMPS simulations in the work of Boinovich and Emelyanenko [13], the wetting properties of closed-cell structures (often closely linked to the syphobic properties of ice) were further investigated. The simulations show that the wetting of these surfaces meets the known Wenzel and Cassie-Baxter theories. However, at the small scale where simulations are made, the effect of adjusting the roughness scale is not as predicted by theory. Also, no comparative advantage could be demonstrated for closed cell surfaces versus open cell constructs. A physical experiment was also conducted; here the density of water droplets on the dynamic behavior of an almost superhydrophobic black silicon surface is tested. The results confirm a well-known problem: Condensation severely impairs the waterproofing of hydrophobic surfaces.

Literature review and experiments in the study of Boinovich and Emelyanenko [13] show that superhydrophobic surfaces have great potential for use in anti-icing applications, with delayed freezing, reduced ice accumulation and reduced ice adhesion. However, major problems remained unresolved, including de-icing from mechanical damage and reduced icing in humid conditions.

Ice formation and accumulation reduces the efficiency of infrastructure components, mechanisms and machinery, including aircraft, ships, offshore oil platforms, wind turbines, dams, power stations, power lines and telecommunications equipment, heat pumps, refrigerators and air conditioners. In recent years, efforts have been made to develop a more detailed understanding of the physicochemical phenomena that regulate icing processes and to develop more efficient systems for icing prevention and/or reducing its consequences [14].

The most popular defrosting strategies are generally power-consuming and not always efficient and environmentally safe. For example, mechanical and electrothermal methods are used to combat factors that adversely affect the operation of overhead transmission lines under propeller conditions. The effectiveness of these methods in preventing wet snow collection, icing, and freezing rain or frost accumulation has been repeatedly discussed in the literature. Mechanical action in an overhead transmission line creates conditions that disrupt the normal operation of a repaired section. Also, many of the mechanical methods even create additional mechanical stress. This stress can cause failure in some cases. In addition, the application of mechanical methods to combat icing of power lines generally requires access to the line and direct transport of wires and electrical transmission towers. Electrothermal methods are based on the use of heat developed during the passage of current through an object protected against icing [15].

In recent years, many electrothermal methods have been proposed to prevent ice formation or accelerated ice melting on structural parts subjected to ice formation. However, these methods require additional power consumption and expensive equipment. The use of electrothermal methods of transporting electrical energy is either accompanied by a redistribution of electrical flow in networks, and in some cases, a temporary blackout of some consumers or a more complex network configuration that allows the network scheme is required, or the parameters of electromagnetic wave propagation will be changed. Therefore, the application of electrothermal methods results in considerable appreciation of the manufacture and process of an icing protected object. In some cases, the use of such methods has adverse effects, such as a reduction in the working life of an object and an automated system that monitors its state [13].

Ice-repellent coatings can have a significant impact on global energy savings and improve safety in many infrastructure, transportation and refrigeration systems. In the development of ice-repellent surfaces, the use of superhydrophobic surfaces most often inspired by lotus leaves has been avoided in recent years, but these surfaces fail in high humidity conditions due to water condensation and frost formation, and even cause increased ice adhesion due to the large surface area. A radically different type of ice-repellent material has been reported based on slippery liquid-filled porous surfaces (SLIPS), in which a stable, smooth, low-hysteresis lubricant top layer is retained by flowing a water-immiscible liquid onto a chemically functionalized nanostructured surface [15,16].

A direct fabrication method has been developed on industrially relevant metals, especially aluminum, one of the most widely used lightweight construction materials. It has been shown that SLIPS-coated Al surfaces not only suppress ice/frost build-up by effectively removing condensed moisture, but also exhibit an order of magnitude lower ice adhesion than state-of-the-art materials. On the basis of a theoretical analysis following extensive icing/de-icing experiments, the particular advantages of SLIPS as anti-icing surfaces due to very low contact angle hysteresis are discussed, with highly reduced floating droplet sizes. Our surfaces have been shown to be non-freezing, antifreeze, where conventional materials accumulate ice. These results show that SLIPS is a promising candidate to develop robust anti-icing materials for wide applications such as refrigeration, aerospace, roofs, wires, outdoor signage, railings and wind turbines [16].

Chen et. al. [17] produced an aqueous lubricating layer with an anti-icing coating. This anti-icing coating can be applied directly to various surfaces that needs treatment. Adhesion strength can be reduced on coated surfaces to a greater extent than on uncoated surfaces. It has been proven for the first time that the ice formed on the anti-icing coating can be formed by a wind movement in the wind tunnel with controllable temperature and wind speed. In addition, even the ice grip of the low anti-icing coating can be maintained when the temperature drops to -53°C. The strength and durability of the anti-icing coating has been proven by icing/ defrosting experiments. The results show that an anti-icing coating with an aqueous lubricating layer is of great importance for practical applications. The accumulation of ice on various surfaces causes serious problems in our daily life. In some cases, it causes catastrophic events such as plane crash and power grid collapse, resulting in severe economic impacts and loss of lives.

In Kibar et al. [18]'s study, the diffusion profiles of liquid jets hitting superhydrophobic/hydrophobic surfaces were examined and the data to be obtained as a result of the experiments were estimated. A liquid jet was sent using a 1.75 mm inner diameter glass tube nozzle on the hydrophobic surfaces with flat and smooth 93, 104 and 117° contact angles. The angles of inclination between the liquid jet and the surface are in the range of 15-45°. As a result of the experiment, it was observed that the azimuth angles, where the widest widths occur, are only affected by the inclination angle. The forward length of the spreading profile of the imping liquid jet increases accordingly with the increase of the inclination angle and becomes higher than at a critical angle. It decreases as the angle of inclination increases. This critical angle is also not affected by the weber number. The theory in the literature is in good agreement with the equation predicted in the study for the azimuth angle at which the largest widths occur.

Allred et al. [19]'s study, hydrophilic surfaces showed promise in capillary wicking and boiling applications, as they increase the maximum heat flow that can be dispersed. Conversely, highly non-wetting (superhydrophobic) surfaces have been found to be largely ignored for these applications, as they have been shown to promote the formation of insulating vapor film, which greatly reduces heat transfer efficiency.

2. Method

With the development of nanotechnology day by day, the range of fields and sectors affected by the studies in this field is expanding. The increase in scientific studies in this field paved the way for new scientific studies and provided the opportunity to work in more specific areas. With the development of nanotechnology, it has become easier to understand the superhydrophobic structures already found in nature, and this advantage has opened the way to be designed and used in line with the needs. The hydrophobic and self-cleaning feature of the leaf of the Lotus flower in nature has increased the interest in hydrophobic and superhydrophobic, and studies in this field have shown that hydrophobic surfaces have many advantages besides being non-wetting and self-cleaning. An exemplary hydrophobic surface is shown in Figure 3.

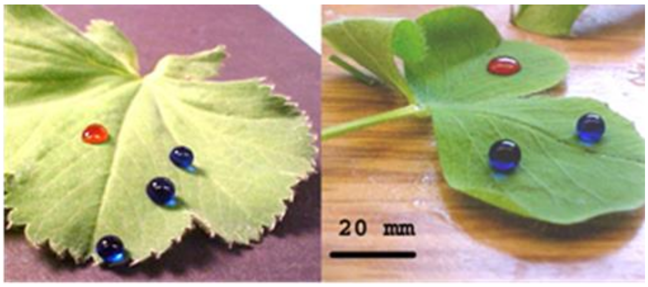

Figure 3. Leaves of Alchemilla vulgaris (a) and crimson clover Trifolium incarnatum (b) have a hairy surface that traps aqueous Methylene Blue solution in superhydrophobic drops and ethanolic Sudan Red solution in hydrophilic drops [20].

It has been determined that a hydrophobic surface provides the opportunity to prevent icing together with its non-wetting property. It is very interesting that a surface being hydrophobic causes non-wetting, preventing icing and also reducing friction between the liquid surface.

2.1 The non-wetting effect of superhydrophobicity

The most important parameter that determines the wettability or non-wetting property of a solid surface is the contact angle resulting from the bark free surface energy. The spreading area on the surface of a drop of liquid and the equilibrium at the contact line are defined by Young's Equation (1) [21,22].

$$cos\theta_E = (\gamma_{SG} - \gamma_{LS}) / \gamma_{GL} \tag{1}$$

In Equation (1), θ_E represents the equilibrium contact angle of the water drop, and γ_{SG}, γ_{LS} and γ_{GL} represents the surface tensions between solid-gas, solid-liquid, liquid-gas phases.

The contact angle obtained by Young's equation gives information about the wettability properties of the surface. If the contact angle obtained is less than 90 degrees, it is called a wetted surface (hydrophilic), if it is greater than 90 degrees but less than 150 degrees, it is called a non-wetted surface (hydrophobic), and if it is greater than 150 degrees, it is called a super-non-wet (superhydrophobic) surface. General view of liquid drop on hydrophilic, hydrophobic and super hydrophobic surfaces are shown in Figure 4.

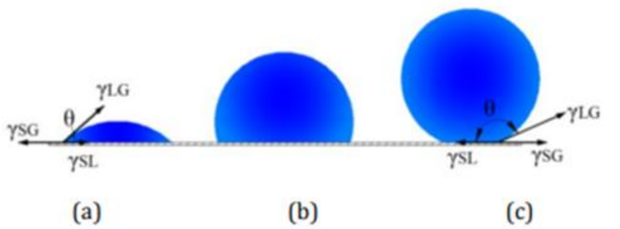

Figure 4. General view of liquid drops on (a) hydrophilic, (b) hydrophobic, (c) super hydrophobic surfaces [23].

The contact angle can reach up to 120° on a solid and smooth surface [22,23]. This contact pain can only be seen in materials such as teflon with very low surface energy. If we want to obtain a larger contact angle, the surface must be rough in micro or nano size [22,23]. This roughness has 2 consequences. The first of these is called the Wenzel state because if the liquid drop fills the micro and nano-sized spaces on the surface, since this increases the contact area of the liquid with the surface, the other is called the Cassie state because it does not fill the micro or nano-sized spaces on the surface, and if air sacs are trapped in these spaces, the contact area of the liquid with the surface decreases considerably [23]. Water drops on hydrophobic surface with regular micro surface is shown in Figure 5.

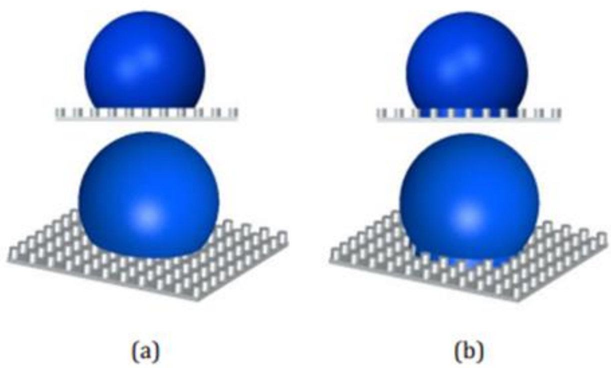

Figure 5. Water drops on hydrophobic surface with regular micro surface (a): Situation on pillars (Cassie Condition), (b): Situation where it penetrates between pillars (Wenzel case) [23].

The achievement of a hydrophobic surface is achieved using many methods, such as micro surface treatment and regular surface fabrication, spray or coating [24]. In the studies carried out by obtaining a regular surface on a smooth surface, the roughness on the surface is obtained by creating regular and repeating columns. Hydrophobic surfaces with different properties can be obtained by changing parameters such as the shape, size, distance between these columns and the applied material.

2.2. Application areas of hydrophobic surfaces

2.2.1. Marine applications

Reducing the drag of a liquid is very important for materials whose surface comes into contact with the liquid, such as ship submarine pipelines and torpedoes [25]. In this direction, in some previous studies, continuous air bubbles were sent on solid surfaces, thereby reducing the contact area between the liquid and solid surface and thus reducing the drag resistance [26]. Today, with the development of nanotechnology, it has been observed that superhydrophobic surfaces appear to be covered with a thin layer of air film when immersed in water. As a result of this observation, having a superhydrophobic surface for surfaces that have to move in the liquid will provide a great advantage as it will reduce the viscous surface friction [25].

2.2.2. Aerospace applications

Brown et. al [27] studied durability of superhydrophobic duplex coating systems for aerospace applications. Superhydrophobic surfaces, have been shown to offer improvements to heating-based anti-icing and de-icing systems, reducing energy requirements for ice prevention and facilitating ice removal.

2.3 Superhydrophobic materials' icing prevention

The materials used in the construction industry, power lines, aviation industry and many other areas are exposed to icing and this creates many disadvantages. In these sectors, materials that are not exposed to icing are of great interest and demand. Defrosting or de-icing methods used today require high amounts of energy or harm the environment. In many studies, it has been investigated how to overcome this problem by examining the dynamics of various cold surfaces and water droplets hitting these surfaces. As a result of the experiments, it was concluded that the superhydrophobic surfaces to be formed with nanostructures can prevent the initial growth of ice. Test of anti-icing properties of superhydrophobic coated material is shown in Figure 6.

While the destruction of ice spread in a thin layer, which may occur as a result of natural or artificial reasons in many materials used today, is unpredictable, the extent of the danger it may pose is also quite large.

Melting removal, which is used as a de-icing method, causes damage to the material and the time this process will take is unpredictable. Melting with salt, which is used as another method, causes corrosion on the material. In addition, ethylene glycol, which is used as another method, is a highly toxic substance.

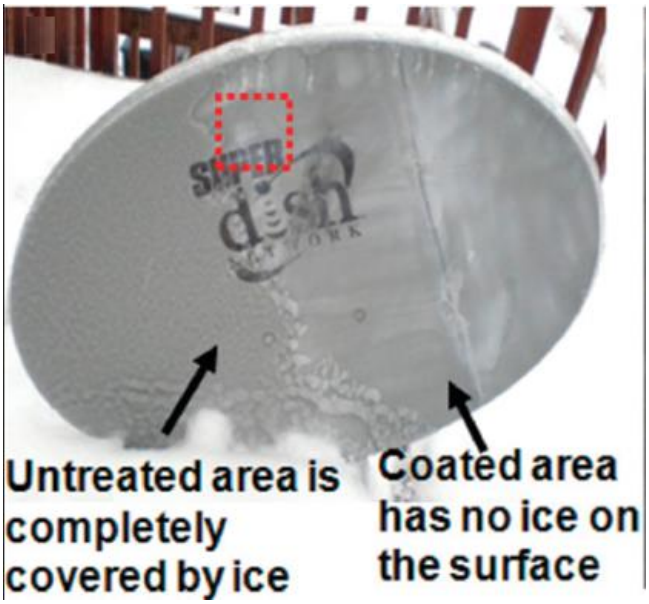

Figure 6. Test of anti-icing properties of superhydrophobic coated material [28].

Scientists are working to eliminate the threat of ice in areas where it is needed, and they are doing many studies to develop more environmentally friendly methods with less energy. Many studies by scientists show that surface geometry can be a solution to the problem of icing formation. Mishchenko et. al. [29] investigated the collision dynamics of the water droplet with a superhydrophobic surface at plus and minus temperatures. According to the results obtained as shown in Figure 7, they hypothesized that a superhydrophobic surface could repel water down to -30°C and thus prevent ice formation.

Mishchenko et. al. [29] created various geometric structures, various types of nanostructures and superhydrophobic surfaces of various sizes on a fluoride-based silicon. They carried out a series of experiments by dropping water droplets in a volume of 15 µl (a few millimeters in radius) onto the silicon surface from a height of 10 cm, with temperatures ranging from +20°C to -35°C. Droplets ranged between -5 °C and +60 °C.

As a result of the experiment, the researchers came to the following conclusions:

On an ordinary, untreated rough aluminum surface, the shrinkage of the drop after expansion does not matter: $r_{max} = r_{min}$. This result leads to a wide field of interaction and as a result, the freezing of the drop occurs within a few seconds (Figure 8).

Although the droplets contract strongly on a smooth silicone hydrophobic surface, they still maintain a non-zero contact area and will freeze sooner or later at any negative substrate temperature (few seconds if the temperature is lower than −10°C) (Figure 8).

In droplets, the superhydrophobic nanostructured surface has a complete contraction (r min = 0) for surface temperatures down to minus 25–30°C (Figure 8). Simply put, after hitting the surface, the droplets bounce off so fast that they don't have time to solidify. This can be verified by monitoring the behavior of the droplets for all three substrate types. Thus, icing does not occur on the surface.

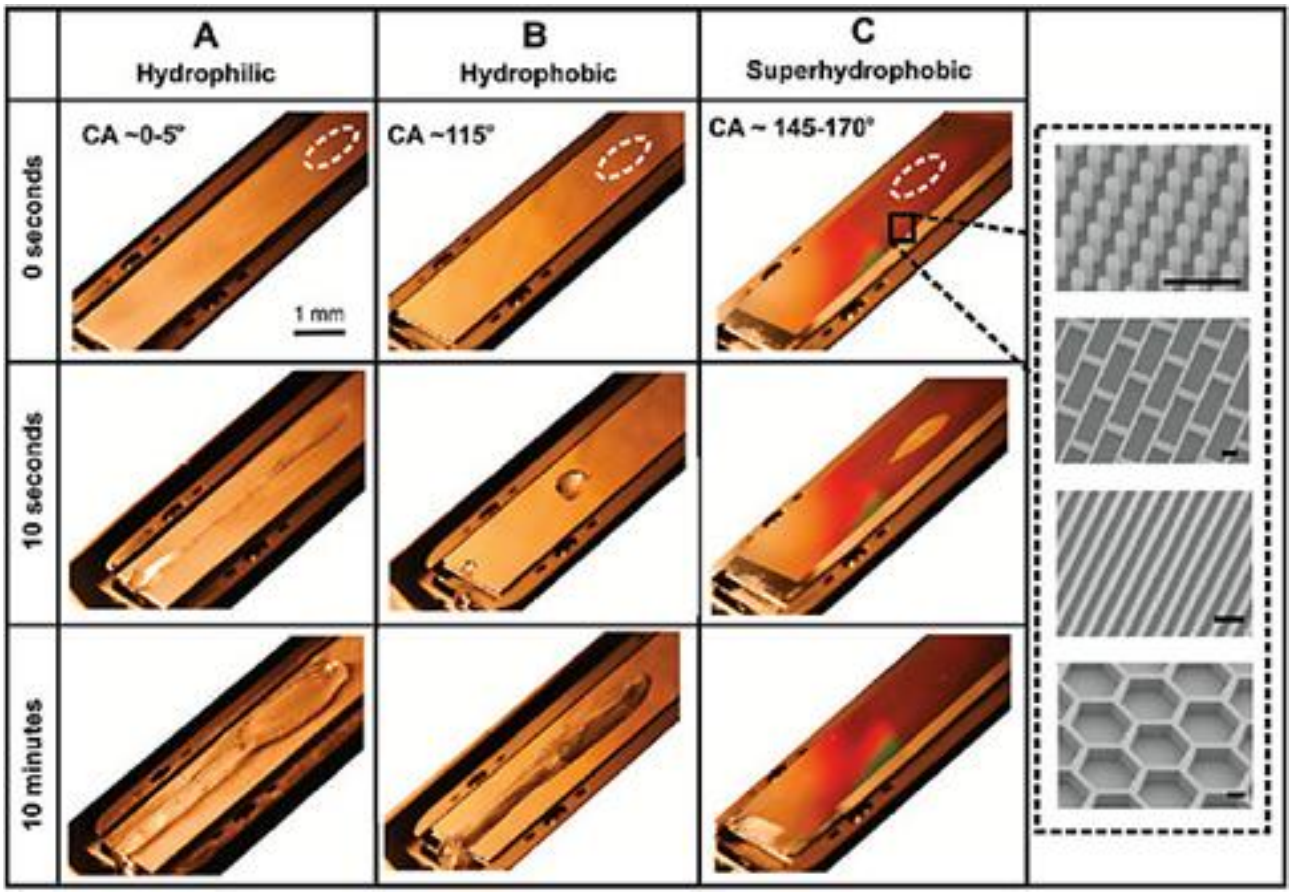

Figure 7. Ice accumulation on flat aluminum (A), smooth fluorinated Si (B), and microstructured fluorinated Si (C) surfaces. The advancing contact angle (CA) of the water droplets on these surfaces is indicated [29].

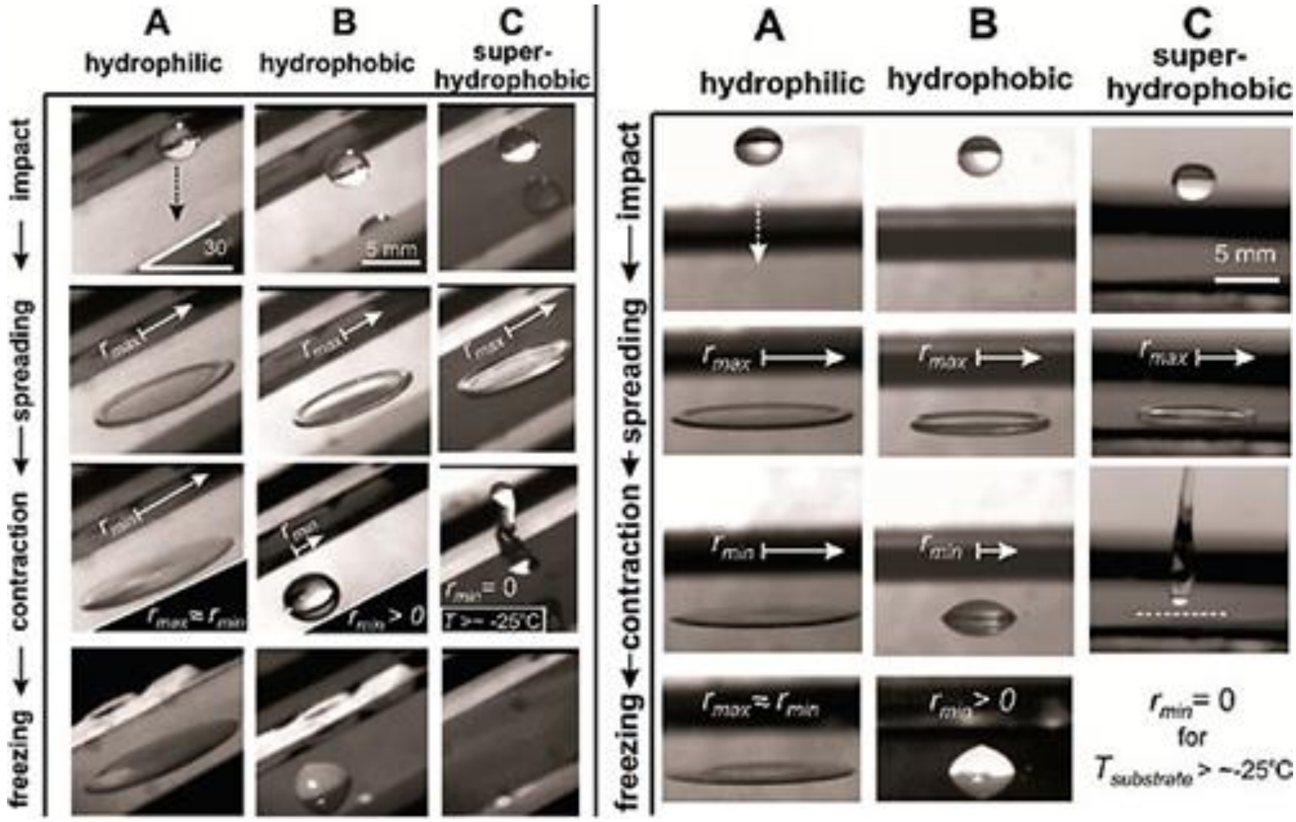

Figure 8. Dynamics of droplet behavior on hydrophilic, hydrophobic and superhydrophobic surfaces placed at an angle of 30° (left) and horizontal (right). The temperature of all surfaces is below zero. Drop temperature 0°C. The top-down photos describe the collision of the drop, the moment of maximum expansion (r_{max}), followed by compression (r_{min}), and freezing. For superhydrophobic surfaces, the compression radius is zero if its temperature is above minus 25 - minus 30°C [29].

During the experiments, scientists achieved a very important result. It has been determined that superhydrophobic surfaces can be an alternative to prevent ice as well as repel water as shown in Figure 7. In the Cassie case, the decrease in the contact area between the liquid and the surface minimizes the contact between the surface and the liquid, thus reducing the contact time of the water with the surface so that the water does not have a chance to freeze. In this way, ice will be prevented from forming without the need for any de-icing method. With superhydrophobic materials, it will be possible to solve engineering problems in many fields, save energy and eliminate the damage to the environment.

2.4 Effect of superhydrophobicity on friction

The advantages of hydrophobic surfaces are seen as a solution to many problems in the field of engineering. For example, the transmission of a fluid from one place to another requires solving many engineering problems. While transporting the fluid from one place to another is carried out with pumps, these pumps constitute 20% of the electricity consumption [30]. Today, with the increase in the need for energy, the use of fossil fuels creates the necessity of being economical in terms of both the greenhouse gas it creates and the unity of being depleted. Reducing friction losses can be a solution to both increasing efficiency and reducing the energy used in pump systems. With the developing surface coating technologies, materials with low surface energy can be produced and superhydrophobic surfaces can be created. In these created surfaces, the non-slip condition created by the fluid with the surface is eliminated, so the shear stress and friction force are reduced.

It is visualized that the flow in a pipe can be laminar and turbulent, with the help of a capillary tube placed in a transparent tube made by Osborne Reynolds and a colored liquid injected through this capillary tube. The line formed by the colored liquid injected through the capillary tube in the transparent tube gives us an idea about the type of flow. At low speeds and flow rates, the line formed by the colored liquid is seen as a straight and sharp line. In this case, the type of flow in the transparent pipe is called laminar flow. At high speeds and flow rates, the line formed by the liquid, on the contrary to appearing as a straight line, follows a random trajectory and its boundaries are broken. This type of flow is called turbulent flow. The transition to laminar flow followed by turbulent flow is called the transition regime [31]. Flow types are shown in Figure 9.

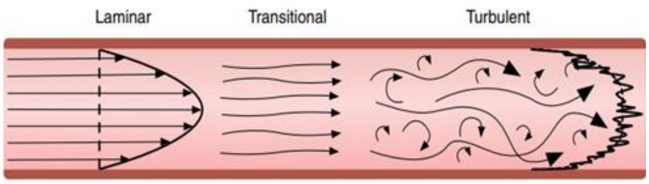

Figure 9. Schematic view of turbulent flow, transitional flow and laminar flow [32].

In many studies, the friction factor observed in laminar flow is higher than in turbulent flow. The reason why it provides the non-slip condition on hydrophobic surfaces is that the area where the liquid contacts the existing hydrophobic surface is small and accordingly liquid drops can roll on the hydrophobic surface. Effect of hydrophobic property on velocity profile is shown in Figure 10. Drops of water that can roll on a solid surface reduce the frictional force on the surface [31].

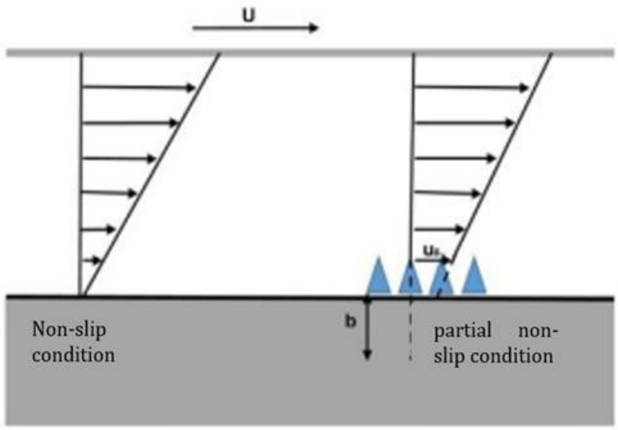

Figure 10. Effect of hydrophobic property on velocity profile [33].

Pehlivan et. al. [34] created turbulent flows between 5000 and 30000 Reynolds numbers from a 1 meter long and 15.8-millimeter diameter Flora polymer-based material (FEP, FEP-C, FEP-G) covered with hydrophobic copper pipe. Pressure losses and variation of friction factor were measured. While the contact angle of a water droplet with the copper surface without hydrophobic coating was 65', the contact angle on the inner surface of the pipe where hydrophobic properties were obtained by coating FEP, FEP-C, FEP-G were measured as 93', 96' and 102'. FEP with the lowest contact angle has the lowest reduction in friction factor compared to the uncoated copper pipe, while the pipe covered with FEP-G with the highest angle has the highest reduction in friction factor. It has been determined that the decrease in the friction factor on the inner surface of the pipe with the increase in hydrophobicity that occurs proportionally with the increase of the contact angle will cause a decrease in the energy that will be spent in the transmission of the fluid from one place to another.

Ou et al. [35] created Micro protrusions parallel to the flow direction on the superhydrophobic surface in microchannels, and this structure was measured with the Micro –PIV technique. The maximum shear velocity in the microchannel was determined to be 60% of the average flow velocity. They emphasized that superhydrophobicity is the most important factor for reducing the sliding friction factor on the surface.

Choi et al. [36] coated various sizes of grid patterns on a flat sheet. They stated that this process reduces the friction factor by 20-30%. In addition, they found that the friction factor decreased more in the flows parallel to the patterns on the nanostructure compared to the transverse flows. They explained this with the air layer formed between the grids.

Chinappi and Casciola [37] covered the uncoated smooth material surface with a hydrophobic coating and calculated the slip lengths on these surfaces by molecular dynamic simulation (MD) method. According to the calculated results, the shift length, measured at 20 nm resulted in values of 0.2-0.5 nm when measured with the help of the MD technique. The reason for these two value differences is explained by the air layer formed between the liquid-solid surfaces.

Nouri et al. [38] analyzed the reduction of friction on hydrophobic surfaces using the Large Eddy Simulation (LES) equations in their study. They also confirmed the friction reduction value, which decreased by 30% in the results they found, with the numerical simulation method (DNS). They stated that the turbulent part of the flow near the wall changes with the shear rate on the surface. They stated that this effect occurs when the slip length exceeds a certain value.

Bidkar et al. [39] stated that there is friction reduction between 20% and 30% on hydrophobic surfaces in the turbulent flow regime. They stated that the higher the Reynolds number, the lower the ability of hydrophobic surfaces to hold air, and the decrease in friction accordingly.

3. Conclusion

Literature researches and studies show that nanotechnology is one of the strongest bridges that can be formed between the present and the future. With the inspiration taken from nature and the discoveries of science, it will become more possible with nanotechnology to meet the needs of humanity and our environment with more effective and more environmentally friendly methods using less energy. Superhydrophobic surfaces also play an important role in achieving this goal. It is quite clear that superhydrophobic surfaces offer more environmentally friendly engineering solutions with less energy, as they do not hold water, prevent icing and reduce friction losses. It is expected that the use of such designed surfaces and materials will become widespread in the future and will open the door to many more innovations.

There are low-cost applications of superhydrophobic materials with low water contact angle and slide angles [40].

Author contributions

Serhat Akinci: Methodology, Writing-Reviewing, Writing-Original draft preparation. **Filiz Karaömerlioğlu:** Methodology, Writing-Reviewing, Writing-Original draft preparation. **Emre Kaygusuz**: Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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