Contribution of Superhydrophobic Surfaces and Polymer Additives to Drag Reduction

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Abstract

Drag reduction has constantly received great attention due to its extensive range of applications in fluid transportation and vehicle industries. The vital role of two different additive and non-additive techniques (polymer additives and superhydrophobic surfaces) to reduce the drag force experienced by underwater vehicles, fluid flow through pipes, ducts, open or closed channels, and other wall-bounded laminar and turbulent flows is highlighted. Reducing the drag resistance can significantly enhance the performance of immersed vehicles and results in saving the energy consumed on a large scale. The progress in theoretical modeling, experimental and computational studies of both techniques are reviewed, together with the surface design, wettability, and influence of the roughness factor of superhydrophobic surfaces and the effect of polymer drag-reducing agents for wall-bounded flows and multiphase flows. General formulations, potential applications, and major issues involved in the aforementioned approaches are summarized.

Keywords: Drag reduction, Polymer additives, Superhydrophobic surfaces, Turbulent flow

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1 Introduction

With the scarcity of energy resources and ever-increasing costs facing the earth today, the scientific community has worked for decades to find solutions to minimize the fuel consumption of transportation systems. As an example, the skin frictional drag for a moving ship (cargo ship) is nearly 90% of the total drag force [1]. Emission of SOₓ and NOₓ from engines of ships during nautical transport accounting for 4% and 7% of total SOₓ and NOₓ containments were reported and are causing dangerous problems to the environment [2]. Therefore, the reduction in the frictional force is a significant problem in the area of the shipping industry to save global energy consumption on a wide scale [3, 4]. Additionally, biofouling is a major cause of drag increase in the underwater environment and leads to higher energy consumption.

In recent decades, the discovery of a turbulent coherent structure has changed the early traditional understanding of turbulence that is completely random. This major discovery not only makes people realize the orderly side of turbulence but also helps to control turbulence through the interference of this large-scale coherent structure more effectively. The effective means of turbulent drag reduction (DR) is to control the turbulent burst events by changing the coherent structure and then affect the flow very close to the wall. The number and intensity of these turbulent burst events are the result of the non-linear automatic generation process of the coherent structure near the wall.

DR researches have focused on exploring effective DR technologies for decades and tried to figure out how the drag force could be minimized and prevent the fouling phenomenon which may reduce the cost of transportation. There are several approaches introduced to overcome this critical issue. By comparison, it can be found that most of the DR schemes can produce a certain DR effect under specific conditions. But in actual engineering applications, various problems will arise, such as...
high technical difficulty, weakened DR effect, poor durability, and it might have a negative impact on other equipment. Therefore, although the research results of various DR schemes have been fruitful in recent years, real practical applications are very limited.

The DR method that meets the engineering needs should have a higher application effect and durability, and the simpler the structure is, the easier it is to implement and generalize. Taking surface and underwater vehicles as examples, suitable DR methods need to be able to cover a larger area in realistic use, lower maintenance cost, and higher environmental adaptability, and do not produce negative effects in the case of complex structural deformation.

Among the DR schemes, superhydrophobic surfaces (SHSs) and polymer additives (PAs) are promising and effective DR technologies. Initially, the surface with micro/nano-bumps (superhydrophobic surface) of natural creatures caught the attention of researchers. Rough structures on the surface of creatures trap the air layer ascribed plastron. The plastron layer minimizes the water-solid interaction and enables aquatic and semiaquatic animals to swim and move on the water surface easily [9]. These natural conditions give us great insights to reduce friction force. There are several methods to prepare artificial SHSs of different textures in laboratories. These prepared surfaces exhibited surprising results in DR. Furthermore, SHSs possess the capability to reduce biofouling, thus prevent contamination of submerged parts of ships from organic contaminants and enhance the durability of ships. Knowledge about how different surface properties such as morphology, roughness, and surface chemistry influence surface wetting and stability is necessary to prepare valuable SHSs.

Polymer-induced DR has attracted continuous attention over several decades since its discovery. DR agents (DRAs) are used at very low concentrations to accelerate significantly the flow in diverse applications such as oil pipeline conduits, flood water disposal, fire fighting, field irrigation, transport of suspensions, slurries, sewer systems, and marine systems. Polymer additives are well-known for controlling wall-bound turbulence in preliminary literature [10]. However, recent studies on PAs have evinced DR efficiency of PAs for open channels as well as flow over bluff bodies [8].

Both aforementioned techniques exhibit the effectual implications and interesting results for reducing skin friction as compared to other DR technologies. The practical benefits of these technologies include higher capacity and smooth flow through pipelines, over marine vessels, and fast-moving ships.

This review article presents advancements involved in both technologies for hydrodynamic flows in friction DR. Much of the work reported here for SHSs is aimed to illustrate external flows of floating and submerged vessels, while the PA study referred to internal hydrodynamic flows. In recent years, researches have demonstrated that SHSs and polymer additive techniques have some limitations due to unsolved problems in the physics of droplet motion and complex chemical composition of polymers, respectively. Due to operative results, these technologies are of great interest for both industrial applications and academic pursuits.

2 Superhydrophobic Surfaces

Low surface energy combined with roughness in micro and/or nanoscale becomes highly water-repellent, known as hydrophobic surfaces (HSs). These surfaces attain the ability to repel water or any kind of liquid effectively due to a large proportion of gas-liquid interfaces and water sites on ridges characteristics.

2.1 Self-Cleaning Plants and Biomimetic Surfaces

It has long been observed that water droplets on the lotus leaf slide over the surface with little resistance. The water drop behaves as an elastic ball while rolling off the lotus leaf due to a high contact angle. When a drop rolls off a tilted rough surface owing to a large contact angle, an effective macroscopic slip occurs. In the case of an ordinary hydrophobic surface, dirt particles are shifted to the sides of the water droplet on account of non-slip conditions (low contact angle) and redeposit on the surface. However, in the water-repellent rough surface case, water forms a spherical droplet which reduces the solid-water interface. It collects the particles from the surface and rolls off the leaf [9].

The rolling-off mechanism is termed as the "lotus effect". A self-cleaning effect is evident for the lotus leaf. The underlying mechanism of this effect of the lotus leaf has been investigated thoroughly [10]. First, a detailed microscopic study has been conducted by Barthlott and Neinhuis in 1997 [11]. The microscopic structure of the lotus leaf is depicted in Fig. 1 (left) [12].

Figure 1. Electron micrograph of a lotus leaf (left). Water droplets almost adopt a spherical shape on the waxy protrusion of the leaf surface [12]. Salvinia biloba found in ponds uses a waxy coating to prevent getting wet (right).
Floating leaf (Salvinia biloba) is another example of a plant having a highly repellent surface found floating in ponds (see Fig. 1, right) [12]. The waxy coating of leaves maintains a gas layer used during the photosynthesis process [13].

The water repellency constituted from bird feathers due to their hierarchical topography of surfaces received great attention since a long time. A scanning electron microscopy (SEM) image of pigeon feathers is presented in Fig. 2. The microstructure of the feather provides a remarkable stability to the wetting transition. A high value of critical pressure of 100 kPa is necessary to get wet and the feather help birds to withstand the high dynamical pressure of rain (Fig. 2) [14].

The physical mechanism of water repellency of lotus leaf and bird feathers is very different. The lotus leaf surface exhibits a true hierarchical surface whereas the surface of bird feathers demonstrates a pseudo-hierarchical relief. This fact compels researchers to think in a new way about sea animals about their swimming process. Additionally, semi-aquatic creatures are allowed to move easily in and on the water surface due to these microfeatures. The leg of water striders contains hierarchical nano- and microstructures, i.e., numerous needle-like setae.

In nature, a large number of animals and plants are observed to have nano- or microscale surface morphology which helps them to reduce the drag force of, e.g., seabirds during their swimming and for self-cleaning of plants. During the past few decades, SHSs have attained much attention for their large variation in applications ranging from self-cleaning to anti-icing and anti-wetting to anticorrosion.

### 2.2 Theoretical Background and Fundamentals

The most important factor on which the nature of a surface depends is its ability to get wet. The contact angle $\theta$ is one of the significant parameters to determine the wettability of a surface. It displays the static equilibrium between three materials, i.e., the liquid, gas, and solid. The contact angle should be larger than 90° to repel liquid while $\theta < 90^\circ$ is for wetting applications. A surface is called hydrophilic if $\theta$ is between 0 to 90°, hydrophobic for 90° < $\theta$ < 150°, and ultra- or superhydrophobic for $\theta > 150^\circ$.

Generally, the contact angle is calculated for a static droplet of a defined size. Shape and size of a droplet alter as the droplet starts to roll off on an inclined plane. It results in a change in contact angle which is called contact angle hysteresis (CAH).

CAH arises from the topographical heterogeneity of a surface and entirely depends on the advancing and receding contact angles (\(\theta_a\) and \(\theta_r\)). Mathematically, CAH is represented by \(\Delta \theta = \theta_a - \theta_r\). A low contact angle hysteresis stabilizes the center of mass above the surface and enables droplets to roll on the surface with low resistance.

The underlying physics of CAH still lacks consensus, thus it complicates the wetting phenomenon. For superhydrophobic surfaces, the angle hysteresis should not exceed 5°. The lotus leaf has a CAH of 2°, hence it is a perfect self-cleaning material [11]. The onset of wetting transition is predicted by a nondimensionalized Weber number. Three different types of roughness are analyzed to understand the dynamic behavior of droplets and their rebound and splashing [15].

Young [16] was the first who proposed force equilibrium at the contact line of three mutually contacted materials for non-textured and chemically homogeneous solid surface as:

$$\gamma_{gs} - \gamma_{sl} = \gamma_{lg} \cos \theta$$

where $g$, $s$, and $l$ represent gas, solid, and liquid phases and $\gamma$ is the interfacial energy. The preceding equation indicates that a material with a high contact angle is qualified as having low surface energy. This implies a lower ability of the surface to bond with other materials and vice versa. Under strong cohesive force and displaying $\theta < 90^\circ$, glass is a perfect hydrophilic surface [17]. Teflon is a well-known material with hydrophobic surface with an average $\theta = 103^\circ$ with large hysteresis [18].

Wenzel [19] argued that no perfectly smooth material exists in real life and proposed a roughness parameter $r$ concerning the projected area $A_p$ and actual wetted area $A_w$ such that $r = A_w/A_p$ [19] where $r > 1$ for rough surfaces and $r = 1$ for perfectly smooth surfaces. For a rough surface, the contact angle for Wenzel’s model is given by:

$$\gamma \cos \theta = \cos \theta_W$$

Water can either suspend above or penetrate the asperities. Limitations and applications of Wenzel states are discussed by Mamur and Wolansky [20]. Despite limitations, Wenzel’s theoretical model is a useful scheme for uniformly distributed rough surfaces.

Cassie and Baxter [21] proposed textured surfaces as not completely wet having some air trapped in between solid and liquid surfaces (Fig. 3). The presence of micro-/nanostructures has a remarkable influence on flow behavior of fluid through

![Figure 2. SEM images of pigeon feathers with scale bars of 100 μm and 10 μm [14].](image)
2.3 Fabrication of Artificial Superhydrophobic Surfaces

Inspired by natural hierarchical structured surfaces with water-repellent properties of plants and animals, coating technology attained great attention in recent decades. Altering the physical topography and chemistry of surfaces produce the liquid-repellent ability of surfaces. A number of artificial superhydrophobic coating surfaces of different textures were developed at laboratories. Generally, the prepared surfaces have either random or patterned micro-/nanogrooves on the surface. Chemical deposition is a commonly applied method in experiments, while riblets and ridges are mostly used for numerical simulations.

2.3.1 Electrochemical and Chemical Deposition

Electrochemical and chemical deposition methods are intensively employed to prepare artificial anti-wetting surfaces experimentally. Several methods are utilized to model robust liquid-repellent rough surfaces in laboratories included photolithography [23], templation [24], plasma treatment (poly(tetrafluoroethylene) (PTFE), poly(ethyleneterephthlate) (PET)) [25, 26], layer-by-layer (LBL) deposition [27], hydrogen bonding, self-assembled monolayers (SAMs), and colloidal assemblies [28–30]. The aforementioned techniques are categorized as bottom-up and top-down methods. Literature has shown that chemical methods of coating are well acceptable in wettability and DR [28, 31–33].

Both the random and micropatterned rough artificial superhydrophobic surfaces are developed with electrochemical and chemical deposition. Studies consistently enlightened that chemical deposition on a surface intensifies its ability to repel liquid over the surface and ensure minimal drag force experienced by fluid while flowing over/through surfaces [34–36]. Chemically prepared SHSs with uniformly distributed grooves may lower the drag force up to 50 % [37, 38].

Two types of rough surfaces (nanogrooves and nanobricks) are constructed by photolithography and chemical decomposition methods (Fig. 4) [37]. A series of tests were performed in a water tunnel. Both surfaces demonstrated promising results in reducing skin friction. However, the silicon nanobrick was found to be more favorable in resisting hydrostatic pressure by trapping air in closed cells (Fig. 4, right). A randomly rough superhydrophobic surface prepared by sanding PTFE method with sandpaper exhibited a maximum of 27 % pressure drop reduction and apparent slip length of $\lambda = 20 \mu m$ for grit size 240 [29].

A random SHS fabricated through electrodeposition aluminum in an ethanol solution containing cerium nitrate hexahydrate and myristic acid is presented in Fig. 5. Results indicated a promising anticorrosion and anticontamination performance of the prepared superhydrophobic surfaces [35].

Recently, some other methods were developed by coupling different prescribed chemical deposition approaches, and various applications have emerged such as water-repellent fabrics, sensors, and optical devices [39–41].

2.3.2 Patterned Microfeatures

Grooves or riblets of square or blade shape of specific length are often considered in the case of numerical studies. Riblets and ridges of certain sizes ensure superhydrophobicity and the capability of surfaces to withstand in a high-pressure environment. Fig. 6a presents various types of riblets utilized to model SHSs [42]. Nano-/micro-sized corrugations trap air between peaks to prevent direct liquid-wall interaction and provide a shear-free water-air interface (meniscus). The existence of the
an air cavity in between liquid and substrates produces a liquid slip [43]. The influence of the meniscus area and its dependence on the slip length are calculated in [44]. Alternating shear-free and no-slip boundary conditions disturb the near-wall cycle [45].

With the gradual increment in spacing ($s$) between ridges (Fig. 6) the liquid slip grows until an optimum spacing is reached. Usually, an optimal spacing is obtained at $10 < s^* < 30$, where $s^* = \frac{s}{\sqrt{\frac{\tau_w}{\rho v^n}}}$ is the kinematic viscosity, $\rho$ is the density of fluid, and $\tau_w$ is the shear stress at the wall.

The amount of liquid slip is measured by the slip length. The effect of slip on a surface to minimize skin friction has been verified through theoretical predictions and numerical simulation. The analytical solution, as well as numerical results, are obtained for multiphase shear flow over longitudinal grooves. Trapped gas is also included in the previous analysis and numerical simulations for both meniscal and flat interfaces. An increase in DR is found with the initial deflection of interface, and with the large deflections DR is decreased. DRs of 9.5 % and 0.35 % are predicted through analytical solutions for $\mu = \mu_{gas}/\mu_{liquid}$ [46]. Here, $\mu_{gas}$ and $\mu_{liquid}$ denote the dynamic viscosity of gas and liquids, respectively.

Boundary conditions of fully slip and slip/no-slip walls have been utilized to predict a reduction in skin friction and flow behavior [47–49]. As much as 30–40 % DR is found in an experimental study in open water [50]. Modern researches demonstrated a slip length in micrometers over SHSs which is larger than the slip length in the case of hydrophobic surfaces. Moreover, the slip length can be extended to 400 $\mu$m and results in frictional DR [51, 52]. The slip in the case of aligned texture was found to be higher than random texture features of similar size and is directly related to the normalized slip length $\lambda_D$ [53, 54].

Reduction in skin force elevates with increasing feature size and spacing up to a certain limit [55, 56], while in a rotational bluff body a higher DR is noted for the low rotational case along with small scaled structure in com-

Figure 6. (a) Generally used $V$, $U$, and $L$-shaped riblets, where $s$ is the spanwise spacing, $h$ is height and AG is the area between the riblets. (b) Schematic and dimensions of the flared pores. (c) Cross-sectional schematic of one sample (not at scale). (d) Slip lengths were calculated in the laminar regime for the control disk and the samples with 10, 100, and 1000 $\mu$m grooves. (e) DR (in %) compared to the control flat sample in the laminar regime [57].
2.4 Turbulent DR by Using SHSs

Unlike the laminar flows, in turbulent flows a number of complex phenomena complicates the flow problem in terms of pressure fluctuations, unsteady three-phase interface, eddy formation, and significant shear stress. Thus, the DR amount in turbulent flows highly depends on both SHS morphology and Reynolds number in contrast to laminar flows. Numerical models and simulations have provided a new way to understand underlying physics and analyze the results along with experimental work. A low surface roughness relative to viscous sublayer thickness together with a Cassie-Baxter state is necessary for successful DR in turbulent flow regime [60].

2.4.1 Computational and Experimental Insights into Turbulent DR

Turbulent DR is a complex phenomenon. Streamwise ridges have been studied numerically in turbulent flows to uncover the underlying mechanism of DR. Slips in the streamwise direction minimize the intensity of turbulent fluctuations and steadily decrease the drag force. On the other hand, an increase in drag force is also observed with regard to the increasing spanwise slip [51]. Consequently, in the presence of complex turbulent structures, the slip direction gives rise to opposite results [61, 62]. However, with the spanwise slip effect, it is found to reduce the drag force when the streamwise slip outweighs the spanwise slip in the presence of SHSs [61].

Researchers found in a near nonslip wall boundary layer that the presence of microfeatures weakens the cross-motion which reveals turbulence controlling [57, 63–65]. At a given Re and width-to-spacing ratio ($\phi_w$), the slip velocity attains a maximum of 75% of bulk velocity for posts and 65% of bulk velocity for ridges. A remarkable decrease in streamwise vortical structure strength and reduction in $Re_c$ is noticed [61,66]. DRs of the order of 5% for $\phi_w = 0.7$ and 75% for $\phi_w = 0.03$ are noted [67]. A DR as high as 70% is reported over silicon-etched fractal microgrooves SHSs for turbulent flows at Re numbers of the order $10^6$ [68].

Suppression of coherent structures bursting in the near-wall region is the key mechanism in reducing the skin friction for a turbulent boundary layer (TBL) over SHSs, and the DR is calculated from $DR = \frac{\tau_{nslip} - \tau_{SHS}}{\tau_{nslip}} \times 100$ [69, 70], where $\tau$ is the shear stress.

The calculation of the slip length defined as $\lambda_l = (\partial \bar{u}/\partial \bar{x})_s$ is laborious to measure from the pressure drop in the turbulent flow case. Here, $i = 1, 2, 3$ and $(\partial \bar{u}/\partial \bar{x})_s$ represent the average tangential fluid speed components, slip length, and tangential velocity gradient in i-th direction [60,70].

Experimental studies demonstrated the dominant effect of slip in the near-wall region [71]. The onset of DR is observed at $Re_c$ where the viscous sublayer thickness approaches to fractal microcorrugation scale [60,69].

Turbulence statistics for channel flow are attained from normalized streamwise velocity $U = \bar{u}/U_{in}$, $U^+ = u'/u_c$, the turbulence intensity $U_{rms}^+ = \sqrt{u'^2}/u_c$, $V_{rms}^+ = \sqrt{v'^2}/u_c$ and the Reynolds shear stress $T_{turb}^+ = -u'v'/T_{90}$, where $T_{90}$ is the measured maximum total shear stress of the smooth surface, $T$ is the total shear stress, $u', v'$ are disturbance velocities, $\bar{U}, \bar{V}$ represent the mean velocity, $U_{in}$ is the free-stream velocity, and $u_c$ denotes the shear velocity. Suppressions in turbulent intensity are observed, and reductions in the Reynolds shear stress $T_{turb}$ obtained are 2.5%, 18.5%, and 23.1% for $Re_d = 810, 990, \text{and } 1220$, respectively [30,72]. Meanwhile, the flow over flexible periodical ridges shows a substantial reduction of $T_{turb}^+$.

The anisotropic process of turbulence and roughness interaction was investigated through experiments. The turbulent kinetic energy (TKE) dampened and partially returned to the smaller scale turbulence through the spanwise oscillation of rough structures [73]. Numerical investigation revealed the relation between contact angle and DR, and an increase in drag force by 40% for a reduction in the contact ratio from 90% to 10% is reported [74].

Four different superhydrophobic surfaces were tested in fully developed turbulent flow for height-based Reynolds numbers of 1–3×10^4. A significant DR based on the morphology of the surface was noticed and DR > 50% was obtained [75]. Overall, it is concluded that to achieve a meaningful turbulent DR, both the roughness and CAH at high pressure must be minimized.

An emerging model, which is termed the shifted-TBL model, is presented by Seo [76] and sheds light on the kinematic characteristics of turbulent flows over SHSs. For the first time, from pattern average data, joint distributions of instantaneous $u_c$ and wall shear strain of over a wide range of texture size $L = 6–30$ are determined. However, homogenized boundary condition (BC) remains unable to capture the bulk behavior of the patterned surface. In another study conducted by the same group for $L = 6–155$, pressure statistics and stagnation pressure distribution are found to be self-similar and insensitive to turbulence [45]. By studying the mean velocity profile with digital holographic microscopy, Ling et al. pointed out that the DR is a result of the competition between the roughness-induced increasing Reynolds stress and slip-induced reducing friction by SHSs [77].

For turbulent DR, multiple researchers have started to evaluate a scalable surface termed NeverWet coating, which is a sprayable suspension of hydrophobic silica nanoparticles immersed within a silicon matrix. The efficiency of NeverWet surfaces was evaluated first by Aljalis [30]. An increment in DR from 10% to 24% was noted by raising the $Re_c = 329$ to 467. In the presence of NeverWet coating and low speed, turbulent structures were significantly modified [72]. Another study illustrates that the reduction in Reynolds shear stress for $20 \leq y' \leq 80$ leads to DR [78], where $y'$ is the nondimensional wall distance. These studies stated that 10–30% DR is produced by the NeverWet surface for low frictional Reynolds numbers.
A positive relationship between speed and DR ratio is observed for turbulent flow through a channel numerically, while the opposite is found for a water tunnel having a fabricated surface in laboratory [37, 63]. Tab. 1 summarizes the contributions of the hierarchical topography of surfaces in reducing the drag force in turbulent flows.

### 2.5 Superhydrophobic Surface-Induced DR over Submerged Bodies

Superhydrophobic surfaces have also become constructive for reducing skin friction in the case of flow over bluff bodies. Reductions of 5–15 % in skin friction are reported for falling solid acrylic spheres through water under the plastron effect [83]. In the case of airfoils, elevation in lift up to 66 % and 45 % decrease in the drag force are observed as the slip increases from 0–50 % for $\alpha < 5$, whereas studies for high angles of incidence ($\alpha$) indicated opposite results [24].

A large number of investigations explored the capability of SHSs providing significant DR for marine vessels [84]. A DR of 38.5 % has been computed for a ship model fabricated with electroless deposition of gold aggregates [85]. The surface of the ship displays efficient non-wetting characteristics with a contact angle of $159.7^\circ$. A comparative study has been conducted through a sailing experiment of submarines with and without SHSs. The DR was obtained as 15 % in the case of surface coated with copper particles onto a precrosslinked polydimethylsiloxane (PDMS) surface [86].

A highly floatable multifaced superhydrophobic metallic assembly was designed and its performance was tested experimentally and predicted theoretically [87]. The assembly showed such high floating potential that it can come back to the surface even forcefully submerged for a long time period. A DR of 27 % was obtained in a recent experiment using a certain microtrench superhydrophobic surface underneath a ship [88].

### 2.6 Metastability and Stability of Plastron

Stabilization of the gas layer between liquid and solid is crucial not only in DR but also in a wide scale of commercial applications. However, for submerged vehicles, the stability of plastron is a challenging issue as underwater metastability obstructs the resisting property of SHSs. The plastron layer can be destroyed due to vibration or squeezing and impact. Furthermore, retaining of gas cavity may fail in turbulent regime and high-pressure environment. An experimental study was conducted by Ling [89] to analyze the effects of entrapped gas due to gas diffusion and compression for a range of Reynolds number and ambient pressure over SHS. The results suggest that wall friction and turbulent diffusion are correlated.

Knowledge about surface chemistry is a key point to understand the stability of air pockets. A large amount of data can be found on the failure of plastron over the superhydrophobic surface in turbulent regimes and irrevocable effect against DR in [90].

Recently, researchers have focused on balancing the chemical connection between low surface energy particles to improve mechanical properties of the surface and prolong the SHSs lifetime under real applications such as the green ship project [69]. However, this method is very costly and limited. A novel chemical method is presented to restore the plastron in situ by employing a decomposition reaction of H$_2$O$_2$ prepared with a catalytic coating on SHSs [91]. Experiments were performed under turbulent conditions in a Taylor-Couette cell. Results demonstrated that half of the skin force due to collapse of plastron was recovered with injection of H$_2$O$_2$ (Fig. 7).

In another study, a new technique was developed to design a self-healing SHS using spray coating of blended fillers and binders. Two parameters, the $S^*$ (miscibility parameter with the...
filler) and $P^*$ (superhydrophobic surface potential) are introduced and defined as $S^* = (AR - R_{\text{binder}} + R_{\text{filler}})/(2R_{\text{filler}})$ and $P^* = 2(D^*_{\text{stat}} - 1)/(rD^*_{\text{stat}} + 1)$. $AR$ is the distance between centers of filler and binder spheres whereas, $R_{\text{filler}}$ and $R_{\text{binder}}$ are the radii of spheres. $D^*_{\text{stat}}$ denotes the statistical porosity of the surface and $r$ represents the ratio between actual and projected area. It is stated that $S^*$ and $P^*$ must be less than 1.0 to provide mechanical durability and a robust non-wetting state [92].

Additionally, the sooting method was discovered to be useful in anticorrosion and self-cleaning of surfaces. The sooting layer could be fragile, and its robustness may be weakened under high pressure in liquid, thus it requires additional chemical treatment [93–97]. Tab. 2 lists sooting measures to enhance the stabilization of SHSs. Although the sooting approach is effective in stabilization, it is highly expensive.

**Table 2.** Recent studies on the sooting process of superhydrophobic surfaces.

| Reference       | Sooting method | Chemical deposition                  | Contact angle |
|-----------------|----------------|--------------------------------------|---------------|
| Xiao et al. [93]| Candle soot    | Methyltrichlorosilane (MTCS)         | 161°          |
| Shen et al. [94]| Flame soot     | Silicone                             | 168 ± 2°      |
| Zulfikar et al. [95]| Carbon soot | Silicone polymer                      | –             |
| Liu et al. [96] | Candle soot    | Polydimethylsiloxane                 | 163°          |
| Li et al. [97]  | Candle soot    | Silicon dioxide nanoparticles        | –             |

Longevity and terminal pressure are responsible for the sustainability of superhydrophobic surfaces [98]. For ultimate restoration and retention of air cavities in underwater circumstances, Lee et al. [99] have proposed the mathematical models (4) and (5) for post structured SHSs under certain criteria as:

\[
\left[\sqrt{2} - 2\sqrt{(1 - \theta)/\pi} - \frac{1 + \sin \theta_{\text{adv}}}{2 \cos \theta_{\text{adv}}} \right] < \frac{H}{L} < \frac{\cos \theta_{\text{rec}}}{2 \sin \theta_{\text{adv}} \left(1 - \sqrt{\pi (1 - \theta)}\right)}
\]  

(4)

Where $\phi = 1 - \pi D^2/AL^2$, and $\theta$, $L$, $D$, and $H$ denote air fraction, contact angle, pitch, diameter of post, and height of posts, respectively; $p$ and $b$ represent the top surface of posts and bottom surface between posts, while the subscripts rec and adv refer to advancing and receding of $\theta$. The Cassie-Baxter equation takes the form:

\[
\cos \theta_c = \theta + (1 - \theta) \cos \theta
\]

(5)

where $\theta_c$ refers to the apparent contact angle. Preceding the proposed theoretical approach can retain the gas layer even for high liquid pressure, tested up to 7 atm. Recently, a porous water-repellent surface was tested and it was found that the air layer could resist hydraulic pressures up to 350 kPa [100]. Several other techniques such as pressurizing gas layer and nano-structuring the sidewall of microstructures have been suggested [101, 102]. However, the experimental implication of such approaches is indispensable for real engineering applications.

### 3 Theoretical Modeling of Polymer Additive-Based DR

Polymers are composed of macromolecules that are based on very simple repetitive chemical units called monomers. The crucial polymer characteristics of DR are (i) flexible linear long-chain structure, (ii) high molecular weight ($5 \times 10^5$ g mol$^{-1}$ or above), and (iii) efficient solubility in solvents. The addition of a small fraction of polymers generates notable effects on a variety of phenomena such as turbulence, vortex formation, and stability of laminar flow and surface pressure fluctuations. The DR by using additives in Newtonian fluid flows was discovered back in 1948 and is ascribed Toms’ phenomenon [103, 104]. Toms discovered DRs up to 30–40% by adding 10 ppm poly(methylmethacrylate) to monochlorobenzene. The drag-reducing effect relies on polymer concentration and molecular weight and has been documented on a wide scale since its discovery. Numerous studies were performed both at the molecular level as well as in terms of constitutive equations during the past decades.

Lumley presented an effective viscosity view that polymers enhance the effective viscosity in TBL, thus damp the small eddies and lead to lower pressure drop [104, 105]. Landahl’s theory proposed the two-scale model. Small-scale disturbances due to secondary inflectional instability were considered as the driving mechanism for large-scale disturbances [106]. Pope presented effective viscosity in terms of a finite tensor polynomial [107]. Camail et al. introduced the polymer stretching model; DR occurs for two consecutive steps, namely, from aggregated to isolated coils and from isolated to stretched coils. However, only large enough energy (critical energy) may induce the DR [108].

The elastic theory of stretched polymers presented by Tabor and Gennes got more importance among all others. According to Gennes’ theory, stretched polymer molecules can absorb and store the kinetic energy of eddies. At small scales $r$, the molecules of polymer solution follow affinely the deformation of a local volume element. When energy flows down to a scale $r^*$, the shear rate $U(r)/r$ becomes equal to the relaxation rate of one coil, with $U$ being the velocity. At a smaller scale $r^\ast$, the Reynolds stresses and elastic stresses in the coils become comparable. The overall result is the increase of the buffer layer, provided that the polymer concentration exceeds a very low but finite threshold [109, 110]. The energy balance theory was further developed to the energy flux balance theory based on the experimental observation [111].

Recently, Zhang et al. [112] proposed a phenomenological explanation of DR based on chemical thermodynamics and kinetics. The DR is presented in terms of the Fourier series:

\[
\text{DR}(x) = a_0 + \sum_{k=1}^{n} c_k \cos(k \omega x - \varphi_k)
\]

(6)
where \( c_k = \sqrt{a_k^2 + b_k^2} \) presents the amplitude (ability of DR), \( \phi_k = \tan^{-1}(b_k/a_k) \) indicates the phase angle, and \( a_k, b_k \) are the fitting parameters. Each cosine term in Eq. (6) demonstrates one polymer with a specific molecular weight. A higher value of \( c_k \) implies a higher DR with a specific molecular weight. Fig. 8 validates the presented theoretical model.

### 3.1 Turbulent DR by Polymer Additives

Homogeneous and non-homogeneous polymer solution injection strategies are adopted to introduce polymer additives in fluid flows [113, 114]. Reduction in drag force is obtained by suppressing turbulence. Fig. 9 demonstrates the mechanism of how polymers in turbulent flows reduce the kinetic energy contained in fluids by stretching and relaxing. As a result, the dissipation of kinetic energy decreases in turbulent flows due to the absorption ability of stretched coils. It increases the effective viscosity in the sublayer and delay turbulence [105]. In the fluid region \( 5 < y^+ < 30 \) is ascribed to the buffer layer between the viscous sublayer and logarithmic layer, and the contribution of polymer effects dominates the DR. Percent DR was determined by comparing results of with and without polymer additive (polyethylene oxide, PEO) as \( \%DR = (\tau_{w} - \tau_{wo})/\tau_{wo} \times 100 \). Here, \( \tau_{w} \) and \( \tau_{wo} \) are the wall shear stresses in the presence and absence of polymer additives [115].

Generally, there are mainly four types of phenomenological explanations that have been reported: (1) the polymer extends the buffer layer thickness of the entire boundary layer, (2) the polymer damps streamwise vortices, (3) the polymer reduces Reynolds stresses, and (4) the reduction of the drag force caused by soluble polymers is purely a near-wall phenomenon [116, 117]. Polymeric solutions obeyed a simple scaling law in terms of function of concentration.

DRs for different concentrations and \( Re \) are illustrated in Fig. 10 [118]. Experimental data and scaling arguments lead to the time criterion for DR [119]. According to the time scale criterion, the coil stretch transition occurs. For this extended state, the elongational viscosity grows by a factor of the order of \( 10^4 \) [120].

For the two types of polymer forms (aggregate and free) in the solution by dissolving a solid polymer in solvent, free polymers and aggregates in solution cause unstable thermodynamic and unstable kinetic environments. An unstable thermodynamic environment gives rise to DR as turbulent flow overcomes the onset point to stretch the free and polymer aggregates, while an unstable kinetic environment causes the degradation of DR as a result of polymer chain scission (Fig. 11) [112, 121]. During the past half century, several numerical and experimental techniques such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) enabled insight and understanding of the origin of polymer additive-based DR and measurement of turbulence statistics [122, 123].

Furthermore, PA solutions introduce elongational viscosity depending strongly on the molecular weight in the Navier-Stokes equation, and elastic turbulence in laminar flows at low Reynolds number and high Weissenberg number [124]. An experimental study based on molecular weight was performed by Dubief [125]. Polymethylmethacrylate (PMMA) and polyethylene oxide (PEO) with molecular weights of \( 4.0 \times 10^6 \text{ g mol}^{-1} \) have been used. The molecular weight is obtained by calculating the intrinsic viscosity \( \eta \) from the Huggins equation [126]. The viscosity \( \eta \) has also been utilized to estimate the overlapped concentration. The maximum polymer concentration...
$c = c_1 + c_2 = 200$ ppm is used for the study. The DR of the mixture depends on the following equation:

$$\text{DR}_{\text{mix}} = \text{DR}_1(c_1) + \text{DR}_2(c_2)$$

where DR$_1$ and DR$_2$ are the obtained DR values for each polymer solution. When DR$_{\text{mix}} < \text{DR}_1(c_1) + \text{DR}_2(c_2)$, the deviation is called negative, and for DR$_{\text{mix}} > \text{DR}_1(c_1) + \text{DR}_2(c_2)$ the deviation is considered to be positive [127]. Some other studies have shown that DR is affected by polymer chains [112, 128]. Results have been derived by comparing the pressure drop for polymers in stretched states ($\Delta P_p$) and the one with coiled states ($\Delta P_s$) instead of viscosity difference of polymeric solution to pure solvent. When DR occurs, $\Delta P_p$ is smaller than $\Delta P_s$, and the equilibrium constant ($K$) is:

$$K = \frac{\Delta P_p}{\Delta P_s} < 1 \quad (7)$$

and the Gibbs energy (energy stored in polymers) is:

$$\Delta G = \Delta G_p - \Delta G_s = -RT\ln K > 0 \quad (8)$$

where $R$ represents the ideal gas constant and $T$ is the Kelvin temperature. A longer polymer chain implies a higher Gibbs energy and can interact with eddies present in turbulent flow. These are known to decrease the skin friction drag in turbulent flows with high efficiency. However, velocity statistics were different for homogeneous and inhomogeneous cases in the turbulent boundary layer.

In fact, as the concentration of polymer increases, the elastic turbulence could be triggered at a very low Reynolds number [124, 129]. In the experiments of elastic turbulence, the drag is sharply enhanced. A similar drag enhancement is also reported in several numerical studies for external flows at high Weissenberg number [130, 131]. For internal flows, it is generally observed that the DR achieves a maximum DR (MDR) asymptote. The DR is not affected by the increasing polymer concentration until recent experimental studies have shown exceptions to the usual limit by unexpected “early turbulence”, which is driven by an elastic instability (Fig. 13) [122, 132].

The flow patterns of polymer-containing water at progressively larger $Re$ have been investigated numerically. For lower polymer concentration, the transition from laminar to turbulent flow moves to higher $Re$, just as expected. However, for moderately higher concentration, the transition state was observed at lower $Re$ values associated with transition in pure water. The researchers explained this unexpected early turbulence and termed it as elastoinertial turbulence (low amplitude turbulence). Thus, elastoinertial turbulence is proposed to

![Viscoelastic Turbulent Flows Becoming Laminarized Elongational Turbulent Flow](image)
explain the lateral MDR limit which was an open question for decades [132, 133].

In confined geometries, the polymer-induced DR depends on the interaction between walls of geometries and polymers. Dilute polymer solutions in pipe flow usually follow the Prandtl-Karman law [120]. The friction factor is defined as:

$$ f = \frac{\Delta \rho}{\rho \omega^2} \frac{r}{l} $$  \hspace{1cm} (9) 

where $\omega$ is the section mean velocity, $\rho$ is the density of fluid, $l$ and $r$ represent the length and radius of a pipe, respectively, and $\Delta \rho$ is the pressure drop.

With the increase in DR, the magnitude decrease of components of Reynolds stress tensor is observed when scaled with outer variables such as channel width and mean velocity [134]. The behavior of log law of mean velocity profile is classified into three regimes: (i) low-DR (LDR) regime, (ii) high-DR (HDR) regime, and (iii) maximum DR (MDR) regime on basis of polymer concentration.

To study the DR of external flow, PEO solutions with a molecular weight of $3.9 \times 10^6 \text{ g mol}^{-1}$ at various concentrations and volumetric fluxes were injected into the flow [135]. Results of mean near-wall velocity profiles at $Re = 1.5 \times 10^5$ depicted distinct behaviors. In the LDR regime, DR appears to be valid with the classical view with logarithmic slope profiles whereas in the HDR regime there is no longer universal behavior observed.

Experimental work indicated that at a certain polymer concentration (so-called optimum concentration) and for a given Reynolds number the DR becomes maximum (MDR asymptote). For example, in pipes, transition for a Newtonian fluid (water) from laminar state to turbulent state occurs at $Re \approx 2000$. An increase in temperature and molecular weight both affect the optimum concentration, and an increment in concentration reduces the skin friction only up to a certain point.

Diffusion of polymers injected in TBL was studied to observe DR in downstream. The process in the turbulent boundary layer is characterized by three regions: development zone, transitional region, and the final region. The DR is displayed in Fig. 14 by the injection process:

$$ K = \frac{Q_i C_i}{X_s U_\infty \rho} \times 10^{-6} \hspace{1cm} (10) $$

where $Q_i$ is the volumetric injection rate, $C_i$ is the polymer concentration, $\rho$ is the density of solvent, $X_s$ is the downstream distance, and $U_\infty$ is the free-stream velocity [136].

Another study determines the dimensionless parameter $K$ as:

$$ K = \frac{Q_i C_i}{(X - X_i) U_\infty \rho} \times 10^{-6} \hspace{1cm} (11) $$

where $X - X_i$ is the streamwise location, and maximum DR was observed at $K = 10^{-7}$ [115]. DR was calculated at different speeds and streamwise locations (see Fig. 12).

Direct numerical simulations provide an explanation of water-soluble or synthetic polymer DR. Oldroyd-B and the family of FENE models are widely used to study DR numerically. The numerical simulations along with these constitutive models can explain qualitatively most of the experimental results on DR. Min et al. investigated turbulent DR and analyzed the molecular stretching characteristic by using the viscoelastic Oldroyd-B model in a channel. Results were interpreted by proposing that polymer molecules absorb elastic energy near
the wall and then were transported and dissipated into the buffer layer which minimizes the vortices [8, 137–140]. Polymer extensibility shows a more complicated influence in turbulent flows for confined geometries and over bluff bodies. For the high extensibility of polymers, growing DR for a constant relaxation time and $Re$ is observed and validated through experimental results [141]. However, diverse drag-reducing agent (DRA) results are also observed under different conditions.

### 3.2 Effect of Polymer Additives on Multiphase Flow

Polymers play a significant role in the transportation of multiphase flow. Greskovich and Shrier [142] were the first to test polymer additives in multiphase flow. A DR of 40 % was reported in experiments conducted for air-water flow through pipes of various sizes ranging from 1.50 to 6.065 inches. Since then several researchers documented DR with different results in a variety of systems [143]. Stratified wavy flow patterns were noticed as a result of polymer additives. Also, PA eliminates the disturbance waves in the liquid film by suppressing interfacial shear stress as well as wall-liquid shear stress in the turbulent region [144]. A recent development on DRAs includes the implementation of a multiphase pipe flow system.

Al-Yari et al. [145] found a decrease in pressure gradient on adding PEO to an oil-mixture flow. The DR reached 65 % with 10–15 ppm of DRA applied to the mixture. The addition of DRA to the multiphase flow can alter the fluid spatial dispersion and affect the boundary regions between different flow patterns. Such capability generates interests in broader applications like oil production, heating, and refrigeration systems. The addition of a small amount of polymer into the flow causes the pressure gradient to drop down and reduces the spreading ability of liquid upward along the wall as well as atomization. In turn, disturbance waves start to disappear.

Fig. 15 indicates that the addition of 40 ppm DR polymers reduces the wave amplitude formation at the oil-water interface at low velocity [146]. Another experimental study stated that a DR as high as 71 % was obtained for 100 ppm concentration of injected polymers in an inclined pipeline with 0.0127 m diameter [147]. Research on three-phase flow (water, oil, and CO$_2$) has also been conducted by Kang et al. [148]. DRs of 35 % at superficial gas velocities of 13 and 14 m s$^{-1}$ were detected [148].

### 3.3 Degradation of Polymers

Polymer additives-based DR technology is of great importance in oil transportation applications. In long-distance transportation, the frictional force between pipeline and oil accounts for 98 % of the total energy loss [149]. Adding a minute quantity of soluble polymer in a long-distance oil pipeline reduces the friction force. As a result, the cost of transportation minimizes since the energy consumed by the power station to pump oil through pipelines reduces [150].

The drag force can be reduced as high as 80 % with the addition of polymers in liquids [151]. However, there are still some shortcomings such as embrittlement, cracking, charring, and chain scission of polymers. One of the main failures of PA was discovered by Peterson et al. [152] in the early 70s. PA faces the problem of mechanical degradation under turbulent flow. When a polymer molecule undergoes a strain more than a characteristic threshold value, it breaks apart. The vulnerability of polymer molecules is a major cause of mechanical degradation leading to minimize the level of DR.

Degradation of most commercially used PEO of structural unit (-O–CH$_2$–CH$_2$-) and polyacrylamide (PAM) are quantified at $Re=3 \times 10^5$ together with higher shear rates of $>10^5$ s$^{-1}$.

![Figure 14. Development of DR in external boundary layer flows with polymer injection. The letters denote data obtained for different grades of PEO (Polyox COAG and Polyox 301) and injection concentrations [136].](image1)

![Figure 15. Stratified wavy flow at $V_{mix} = 0.2$ m s$^{-1}$, $X_0 = 0.3$. (a) without DRP. (b) The amplitude of the wave reduces after 40 ppm DRP addition [146].](image2)
An experiment was conducted in a pipe of 2.72 cm diameter [153]. Less influence on degradation was observed in the case of seawater solution as compared to pure water solution. According to the scaling law proposed by Vanapalli [121], chain scission occurs on the Kolmogorov scale and generates maximum skin friction $F_{\text{max}}$ on polymer chain as $A^{3/2} \frac{\mu\nu^3}{2Re^{3/2}L^2}$. Here, $L$ is the contour length of the polymeric chain, $A$ is a proportionality constant, $\mu$ is the solvent viscosity, and $a$ denotes the polymer chain diameter. Results obtained in [153] support the scaling law of Vanapalli for chain scission.

Responsible parameters for degradation are polymer concentration, molecular weight, distribution of molecular weight, intensity and structure of turbulent flow, chemical composition, polymer-solvent interaction, and some other parameters such as temperature, salinity, and pH [154–156]. In the case of interrupted deformation, $f_{\text{reatr.}} > f_{\text{ent}} \approx k_B T/\ell_{\text{ent}}$ estimates the failure of entanglement, where $f_{\text{reatr.}}$, $f_{\text{ent}}$, and $\ell_{\text{ent}}$ indicate the retractive force built by strand deformation, cohesive force, and length of a strand having an entropy equal to $k_B T$ [157].

The effect of temperature on the degradation rate was studied by Hasan et al. [158]. The concentration of a critical micelle concentration (CMC) solution dropped at 37.8°C by 17.7%. The decrease in CMC was also observed at 104.4°C by 36.2% [156]. At high temperatures, the faster degradation rate for synthetic polymers has already been verified [157]. A drop in the DR rate from 58% to 0% was found for the circulation of aqueous PAM solution with various concentrations (Fig. 16) [154].

To address the scission anomaly between experimental studies and theories, the flow field stability was examined in the contraction-expansion (CE) and cross-slot (CS) geometries over a range of $Re$. The critical $Re$ values are 370 and 25 for instability in CE and CS geometries, respectively. A simple scaling theory for polymer chain scission was proposed in turbulence [121]. Estimation of the drag force $F_d = \mu \dot{\gamma} R^2$ is predicted by considering the fully extended test chain interaction with each spatial scale of the inertial range. Here, $\mu$ is the solvent viscosity, $\dot{\gamma}$ is the strain rate of velocity fluctuations, $r$ represents the length scale of a Kolmogorov cascade, and $R$ is rod half-length.

The aforementioned issues are still the subject of current research in progress. It is a matter of discussion that how much the breakup of polymer aggregates and mechanical degradation of polymer molecules are responsible for the drop in DR level. Although a large number of efforts have been made to explain the mechanism, the polymer additives DR technique is still not mature enough due to the complex structure of both flows and molecules as well as nonlinear interaction.

### 4 Coupling of PA and SHSs Techniques

Since the various DR technologies possess distinct parameters, characteristics, and limitations, they may show an effective impact on DR and lead to an intuitive development to explore a synergy when working together. The joint impact of different technologies and the coupling of varying DR technologies performed together demonstrated a better DR ability or practicability than the single DR method [156–161].

For instance, the previous study disclosed the remarkable stabilization of the air layer and optimized DR for the combined technology. Collaborative effects of polymer additives with other DR techniques such as microbubbles and compliant coatings have already been investigated [156, 162, 163]. Compliant coatings possess high anticorrosion abilities and affect the long-wave disturbances. One-layer viscoelastic coatings already displayed excellent resistance to damage resulted from the use of alkalis and acids.

Gas bubbles have the property to destruct the long-wave powerful fluctuations. Furthermore, for different exploitation conditions, injection of microbubbles into the near wall establishes a stable DR action of compliant coatings. Mutual intensification of microbubbles and polymers for DR in flow impedes the bubble rising and prevents bubble coalescence. An experiment was carried out over a flat plate in a tunnel. The DR level was found to be higher than the reduced drag level obtained with only polymers or air injection in the boundary layer [163]. In the case of compliant walls, the DR efficiency depends on polymer concentration, the thickness of the coating, coating material, and the speed of the object.

Polymer additives are well-known to reduce the turbulence characteristics significantly and regulate the DR level when combined with other technologies as mentioned. However, it makes no contribution to the DR for laminar flow. On the other hand, SHSs are a promising DR technique of effective DR mechanism for both laminar and turbulent flows. Therefore, it is encouraging to combine these two DR technologies with different mechanisms to extend the range of application on the one side and enlarge the DR on the other side. Or, the mixture methods supply more reliable DR as the failure for one of them occurs.

Recently, the combination of SHSs and PA demonstrates superior DR characteristics as both the
SHSs and polymer are well selected [158]. In this study, two frequent applied polymer additives, PEO and PAM, were combined with both a scalable randomly (R) textured superhydrophobic surface and a grooved (G) one. The DR results suggest that PAM demonstrated better cooperative characteristics along with SHSs than PEO as displayed in Fig. 17. The synergistic DR for PAM and scalable random textured SHSs is impressive in the whole Reynolds number range from 15,000 to 52,000 in the experiments. On the other hand, the severe surfactant effect of the PEO chain may adversely affect the air-water interface and reduce the slip length of random textured SHSs, which could be the possible reason as the synergistic DR is limited by the PEO additive in the previous study [159].

Considering the metastability of the gas layer into water under high pressure on the surface of superhydrophobic material, so that the gas layer disappears and fails to retain the superhydrophobic property, being the main barrier in the application of SHSs, the suppression of turbulence for the PA on the boundary may play a positive role to reduce the peak pressure near the boundary. Thus, a joint action of SHSs and PA may suppress the superhydrophobic surface failure, and polymer coating along with nano/microstructures on the surface can remain a large liquid slip to maintain the characteristics of SHSs.

Moreover, the problem of mechanical degradation due to the vulnerability of polymers to high strain turbulent flow could be relieved by the liquid-slip characteristic of SHSs. The slip near the boundary is supposed to reduce the maximum strain rate of flow, which is promising to prevent the breakage of polymers under high strain rate and may become possible by investigation for higher Reynolds numbers.

5 Summary and Outlook

Fabricated SHSs show a strong tendency to repel liquids. Artificial SHSs are not only restricted to water repellency but also are successfully employed for anticorrosion, antifogging, self-cleaning, water-resistant fabrics, antibiofouling, biomedical applications, icephobic, DR, and omniphobic applications. The roughness of material can increase the liquid slip on microscale, which can alter flow patterns on the macroscale. Cassie and Wenzel states on such surfaces open up perspectives in the DR technological development. However, there are some aspects that cause the failure of artificial SHSs.

Higher DRs as 80% can be achieved through PAs as compared to nonadditive techniques. PA-based DR for open as well as closed turbulent flows is under discussion for several decades. A PA intensifies the heat transfer without altering the fluid friction in laminar noncircular flow. During the past few decades, improvements in research paradigm and perspectives have triggered new advancements in the additive approach. Soluble polymers found remarkable applications in the medicine area. Several recent developments brought fresh insights into long-standing issues since PA is a more effective method to reduce the frictional force.

Fluid flow in turbulent state results in a higher frictional force, which consumes more energy. Overall, the mechanism of these two types of DR technologies are different. When working together, it is possible to expect a wider application range and larger DR. Additionally, the coupling of PA and SHSs may provide prevention from fouling, which implies an optimized lifetime, e.g., for a ship.

In association with the present study on the coupling of SHSs and PA, the combination is promising but there are many aspects to explore such as mechanical degradation of polymer molecules and flows at higher Reynolds numbers as well as the optimum combination for their commercial applications. The superhydrophobic surface shows satisfactory DR results not only for confined geometries but also for

![Figure 17. Combination of DR ability of superhydrophobic surface and PA. (a) DR experimental results by 50 ppm PAM PA and grooved superhydrophobic surface and its combination. (b) DR results by grooved superhydrophobic surface and the combination with 50 and 200 ppm PEO PA. (c) DR results by 50 ppm PAM PA and scalable random superhydrophobic surface and its combination. (d) DR results by 50 ppm PEO PA and scalable random superhydrophobic surface and its combination [158].](image-url)
external flows. The current practical application is more likely to be bound to laminar flow.

Degradation is a serious issue of PA technology, while the superhydrophobic surface DR is affected by the air loss in the surface microstructure. The biggest drawbacks of these two DR technologies could be treated by combining both two techniques and enhance the DR capability.

The following important aspects need to be clarified for further investigations:

1) Mechanical durability and robustness of scalable artificial SHSs are still not ensured. Mostly the fabrication methodologies are expensive and are only suitable for small-scale surfaces. Therefore, these methods are not applicable on a large scale which limits the SHSs to be commercially successful.

2) The turbulent DR mechanism of PAs is still under debate. The elastic and elastoinertial turbulence by PAs suggests that the understanding of the role of elasticity in the flow is not adequate.

3) The DR by polymers is obtained by high shear and stretching under high Reynolds numbers, but long-chain molecules are cut off. The influence of the broken molecular chain on DR and how to accurately predict the degradation of a PA and its influence on DR is important.

4) The potential of DR for the combination of PA and SHSs and how the molecular structure and the concentration of PA and texture structure affect the combinational DR in different Reynolds ranges must be clarified.

5) There are wide applications in association with the DR that could be more explored along with these two DR techniques, from life safety to industrial application, e.g., the discovery of blood soluble drag reduction polymers (DRP) to prevent lethality from hemorrhagic shocks, the influence of SHSs and PA on cavitation and hydrodynamic noise, and so on.

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Conflicts of Interest

The authors declare no conflict of interest.

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Symbols used

- $A_p$ [m$^2$] projected area
- $A_w$ [m$^2$] wetted area
- $b/d$ [-] slip length of hydrophobic surface
- $c, C_i$ [ppm] polymer concentration
- $f_{\text{retract}}, f_{\text{ent}}$ [N] retractive force built by strand deformation and cohesive force
- $f_{\text{sl}, f_{\text{lg}}}$ [-] fractions of solid-liquid and liquid-gas interfacial area
- $G$ [-] Gibbs energy
- $H, L$ [m] height and pitch of the posts
- $K$ [-] equilibrium constant
- $K$ [-] dimensionless parameter
- $k_B$ [J K$^{-1}$] Boltzmann constant
- $l_{\text{ent}}$ [m] length of a strand
- $\Delta P_p$ [Pa] pressure drop for polymers in stretched states
- $\Delta P_s$ [Pa] pressure drop for polymers in coiled states
- $Q_i$ [m$^3$s$^{-1}$] volumetric polymer injection rate per unit span
- $r$ [m] Wenzel’s roughness parameter

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Greek letters

\( \alpha \) \quad [\circ] \quad \text{angle of attack} \\
\( \phi \) \quad [-] \quad \text{gas fraction} \\
\( \theta \) \quad [\circ] \quad \text{contact angle} \\
\( \theta_a, \theta_{adv} \) \quad [\circ] \quad \text{advancing contact angle} \\
\( \theta_r, \theta_{rec} \) \quad [\circ] \quad \text{receding contact angle} \\
\( \theta_W \) \quad [\circ] \quad \text{contact angle of Wenzel state} \\
\( \theta_{CB} \) \quad [\circ] \quad \text{contact angle of Cassie-Baxter state} \\
\( \gamma \) \quad [J m^{-2}] \quad \text{interfacial energy} \\
\( \gamma_{lv} \) \quad [J m^{-2}] \quad \text{liquid-vapor interfacial energy} \\
\( \gamma_{sv} \) \quad [J m^{-2}] \quad \text{solid-vapor interfacial energy} \\
\( \gamma_{ld} \) \quad [J m^{-2}] \quad \text{solid-liquid interfacial energy} \\
\( \phi_s \) \quad [-] \quad \text{spacing ratio} \\
\( \nu \) \quad [m s^{-1}] \quad \text{kinematic viscosity of fluid} \\
\( \rho \) \quad [kg m^{-3}] \quad \text{density of fluid} \\
\( \lambda \) \quad [nm] \quad \text{apparent slip length} \\
\( \tau_w \) \quad [Pa] \quad \text{wall shear stress} \\
\( \phi_K \) \quad [\circ] \quad \text{phase angle of Fourier series} \\
\( \omega \) \quad [m s^{-1}] \quad \text{section mean velocity} \\

Abbreviations

CAH \quad \text{contact angle hysteresis} \\
CMA \quad \text{critical micelle concentration} \\
DR \quad \text{drag reduction} \\
DRA \quad \text{drag-reducing agent} \\
DRP \quad \text{drag reduction polymers} \\
MDR \quad \text{maximum drag reduction} \\
PA \quad \text{polymer additive} \\
PAM \quad \text{polyacrylamide} \\
PEO \quad \text{polyethylene oxide} \\
SEM \quad \text{scanning electron microscopy} \\
SLS \quad \text{superhydrophobic surface} \\
TBL \quad \text{turbulent boundary layer} \\

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Among the drag reduction schemes, superhydrophobic surfaces and polymer additives are promising and effective technologies. Drag reduction enables an extensive range of applications in fluid transportation, vehicle industries etc. Advancements in both technologies for hydrodynamic flows in friction drag reduction are reviewed, together with general formulations, potential applications, and major issues.

**Contribution of Superhydrophobic Surfaces and Polymer Additives to DR**

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