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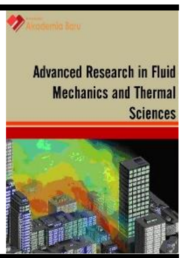

Drying Droplets: A Review on its Numerical and Experimental Studies to Remove Coffee Ring Effect

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ABSTRACT

It is widely known that significant rejection percentage of substrates in the hard disk manufacturing industry is due to the stain appeared during drying of cleaning solution after platting process. Comparison of the characteristics and the causes of these stains suggested that the study of coffee ring effect (CRE) and droplets analysis are needed before any further analysis is carried out. In this review on CRE and droplets, both numerical and experimental works were critically analyzed. Previous studies have highlighted that the drying process of the water droplets are affected by the properties of the water droplets, substrate and temperature. Manipulation of Constant Contact Angle, Constant Contact Radius, advanced contact angle and receding contact angle by varying the arrangement of the substrates and the position of the drying equipment is required to attain the optimum setup to eliminate CRE. Furthermore, manipulation of the temperature of the substrates can enhance the drying process of the droplets before the formation of CRE but the process must not change the properties of the substrates. CRE formation also depends on the properties of the substrates and water droplets. Changing the chemical properties substrates are not advisable to eliminate CRE due to its complex design of the substrates for data storing. All the numerical tests have to be performed according to correct procedures to ensure accurate and acceptance by the industries. Verified and validated results from the evaluation will help to accurately predict the real consequences for further optimization. Knowing that the formation of CRE is caused by the evaporating of the water droplets, we need to find ways to eliminate the formation of water droplets before the heating process, in order to eliminate CRE.

Keywords:
Numerical evaluation analysis; coffee ring effect; substrates; hard disk

1. Introduction

In hard disk manufacturing industries, substrates need to undergo cleaning process for enhancement [1]. The cleaning process consists of sub processes such as rinsing, blowing and

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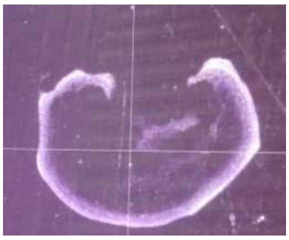
heating. The rinsing process, will wash away any non-volatile solute particles remaining on the substrates. The substrates then conveyed through the air blowing process to wipe away the cleaning solution before heating process to dry the substrate. For any data recording substrates or any high quality surface substrates, it is important for the surface of the substrate to remain clean and stainless [2]. However, stains appeared on the substrates after the heating process. The stains then become permanent. This paper discusses related questions with regards to this issue including what are these stains, what are the causes of the stains, what are the ways to suppress it and the simulation analysis used to evaluate the current cleaning process.

Often stains on substrates, are known as coffee-ring effect or CRE. However, we can never conclude anything before comparing the physical characteristics of these stains and the physical characteristics of CRE. Deegan *et al.,* [3-6] reported that the CRE is attributable to a pinned contact line during evaporation and nonuniform evaporation flux on the droplet surface, which is considered as an evaporating sessile droplet with its edge pinned on the substrate. The liquid contains dispersed non-volatile solute particles move towards the drop edge and deposit the particles there. At the end of the evaporation process a ring-like residue of the particles is left on the substrate. According to this definition of CRE, Table 1 below shows the comparison of the stains and CRE.

Table 1
Comparison of the stains and CRE

Physical Characteristics	Stain on the substrates	Coffee ring effects
Pinned contact line	The actual view of stain on the substrate  The microscope view of stain on the substrate 	 Pratibha Mahale (2017). Suppression of the Coffee-Ring Effect and Evaporation-Driven Disorder to Order Transition in Colloidal Droplets [7].
Non-uniform evaporation flux	Yes	Yes
sessile droplet	Present before evaporation	Present before evaporation
Surface	Substrates with multiple coated surface	Can be various : polymer, glass and substrates [8]
Shape of the stains	ring-like residue	ring-like residue
Physical process	An evaporation of sessile droplet under a high heat	An evaporating sessile droplet with its edge pinned on the substrate
non-volatile solute particles on the substrates	Assume to be absent as the substrate go through rinsing process	Present
Outcome after evaporation or heating	The present of Permanent stains	Depend on the surface. Hardly clean or removed.

The difference on the comparison shown in Table 1 is relevant when we assume that the substrates have no non-volatile solute particles after going through the rinsing process. However, during the production, the substrates were never examined under the microscope after the rinsing and blowing process. Other than the differences mentioned, the characteristics show that both CRE and stains are alike in nature. We might not able to draw a conclusion that these stains are CRE, but these similarities show that CRE can be a reference for elimination of these stains through eliminating the water droplets or manipulating the evaporation flux of the water droplets.

According to the hard disk manufacturer, the stains appeared when there exist remaining water droplets on the substrates before the heating process which is tally with what we conclude from Table 1. Hence, this paper covers the discussion on the physical properties of the substrate and the physical properties of the droplets which is important in the aspect for both the stains and CRE. Through these findings, we able to come out with a better solution to eliminate the stains. This review article will focus on gathering literature on various aspects and knowledge of droplets on the substrate, ways to eliminate droplets and numerical model that used to evaluate droplets procedures which can later be used to develop the frame work of the numerical evaluation and optimization analysis for cleaning process of hard disk substrates. This paper filter off any methods and analysis available for removing CRE yet not suitable to be implement on the hard disk substrates. There are many previous works and studies made on hard disk substrate as well as droplets. However, this paper focus more on the physical process of the cleaning of hard disk substrates which contribute to the formation of the stains by relating it with the formation of droplets. Those methods to suppress the CRE, are not practical to be carried out in hard disk substrates that will be discussed in this paper as well. It is also obvious that, in hard disk substrates industries, we are not going to utilize the CRE for any positive outcome as some industries does. Utilizing the CRE meaning encouraging the formation of CRE. This paper is aimed to guide hard disk manufacturer whether to retain the current cleaning process system with optimized condition or to change the whole cleaning process system.

2. The Study on Droplets.

Controlling the process of solute deposition in the presence of droplets is important especially when it involves evaporation on surfaces. Drying of droplet is actually a complex, non-equilibrium and difficult-to-control process [8], the control of the deposition morphology of droplet has significant influence. Further studies on this non-uniform redistribution process indicate that inner flows, including capillary flow [9] and Marangoni flow [10], dynamics of the three-phase contact line [11], and particle-particle/particle-interface interaction [12] will influence the final particle distribution.

Other worthy suppressing methods that we can consider are electro-wetting, electro-osmotic flow, vibrations interactions at solid-liquid and liquid-gas interfaces, humidity cycling and porous substrates [13]. Before these methods are suggested, it is important to understand the cleaning process of the hard disk substrate and study the droplets on these substrates. This is what this paper is all about. Even though it is considered as fundamental, but it directs us straight in relating the theory and the solution to the actual problem in the industry. As the results, none of the suppressing methods mentioned above is suitable in contribute to the effectiveness of cleaning hard disk substrates.

2.1 Drying Droplets Phenomenon on the Substrate

Droplet evaporation characteristics depend on surface wettability, contact angle hysteresis (CAH), [14] and surface roughness [15]. There are many ways to measure the surface wettability on substrates such as contact angle measurements, microscopic examination, glass slide method and nuclear magnetic resonance. However, to known the wettability of the hard disk substrates, we can simply just by using glass slide method. This draw the conclusion that the structured of the hard disk substrates are superhydrophilicity due to the water droplets hardly slip out of the substrates even with the tilting angle of 90 deg and under the blowing of a high pressure blowers.

On experiments of droplet evaporation on a structured superhydrophobic surface that displays very high contact angle (CA ∼ 160 deg), and negligible CAH (<1 deg) [11]. The droplet evaporation is observed to occur in a constant-contact-angle mode, with contact radius shrinking for almost the entire duration of evaporation [16]. Contact angle hysteresis cannot be measured directly but through the measurement of advancing and recending contact angles. Surface roughness is a component of surface texture [17]. According to the previous works, the structured of superhydrophobic surface, the experiments indicate that the time taken for complete evaporation of the droplet is greater than the predicted time, across all droplet volumes [18]. With this, it indicates that the hard disk substrates is superhydrophilicity as the rate of evaporation is high.

Picknett and Bexon [19] were among the first researchers to study the evaporation of a droplet placed on a substrate in still air. They identified two modes of evaporation of a droplet resting on a smooth homogeneous surface, namely, the constant contact angle (CCA) mode and the constant contact radius (CCR) mode. McHale *et al.,* [20] concluded that the evaporation rate on a hydrophobic surface is proportional to the droplet height during evaporation and that the mode of evaporation is determined by the initial contact angle of the droplet. Yu *et al.,* [21] also reported the droplet evaporation rate on a hydrophobic surface to be proportional to the droplet height. Popov [22] drew attention to the nonuniformity of evaporation flux along the droplet surface. In his report, reported a closed-form solution to describe the rate of evaporation valid over the entire range of contact angles [23].

The transient evaporation of a droplet is affected by the initial contact angle of the droplet as well as the contact angle hysteresis [24]. Most studies in the past have focused on droplet evaporation in a constant contact radius mode [22-25]. Another intermediate mode—Stick-Slide (SS) or mixed mode is also commonly observed. Therefore, Saptarshi Basu *et al.,* [26] are able to provide a graphical representation to these modes, named as MOE plot. Thus, various substrates can now be compared based on mode of evaporation, which are governed by fluid property and surface characteristics.

CRE can be eliminated due to the increasing the hydrophobicity of surfaces which accompanied by decreasing CAH [27]. Lower CAH in essence means reduced contact line pinning which leads to suppression of CRE. It can be achieved by patterning of controllable surface wettability as reviewed previously by Tial *et al.,* [28]. However, the preparation of superhydrophobic surfaces is expensive. Comprehensive study the physical properties of the surface of the hard disk substrates is needed to eliminate the effect on other properties of the substrates. Thus, suppression of CRE in hard disk substrates using of hydrophobic surfaces is a challenge.

2.2 The Effect of Temperature on the Drying Phenomenon of Droplets

Xu *et al.,* [29] experimentally investigated internal flow in evaporating water droplets. The authors demonstrated the existence of Marangoni convection in evaporating deionized water droplets seeded with fluorescent particles on glass substrates. They have also shown the existence of a stagnation point on the interface where the surface flow, surface tension and interfacial temperature gradients change direction. The investigated droplets were at room temperature (28°C) and have a base radius of 2 mm and 10° of initial contact angle. In recent studies, the conductivity of the substrate has been reported to be of importance in determining the rate of evaporation of pinned sessile droplet. [30,31] The thermal Marangoni flow can be enhanced by elevating the temperature of the substrate [18] resulting in an increased solute concentration near the center of the droplet [20]. An increased temperature also increases the outwards capillary flow producing a ring as well. The result is a spot-inside-ring. The effect of buoyant motion of the liquid from the hot substrate to relatively cooler liquid-air interface is often negligible [30].

It is worth noting that Savino *et al.,* [32] have experimentally shown that in the case of pendent drops, the existence of Marangoni flows is observed in organic liquids (n-octane) but not in water. Risten part *et al.,* [33], argued that, for organic liquids, non-uniform evaporation along the surface induces temperature variations along the droplet interface. These variations are found to generate a thermocapillary flow within the drop. The droplets were deposited on substrates and have typical initial volume of 2 µL. They were seeded with 1 µm solid particles to reveal Marangoni convection patterns after drying out. Moreover, the authors introduced a criterion to determine the occurrence and direction of Marangoni flow, with the latter being the ratio of thermal conductivities of the substrate and the liquid [34]. Hu *et al.,* [35] studied both experimentally and theoretically the formation of particles deposits near the edge of a drying droplet on glass substrates. They demonstrated that surface Marangoni flow can redirect evaporation-driven deposition and assembly of suspensions. This will undoubtedly affect pattern formation, resulting from the dry out of droplets containing suspensions.

Hu *et al.,* [36,37] also analysed the effect of Marangoni stresses on the flow in an evaporating droplet. The authors described the effect of Marangoni stress on the flow of an evaporating droplet using a numerical approach. The temperature field within the droplet was computed and the role of surfactant contamination was also addressed. The authors showed that small contamination tends to prevent Marangoni convection. Moreover, when the contact angle is below a critical value of approximately 14°, Marangoni flow disappears. Girard *et al.,* [38] numerically investigated the evaporation dynamics of small sessile water droplets under microgravity conditions. The numerical analysis revealed temperature gradients on the free interface and as a result, Marangoni convection is generated within the droplet. The authors also found a slowdown in evaporation toward the end of the droplet lifetime.

At room temperature, the presence of coffee rings in lines and drops by utilizing Deegan's explanation. However, with a heated or cooled substrate, evaporating features are now subject to a heat flux from the surface, breaking the symmetry that permitted Deegan's exact solution. In evaporating drops and lines, heat is readily transferred from the substrate to the thin pinned edge of the drop, leading to enhanced evaporation near the drop's edge compared to that at the center.

In the case of cooling, decreased rim evaporation eliminates CRE formation altogether because the cooled substrate retards edge evaporation more than that in the center. Comparing the line and drop cross sections, the effect of temperature on CRE formation is enhanced in drops. Hence, the drop shows a greater transfer of solute to its edge when subjected to heating. The effect of temperature on CRE deposits does not require a consideration of the temperature dependence of surface tension. However, published research on the CRE warrants a discussion of surface tension-driven flow, known as the Marangoni effect. Previous work has shown that the coffee ring effect can be controlled or eliminated through engineering an appropriate Marangoni flow. Hu and Larson [36] show that Marangoni flows in an evaporating octane drop lead to a deposition of solute at its center rather than a coffee ring at its perimeter. However, in the same letter they found no such effect in an evaporating water droplet, even when avoiding surfactant contamination. Other work by Savino *et al.,* [32] presented a similar conclusion, witnessing Marangoni flows in drops of evaporating organic solvent but not water. The weak influence of thermal Marangoni flow on the drying of a sessile droplet could be attributed to the following reasons. Firstly, the Marangoni flow is weak in an evaporating water droplet. Secondly, it is partially counteracted by the enhanced edge aggregation because of the accelerated evaporation due to the hot edge near the heated plate.

By controlling the substrate temperature beneath the drying feature, Dan Soltman and Vivek Subramanian [18] demonstrated control of its topology, reversing or enhancing the CRE of Inkjet-Printed. A heated substrate leads to greater evaporation at the bead's edge, which then yields an enhanced coffee ring, compared to room-temperature drying. Analogously, a cooled substrate suppresses edge evaporation and eliminates the coffee ring at the feature's edge. These effects occur more strongly in a circular drop than in a straight line because of the greater ratio of edge length to center area in the drop. David *et al.,* [39] experimentally investigated the effect of thermal properties of the substrate on the wetting and evaporation of sessile drops. The authors measured the temperature field inside millimeter sized evaporating water and organic liquid droplets using a miniature thermocouple. Substantial evaporative cooling was observed and a strong influence of the substrate thermal properties was demonstrated. It is clear from the available literature that the evaporation of liquid sessile droplets is accompanied by internal convection. Girard *et al.,* [40] investigated water droplets evaporating on heated substrates. The role played by the substrate temperature as well as droplet radius was investigated.

However, the heating process is to enhance the properties of the hard disk substrates. It is not for drying purposes. Therefore, during blowing process, all droplets must be clear before going to the heating process. There is a discussion of reversing the process by going through heating process first, then only rinsing and blowing. In contrast to the expecting result the effect of suppressing the stain are very minor due to the waiting time of transferring the substrates from heating process to rinsing process and blowing process. The humidity of the rinsing process is very high and the effect of the heated substrates become negligible. Even though there might be a possibility of manipulating the waiting time to suppress the CRE. Nevertheless, changing the cleaning process will affect the other process. Other than this, manipulating the waiting time for mass production in industries is a difficult task. Theoretically, it might work. However, practically in industries is a challenge.

2.3 The Physical Properties of the Droplet

Liquid properties such viscosity and pH and altering temperatures of substrate and droplet are studied to investigate CRE. Cui *et al.,* [41] demonstrated when an added hydrosoluble polymer increased the solution viscosity, resulting in a large resistance to the radially outward flow and subsequently a small amount of spheres deposited at droplet edge. This result shows how the drying behaviour of the droplet will determine the pressure distribution within the water phase and this will, when combined with the mechanical properties of the other surfactant concerned, determine the dried shape of the drop. Whilst such drying behaviour is interesting scientifically, there are also numerous potential uses for such 3D structures that are created, merely through evaporation. Also, Bhardwaj *et al.,* [42] demonstrated the effect of the pH of the solution on the deposit pattern, which is the results of force interactions between substrate and particles such as the electrostatic and van der Waals forces. Parsa *et al.,* [43] reported that depending on the substrate temperature, three distinctive deposition patterns are observed: a nearly uniform coverage pattern, a "dual-ring" pattern, and multiple rings corresponding to "stick–slip" pattern. Hu *et al.,* [35-37] utilized the temperature-dependent surface tension of liquid and reported a repulsive Marangoni force in the evaporating droplet by the latent evaporation heat. Meanwhile, Still *et al.,* [44] visualized the surfactant-driven Marangoni effect using suspended microparticles. A small ionic surfactant (i.e., Sodium dodecyl sulfate, SDS) induced the Marangoni flow because of a surface tension gradient at a droplet's air–water interface. The result of the evaporation induced outward flow and the inward Marangoni flow is the "Marangoni vortex (eddy)" phenomenon. This phenomenon induces a uniform deposition of the evaporating droplet by forming tree-like multiple rings.

Kajiya *et al.,* [45,46] developed a method to determine the concentration profiles in the evaporating droplets of polymer solution by combining the fluorescence intensity measurement and the lateral thickness profile measurement of a droplet. This experimental protocol was exactly adopted in the present study to determine polymer concentration profile in a droplet. Recently, Kim *et al.,* [47] reported that multiple sequential Marangoni flows and particle-surface interactions are key parameters to achieve uniform particle coatings in a droplet and suggested a small concentration of surfactant and surface-adsorbed polymer via physisorption for a uniform deposit in a binary mixture. Zhiliang Zhang *et al.,* [48] propose an effective and facile strategy to deposit silver nanoparticles in various patterns by utilizing the coffee-ring effect with an inkjet printing technique based on investigation of the influence of substrate wettability on the coffee-ring effect. The droplets of silver nanoparticle ink are inkjet-printed on the substrate; subsequently, capillary fluid flows are induced to replenish the evaporation loss at the edge owing to the CRE, originating from the differential evaporation rates across the droplets [49].

When a liquid droplet impacts a non-wetting surface, it generally spreads on the surface and then retracts back. Eventually, the droplet either stick to or rebound from the surface depending on the impact velocity, surface wettability and liquid viscosity. Kuan-Ming Huang [50], conducted a systematic study of droplet impact of pure water and various glycerol-water mixtures on the superamphiphobic surface. They found that droplets could only rebound from the surface above a critical impact velocity, below which droplet deposition was observed. However, further increase of the impact velocity led to the occurrences of partial rebound, sticking and splashing of droplets. Comparative investigation on the impact dynamics of various viscous droplets on superamphiphobic surfaces, found that the droplets with highviscosity spread and retract slower, take off the surface later and eventually rebound lower and less times than droplets with low viscosity. This phenomenon demonstrates that the viscous dissipation within droplet can strongly affect the impact process. Experiments also showed that the critical impact velocity for droplet rebound linearly increases with the liquid viscosity, which can be explained by a scaling argument. Furthermore, the maximum spreading factor of various viscous droplets on superamphiphobic surfaces cannot be described by the scaling analyses recently reported in the literatures [50].

Changdeok Seo [51], made an effort to deposit suspended particles more uniformly by adding polyethylene glycol (PEG). PEG is known as a non-toxic and non-immunogenic polymer widely used in food, cosmetic, and pharmaceutical research fields. It is worthy to note that PEG molecules in water, which are solution-like surfactants cause to decrease surface tension and to increase the solution viscosity in a concentration-dependent manner. Also, adding PEG would induce Marangoni flow, resulting in change of de-pinning characteristics of contact line. They added a biocompatible surfactant polymer in a droplet solution and expected to obtain a better homogenous coating of suspended microparticles because of the combined effects of surface tension and viscosity changes in the evaporation process. Therefore, different fluid have different existing mechanisms of the internal flow and coating pattern, concentration profile [52].

Addition of a surfactant introduced a Marangoni flow which counteracts the outward capillary flow. Altering the pH 18,19 can influence the DLVO interactions (the force between charged surfaces interacting through a liquid medium) and introduce an attraction between the nonvolatile component and the substrate, which dominates the capillary flow. Recently, it has been shown that through careful selection of an electric field, the coffee-ring can be suppressed. Electrowetting can be used to prevent pinning. Changing particle shape, such as using ellipsoids rather than spheres, can also prevent CRE formation. The transport in, and residual patterns left by, droplets has been an area of significant research interest since there are plethora of phenomena that could influence the dynamic behavior of the drying process.

There is a significant debate about the exact nature of the evaporative flux distribution across a droplet. For the final shape, knowing the droplets' internal flow profile is important and this depends on the evaporative flux distribution. A spatially uniform or edge enhanced evaporation profile leads to an outward flow. If the evaporation is somehow enhanced at the center of the droplet, there is an inward flow. For large droplets with significant ventilation, one expects a uniform evaporation profile. For small droplets with stagnant surroundings, one expects larger evaporation toward the droplet edge. The drops coming out of the nozzle are measured with all kind of optical techniques. The drop formation with sized droplets at high repetition rates (up to 100 kHz) is measured with ultra-high speed cameras (up to 25 Mfps) or with a laser induced fluorescent stroboscopic recording.

Many authors argue that when the atmosphere is stagnant and the liquid side mass transfer resistance is negligible, evaporation is controlled by diffusion of vapour away from the droplet surface, while consider an appreciable liquid side mass transfer resistance [53]. The general situation is not straight forward and it has been shown experimentally that for ambient conditions, the evaporative profile differs significantly from vapour diffusion models. For all physically realizable situations, the magnitude of the capillary number is small and surface tension dominates viscous effects. If the magnitude of the viscosity, surface tension, and volatility of the liquid have little influence.

In spite of all that mentioned above, hard disk manufacturers had tried to manipulate the physical properties of the fluid by adding surfactant but the results are not very encouraging. As mentioned earlier, the hard disk substrates are superhydrophilicity and the humidity of the rinsing process are very high, these affect the outcome.

3. The Numerical Analysis of Water Droplet in Cleaning Process

The earliest significant work attempting to understand the mechanisms of drop generation was by Fromm [54]. He identified the Ohnesorge number, Oh. It is regarded as the appropriate grouping of physical constants to characterize drop formation. He used the parameter Z=1/Oh and proposed that Z > 2 for stable drop generation. This analysis was further refined by Reis & Derby [55], who used numerical simulation of drop formation to propose the following range, 10> Z > 1, for stable drop formation. At low values of Z, viscous dissipation prevents drop ejection, whereas at high values the primary drop is accompanied by a large number of satellite droplets. Numerical solution is invariably required to predict the final profile. Among the small number of investigations that considered asymmetric sessile droplets, Deegan Thesis [56] numerically examined the drying of (and the resulting flow field inside) two-dimensional colloidal droplets on inclined substrates. Also, S´aenz *et al.,* [57] studied, both experimentally and numerically, the evaporation kinetics of non-axisymmetric drops placed on a flat surface and presented a general scaling law for the integrated evaporative flux.

In the cleaning process of hard disk substrates, it involves blower to dry the droplets. In the blowing process, the blower (gas phase), substrates (structure) and water droplets. In the case of a liquid discrete phase and a gas continuous phase, these stresses are the drag and turbulent stresses [58]. Many multiphase break-up models can be found in the literature. Coulaloglou & Tavlarides [59] proposed a break-up model for liquid-liquid dispersion systems in which the break-up frequency is defined by the fraction of particles breaking divided by a characteristic time scale. Luo & Svendsen [60] devised a kinetic theory-type model for bubbles break-up. In their model, the break-up frequency is calculated as a collision frequency between eddies and particles multiplied by a collision efficiency. Martinez *et al.,* [61,62] proposed a break-up model for bubbles based on kinematic ideas (energy balance).

There are also other modeling liquid droplets in gas systems such as spray systems. A mathematical model was devised by Hossam S. Aly *et al.,* [63] for predicting liquid droplets breakup in spray systems without neglecting the contribution of the drag stresses [64]. This model is used to quantitatively compare the roles of turbulent and drag stresses in the break-up process. The model takes into account the effects of both drag and turbulence induced fragmentation stresses on droplet break-up. The model is coupled with an Eulerian-Eulerian CFD model that solves the governing Navier-Stokes equations for all the phases. A reasonable agreement has been reached with experimental data of SMD values. Likewise, the water droplets on the hard disk substrates under the blower, the same method can be applied.

Eq. (1) below takes into account momentum transfer due to mass transfer between the droplets phases. In this equation, the liquid phase is treated as one dispersed phase rather than multiple droplet phases, this term is set to zero in all the simulations. The drag contribution is calculated based on the Schiller-Naumann model [65-67] In order to track the droplets diameter in the Eulerian solver, a conservation equation for the droplet numbers that governs the distribution function of the droplets must be solved. Such equation is known as the population balance equation [68] and can be written in the following form:

$$\frac{\partial}{\partial t}n(d,U_i)+\frac{\partial}{\partial x}[U_i n(d,U_i)]+\frac{\partial}{\partial U_i}[F_i n(d,U_i)]=S\,(d,U_i) \tag{1}$$

S. Sharafatmandjoor [69] study the effect of surface tension and gravity on the kinematics of a droplet. The results of his study, can observe that the droplet's deformation phenomenon has a definite effect on the wake dynamics and the surrounding gas. On the other hand, the co-effect of different droplets strongly affects their acceleration, which is observable in the long time behavior of the system. When droplets are exposed to a gaseous high velocity flow, they show certain characteristics which have been extensively studied by experiments [70-75]. Simulations of such a process have been done in the past [75-82]. Jozsef Nagy [83] presents the computational simulation results of turbulent phenomena in a high velocity multiphase flow, where the predominantly turbulent phase is the gaseous phase. When liquid droplets are suddenly exposed to high speed gas flows, they shatter. However, in hard disk substrates, the water droplets cannot slip completely out substrates due to the superhydroplilicity surface. Proper speed gas should be applied, not to cause any damage to the substrates.

Alejandro Acevedo-Malavé [84] study the interaction between three unequal-size drops is studied. In his paper he modelled of the coalescence process using the Smoothed Particle Hydrodynamics method. This method is used to solve the equations of fluid dynamics using a set of particles that interacts between them depending on the value for the smoothing length, h. Which is very similar to the cleaning process of the hard disk substrates. The model reported in his paper is performed in 3D and it is used the cubic B-spline kernel Monaghan [85]. In his work water drops are considered. An adequate methodology has been proposed for the modeling of hydrodynamical collisions between liquid drops using the SPH formalism in three-dimensional space. Two scenarios for the collisions of liquid drops in three dimensions have been carried out in the simulations. A flat circular section arises as the initial stage in all SPH calculations reported in this work. This flat circular section appears due to the existence of surface tension forces acting on each droplet. Arrange of values for the collision velocity is chosen and the possible outcomes for the collision process are obtained: coalescence and flocculation of drops. The velocity vector fields were constructed by different calculations. It can be seen that the fluid inside the drops tends to accelerate the SPH particles at the zone of contact between the droplets. This behavior is due to the nonuniform pressure differential inside the drops. At the zone of the drops which have no interaction with any other drop, the fluid tends to diminish the internal velocity. This can be explained by the behavior of the pressure field inside the drops, in fact, in that zone of the droplets, the inhomogeneous pressure field has a minimal value.

Mohd. Seraj [86] had designed a self-cleaning filter, whereby the liquid droplets collect on the filter and drain down onto some collecting device. The underlying need for all these applications is estimation of the velocity of a drop along the fiber axis. The different between his study and the the cleaning process of the substrates is the surface. He had dedicated to investigate the role of micro scale droplet motion in non-woven fibrous media and their effect on saturation and collection efficiency. Therefore, the hard disk substrates can be investigate under micro scale using numerical analysis as well.

3.1 Numerical Analysis of CRE

Yunker *et al.,* [87] has demonstrated that the use of ellipsoidal particles suppresses the transport of particles to the edge - Three-dimensional Monte Carlo model of the CRE in evaporating colloidal droplets. The previous attempts to simulate the effect were commonly based on the numerical techniques, such as the finite-element method, applying the analytical equations to figure out the evolution of the average particle density profile. Another family of approaches, based on the Monte Carlo methods, uses randomly distributed particles on the discrete lattice and calculates the probabilities of the possible particle motion directions on each simulation step. One recent attempt to build a Monte Carlo model of the droplet evaporation, capillary flow and contact line deposition has been performed by Kim *et al.,* [47] The model used a simple power-law assumption about the particle motion on the basis of the flow analysis of Deegan *et al.,* [5,6] and reproduced the contact line deposition profile. However, the simulation has been limited to the simplified radial particle motion and has not considered the vertical velocity component and dependence on the vertical coordinate. In the work of Yunker *et al.,* [87] , the CRE growth was modelled in two dimensions (2D) as the Poisson-like process of random particle deposition coupled with the surface diffusion. The model, focusing only on the vicinity of the contact line, has not considered the droplet evaporation and inward flow dynamics. The Monte Carlo approach based on the biased random walk (BRW) has been recently used to investigate the transition from the coffee-ring deposition towards the uniform coverage in 2D. We further develop the BRW method into the more realistic 3D domain and use the flow analysis of Hu and Larsson [88] to calculate the corresponding probabilities of the sampled particle moves on each Monte Carlo Step (MCS). This advancement allows achieving a full 3D structure of the coffee ring and analyzing the thickness profile of the structure. The evolution of the ring shape and dimensions is observed during the entire time period of the droplet drying.

To summarize, the CRE is simulated in the 3D domain, while including both particle diffusion and the capillary particle transport towards the three-phase contact line. The spatial domain of the model is the evaporating sessile droplet represented as a spherical cap. The time scale of the simulation is the full drying process, from the placement of the drop onto a substrate till the final dry-out of the remaining solvent. The simulation result provides a full 3D model of the CRE, and the vertical ring thickness profile is measured. The final shape of the simulated ring structure shows a reasonable dependence on the volumetric particle concentration and colloidal aggregation parameter.

Several models have been proposed to describe the evaporation process of a droplet. Popov [23] proposed an analytical diffusion model for quasi-steady natural evaporation of a droplet based on the solution to the Laplace equation describing the concentration field at the droplet surface in a toroidal coordinate system. The model accounts for the nonuniform vapor concentration field around the droplet. The evaporation flux J(r) on the surface of a droplet in a toroidal coordinate system according to the diffusion-only model for evaporation is given as

$$J(r) = \frac{D(Cs-C\infty)}{Rc}[\frac{1}{2}\sin\theta + \sqrt{2}\,(\cosh\alpha + Cos\,\theta)1^{3/2}\int_0^\infty \frac{\cosh\theta\tau}{\cosh\pi\tau}\tanh\big((\pi-\theta)\tau\big)\,P_{-1/_{2+i\tau}}(Cosh \propto)\tau d\tau \quad (2)$$

where D is the coefficient of vapor diffusion, cs is the saturated vapor concentration on the droplet surface, c∞ is the concentration of water vapor at infinity, Rc is the contact radius of the droplet, θ is the contact angle of the droplet, and r is the radial coordinate at the baseline of the droplet such that r= Rc at the contact line. α and β are toroidal coordinates and are related to the height (h), contact radius Rc, and contact angle θ of the droplet as

$$\cosh \propto = \frac{\sin\theta}{(\frac{h}{Rc})} - cos\theta \quad (3)$$

The expression for droplet evaporation rate, obtained by integration of evaporation flux over the droplet surface area, is based on the contact angle θ and contact radius Rc and is valid over the entire range of contact angles. It is noted that the contact-angle dependence of the evaporation rate as obtained by Picknett and Bexon converges to Popov's solution, although the final expressions are in different forms: The dependence of the evaporation rate on CA given by Picknett and Bexon is in the form of an approximate series solution, while Popov provided a closed-form expression. For any contact angle, the rate of mass loss as given by Popov is

$$\frac{d\theta}{dt} = -\frac{D(Cs-C\infty)}{\rho_L Rc1^2}\,(1+\cos\theta)1^2 f(\theta) \quad (4)$$

The model used in the present investigation is based on classical hydrodynamics. Two main approximations are made: droplets are supposed to be small with a spherical geometry and a fast relaxation of mass flows and temperature profiles inside and in the vicinity of the droplets interface is assumed. Based on mentioned assumptions, hydrostatic pressure gradients are neglected and quasi-stationary hypothesis is justified. Convection is neglected in the gas phase and assumed to be slow enough inside the droplets for viscous dissipation contributions to be negligible. The liquid phase is described using stationary Navier-Stokes and heat equations. Table 2 below shows the numerical analysis and the results.

Table 2
The numerical analysis and the results

Numerical analysis	Result/outcome
The 3D Monte Carlo model is developed in the spherical-cap-shaped droplet [9]	The CRE is simulated in the 3D domain, while including both particle diffusion and the capillary particle transport towards the three-phase contact line. The spatial domain of the model is the evaporating sessile droplet represented as a spherical cap. The time scale of the simulation is the full drying process, from the placement of the drop onto a substrate till the final dry-out of the remaining solvent. The simulation result provides a full 3D model of the coffee ring, and the vertical ring thickness profile is measured. The final shape of the simulated ring structure shows a reasonable dependence on the volumetric particle concentration and colloidal aggregation parameter.
computational fluid dynamics and the finite element method (FEM) [10]	Study on the Effect of Marangoni Flow on Evaporation Rates of Heated Water Drops
commercial computational fluid dynamics software, Flow3D. [18]	Solve 3D Navier-Stokes and mass continuity equations for a predetermined mesh using a finite difference approximation with the volume-of-fluid method to study the Inkjet-Printed Line Morphologies and Temperature Control of the CRE
OpenFOAM 2.1 [31]	While this approach should not be considered trustworthy neither too close to the contact line nor in the center of the drop, nevertheless it gives quantitative results in the remaining portion of the interface. The droplet shape used is always adopted from the experiment. Quasi-stationarity is assumed at each moment during the droplet evaporation. Three different sets of interfacial conditions are examined for this analysis.
custom-programmed software based on MATLAB (version 2011a, Mathworks Inc., USA) which A Gaussian filter was applied [52]	The images and trajectories were calculated using the nearest-neighbour algorithm as the study on biosurfactants reverses the CRE in a bacterial system.
MAPLE (version 14, Maplesoft, Canada) which adaptations to the model developed by Hu and Larson [88]	Flow profiles and streamlines of the surfactant as the study on biosurfactants reverses the CRE in a bacterial system.
COMSOL Multiphysics (version 4.2, COMSOL Group, USA) which 1D diffusion equation was used, using parameters obtained from Stebe *et al.,* [89]	Diffusion analysis of the biosurfactant concentration and surface tension evolution over time as the study on biosurfactants reverses the CRE in a bacterial system
MATLAB using a spherical-cap assumption, [90]	The droplet height and contact radius are also calculated and verified. Droplet mass, liquid density, the droplet volume, and the functional variation of CA evaluated as the study on droplet evaporation dynamics on a super hydrophobic surface with negligible Hysteresis
CFD modeling with the commercial codes Flow3D and Fluent [91]	Fluent include wall-flexibility, free surface flow, and two- phase flow with surface tension. Numerical simulations are done with the volume of fluid method on the continuum scale and with lattice Boltzmann and Cahn Hilliard on the meso-scale. Main challenge is to bridge the gap between continuum modeling and molecular dynamics to resolve the details of contact line dynamics, which are the driving mechanism behind the displacement of small drops.

4. Conclusions

The physics behind drying process of the water droplets during washing process are the game changing criteria to further understand the formation of CRE and ways to eliminate it. Previous studies have highlighted that the drying process of the water droplets are affected by the properties of the water droplets, substrate and temperature. In order to collaborate CCR, CCA, advancing contact angle and receding contact angle, the arrangement of the substrates, the position of the drying equipments can be manipulated to eliminate CRE. Furthermore, manipulation of the temperature of the substrates can enhance the drying process of the droplets before the formation of CRE. However, heating is an essential process for substrates enhancement. Therefore, manipulation of substrates temperature in eliminating CRE must not changes the properties of the substrates.

It actually creates lot of concern to the industries once the temperature and chemical were manipulated as hard disk substrates are very sensitive part of the hard disk. Therefore, this paper suggested to optimize or replace the current cleaning physical process. As the substrates was blow under a humid environment, which prevent the elimination of water droplets, this paper suggests to increase the flow rate of the blower. According to the manufacturer, manipulating the flow rate do show improvement but not complete. Therefore, they replaced the current cleaning process with a new one which is more effective as the substrates are dried piece by piece.

To conclude, CRE can be studied using numerical analysis. The results can be verified using previous studies and validated by using the actual results provided by the industries. CRE formation also depends on the properties of the substrates and water droplets. Moreover, knowing the properties of the substrates and water by undergoing the wettability test and CAH testing as mentioned above are important. In this case, changing the chemical properties substrates are not advisable to eliminate CRE due to its complex design of the substrates for data storing. All the numerical tests have to be performed according to correct procedures to ensure accurate and acceptance results from the industries. Verified and validated results from the evaluation will help to predict the real consequences more accurately for further optimization. Knowing that the formation of CRE is caused by the evaporating of the water droplets, we need to find ways to eliminate the formation of water droplets before the heating process, in order to eliminate CRE.

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