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REVIEW ARTICLE

Thermofluidic Transport in Droplets under Electromagnetic Stimulus: A Comprehensive Review

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Abstract | In the vast expanse and scope of fluid mechanics, thermal and species transport, droplets have carved out an important niche for themselves. These microscopic fluid entities, bounded to shape by surface tension and/or interfacial forces, play important roles in variant capacities in the physical world, biological systems as well as man-made technological applications. Thereby, understanding of droplet dynamics is an essential area in research and development. To add to the complexity of interfacial thermofluidic transport in droplets, presence of electric and/or magnetic fields yields interesting and rich physics to the problem. Additionally, such field-induced transport in droplets has found applications in several systems, ranging from macro- to micro-scale. Consequently, research on the physics of thermofluidic transport in the presence of electromagnetic stimulus has gained wide attention in the academic community. The present article discusses the present status of research, development and knowledge base on the topic. The physics of the problem, scope and extent of work realized by the academic community till date, potential applications and future directions have been discussed in an effort to provide a comprehensive review. The article shall be able to provide the readers a precis of the research and developmental work in the field thus far and acquaint them with an idea of the path ahead.

Keywords: *Droplets, Pendant drop, Sessile drop, Electric field, Magnetic field, Microfluidics, Electrohydrodynamics, Magnetohydrodynamics, Transport phenomena*

1 Introduction

"*You are not a drop in the ocean. You are the entire ocean in a drop*"—Immortal words by the thirteenth-century Persian scholar and mystic, Rumi. While the philosopher might have aimed his words towards the generic human spirit, the quote in itself is very true for drops as well. *Droplets*[1–3] despite being minuscule fluid entities are among the most important elements in the vast gamut of fluid dynamics and thermal sciences. In fact, droplets constitute the final component of the water cycle, whereby water is shed by clouds in the form of raindrops. Thus, in a sense, droplets hold the key to the essence of life force and of the human civilization. Such is the significance of these small fluid elements to life as we know. The present article shall, however, aim to discuss the more techno-scientific aspects of droplets, mostly bordering on the latest research and developments in a small niche of the field. The crux of this perspective article shall be to comprehend the rich thermofluidic multiphysics phenomena in droplets under the influence of electric and/or magnetic fields.

Droplets are the direct manifestation of the *surface tension* of a fluid. A sphere has the minimum

A **drop** may be defined as a small mass of liquid, bounded completely or nearly completely by free surfaces by virtue of surface/interfacial forces.

A **droplet** is a diminutive drop with diameter less than ~ 0.5 mm.

Surface tension of a fluid maybe defined as the elastic characteristics of a fluid surface by virtue of which it attains the least surface area possible under a given thermodynamic scenario.

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An excellent example of an **emulsion** is milk, wherein minute fatty globules are dispersed stably in watery medium containing carbohydrates, proteins and minerals.

Ultrasonic levitation is the method of utilizing the acoustic pressure generated by high-frequency sound waves to suspend materials against the gravitational pull.

The **contact angle** is the angle extended from the solid–liquid interface, through the liquid, up to the gas–liquid interface of a sessile droplet. Acute angles, typically up to 70°–80°, indicate hydrophilic surfaces, the range of 90°–120° constitutes hydrophobic, 120°–150° constitute superhydrophobic and beyond that indicates ultrahydrophobic.

surface area per unit volume among three-dimensional symmetric shape forms, and thereby surface/interfacial tension ensures that droplets are spherical (or near spherical) at rest. From a technical perspective, two generic static drop shapes are possible, the pendant and the sessile. The pendant shape is realized when a droplet is suspended from the end of a thin tube (such as needles) and it rests hanging in the ambient phase[4–7]. The pendant remains stably suspended as long as the surface tension force dominates over the weight of the droplet. In a pendant drop, only a minute portion of the liquid is in contact with the tube (or needle) and nearly > 95% of the surface area is in contact with the ambient phase. Thus, the pendant drop provides the closest scientific approach to realizing a droplet in free suspension (like raindrops). Of course, it is possible to realize freely suspended droplets using *ultrasonic levitation*; however, such droplets exhibit oscillatory behavior and thus fall under a different umbrella of research[8–11]. Accordingly, in recent times, research on pedant drops has seen steadfast growth since the thermofluidics and species transport features, such as internal advection[12–15], heat transfer and evaporation dynamics[16–18], in case of pendant droplets are devoid of surface effects. This is very important for understanding spray evaporations and combustion[19, 20], aerosols[21], fumigants[22], aeroponics[23], mist and fog formation[24], cloud dynamics[25], etc. Additionally, the pendent drop method has proven to be the most robust mechanism to deduce surface tension of fluids.

The sessile drop, on the contrary, is linked innately to an additional surface. The typical static sessile drop rests on a surface in the form of a spherical cap. The angle that the cap makes with the solid surface, called the *contact angle*. The contact angle for a droplet under equilibrium is governed by Young's equation and is a function of the interfacial energies of the gas–liquid, gas–solid and solid–liquid pairs. Such interactions thereby make the sessile droplet a more complex system in comparison to the pendant drop. In fact, the sessile drop method is the most effective way to determine the wettability of a solid with respect to a liquid, in the ambience of a given gas phase, and the associated phenomena, such as wetting and spreading[26–29]. As a consequence of the surface playing a major role, the thermofluidic behavior of the sessile drop is largely regulated by the characteristics of the surface. Recent developments have seen attempts to tune the wettability of a liquid on solid surfaces, giving rise to asymptotic wettability regimes from superhydrophilic[30–32] to super/ultrahydrophobic[33–35]. Sessile droplets have been studied to understand droplet evaporation[36, 37], heat transfer[38, 39] and deposition patterns[40, 41], self-cleaning surfaces[42, 43], scaling[44], condensation and water harvesting[45, 46], microscale device thermal management[47, 48], bio-diagnosis[49, 50], etc.

Apart from these two fundamental droplet forms, it is also possible to envisage droplets dispersed in another liquid. In fact, mist and fog droplets are dispersed in a gas media, and liquid droplets dispersed in another continuous liquid medium constitute an emulsion. In recent times, research on such individual liquid globules or vesicles dispersed in continuous liquid media has gained a lot of attention, typically due to their importance in pathological diagnostics[51, 52], medical treatment[53–55], microscale testing of industrial processes[56–59], etc. Of course, research in the area is focused on understanding the dynamics of single or a few dispersed droplets and not on a collective system such as a true emulsion. In fact, the whole area of understanding dispersed individual droplet behavior in microscale flow domains and engineering application from such flows has constituted the field commonly described as droplet microfluidics[60–62]. A large volume of literature has been dedicated to the study of such solitary droplets dispersed in another liquid phase and the majority of the works employ microfluidic devices and systems to study such systems.

Electromagnetic interactions with thermofluidic transport phenomena pose several interesting physical insights. Droplet interaction with electromagnetic fields serves as an area of rich multiphysics, where fluid dynamics, interfacial phenomena and their co-existence with electromagnetism generate atypical thermal and species transport regimes. With the advent of microscale device systems, droplet dynamics, their control, actuation and manipulation have found important roles in systems such as micro-nano-lithography, deposition techniques, printing, thermal management of devices, liquid displays and logic control. Such techniques require accuracy and precision in control. Further, microscale fluid droplets require robust manipulation with accurate spatio-temporal variation, which cannot be achieved by direct contact methods at reduced dimensions. In such scenarios, non-contact method of manipulation, such as by electromagnetic fields, acoustic techniques and optical control are very popular. Among these, the use of electric and magnetic fields to manipulate microscale fluid systems has received wide attention due to the ease of use and control and easy integration of such systems into microscale devices. However, before directly using at a device level, the intrinsic physics of fluid transport and heat transfer in droplets due to such electromagnetic fields needs thorough understanding. Accordingly, a populous array of literature on the topic exists and the present article puts forth a comprehensive review on the subject matter, as to where droplet thermofluidics under electromagnetic stimulus stands and what are the future avenues.

2 Influence of Magnetic Field

The influence of magnetic fields on droplets and its implications vis-à-vis thermofluidic transport is an area of academic interest and research which has been in the limelight for quite some time now. Rich multiphysics phenomena such as magnetohydrodynamics, magnetic advection, and magneto-solutal transport have been reported in case of droplets of magnetically active fluids. A major portion of studies on the conglomeration of droplet dynamics and magnetic field has been the evolution of shape and behavior of sessile droplets under the intervention of a magnetic field. The basic genesis of the field may be traced back to the controlled shaping of liquid metallic droplets by high-frequency alternating magnetic field[63]. It has been discussed that in liquid metals, the Lorentz forces induced within the droplet is confined along its periphery (due to the skin effect in conductors), which manifests itself as a form of magnetic pressure on the droplet surface. It is shown that such alternating magnetic fields can squeeze a metallic droplet to the desired shape while conserving the volume. It was further noted that high field amplitude and frequency can induce oscillations in the droplet, leading to complex mode shapes. A similar analysis on the droplet oscillation mode shapes in case of magnetically levitated liquid metal droplet has also been reported[64]. It is reported that the magnetic force deforms the droplet and the shape at static equilibrium shape is aspherical and asymmetric. The oscillation spectrum under the influence of the Lorentz force induced by the field has also been reported for different electrical conductivity and viscosity values (or in other words, for different *Hartmann numbers*). A similar report discusses the flow dynamics in an electromagnetically levitated droplet due to the alternating magnetic field component[65]. The linear stability analysis presented yielded that the flow became unconditionally unstable at and above Reynolds numbers of ~100. It was further noted that an additional direct magnetic field may be applied along the droplet axis to subdue such instabilities. Studies also reveal that wettability[66] as well as movement[67] of liquid metal droplets can be tuned and governed by application of magnetic field environments. The major application of such manipulation and control of liquid metal droplets using magnetic fields is in the areas of arc welding[68], microscale circuit patterning[69], etc. Another important area with rich physics where droplet dynamics under the influence of magnetic field is important is the case of magnetic colloidal droplets, also termed as ferrofluids (in the event the dispersed particles contain iron and are nanoscale in size). Some very interesting reports on the fluid dynamics of ferrofluid droplets exist in the literature when in the form of a liquid marbles. Liquid marbles synthesized using commercially available ferrofluids and polytetrafluorethylene microparticles were experimented upon in the presence of magnetic field[70, 71]. It has been shown that an external magnetic field can deform the shape of the marble and lead to large degrees of distortion and spread despite the hydrophobic nature of the marble. It is further observed that the non-dimensionalized forms of the marble radius and height scale to the fourth root and the inverse second root of the magnetic *Bond number*, respectively. It was, however, observed that in case of a dynamic marble in motion under the actuation of a magnet, the deformation is proportional to the *Capillary number*.

A large body of literature exists on the actuation dynamics, distortion, deformation and instabilities of ferrofluid droplets under the influence of magnetic field. Such studies can be further categorized into sessile droplet behavior and behavior of droplets dispersed in another liquid, which could be static or in motion. Novel flow focusing and control devices for ferrofluid droplet actuation have been widely reported[72–74], with the essence being the achievement of one-dimensional droplet motion with control over shape and velocity. The spreading dynamics and motion of ferrofluid droplets on generic surfaces under the effect of magnetic field have also been widely studied[75–78]. Fluid dynamics and magnetohydrodynamic interactivities such as deformation and subsequent breakup of the ferrofluid droplets with increasing field strength have been reported. The breakup pattern and kinetics of the sister droplets have been explained on the basis of the classical Rosensweig instability in ferrofluids under field stimulus. It is reported that the interaction of the magnetic Bond number and surface wettability governs the breakup mode. Analysis

The **Capillary number** (**Ca**) is a non-dimensional number in interfacial physics which determines the relative importance of viscous forces over surface or interfacial tension force.

The **Hartmann number (Ha)** is an important dimensionless number in magnetohydrodynamics and is the ratio of the electromagnetic force to the viscous force in a fluid.

In interfacial physics, the **Bond number (Bo)** describes the relative importance of gravitational forces over the surface or interfacial tension force, and is used to determine the shapes of drops and bubbles with respect to an ambient fluid.

of droplet motion under the action of a moving field showed that the deformation of the droplet shape, change in height and contact radius varies non-linearly with the magnetic field intensity. It was further observed that the advancing and receding contact angles during the field actuated motion responded differently to the field velocity and showed different behavior with respect to field intensity.

In fluid dynamics, very low Reynolds number flows (Stokes flow) through the infinitesimally small separation between two large parallel plates constitute the **Hele-Shaw flows.**

Breakup dynamics of ferrofluid droplets in a magnetic field also poses excellent fluid dynamics aspects. It has been reported that a pendant ferrofluid droplet breaks up and ruptures in a magnetic field environment[79, 80]. It has been discussed that magnetic fields can induce droplet separation instabilities in ferrofluid jets and can lead to oscillations of freely suspended ferrofluid droplets. Studies also show[81] that magnetic fields can induce freestanding surface waves on ferrofluid droplets. Even more interesting physical phenomena are observed in case of ferrofluid droplets traveling through fluid columns under the influence of external field[82–86]. It is reported that for immiscible droplet and surrounding fluid system, the droplet conforms to the asymptotic small deformation theory under low field strength. At high fields, the interfacial tension is a strong function of the magnetic field strength, and the deformation observed is pronounced and the droplet distorts in shape. It is further shown that the nature of deformation and regime of transport (inertia dominated or magnetic body force dominated) can be identified from the relative values of the magnetic Laplace number (La) [or magnetic Suratman number (Su)] and magnetic Bond numbers. It is further discussed that the magnetic susceptibility of the ferrofluid material strongly governs the deformed shape, and can lead to teardrop or distorted oblate shapes in case of high-susceptibility fluids. In case of highly viscous external fluid medium and strong fields, the teardrop shape in conjunction with viscous drag often leads to pinch-off to form microscale daughter droplets at the tail of the tear. The motion of minute ferrofluid droplets through such viscous media has been shown to have promise in field-guided treatment for retinal detachment[87, 88].

Ferrofluid droplets are also known to show intriguing physics in the presence of rotating or spatially variant magnetic fields[89–92]. Simulations and experimental observations reveal that the dynamics of a ferrofluid droplet in the presence of a rotating magnetic field is complex and intriguing. Analysis of the angular momentum of the droplet with respect to the fields and correlating with the magnetic Bond number reveals transition to chaotic behavior in the droplet's rotation. For ferrofluid droplets miscible in the ambient fluid, a rotating magnetic field induces visco-capillary fingering instabilities. Star-shaped evolution of the initially spherical droplet is reported due to field rotation and the process is found to corroborate to a universal 4/3 power law with field intensity and time. Reports also discuss that in case of Hele-Shaw flows for ferrofluid droplets in the presence of a rotating magnetic field, the droplet may assume a ring shape under certain flow and field conditions. For immiscible droplet and fluids, the physics is observed to be even more interesting. In the event, the viscosity of the ferrofluid is greater than the surrounding liquid, the droplet distorts and exhibits bending instability. It distorts to an S shape under the influence of the external rotating magnetic field. Instabilities in ferrofluid droplets under the influence of rotating magnetic field can also exhibit novel patterns and modes[93–96]. Depending on the field rotational parameters, the droplets have been observed to assume variant shapes, such as starfish, rod-like or pancake (in rotating with the applied field), creeping snakes, swirling loops, and rings and polygons. The interplay of capillary and elastic forces within the droplet at different magnetic fields can induce excellent patterns, folds and striations in ferrofluid droplets. It has been shown that magnetic fields can be employed to induce such capillary origami in ferrofluid droplets. In the event, the droplet is immersed in a thin layer of non-magnetic fluid; the droplet exhibits ferrohydrodynamic instability under field effect. It has been shown that peculiar labyrinth structures and peaks are formed due to the field.

Understanding the dynamics of magnetic fluid droplets in the presence of magnetic fields can lead to strong implications in different applications. It has been shown that actuating ferrofluid droplets can behave as a print head and can be manipulated to create intricate patterns on elastomer matrices[97]. Such processes require intrinsic knowledge of droplet coalescence and merging and it has been shown that the magnetic field strength directly influences the coalescence behavior in ferrofluids[98, 99]. It has been also shown that such magnetic fluid droplets undergo self-assembly under a static external magnetic field to form simple patterns. This can be further switched to complex dynamic structures in the presence of a time-varying magnetic field[100, 101]. It has also been shown that the coalescence and decoalescence of such droplets can be modulated using external fields[102]. The elongation of laterally confined droplets is observed to scale logarithmically with the ratio of the droplet thickness to its original radius. This is also found to be unlike the behavior of unconfined droplets[103, 104]. In fact, the fingering instability is also found to be controllable by the field direction, strength and frequency. Increase in vertical field strength has been shown to modulate the wetting and wetting hysteresis behavior of oleic ferrofluid droplets on water-wetted surfaces[105]. It is additionally observed that Cassie to Wenzel wetting state transition occurs when the excitation frequency of the magnetic field is in close vicinity of the resonant frequency for the droplet. It is theorized that such transition occurs due to change in the Laplace pressure caused by the large deformation in droplet shape[106, 107]. Ferrofluid droplet hydrodynamics has been shown to modulate heat transfer features, combustion dynamics, opto-acoustic transport characteristics[108–111] and so on.

Dispersed magnetic fluid droplets in microscale flow domains or microfluidic systems have also gathered much interest and have shown excellent magnetic field-influenced thermofluidics phenomena. It has been shown that ferrofluid droplet sizes linearly decrease with increase in continuous flow velocity at a microscale junction. In the presence of field, the droplet size can be controlled as a function of material magnetization, field strength and gradient[112, 113]. The attractive magnetic force acts as a body force, which tunes the surface forces at the interface and controls the droplet size. It is observed that radial magnetic field at the junction controls the droplet expansion process while an axial field governs the breakup process[114]. The width of the ferrofluid thread formed by the sheared detachment of the droplet is found to scale as a power law with time under field effect. It is also possible to convert the time-asymmetric breakup dynamics under zero-field to a time-symmetric breakup event at finite fields[115–117]. The formation frequency and size of the daughter droplets formed are found to scale to the magnetic Bond number and magnetic capillary number[118]. For coalescence of ferrofluid droplets in a microscale channel, it is observed that a critical separation and magnetic field strength govern the coalescence process[119]. Magnetic field can be effectively used to process and synthesize stable and size-controlled ferrofluid emulsion droplets in micro-mixers[120]. It is demonstrated that such precise control of ferrofluid microdroplets in microscale flow systems can be effectively used in liquid logic circuits[121] and functional opto-magnetic lenses[122].

3 Influence of Electric Field

The inherent dielectric behavior of most fluids ensures that the transport phenomenon of droplets under electric field stimulus is wide and rich in multiphysics phenomena. Physical phenomena such as electrohydrodynamics, electrokinetics, electroosmotic flows, electrodiffusion, electrophoresis, dielectrophoresis, and electro-solutal effect form a rich envelope of transport events in case of electric field-modulated thermofluidics. In case of droplet transport, it has been shown that microscale methanol droplets can be distorted, can be split to form daughter droplets and even form microscopic jets and Taylor cones from the droplet surface. The polarity of the field also determines the directionality of distortion in the droplet[123]. It is further shown that usage of electric fields can modulate the jetting and spray formation behavior at nozzle tips by tuning the surface tension force[124]. Droplets can be forced to exhibit rhythmic behavior between electrodes and undergo small amplitude oscillations[125]. For a fluid droplet suspended in another leaky dielectric fluid, charge buildup at the interface leads to electrohydrodynamic advection cells within the droplet[126]. Another important aspect of droplet dynamics under electric stimulus is the electro-Leidenfrost effect. It has been shown that increasing the electric field strength across a droplet undergoing Leidenfrost bouncing reduces the vapor layer thickness[127]. Beyond a certain voltage level, the Liedenfrost effect is suppressed and the droplet undergoes boiling. Such observations are important from aspects of metallurgical cooling, nuclear thermal reactors, turbines, etc., where film boiling and Leidenfrost effects are undesirable.

Hydrophobicity and strip electrode arrays can be combined to obtain electric field-governed propulsion of droplets. Such propulsion finds importance in cooling of micro devices via targeted droplet actuation. Direct voltages can be employed on the strip electrodes, which induce deformation of the droplet. The deformation leads to imbalanced Maxwell stresses, leading to translation of the droplet[128, 129]. Increased voltages applied to a superhydrophobic surface are reported to propel droplets vertically away from the surface due to electrical stress developed at the solid–liquid interface[130]. In case of partially hydrophobic surface, the droplet tends to oscillate on the surface than be propelled away[131]. Application of electrical discharge across a mist of microscale droplets is found to enhance the inter-droplet collision frequency and has implications towards understanding cloud dynamics during thunderstorms[132]. Similar droplet deformations and distortions are also observed for individual aerosol droplets[133] which may lead to coalescence, thereby leading to excellent water harvesting techniques from fog and mist. Such philosophies of electrostatic manipulation of capillary waves for droplet and spray ejection systems have been proposed as well[134]. Nematic liquid crystal droplets are also observed to respond to electrical stimulus and exhibit internal alignment and external distortions[135, 136]. In the event of droplet dispersed in a leaky dielectric continuous phase, two types of distortion phenomena are reported, the continuous deformation and deformation hysteresis[137, 138]. Likewise, for a double component emulsion annular droplet dispersed in a different continuous phase, the electric field is potent enough to induce differential circulation patterns within the two components of the droplet[139].

In case of sessile droplets resting on surfaces and under the influence of strong electric fields, the wettability is shown to be modulated. Under field effect, the polar water molecules realign themselves along the surface and along with intermolecular interactions, cause the droplet to deform, spread and induce enhanced wetting[140]. For an alternating field applied across a droplet resting on hydrophobic surface, resonant vibrations of the droplet within a certain frequency band are noted[141]. The Taylor–Melcher leaky dielectric model with finite charge relaxation has been found to be accurate to model the electro-deformation of droplets[142]. Electric field is also observed to modulate heat transfer processes in droplets[143, 144]. Hydrophobic surfaces in conjunction with electric fields are shown to largely improve the droplet condensation heat transfer rates. The field-induced coalescence and removal by jumping off the surface due to enhanced interfacial tension lead to improved condensation heat transfer similar to dropwise condensation. The field strength is noted to modulate the coalescence rate, jumping caliber and heat transfer rates. Electrohydrodynamics within a pendant droplet leads to formation of distinct circulation cells in the droplet interior, leading to improved heat transfer to and from the droplet due to internal advection. Strong electric fields can produce excellent applications of droplets, such as electrospraying of extremely fine mist[145–147] and electric control of microliquid crystal droplet-based lenses[148, 149]. It is further shown that the electrospraying phenomenon under alternating field is greatly governed by the electric Reynolds number and the Strouhal number[150]. Optimal spray discharge is observed when the product of the electric Re and the St scales as the order of 1·

In fluid dynamics, the **Strouhal number (St)** is a non-dimensional entity which governs oscillatory flow phenomena.

Presence of electric fields across droplets is also reported to bring about Cassie to Wenzel state transitions as well as modify the rate of evaporative mass flux from the droplet[151, 152]. Electric field can be used to switch on and off the adhesion of droplets on superhydrophobic surfaces[153] and stability criteria for the field strength, direction and vortex structures inside the droplet during actuation have been established[154]. For a droplet dispersed in another viscous liquid, a direct field above a critical strength is shown to induce ellipsoid formation of the droplet, leading to rotational flow field around the droplet[155]. With increase in field strength, the droplet continues to elongate and finally distorts and disintegrates by jetting from the ends[156]. Charging of a sessile liquid droplet surface via ion bombardment is shown to lead to buildup of interfacial electric pressure, which causes the resting drop to spread out and the spread event is found to be similar to squeezed spreading between two parallel plates[157]. Electrowetting of a sessile droplet is also observed to be strong functions of the zero-field wetting hysteresis for the surface as well as the frequency of the applied field[158]. Apart from fluid dynamics and heat transfer processes, electric field is also observed to strongly influence droplet combustion processes. The electric field induces a body force on the flame, thereby compressing it and changing the combustion dynamics on a whole[159]. It is shown that the flame deformation scales directly to the electric field strength and inversely to the 1.5th power of the electrode spacing. Variant modes of atomization using electric field have been studied and the effect of field parameters on final droplet distribution is widely probed[160, 161]. The electrohydrodynamic behavior of the ensuing jet stream of mist and droplet coalescence behavior downstream under field effect are also found to have excellent utilities in dust and foreign particle capture[162].

Wettability and electric field can interplay to form fascinating fluid dynamics in dielectric droplets. Under the effect of electric field, a dielectric droplet dispersed in a magnetic fluid exhibits new modes of instabilities. With increasing electric field strength, the droplet deforms to form an oblate, further a toroid, further a thin and long closed loop, and beyond this it shatters to form multiple daughter droplets[163]. Electro-elastocapillarity is another novel phenomenon to induce motion to resting droplets employing electric fields. Droplets have been made to oscillate and rebound with quick repetitions on electrically actuated substrates[164]. At weak fields, the droplets deform but attain a steady-state shape, while in case of strong fields; the Maxwell stresses lead to rupture of the droplet by jetting, and such phenomena are strongly governed by the wettability of the surface at zero-field condition[165, 166]. It is also shown that for strong alternating fields, the droplet can exhibit corona discharge from its apex, and jetting of microscale droplets from the droplet surface is possible, leading to shattering of the droplet[167]. Droplet actuation using opto-electrowetting is also shown to be possible with the help of laser actuation using photoconductive substrates[168]. Other important applications of electrowetting and electrospray are the formation of droplets and control process in case of electric arc wire spraying[169]. As such, electric fields are so potent in distorting the shape of pendant or sessile or dispersed droplets; a vast spectrum of works has focused on understanding the very nature of such droplets at steady state in the presence of field[170–174]. While the electrowettability of polar liquids on polar surfaces has been understood to some extent, the scenario for insulating surfaces and non-polar fluids is yet to yield conclusive physics. Determination of equilibrium drop shapes under electric field stimulus is widely studied[175–177] in terms of the electric Bond number and droplet deformation employing field has been found to have use in stabilization of fuel droplets in zero-gravity conditions[178].

Sessile droplet electrohydrodynamics or electrowetting has been an active area of research and development. Applications such as targeted cooling of micro devices, actuation of chemical droplets in requisite volumes within microfluidic devices, and control of wetting and patterning have rapidly evolved as utilities of droplet electrowetting. A very wide area of research is electrowetting on dielectrics (EWOD) [179–181] where the sessile drop rests on a dielectric surface and the charge developed at the interface due to field leads to electrowetting or actuation. In the event of rotating electric field and a sessile droplet, the rotating field induces oscillations, drop rotations as well as rotation-induced coalescence of neighboring droplets along with deformation of the coalescence droplet[182]. It is also established theoretically that the droplet aspect ratio after deformation scales to the 6/7th power of the applied field intensity[183]. Droplet formation dynamics in the presence of an electric field also leads to different droplet behavior, due to morphed jetting dynamics caused by electro-capillarity[184, 185]. In case of non-Newtonian droplets or submerged sessile droplets in immiscible media, the viscous behavior of the fluid in conjunction with field strength is observed to have a profound effect on droplet behavior[186, 187]. It is reported that critical field strength exists beyond which electrowetted droplets exhibit instability and nonlinear oscillations lead to droplet deformation, detachment or rupture[188, 189]. Additionally it is shown that the electrostatic force can be employed to levitate a conducting fluid droplet submerged in another dielectric fluid[190, 191]. Detachment of droplets from wetted surfaces by tuning the capillary forces by electric field is also shown to be possible[192]. Such electrowetting phenomena may find applications in dewetting of electrical components for safety[193], in guided traverse of droplets in electronic systems[194], and in enhancement of heat transfer by internal electro-advection[195].

Like any droplet-based systems, the biggest exploited and studied electrohydrodynamics of droplets is in the field of microfluidics. Formation[196], size control[197], reaction and bio-synthesis[198], targeted transport[199], actuation[200] and controls of droplets within microfluidic devices have got immense attention from the research community and numerous applications[201–204] as well as rich physics[205–209] has been brought forth. Given the rapid actuation, fast control and ease of integration, electro-microfluidic devices have become exceedingly ubiquitous in today's research endeavors to bring forth newer innovations in microfluidic engineering and medical systems. Microfluidic devices have been shown to cater to several applications and utilities employing droplets and electric fields, such as coalescence and mixing[210, 211], generation of droplets[212–214], droplet sorting and distribution[215–217], biological assays at droplet and emulsion interfaces[218–220], and similar other applications[221–225]. Large-scale research and development of such lab-on-a-chip devices and systems have led to electrical modules being integrated to the devices to harness control and actuation of droplets for engineering[226–228] and biomedical[229, 230] applications.

4 Perspectives and Future Directions

The present article attempts to paint a fairly comprehensive landscape of the research developments and knowledge base with respect to fluid dynamics and thermal transport in droplets in the presence of electric and/or magnetic field stimulus. Initially, a fairly complete review of droplets has been presented to introduce the reader to the vast expanse of the field and to get acquainted with the intricacies. Typical physical phenomena and applications of droplets have also been put forward in the introduction. Next, magnetohydrodynamics of ferrofluids and other magnetic fluid droplets have been reviewed. Important physics, innovative applications and essential theories available have been put forward. Next, the same protocol has been traced for the topic on electrohydrodynamics of droplets. By this point, the author hopes that the potential reader has achieved a fair picture of the research and development in the area of droplet thermofluidics and electromagnetism multiphysics. Although a huge amount of work has been presented by the research community, there is a vast scope for droplet electromagnetic multiphysics. Several future directions maybe mapped; however, the author would like to put forward a few potential and important aspects. Miniaturization of microfluidic devices as well as advent of flexible microfluidics, understanding the fluid dynamics and heat transfer aspects in droplets in conjunction with elastocapillarity is essential. In case of sessile droplets, the understanding of wettability, wetting hysteresis, drying and pattern formation is important for several applications such as patterning and colloidal assembly for nanostructures. In both cases, the presence of electromagnetic fields can influence fluid–structure interaction patterns, thereby yielding richer physics well as potential applications in nanotechnology, microfluidics, patterning, etc. Flow dynamics of non-Newtonian droplets in the presence of electromagnetic fields as well as oscillatory transport of droplets is yet another area fairly untouched, and has excellent potential in understanding vesicle dynamics and reactions under field influence within microfluidic systems. Manipulation of biological cells has been shown to respond to electromagnetic fields within droplet microfluidic systems. Applications such as targeted drug reaction within microscale droplets, cell and droplet sorting employing field effects, and synthesis of field-mediated nanostructures and emulsions as potential drugs are all new directions where the field can grow exponentially.

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References

1. Sirignano WA (1999) Fluid dynamics and transport of droplets and sprays. Cambridge University Press, Cambridge
2. Abramzon B, Sirignano WA (1989) Droplet vaporization model for spray combustion calculations. Int J Heat Mass Transf 32(9):1605–1618
3. Tolman RC (1949) The effect of droplet size on surface tension. J Chem Phys 17(3):333–337
4. Roe RJ, Bacchetta VL, Wong PMG (1967) Refinement of pendent drop method for the measurement of surface tension of viscous liquid. J Phys Chem 71(13):4190–4193
5. Boucher EA, Evans MJB (1975) Pendent drop profiles and related capillary phenomena. Proc R Soc Lond A 346(1646):349–374
6. Harikrishnan AR, Dhar P, Agnihotri PK, Gedupudi S, Das SK (2017) Effects of interplay of nanoparticles, surfactants and base fluid on the surface tension of nanocolloids. The Eur Phys J E 40(5):53
7. Stauffer CE (1965) The measurement of surface tension by the pendant drop technique. J Phys Chem 69(6):1933–1938
8. Yarin AL, Pfaffenlehner M, Tropea C (1998) On the acoustic levitation of droplets. J Fluid Mech 356:65–91
9. Yarin AL, Brenn G, Kastner O, Rensink D, Tropea C (1999) Evaporation of acoustically levitated droplets. J Fluid Mech 399:151–204
10. Benmore CJ, Weber JKR (2011) Amorphization of molecular liquids of pharmaceutical drugs by acoustic levitation. Phys Rev X 1(1):011004
11. Basu S, Saha A, Kumar R (2012) Thermally induced secondary atomization of droplet in an acoustic field. Appl Phys Lett 100(5):054101
12. Mandal DK, Bakshi S (2012) Internal circulation in a single droplet evaporating in a closed chamber. Int J Multiph Flow 42:42–51
13. Mandal DK, Bakshi S (2012) Evidence of oscillatory convection inside an evaporating multicomponent droplet in a closed chamber. J Colloid Interface Sci 378(1):260–262
14. Jaiswal V, Harikrishnan AR, Khurana G, Dhar P (2018) Ionic solubility and solutal advection governed augmented evaporation kinetics of salt solution pendant droplets. Phys Fluids 30(1):012113
15. Yamamoto Y, Abe Y, Fujiwara A, Hasegawa K, Aoki K (2008) Internal flow of acoustically levitated droplet. Microgravity Sci Technol 20(3–4):277
16. Raj MD, Mandal DK, Navaneethakrishnan S, Bakshi S (2010) Measurement of the surface concentration (liquid) of an evaporating multicomponent droplet using pendant droplet method. Exp Fluids 48(4):715–719
17. Somasundaram S, Anand TNC, Bakshi S (2015) Evaporation-induced flow around a pendant droplet and its influence on evaporation. Phys Fluids 27(11):112105
18. Harikrishnan AR, Dhar P (2018) Optical thermogeneration induced enhanced evaporation kinetics in pendant nanofluid droplets. Int J Heat Mass Transf 118:1169–1179
19. Godsave GAE (1953) Studies of the combustion of drops in a fuel spray—the burning of single drops of fuel. In: Symposium (International) on Combustion, vol 4, no. 1, pp 818–830. Elsevier

20. Williams FA (1958) Spray combustion and atomization. Phys Fluids 1(6):541–545
21. Martinsson BG (1996) Physical basis for a droplet aerosol analysing method. J Aerosol Sci 27(7):997–1013
22. Munthali DC, Scopes NE (1982) A technique for studying the biological efficiency of small droplets of pesticide solutions and a consideration of the implications. Pest Manag Sci 13(1):60–62
23. Weathers PJ, Zobel RW (1992) Aeroponics for the culture of organisms, tissues and cells. Biotechnol Adv 10(1):93–115
24. Kumai M (1973) Arctic fog droplet size distribution and its effect on light attenuation. J Atmos Sci 30(4):635–643
25. Charlson RJ, Seinfeld JH, Nenes A, Kulmala M, Laaksonen A, Facchini MC (2001) Reshaping the theory of cloud formation. Science 292(5524):2025–2026
26. Harikrishnan AR, Dhar P, Agnihotri PK, Gedupudi S, Das SK (2017) Wettability of complex fluids and surfactant capped nanoparticle-induced quasi-universal wetting behavior. J Phys Chem B 121(24):6081–6095
27. Harikrishnan AR, Dhar P, Gedupudi S, Das SK (2018) Governing influence of thermodynamic and chemical equilibria on the interfacial properties in complex fluids. J Phys Chem B 122(14):4141–4148
28. Harikrishnan AR, Dhar P, Agnihotri PK, Gedupudi S, Das SK (2018) Correlating contact line capillarity and dynamic contact angle hysteresis in surfactant-nanoparticle based complex fluids. Phys Fluids 30(4):042006
29. Harikrishnan AR, Dhar P, Gedupudi S, Das SK (2017) Effect of interaction of nanoparticles and surfactants on the spreading dynamics of sessile droplets. Langmuir 33(43):12180–12192
30. Zhang W, Zhu Y, Liu X, Wang D, Li J, Jiang L, Jin J (2014) Salt-induced fabrication of superhydrophilic and underwater superoleophobic PAA-g-PVDF membranes for effective separation of oil-in-water emulsions. Angew Chem Int Ed 53(3):856–860
31. Xu Z, Zhao Y, Wang H, Wang X, Lin T (2015) A superamphiphobic coating with an ammonia-triggered transition to superhydrophilic and superoleophobic for oil-water separation. Angew Chem 127(15):4610–4613
32. Cheng Z, Wang J, Lai H, Ying D, Hou R, Li C, Zhang N, Sun K (2015) pH-controllable on-demand oil/water separation on the switchable superhydrophobic/superhydrophilic and underwater low-adhesive superoleophobic copper mesh film. Langmuir 31(4):1393–1399
33. Zhao L, Cheng J (2018) The mechanism and universal scaling law of the contact line friction for the Cassie-state droplets on nanostructured ultrahydrophobic surfaces. Nanoscale 10(14):6426–6436
34. Tian X, Verho T, Ras RH (2016) Moving superhydrophobic surfaces toward real-world applications. Science 352(6282):142–143
35. Chen S, Li X, Li Y, Sun J (2015) Intumescent flame-retardant and self-healing superhydrophobic coatings on cotton fabric. ACS Nano 9(4):4070–4076
36. Sáenz PJ, Wray AW, Che Z, Matar OK, Valluri P, Kim J, Sefiane K (2017) Dynamics and universal scaling law in geometrically-controlled sessile drop evaporation. Nat Commun 8:14783
37. Sáenz PJ, Sefiane K, Kim J, Matar OK, Valluri P (2015) Evaporation of sessile drops: a three-dimensional approach. J Fluid Mech 772:705–739
38. Al-Sharafi A, Yilbas BS, Sahin AZ, Ali H, Al-Qahtani H (2016) Heat transfer characteristics and internal fluidity of a sessile droplet on hydrophilic and hydrophobic surfaces. Appl Therm Eng 108:628–640
39. Adhikari S, Nabil M, Rattner AS (2017) Condensation heat transfer in a sessile droplet at varying Biot number and contact angle. Int J Heat Mass Transf 115:926–931
40. Larson RG (2014) Transport and deposition patterns in drying sessile droplets. AIChE J 60(5):1538–1571
41. Lequien F, Virginie Soulié G, Moine A, Lequien D, Feron P Prene, Moehwald H, Riegler H, Zemb T (2018) Corrosion influence on the evaporation of sessile droplet. Colloids Surf, A 546:59–66
42. Al-Sharafi A, Yilbas BS, Sahin AZ, Ali H (2017) Flow field inside a sessile droplet on a hydrophobic surface in relation to self-cleaning applications of dust particles. J Heat Transf 139(4):042003
43. Lu Y, Sathasivam S, Song J, Crick CR, Carmalt CJ, Parkin IP (2015) Robust self-cleaning surfaces that function when exposed to either air or oil. Science 347(6226):1132–1135
44. Soulié V, Karpitschka S, Lequien F, Prené P, Zemb T, Moehwald H, Riegler H (2015) The evaporation behavior of sessile droplets from aqueous saline solutions. Phys Chem Chem Phys 17(34):22296–22303
45. Chen X, Weibel JA, Garimella SV (2015) Exploiting microscale roughness on hierarchical superhydrophobic copper surfaces for enhanced dropwise condensation. Adv Mater Interfaces 2(3):1400480
46. Azad MAK, Barthlott W, Koch K (2015) Hierarchical surface architecture of plants as an inspiration for biomimetic fog collectors. Langmuir 31(48):13172–13179
47. Czerwiec T, S Tsareva, A Andrieux, GA Bortolini, PH Bolzan, G Castanet, M Gradeck, G Marcos (2017) Thermal management of metallic surfaces: evaporation of sessile water droplets on polished and patterned stainless steel. In: IOP Conference Series: Materials Science and Engineering, vol 258, no. 1, p 012003. IOP Publishing
48. Chakraborty S, Rosen MA, MacDonald BD (2017) Analysis and feasibility of an evaporative cooling system with diffusion-based sessile droplet evaporation for cooling microprocessors. Appl Therm Eng 125:104–110
49. Lanotte L, Laux D, Charlot B, Abkarian M (2017) Role of red cells and plasma composition on blood sessile droplet evaporation. Phys Rev E 96(5):053114

50. Chen R, Zhang L, Zang D, Shen W (2016) Blood drop patterns: formation and applications. Adv Coll Interface Sci 231:1–14
51. Joensson HN, Svahn HA (2012) Droplet microfluidics—a tool for single-cell analysis. Angew Chem Int Ed 51(49):12176–12192
52. Schneider T, Kreutz J, Chiu DT (2013) The potential impact of droplet microfluidics in biology. Anal Chem 85(7):3476–3482
53. Chokkalingam V, Tel J, Wimmers F, Liu X, Semenov S, Thiele J, Figdor CG, Huck WT (2013) Probing cellular heterogeneity in cytokine-secreting immune cells using droplet-based microfluidics. Lab Chip 13(24):4740–4744
54. Srisa-Art M, Bonzani IC, Williams A, Stevens MM, Edel JB (2009) Identification of rare progenitor cells from human periosteal tissue using droplet microfluidics. Analyst 134(11):2239–2245
55. Rane TD, Zec HC, Puleo C, Lee AP, Wang T-H (2012) Droplet microfluidics for amplification-free genetic detection of single cells. Lab Chip 12(18):3341–3347
56. Shum HC, Abate AR, Lee D, Studart AR, Wang B, Chen C-H, Thiele J, Shah RK, Krummel A, Weitz DA (2010) Droplet microfluidics for fabrication of non-spherical particles. Macromol Rapid Commun 31(2):108–118
57. Cheow LF, Yobas L, Kwong D-L (2007) Digital microfluidics: droplet based logic gates. Appl Phys Lett 90(5):054107
58. Dangla R, Cagri Kayi S, Baroud CN (2013) Droplet microfluidics driven by gradients of confinement. Proc Natl Acad Sci 110(3):853–858
59. Sjostrom SL, Bai Y, Huang M, Liu Z, Nielsen J, Joensson HN, Svahn HA (2014) High-throughput screening for industrial enzyme production hosts by droplet microfluidics. Lab Chip 14(4):806–813
60. Teh S-Y, Lin R, Hung L-H, Lee AP (2008) Droplet microfluidics. Lab Chip 8(2):198–220
61. Guo MT, Rotem A, Heyman JA, Weitz DA (2012) Droplet microfluidics for high-throughput biological assays. Lab Chip 12(12):2146–2155
62. Baroud CN, de Saint Vincent MR, Delville J-P (2007) An optical toolbox for total control of droplet microfluidics. Lab Chip 7(8):1029–1033
63. Conrath M, Karcher C (2005) Shaping of sessile liquid metal drops using high-frequency magnetic fields. Eur J Mech-B/Fluids 24(2):149–165
64. Bratz A, Egry I (1995) Surface oscillations of electromagnetically levitated viscous metal droplets. J Fluid Mech 298:341–359
65. Shatrov V, Priede J, Gerbeth G (2003) Three-dimensional linear stability analysis of the flow in a liquid spherical droplet driven by an alternating magnetic field. Phys Fluids 15(3):668–678
66. Kim D, Lee J-B (2015) Magnetic-field-induced liquid metal droplet manipulation. J Korean Phys Soc 66(2):282–286
67. Gao D, Morley NB, Dhir V (2004) Understanding magnetic field gradient effect from a liquid metal droplet movement. J Fluids Eng 126(1):120–124
68. Haidar J, Lowke JJ (1996) Predictions of metal droplet formation in arc welding. J Phys D Appl Phys 29(12):2951
69. Smith TM, Winstead RE (1995) Electrodynamic pump for dispensing molten solder. U.S. Patent 5,377,961, issued 3 Jan 1995
70. Nguyen N-T (2013) Deformation of ferrofluid marbles in the presence of a permanent magnet. Langmuir 29(45):13982–13989
71. Bormashenko E, Pogreb R, Bormashenko Y, Musin A, Stein T (2008) New investigations on ferrofluidics: ferrofluidic marbles and magnetic-field-driven drops on superhydrophobic surfaces. Langmuir 24(21):12119–12122
72. Nguyen N-T, Ng KM, Huang X (2006) Manipulation of ferrofluid droplets using planar coils. Appl Phys Lett 89(5):052509
73. Nguyen N-T, Beyzavi A, Ng KM, Huang X (2007) Kinematics and deformation of ferrofluid droplets under magnetic actuation. Microfluid Nanofluid 3(5):571–579
74. Beyzavi A, Nguyen N-T (2008) One-dimensional actuation of a ferrofluid droplet by planar microcoils. J Phys D Appl Phys 42(1):015004
75. Zhu G-P, Nguyen N-T, Ramanujan RV, Huang X-Y (2011) Nonlinear deformation of a ferrofluid droplet in a uniform magnetic field. Langmuir 27(24):14834–14841
76. Chen C-Y, Cheng Z-Y (2008) An experimental study on Rosensweig instability of a ferrofluid droplet. Phys Fluids 20(5):054105
77. Falcucci G, Chiatti G, Succi S, Mohamad AA, Kuzmin A (2009) Rupture of a ferrofluid droplet in external magnetic fields using a single-component lattice Boltzmann model for nonideal fluids. Phys Rev E 79(5):056706
78. Nguyen N-T, Zhu G, Chua Y-C, Phan V-N, Tan S-H (2010) Magnetowetting and sliding motion of a sessile ferrofluid droplet in the presence of a permanent magnet. Langmuir 26(15):12553–12559
79. Havard N, Risso F, Tordjeman P (2013) Breakup of a pendant magnetic drop. Phys Rev E 88(1):013014
80. Fabian M, Burda P, Šviková M, Huňady R (2017) The influence of magnetic field on the separation of droplets from ferrofluid jet. J Magn Magn Mater 431:196–200
81. Potts HE, Diver DA (2001) Large-amplitude ferrofluid surface waves and jets. New J Phys 3(1):7
82. Afkhami S, Tyler AJ, Renardy Y, Renardy M, St Pierre TG, Woodward RC, Riffle JS (2010) Deformation of a hydrophobic ferrofluid droplet suspended in a viscous medium under uniform magnetic fields. J Fluid Mech 663:358–384

83. Afkhami S, Renardy Y, Renardy M, Riffle JS, St Pierre T (2008) Field-induced motion of ferrofluid droplets through immiscible viscous media. J Fluid Mech 610:363–380
84. Shi D, Bi Q, Zhou R (2014) Numerical simulation of a falling ferrofluid droplet in a uniform magnetic field by the VOSET method. Numer Heat Transf, Part A: Appl 66(2):144–164
85. Korlie MS, Mukherjee A, Nita BG, Stevens JG, David Trubatch A, Yecko P (2008) Modeling bubbles and droplets in magnetic fluids. J Phys: Condens Matter 20(20):204143
86. Shi D, Bi Q, He Y, Zhou R (2014) Experimental investigation on falling ferrofluid droplets in vertical magnetic fields. Exp Thermal Fluid Sci 54:313–320
87. Mefford OT, Woodward RC, Goff JD, Vadala TP, St Pierre TG, Dailey JP, Riffle JS (2007) Field-induced motion of ferrofluids through immiscible viscous media: testbed for restorative treatment of retinal detachment. J Magn Magn Mater 311(1):347–353
88. Voltairas PA, Fotiadis DI, Massalas CV (2001) Elastic stability of silicone ferrofluid internal tamponade (SFIT) in retinal detachment surgery. J Magn Magn Mater 225(1–2):248–255
89. La-Barcis S, Bacri JC, Ce-Barbers A, Perzynski R (1997) Frequency locking and devil's staircase for a two-dimensional ferrofluid droplet in an elliptically polarized rotating magnetic field. Phys Rev E 55(3):2640
90. Chen C-Y, Yang Y-S, Miranda JA (2009) Miscible ferrofluid patterns in a radial magnetic field. Phys Rev E 80(1):016314
91. Lacis S (1999) Bending of ferrofluid droplet in rotating magnetic field. J Magn Magn Mater 201(1–3):335–338
92. Jackson DP, Miranda JA (2003) Controlling fingering instabilities in rotating ferrofluids. Phys Rev E 67(1):017301
93. Janiaud E, Elias F, Bacri JC, Cabuil V, Perzynski R (2000) Spinning ferrofluid microscopic droplets. Magnetohydrodynamics 36(4):301–314
94. Jamin T, Py C, Falcon E (2011) Instability of the origami of a ferrofluid drop in a magnetic field. Phys Rev Lett 107(20):204503
95. Lira SA, Miranda JA, Oliveira RM (2010) Stationary shapes of confined rotating magnetic liquid droplets. Phys Rev E 82(3):036318
96. Chen C-Y, Tsai W-K, Miranda JA (2008) Hybrid ferrohydrodynamic instability: coexisting peak and labyrinthine patterns. Phys Rev E 77(5):056306
97. Fattah AR, Abdel SG, Puri IK (2016) Printing microstructures in a polymer matrix using a ferrofluid droplet. J Magn Magn Mater 401:1054–1059
98. Ghaffari A, Hashemabadi SH, Bazmi M (2015) CFD simulation of equilibrium shape and coalescence of ferrofluid droplets subjected to uniform magnetic field. Colloids Surf, A 481:186–198
99. Ray A, Varma VB, Wang Z, Wang Z, Jayaneel PJ, Sudharsan NM, Ramanujan RV (2016) Magnetic droplet merging by hybrid magnetic fields. IEEE Magn Lett 7:1–5
100. Timonen JV, Latikka M, Leibler L, Ras RH, Ikkala O (2013) Switchable static and dynamic self-assembly of magnetic droplets on superhydrophobic surfaces. Science 341(6143):253–257
101. Guo Z-G, Zhou F, Hao J-C, Liang Y-M, Liu W-M, Huck WTS (2006) "Stick and slide" ferrofluidic droplets on superhydrophobic surfaces. Appl Phy Lett 89(8):081911
102. Ray A, Varma VB, Jayaneel PJ, Sudharsan NM, Wang ZP, Ramanujan RV (2017) On demand manipulation of ferrofluid droplets by magnetic fields. Sens Actuators B: Chem 242:760–768
103. Banerjee S, Fasnacht M, Garoff S, Widom M (1999) Elongation of confined ferrofluid droplets under applied fields. Phys Rev E 60(4):4272
104. Jackson DP, Miranda JA (2007) Confined ferrofluid droplet in crossed magnetic fields. Eur Phys J E 23(4):389–396
105. Manukyan S, Schneider M (2016) Experimental investigation of wetting with magnetic fluids. Langmuir 32(20):5135–5140
106. Poesio P, Wang EN (2014) Resonance induced wetting state transition of a ferrofluid droplet on superhydrophobic surfaces. Exp Therm Fluid Sci 57:353–357
107. Rigoni C, Pierno M, Mistura G, Talbot D, Massart R, Bacri J-C, Abou-Hassan A (2016) Static magnetowetting of ferrofluid drops. Langmuir 32(30):7639–7646
108. Cristaldo CFC, Fachini FF (2013) Ferrofluid droplet heating and vaporization under very large magnetic power: a thermal boundary layer model. Phys Fluids 25(3):037101
109. Cristaldo Cesar FC, Fachini Fernando F (2013) Analysis of ferrofluid droplet combustion under very large magnetic power. Combust Flame 160(8):1458–1465
110. Brunet T, Zimny K, Mascaro B, Sandre O, Poncelet O, Aristégui C, Mondain-Monval O (2013) Tuning Mie scattering resonances in soft materials with magnetic fields. Phys Rev Lett 111(26):264301
111. Romankiw LT, Slusarczuk MMG, Thompson DA (1976) "Ferrofluid display device." US Patent 3,972,595, issued 3 Aug 1976
112. Tan S-H, Nguyen N-T, Yobas L, Kang TG (2010) Formation and manipulation of ferrofluid droplets at a microfluidic T-junction. J Micromech Microeng 20(4):045004
113. Liu J, Tan S-H, Yap YF, Ng MY, Nguyen N-T (2011) Numerical and experimental investigations of the formation process of ferrofluid droplets. Microfluid Nanofluidics 11(2):177–187
114. Wu Y, Taotao F, Ma Y, Li HZ (2013) Ferrofluid droplet formation and breakup dynamics in a microfluidic flow-focusing device. Soft Matter 9(41):9792–9798

115. Wu Y, Taotao F, Ma Y, Li HZ (2015) Active control of ferrofluid droplet breakup dynamics in a microfluidic T-junction. Microfluid Nanofluid 18(1):19–27
116. Yan Q, Xuan S, Ruan X, Jie W, Gong X (2015) Magnetically controllable generation of ferrofluid droplets. Microfluid Nanofluid 19(6):1377–1384
117. Varma VB, Ray A, Wang Z, Wang Z, Wu R, Jayaneel PJ, Sudharsan NM, Ramanujan RV (2016) Control of ferrofluid droplets in microchannels by uniform magnetic fields. IEEE Magn Lett 7:1–5
118. Li H, Yining W, Wang X, Zhu C, Taotao F, Ma Y (2016) Magnetofluidic control of the breakup of ferrofluid droplets in a microfluidic Y-junction. Rsc Adv 6(1):778–785
119. Kadivar E (2014) Magnetocoalescence of ferrofluid droplets in a flat microfluidic channel. EPL (Europhys Lett) 106(2):24003
120. Tan SH, Nguyen N-T (2011) Generation and manipulation of monodispersed ferrofluid emulsions: the effect of a uniform magnetic field in flow-focusing and T-junction configurations. Phys Rev E 84(3):036317
121. Katsikis G, Cybulski JS, Prakash M (2015) Synchronous universal droplet logic and control. Nat Phys 11(7):588
122. Seo HW, Chae JB, Hong SJ, Rhee K, Chang J, Chung SK (2015) Electromagnetically driven liquid iris. Sens Actuators A: Phys 231:52–58
123. Grimm RL, Beauchamp JL (2005) Dynamics of field-induced droplet ionization: time-resolved studies of distortion, jetting, and progeny formation from charged and neutral methanol droplets exposed to strong electric fields. J Phys Chem B 109(16):8244–8250
124. Reznik SN, Yarin AL, Zussman E, Bercovici L (2006) Evolution of a compound droplet attached to a core-shell nozzle under the action of a strong electric field. Phys Fluids 18(6):062101
125. Hase M, Watanabe SN, Yoshikawa K (2006) Rhythmic motion of a droplet under a dc electric field. Phys Rev E 74(4):046301
126. Supeene G, Koch CR, Bhattacharjee S (2008) Deformation of a droplet in an electric field: nonlinear transient response in perfect and leaky dielectric media. J Colloid Interface Sci 318(2):463–476
127. Celestini F, Kirstetter G (2012) Effect of an electric field on a Leidenfrost droplet. Soft Matter 8(22):5992–5995
128. Gunji M, Washizu M (2005) Self-propulsion of a water droplet in an electric field. J Phys D Appl Phys 38(14):2417
129. Warshavsky VB, Shchekin AK (1999) The effects of external electric field in thermodynamics of formation of dielectric droplet. Colloids Surf, A 148(3):283–290
130. Takeda Koji, Nakajima Akira, Hashimoto Kazuhito, Watanabe Toshiya (2002) "Jump of water droplet from a super-hydrophobic film by vertical electric field. Surf Sci 519(1–2):L589–L592
131. Nazemi MH, Hinrichsen V (2013) Experimental investigations on water droplet oscillation and partial discharge inception voltage on polymeric insulating surfaces under the influence of AC electric field stress. IEEE Trans Dielectr Electr Insul 20(2):443–453
132. Plumlee HR, Semonin RG (1965) Cloud droplet collision efficiency in electric fields. Tellus 17(3):356–364
133. O'Konski CT, Thacher HC Jr (1953) The distortion of aerosol droplets by an electric field. J Phys Chem 57(9):955–958
134. Quate CF (1996) "Method and apparatus for ejecting a droplet using an electric field." US Patent 5,541,627, issued 30 July 1996
135. Kitzerow H-S, Crooker PP (1993) Electric field effects on the droplet structure in polymer dispersed cholesteric liquid crystals. Liq Cryst 13(1):31–43
136. Ambrožič M, Formoso P, Golemme A, Žumer S (1997) Anchoring and droplet deformation in polymer dispersed liquid crystals: NMR study in an electric field. Phys Rev E 56(2):1825
137. Bentenitis N, Krause S (2005) Droplet deformation in dc electric fields: the extended leaky dielectric model. Langmuir 21(14):6194–6209
138. Benselama AM, Achard J-L, Pham P (2006) Numerical simulation of an uncharged droplet in a uniform electric field. J Electrostat 64(7–9):562–568
139. Ha J-W, Yang S-M (1999) Fluid dynamics of a double emulsion droplet in an electric field. Phys Fluids 11(5):1029–1041
140. Song FH, Li BQ, Liu C (2013) Molecular dynamics simulation of nanosized water droplet spreading in an electric field. Langmuir 29(13):4266–4274
141. Yamada T, Sugimoto T, Higashiyama Y, Takeishi M, Aoki T (2003) Resonance phenomena of a single water droplet located on a hydrophobic sheet under ac electric field. IEEE Trans Ind Appl 39(1):59–65
142. Zhang J, Zahn JD, Lin H (2013) Transient solution for droplet deformation under electric fields. Phys Rev E 87(4):043008
143. Oliver DLR, De Witt KJ (1993) High Peclet number heat transfer from a droplet suspended in an electric field: interior problem. Int J Heat Mass Transf 36(12):3153–3155
144. Birbarah P, Li Z, Pauls A, Miljkovic N (2015) A comprehensive model of electric-field-enhanced jumping-droplet condensation on superhydrophobic surfaces. Langmuir 31(28):7885–7896
145. Hager DB, Dovichi NJ (1994) Behavior of microscopic liquid droplets near a strong electrostatic field: droplet electrospray. Anal Chem 66(9):1593–1594
146. Hayati I, Bailey AI, Tadros TF (1987) Investigations into the mechanisms of electrohydrodynamic spraying of liquids: I. Effect of electric field and the environment on pendant drops and factors affecting the formation of stable jets and atomization. J Colloid Interface Sci 117(1):205–221
147. Grace JM, Dunn PF (1996) Droplet motion in an electrohydrodynamic fine spray. Exp Fluids 20(3):153–164

148. Cheng C-C, Chang CA, Yeh JA (2006) Variable focus dielectric liquid droplet lens. Opt Express 14(9):4101–4106
149. Drzaic PS, Muller A (1989) Droplet shape and reorientation fields in nematic droplet/polymer films. Liq Cryst 5(5):1467–1475
150. Forbes TP, Degertekin FL, Fedorov AG (2011) Droplet charging regimes for ultrasonic atomization of a liquid electrolyte in an external electric field. Phys Fluids 23(1):012104
151. Law SE (1989) Charge and mass flux in the radial electric field of an evaporating charged water droplet: an experimental analysis. IEEE Trans Ind Appl 25(6):1081–1087
152. Yen T-H (2012) Investigation of the effects of perpendicular electric field and surface morphology on nanoscale droplet using molecular dynamics simulation. Mol Simul 38(6):509–517
153. Heng L, Guo T, Wang B, Fan L-Z, Jiang L (2015) In situ electric-driven reversible switching of water-droplet adhesion on a superhydrophobic surface. J Mater Chem A 3(47):23699–23706
154. Gouz HN, Sadhal SS (1989) Fluid dynamics and stability analysis of a compound droplet in an electric field. Q J Mech Appl Math 42(1):65–83
155. He H, Salipante PF, Vlahovska PM (2013) Electrorotation of a viscous droplet in a uniform direct current electric field. Phys Fluids 25(3):032106
156. Adamiak K, Floryan JM (2011) Dynamics of water droplet distortion and breakup in a uniform electric field. IEEE Trans Ind Appl 47(6):2374–2383
157. Mahmoudi SR, Adamiak K, Castle GSP (2011) Spreading of a dielectric droplet through an interfacial electric pressure. In: Proceedings of the Royal Society of London A: mathematical, physical and engineering sciences. The Royal Society, 2011, p rspa20110220
158. Arzpeyma A, Bhaseen S, Dolatabadi A, Wood-Adams P (2008) A coupled electro-hydrodynamic numerical modeling of droplet actuation by electrowetting. Colloids Surf, A 323(1–3):28–35
159. Imamura O, Chen B, Nishida S, Yamashita K, Tsue M, Kono M (2011) Combustion of ethanol fuel droplet in vertical direct current electric field. Proc Combust Inst 33(2):2005–2011
160. Borra J-P, Ehouarn P, Boulaud D (2004) Electrohydrodynamic atomisation of water stabilised by glow discharge—operating range and droplet properties. J Aerosol Sci 35(11):1313–1332
161. Shchekin AK, Kshevetskiy MS, Warshavsky VB (2002) The macroscopic effects of internal and external electric fields on profile and thermodynamics of a dielectric droplet. Aerosol Sci Technol 36(3):318–328
162. Sumiyoshitani S (1994) Effects of an applied electric field on collection efficiency by a charged droplet for dust particles in charged droplet scrubbers. Aerosol Sci Technol 20(1):71–82
163. Zakinyan A, Tkacheva E, Dikansky Y (2012) Dynamics of a dielectric droplet suspended in a magnetic fluid in electric and magnetic fields. J Electrost 70(2):225–232
164. Wang Z, Wang F-C, Zhao Y-P (2012) Tap dance of a water droplet. Proc R Soc A 468(2145):2485–2495
165. Reznik SN, Yarin AL, Theron A, Zussman E (2004) Transient and steady shapes of droplets attached to a surface in a strong electric field. J Fluid Mech 516:349–377
166. Mohseni K, Arzpeyma A, Dolatabadi A (2006) Behaviour of a moving droplet under electrowetting actuation: numerical simulation. Can J Chem Eng 84(1):17–21
167. Zhu Y, Haji K, Otsubo M, Honda C, Hayashi N (2006) Electrohydrodynamic behaviour of water droplet on an electrically stressed hydrophobic surface. J Phys D Appl Phys 39(9):1970
168. Chiou PY, Park S-Y, Wu MC (2008) Continuous optoelectrowetting for picoliter droplet manipulation. Appl Phys Lett 93(22):221110
169. Newbery AP, Grant PS (2003) Large arc voltage fluctuations and droplet formation in electric arc wire spraying. Powder Metall 46(3):229–235
170. Bateni A, Amirfazli A, Neumann AW (2006) Effects of an electric field on the surface tension of conducting drops. Colloids Surf, A 289(1–3):25–38
171. Bateni A, Laughton S, Tavana H, Susnar SS, Amirfazli A, Neumann AW (2005) Effect of electric fields on contact angle and surface tension of drops. J Colloid Interface Sci 283(1):215–222
172. Tsakonas C, Corson LT, Sage IC, Brown CV (2014) Electric field induced deformation of hemispherical sessile droplets of ionic liquid. J Electrostat 72(6):437–440
173. Bormashenko E, Whyman G (2008) Variational approach to wetting problems: calculation of a shape of sessile liquid drop deposited on a solid substrate in external field. Chem Phys Lett 463(1–3):103–105
174. Bateni A, Susnar SS, Amirfazli A, Neumann AW (2004) Development of a new methodology to study drop shape and surface tension in electric fields. Langmuir 20(18):7589–7597
175. Mugele F, Buehrle J (2007) Equilibrium drop surface profiles in electric fields. J Phys: Condens Matter 19(37):375112
176. Wohlhuter FK, Basaran OA (1992) Shapes and stability of pendant and sessile dielectric drops in an electric field. J Fluid Mech 235:481–510
177. Basaran OA, Scriven LE (1990) Axisymmetric shapes and stability of pendant and sessile drops in an electric field. J Colloid Interface Sci 140(1):10–30
178. Bateni A, Ababneh A, Elliott JAW, Neumann AW, Amirfazli A (2005) Effect of gravity and electric field on shape and surface tension of drops. Adv Space Res 36(1):64–69
179. Chakraborty Debapriya, Sudha Gogineni Sai, Chakraborty Suman, DasGupta Sunando (2011) Effect

of submicron particles on electrowetting on dielectrics (EWOD) of sessile droplets. J Colloid Interface Sci 363(2):640–645
180. Imano AM, Beroual A (2006) Deformation of water droplets on solid surface in electric field. J Colloid Interface Sci 298(2):869–879
181. Sen P, Kim C-JCJ (2009) Capillary spreading dynamics of electrowetted sessile droplets in air. Langmuir 25(8):4302–4305
182. Ghazian O, Adamiak K, Castle GSP, Higashiyama Y (2014) Oscillation, pseudo-rotation and coalescence of sessile droplets in a rotating electric field. Colloids Surf A: Physicochem Eng Asp 441:346–353
183. Stone HA, Lister JR, Brenner MP (1999) Drops with conical ends in electric and magnetic fields. In: Proceedings of the Royal Society of London A: mathematical, physical and engineering sciences, vol 455, no. 1981. The Royal Society, 1999, pp 329–347
184. Notz PK, Basaran OA (1999) Dynamics of drop formation in an electric field. J Colloid Interface Sci 213(1):218–237
185. Kim H, Yang J, Chung J (2014) Resonant oscillation phenomena of a sessile droplet on electrohydrodynamic jetting nozzle. Jpn J Appl Phys 53(5S3):05HC03
186. Ha J-W, Yang S-M (2000) Deformation and breakup of Newtonian and non-Newtonian conducting drops in an electric field. J Fluid Mech 405:131–156
187. Hong J, Kim YK, Kang KH, Kim J, Lee SJ (2014) Spreading dynamics and oil film entrapment of sessile drops submerged in oil driven by DC electrowetting. Sens Actuators B: Chem 196:292–297
188. Feng J-T, Zhao Y-P (2008) Experimental observation of electrical instability of droplets on dielectric layer. J Phys D Appl Phys 41(5):052004
189. Lee J, Park JK, Hong J, Lee SJ, Kang KH, Hwang HJ (2014) Nonlinear oscillations of a sessile drop on a hydrophobic surface induced by ac electrowetting. Phys Rev E 90(3):033017
190. Corson LT, Tsakonas C, Duffy BR, Mottram NJ, Sage IC, Brown CV, Wilson SK (2014) Deformation of a nearly hemispherical conducting drop due to an electric field: theory and experiment. Phys Fluids 26(12):122106
191. Basaran OA, Scriven LE (1989) Axisymmetric shapes and stability of charged drops in an external electric field. Phys Fluids A 1(5):799–809
192. Baret J-C, Mugele F (2006) Electrical discharge in capillary breakup: controlling the charge of a droplet. Phys Rev Lett 96(1):016106
193. Ndoumbe J, Beroual A, Imano AM (2012) Behavior of water droplets on insulator surfaces submitted to DC voltage-coalescence. In: Annual report conference on electrical insulation and dielectric phenomena (CEIDP), IEEE, 2012, pp 725–728
194. Fan S-K, Yang H, Wang T-T, Hsu W (2007) Asymmetric electrowetting—moving droplets by a square wave. Lab Chip 7(10):1330–1335
195. Gibbons MJ, Howe CM, Di Marco P, Robinson AJ (2016) Local heat transfer to an evaporating sessile droplet in an electric field. J Phys Conf Ser 745(3):032066 (**IOP Publishing**)
196. Cho SK, Moon H, Kim C-J (2003) Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits. J Microelectromechanical Syst 12(1):70–80
197. Link DR, Grasland-Mongrain E, Duri A, Sarrazin F, Cheng Z, Cristobal G, Marquez M, Weitz DA (2006) Electric control of droplets in microfluidic devices. Angew Chem Int Ed 45(16):2556–2560
198. Guo F, Ji X-H, Liu K, He R-X, Zhao L-B, Guo Z-X, Liu W, Guo S-S, Zhao X-Z (2010) Droplet electric separator microfluidic device for cell sorting. Appl Phys Lett 96(19):193701
199. Pollack MG, Fair RB, Shenderov AD (2000) Electrowetting-based actuation of liquid droplets for microfluidic applications. Appl Phys Lett 77(11):1725–1726
200. Pollack MG, Shenderov AD, Fair RB (2002) Electrowetting-based actuation of droplets for integrated microfluidics. Lab Chip 2(2):96–101
201. Kim H, Luo D, Link D, Weitz DA, Marquez M, Cheng Z (2007) Controlled production of emulsion drops using an electric field in a flow-focusing microfluidic device. Appl Phys Lett 91(13):133106
202. Kim H, Luo D, Link D, Weitz DA, Marquez M, Cheng Z (2007) Controlled production of emulsion drops using an electric field in a flow-focusing microfluidic device. Appl Phys Lett 91(13):133106
203. Kim C-J, Gong J (2016) Method and apparatus for real-time feedback control of electrical manipulation of droplets on chip. US Patent 9,266,076, issued 23 Feb 2016
204. Shah GJ, Ohta AT, Chiou EP-Y, Wu MC (2009) EWOD-driven droplet microfluidic device integrated with optoelectronic tweezers as an automated platform for cellular isolation and analysis. Lab Chip 9(12):1732–1739
205. Wheeler AR (2008) Putting electrowetting to work. Science 322(5901):539–540
206. Zagnoni M, Le Lain G, Cooper JM (2010) Electrocoalescence mechanisms of microdroplets using localized electric fields in microfluidic channels. Langmuir 26(18):14443–14449
207. Fan S-K, Hsieh T-H, Lin D-Y (2009) General digital microfluidic platform manipulating dielectric and conductive droplets by dielectrophoresis and electrowetting. Lab Chip 9(9):1236–1242
208. Chabert M, Dorfman KD, Viovy J-L (2005) Droplet fusion by alternating current (AC) field electrocoalescence in microchannels. Electrophoresis 26(19):3706–3715
209. Zeng J, Korsmeyer T (2004) Principles of droplet electrohydrodynamics for lab-on-a-chip. Lab Chip 4(4):265–277

210. Zagnoni M, Cooper JM (2009) On-chip electrocoalescence of microdroplets as a function of voltage, frequency and droplet size. Lab Chip 9(18):2652–2658
211. Bjørklund E (2009) The level-set method applied to droplet dynamics in the presence of an electric field. Comput Fluids 38(2):358–369
212. Scott TC (1987) Surface area generation and droplet size control using pulsed electric fields. AIChE J 33(9):1557–1559
213. Scott TC, Sisson WG (1988) Droplet size characteristics and energy input requirements of emulsions formed using high-intensity-pulsed electric fields. Sep Sci Technol 23(12–13):1541–1550
214. He M, Kuo JS, Chiu DT (2005) Electro-generation of single femtoliter-and picoliter-volume aqueous droplets in microfluidic systems. Appl Phys Lett 87(3):031916
215. Ahn B, Lee K, Panchapakesan R, Kwang W (2011) On-demand electrostatic droplet charging and sorting. Biomicrofluidics 5(2):024113
216. Wang W, Yang C, Li CM (2009) On-demand microfluidic droplet trapping and fusion for on-chip static droplet assays. Lab Chip 9(11):1504–1506
217. Niu X, Zhang M, Peng S, Wen W, Sheng P (2007) Real-time detection, control, and sorting of microfluidic droplets. Biomicrofluidics 1(4):044101
218. Im DJ, Noh J, Yi NW, Park J, Kang IS (2011) Influences of electric field on living cells in a charged water-in-oil droplet under electrophoretic actuation. Biomicrofluidics 5(4):044112
219. Lee C-P, Chang H-C, Wei Z-H (2012) Charged droplet transportation under direct current electric fields as a cell carrier. Appl Phys Lett 101(1):014103
220. Fan S-K, Huang P-W, Wang T-T, Peng Y-H (2008) Cross-scale electric manipulations of cells and droplets by frequency-modulated dielectrophoresis and electrowetting. Lab Chip 8(8):1325–1331
221. Ahn B, Lee K, Louge R, Kwang W (2009) Concurrent droplet charging and sorting by electrostatic actuation. Biomicrofluidics 3(4):044102
222. Thiam AR, Bremond N, Bibette J (2009) Breaking of an emulsion under an ac electric field. Phys Rev Lett 102(18):188304
223. Edwards ME, Wu XL, Wu J-S, Huang JS, Kellay H (1998) Electric-field effects on a droplet microemulsion. Phys Rev E 57(1):797
224. Poncelet D, Neufeld R, Bugarski B, Amsden BG, Zhu J, Goosen MFA (1994) A parallel plate electrostatic droplet generator: parameters affecting microbead size. Appl Microbiol Biotechnol 42(2–3):251–255
225. Bugarski B, Li Q, Goosen MFA, Poncelet D, Neufeld RJ, Vunjak G (1994) Electrostatic droplet generation: mechanism of polymer droplet formation. AIChE J 40(6):1026–1031
226. Jung Y-M, Oh H-C, Kang S (2008) Electrical charging of a conducting water droplet in a dielectric fluid on the electrode surface. J Colloid Interface Sci 322(2):617–623
227. Jayasinghe SN, Qureshi AN, Eagles PAM (2006) Electrohydrodynamic jet processing: an advanced electric field driven jetting phenomenon for processing living cells. Small 2(2):216–219
228. Wang W, Yang C, Liu YS, Li CM (2010) On-demand droplet release for droplet-based microfluidic system. Lab Chip 10(5):559–562
229. Tan W-H, Takeuchi S (2006) Timing controllable electrofusion device for aqueous droplet-based microreactors. Lab Chip 6(6):757–763
230. Aghdaei S, Sandison ME, Zagnoni M, Green NG, Morgan H (2008) Formation of artificial lipid bilayers using droplet dielectrophoresis. Lab Chip 8(10):1617–1620

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