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Kitchen flows: Making science more accessible, affordable, and curiosity driven

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I. INTRODUCTION

Culinary fluid mechanics is the study of everything that flows related to food, covering a wide range of surprising phenomena that can be harnessed for the benefit of gastronomy, or to further science itself.[1] Especially since the COVID-19 pandemic, the kitchen offers a rich lab environment where flows are omnipresent and widely accessible.[2] The phenomena emerging in the kitchen inspire fundamental research,[3,4] which in turn improved gastronomy ever since.[5–7] Immersing ourselves in this special research setting, we can deal with high-interface materials and thin films,[8,9] we mix fluids to make emulsions,[10] we work with bubbles,[11] highly viscous and non-Newtonian materials,[12,13] we explore heat transfer in fluids,[14] we stabilize foam structure in bread[15] and beverages, and we produce novel food from basic ingredients.

In this Special Issue,[16] we celebrate the connection between the physics of fluids, food science, and education. We received over 30 articles concerning all types of kitchen flows, from simple to complex, from small to large scale. They include research articles, short reviews, educational articles, methods papers, and expert tutorials. In the remainder of this editorial, we will summarize these works and highlight some exciting new opportunities in this effervescently growing branch of science.

II. KITCHEN FLOWS

The routine act of handwashing dishes involves numerous flow processes, among which is the classic hydraulic jump that forms when a jet of water impinges on the sink. This phenomenon has a long history of investigation and analysis, beginning with Lord Rayleigh's theoretical explanation. Nonetheless, the potential influence of the downstream film on the jump has been largely overlooked, and by combining theory with experiments, Bhagat and Linden[17] address this important literature gap. They find that for all practical purposes, the downstream film remains flat and does not affect the jump, while for highly viscous fluids, the viscous dissipation could increase the jump height, which leads to a smaller jump radius.

Whereas most experiments and analyses of the hydraulic jump have considered the case where the jet strikes a planar substrate at normal incidence, it is common that the jet will intersect the surface at an angle other than 90°. Inclined jets lead to a number of characteristics of the hydraulic jumps that distinguish them from jumps associated with normal incidence. Immediately obvious is that jumps generated by inclined jets will be elliptical, as opposed to circular in the case of normal incidence. Less visible to the naked eye will be azimuthal flows within the jump caused by gravitational forces. When gravity is sufficiently important within the jumps caused by "upward pointing inclined jets," azimuthal flows develop that can sweep liquid from the apex of the elliptical jump back toward the aft of the jump. This phenomenon is nicely revealed in Fig. 16 b of the paper by Abdelaziz and Khayat,[18] and the simulations presented in this paper are nicely aligned with the earlier experimental work by Kate *et al.*[19]

Also using the kitchen sink as experimental setup, Mohd *et al.*[20] investigate the flow features during the washing of vials and identify a new bell shape which they coin an "open inverted bell." These water bells are produced when a laminar jet impinges on the surface of the liquid in the vial of marginally larger or similar diameter.

In a different aspect of washing, to prevent disease, we sometimes also rinse off poultry such as chicken with tap water; however, Carmody *et al.*[21] show that this procedure can have the opposite effect as harmful bacteria can be transferred from the surface of raw chicken though splashing. To help mitigate this risk, the authors identify washing routines that can limit splashing, and their paper is a good example of how fluid mechanics can be leveraged to improve food safety.

Three papers in this issue concern kitchen scale vortex flows. In the first paper, Okulov *et al.*[22] investigate the influence of roughness on vortex generation and especially how the shape and height of various roughness elements can enhance the mixing efficiency. They show that roughness-enhanced vortex mixing can replace impellers used in traditional mixing devices, thereby offering a new avenue of soft mixing, with applications including the preparation of food delicacies. In the second paper on vortex flows, Tyvand[23] explores the time evolution of a bathtub (kitchen sink) vortex, which the author shows can be idealized as a viscous Rankine vortex when the drain flux is sufficiently small that the surface remains flat. In the third and final paper on vortex flows, Naumov *et al.*[24] investigate two-phase vortices, which they create by rotating a layer of cooking oil on top of an aqueous glycerin solution. They spin the container at sufficiently high speed that the liquid–liquid interface touches the bottom of the container, which induces a Rayleigh–Taylor instability. This, in turn, causes oil drops to disperse in the solution by a capillary breakup mechanism.

III. KITCHEN BUBBLES

Next we turn to the familiar fluid dynamics phenomenon of bubbles and droplets, specifically in the kitchen. The exquisite flow patterns in soap bubble films have fascinated us throughout history. Seimiya and Seimiya[25] revisited draining soap bubble films, and specifically focused on studying the "pearl string"—a phenomenon first witnessed by Sir James Dewar some 100 years ago. The authors have carried out careful soap film experiments utilizing a chemically stable aqueous surfactant. They have generated stunning photos and videos that will find their way into the famous Gallery of Fluid Motion. The authors explain that the pearl string phenomenon arises due to stick-slip sliding at the boundary of the films, which is a resultant of gravity-induced syneresis.

Cooking in the kitchen generates many spatters and spills of droplets. Durian *et al.*[26] studied the spreading dynamics for partially wetting droplets, where the droplet spreading eventually stops and contact angle reaches an nonzero equilibrium value. They considered small droplets driven by capillarity and large droplets driven by gravity. They developed dimensional analyses and models that found a very good agreement with their experiments (carried out in their kitchen). Their results will be crucial to characterize droplet contact angles, dissipation mechanisms, and droplet spreading behaviors beyond the kitchen context, with broad applications in industrial processes and in understanding natural phenomena.

There are several instances in the kitchen when drops of one liquid come in contact with a second miscible liquid, for example, when honey is added into tea or when dish washing liquid is mixed with water. Mossige *et al.*[27] studied the dynamics of freely suspended drops translating through miscible environments. Their experimental study focuses specifically on droplets (water) freely rising through a miscible liquid with higher viscosity (glycerol and corn syrup). The water droplets were initially found to rise with a constant velocity without expanding in size. They observed that after a critical time, the drops continually grow in size as they mix with ambient fluid and rise with decreased velocities. The authors carry out scaling analyses that help explain the experimental observations. Once again, their results have implications beyond the kitchen, in both natural and industrial systems.

IV. KITCHEN RHEOLOGY

Restaurants and chefs eagerly experiment with form and shape, hoping to serve a well-known and perhaps popular product in a novel or innovative way. Examination by and interaction of the consumer with resulting dishes form part of the gourmet cuisine experience. Thus, efforts in food science often focus on tuning the properties of kitchen fluids to achieve the desired stable shape. To this end, D'Angelo *et al.*[28] devised methods to generate flexible helices made of sodium alginate or a mixture of alginate with agar–agar. These food gels are typically prepared in the form of spheres or spaghetti. Using 3D printed molds, they were able to control the length, pitch, and diameter of helices. They also proposed a mechanical model for the determination of the Young's modulus from the deformation of a helix hanged vertically under its own weight.

Macroscopic properties of a material depend heavily on its microstructure. The relationship between chemical composition and rheological properties underlie the rheological response of food products, with a major food example being wheat gluten. Gluten is a mixture of two families of proteins, monomeric gliadins and polymeric glutenins. Louhichi *et al.*[29] took up the task of characterizing the linear and nonlinear viscoelastic properties of an aqueous gluten solution depending on the relative contents of the two ingredients. From the rheological response, they draw analogies to gels made of polymer clusters to purely viscoelastic gel, when increasing the fraction of glutenins.

Rheology is also important from the point of view of industrial processing of large fluid quantities of food products. In this Issue, Wilson and Strasser[30,31] study banana puree as an example of a yield stress fluid. Its non-Newtonian nature can be quantified by the

Herschel–Bulkley model, which describes the puree as a fluid that is shear-thinning but only flows when the stress exceeds a critical yield stress value. They examine numerically the industrially relevant process of annular injection of the banana puree into a transonic pipe flow of steam in a twin-fluid atomizer using the ANSYS Fluent CFD solver. The first paper[30] focuses on the numerical analysis of the instability of the injected stream. When the puree meets the rapid gas flow, they observe the formation of annular periodic waves at the interface and their subsequent growth driven by the Kelvin–Helmholtz instability. In this case, however, no wave trains are seen. Instead, waves form separately, upon the collapse of the preceding waves. This life cycle of subsequent waves introduces pulsations in the bulk system, which interact back with the destabilized stream. Despite every wave being unique, the system seems to select a particular frequency of wave formation of 1000 Hz. Wilson and Strasser use the knowledge on the nature of this instability in their second contribution,[31] devoted to wave-augmented atomization when the mixture leaves the nozzle. The pulses discussed earlier drive the stretching, radial outward bulging, and eventually bursting of the annular puree sheet stretching down from the nozzle exit. They characterize subsequent stages of evolution of the sheet and the resulting spraying geometry. Given the high degree of complexity, studies of instabilities in multicomponent systems involving transonic flows and non-Newtonian fluids are rather scarce. The contributions of Wilson and Strasser take a step in this direction but at the same time address a well-defined industrial challenge. Further development of this work may help optimize the process itself by tuning the flow parameters or the nozzle geometry.

Another kitchen substance of perhaps utmost importance is coffee. It is a truly multifaceted drink because its preparation combines granular physics of grinding, thermodynamics of brewing, chemistry of coffee extraction, mechanics of its pouring physiology of taste and aroma sensing, and psychology of its consumers. In this issue, Mo *et al.*[32] investigate the relationship between swelling of ground coffee and its extraction. Although swelling is well known to all those brewing their coffee in an open pot or using a filter, its impact on intra-grain and inter-grain transport is not clear. To elucidate these processes, they propose a coarse-grained theoretical model for swelling. They combine hydrodynamic flow, modeled with smoothed particle hydrodynamics, with a network model for a porous medium, supplemented by a model of swelling based on volume expansion during the diffusion of excess water into a coffee grain, and a model of extraction involving the diffusion of soluble material out from the grains into the flow. They employ it to examine the swelling of a spherical grain, and then a porous medium for a range of Péclet numbers. The resulting yield curves are used to quantify the "strength" of the resulting beverage. They conclude that even a small degree of swelling can affect the extraction at typical brewing conditions and enhance the coffee strength at both fixed brewing time and fixed brewing fluid volume. Although microscopic details of the process remain to be investigated, the paper highlights the need for further studies of flow-induced chemical extraction.

Several papers in this issue consider real food as samples for thoughtful rheology experiments. Scientists demonstrate that interesting results can be obtained while playing with the food stuff bought in a local supermarket. Over the course of a day, you can really appreciate high quality science made with what you have for lunch or dinner.

Griebler and Rogers[33] use two of the most popular in the US dairy products, Cool Whip and Philadelphia cream cheese, to conduct detailed experiments and analysis and show the wealth of non-linear rheology to fully characterize yield stress fluids. As a first dish, you may have pasta. Hwang *et al.*[34] investigate experimentally and theoretically model the softening of noodles during coating due to water imbibition. Measuring the shape evolution with cooking time, they can even assess the optimal cooking time!

Would you take a meat sausage, a vegetarian, or a vegan sausage? Ghebremedhin *et al.*[35] investigate the shear viscoelasticity, tensile properties, and tribology of these three types of commercially available sausages, and rationalize their mechanical responses, in relation to their sensory properties and their distinctive structures. On the sweet side, Bhattacharyya and Joshi[36] investigate the time dependent rheological properties of commercial chocolate, and compare the response of the material following a thermal or mechanical quench from a solid to a liquid state, drawing analogies with polymer glasses. Still on the sweet side, take a sandwich cookie. Using the two wafers as the plates of a rheometer, Owens *et al.*[37] study the rheological properties of the creme in between the two wafers, how the creme creeps, fails or detaches from the wafers depending on the conditions, investing a new field coined "oreology," from the trade mark of one of our favorite sandwich cookie.

With the aim of understanding the relation between microstructure and sensory properties of food materials, Via *et al.*[38] analyzed duck liver based products, more specifically home-made patè and commercial foie gras. These products showed pronounced textural differences, i.e., the patè being less elastic but more resistant than foie gras. Using minimally invasive coherent anti-Stokes Raman scattering (CARS) microscopy, the authors were able to perform quantitative image analysis on the fatty liver-based emulsions. The microstructural characterization performed on the fat droplets (abundance, shape, and size) provided deeper insight into the causes of the textural differences observed.

Another experimental work is by Benabdelhalim and Brutin,[39] dealing with the spreading dynamics and the phase separation of vinaigrette. These phenomena were described based on the outward spreading of a portion of olive oil from the main film. The experimental protocol involved films of vinaigrette placed on a white tile substrate in a controlled environment (50% humidity and 21 °C). Different formulations were prepared by varying the relative quantities of vinegar and mustard, and the spreading factor and the phase separation studied as a function of the composition. The authors found that phase separation occurred because of the competition between the oil flow during the spreading of the vinaigrette and the interactions between the droplets of the dispersed phase (vinegar). The mustard addition can improve the stability, preventing phase separation, because of its emulsifying and thickening tendencies.

The article by Feneuil *et al.*[40] deals with the linear rheological properties of Lutefisk, a traditional Norwegian Christmas dish, which is challenging to cook at home, made of dry cod soaked in a lye solution before re-hydrated. The authors performed rheological measurements on different type of fish fillet (size and fishing season), tuning the cooking time, cooking temperature, and the amount of salt. Although salting and cooking of the Lutefisk strongly affect the visual aspect of fish fillets, these changes are not found to be correlated with the elastic modulus of the lutefisk, which seems strongly dependent on the thickness of the fish piece, i.e., the fillet size.

Eggs are key ingredients in our kitchens because of their nutritional values and functional properties. They also constitute ideal objects as the liquids contained inside the eggshell can be used to perform various experiments and illustrate a myriad of scientific concepts. In the article by Bertho *et al.,*[41] several rheological experiments (eggsperiments) were performed on such liquids: the dynamics of a hanging filament of egg white (stretch), the cracks formation in a thin film of egg white after it dries (crack), and the spin test that allows to distinguish between raw and hard-boiled eggs (spin). The authors explain that the presence of long entangled proteins confers an elastic modulus to the egg white and allows the creation of long filaments under stretching. The alignment of the eggs proteins as the film of egg white is deposited and let dried is responsible for the anisotropic crack. Finally, they show that the residual rotation of a spinning raw egg after a short stop reflects the viscous damping of the internal flow.

Dissipative Particle Dynamics (DPD) and Molecular Dynamics (MD) simulations were performed by Ferrari *et al.*[42] on an oil/water interfacial system where the emulsifier is one of the most surface-active proteins from the egg yolk low-density lipoproteins (LDL), the so-called Apovitellenin I. The authors simulate large systems over long time scales and obtained the dynamic and structural properties of these proteins via DPD and MD. The simulations were able to properly describe the protein surfactant behavior in terms of interfacial tension decrease at increasing protein surface concentration, to estimate the absorption time of a free protein molecule, and to explain the DLD particle adsorption mechanism.

V. KITCHEN THIN FILMS

Many liquid food products can form interfacial films as a consequence of the surface activity of their constituent components. In some cases, this behavior is beneficial, as in the stabilization of emulsions, such as mayonnaise. Giacomin and Fischer[43] explore an example, the formation of visible film on the surface of black tea, where this phenomenon, although not strongly affecting the taste of the beverage, may be disagreeable in appearance to some. In this investigation, the authors employ surface interfacial shear rheometry to measure the interfacial viscoelastic moduli of black teas and the influence of water hardness and preparation steps (presence of tea leaves). They determine that these films are very brittle, breaking upon the application of very small strains, and that they exhibit yield stresses.

The contribution by Avallone *et al.,*[44] which investigates a newly developed process for the production of yeast-free pizza dough, aptly comes from Naples, which is the origin of this food favorite. The motivation for this research is the desire to create a "yeast-free pizza dough," for two reasons. First, although introducing bubbles of the right size and number within pizza crust is desirable, the use of yeast is a slow process and there is an interest in faster, alternative processes. Second, marketing surveys indicate there is consumer interest in yeast-free products. The authors of this paper report on the use of an unlikely, analogous foam processing strategy: the creation of solid polyurethane foams where chemical blowing agents are used, followed by a thermosetting procedure. For this purpose, foaming equipment was designed to regulate the temperature and pressure of injected blowing agents (helium, and carbon dioxide) to yield optimal pizza dough properties in a timely fashion. The outcomes were guided using rheological measurements where the results of this foaming/baking strategy were favorably compared against traditional, yeast-based methods.

The feelings of anticipation and satisfaction associated with the uncorking of a bottle of champagne are common, shared experiences. The paper by Benidar *et al.*[45] analyzes the flow physics surrounding the celebratory popping sound that is the signature of celebrations involving champagne. This is accomplished using computational fluid dynamics simulations that are compared against high-speed video acquisition experiments carried out by the same group (see Liger-Belair *et al.*[46]). The uncorking process is remarkably complex and rapid, with a supersonic free jet of a gaseous mixture rapidly issuing from the bottle orifice to propel the cork upward. The computational modeling is understandably complex, requiring the bringing together of high-speed compressible flow, adiabatic expansion, and energy conservation. The work identifies three phases beginning with the initial separation of the cork from the neck of the bottle where there is a strong interaction between the escaping gas and the blocking presence of the cork. This limits the gas velocity to remain subsonic but leads to a cascade of shock waves. This initial event transitions toward supersonic gas velocities as the impeding influence of the stopper diminishes only to be followed by subsonic velocities and the development of a detached shock. Finally, the pressure within the bottle subsides and a rarefaction wave develops within the container. This paper is well-worth reading and will make you the "life of the party" as you enlighten your fellow revelers about the fascinating fluid mechanics they've just witnessed!

Briceño-Ahumada *et al.*[47] describe the design, creation, and properties of edible foams—materials that are ubiquitous to cuisines throughout the world. Central to the success of a foam is its stability and edible foams are characterized by an enormous range of time scales, as emphasized in Fig. 2 of this paper. These range from seconds in the case of wine foams to years in the case of meringues. Although most edible foams have their origin through accidental kitchen experimentation over the history of mankind, understanding the physical bases behind their stability brings together many scientific principles, including capillarity, interfacial fluid mechanics, coarsening phenomena (coalescence and Ostwald ripening), and rheology (both bulk and interfacial rheology). As the title implies, this paper focuses on the rheological character of the suspending phase into which bubbles are presented. Within this continuous phase, a wide variety of constituents can be present, including hydrocolloids (water soluble biopolymers) that enhance viscosity and diminish drainage, fat globules that stabilize the bubbles in ice-cream through the Pickering effect, and gelling particles that can form yield stress networks. The reader is encouraged to study this review and to be introduced to the fascinating science of foam gastronomy and the mechanical responses of this enjoyable class of soft matter.

VI. KITCHEN HEAT

Cooking often involves heat, probably since the discovery of fire. Consequently, thermally driven flows are ubiquitous in the kitchen, and in fact many important inventions in thermodynamics find their roots in culinary science. For example, the steam digester by Denis Papin (1647–1713) was the forerunner of the piston-and-cylinder steam engine[48] as well as the modern autoclave to disinfect medical instruments. In this Special Issue, Abu-Farah and Germann[49] perform simulations of thermally driven flows and bacterial inactivation in superheated steam dishwashers. This equipment has great future potential for restaurants and hotels, because they can significantly reduce water consumption and cleaning times. The authors analyzed the flow pattern of the injected steam jet, and they found that strong steam shocks result in a temperature increase and lower bacterial concentrations. Hence, this strategy could reduce the need for detergents while providing efficient sterilization.

Another kitchen appliance that features rich thermal flows is the deep-fat fryer, famous for turning potatoes and peas into feisty foods like French fries and samosas with a delicious "crunch." Obtaining this "perfect crunch" depends on many parameters, but arguably the most important one is cooking temperature. Kiyama *et al.*[50] address this important question by studying the morphology of bubble dynamics and sound in heated oil. A common technique to estimate the temperature of the heated cooking oil is to insert moist chopsticks and listen to the crackling sound, and observe the bubbles around the sticks. While experienced cooks qualitatively "know" when the perfect frying temperature has been attained, Kiyama *et al.*[50] have quantitatively studied the physics behind this phenomenon. In a well-controlled laboratory experiment, they study the interplay between bubble dynamics in a heated oil bath, the sound that is generated, and the oil expulsion to the surrounding air. They found that a stand-off parameter h/R, where h is the location of the water droplet and R is the maximum radius of the bubble, largely determines how the bubble behaves and how the heated oil is expelled.

A perfect crunch can elevate our sensory perception, but it cannot make up for the health concerns associated with eating high calorie foods like cooking oils. Additionally, thermal flows inside a deep-fryer tend to transport oxygen from the air interface into the hot oil, leading to reactive hydroperoxides, odors, fouling, and the generation of several toxic compounds. Therefore, Touffet *et al.*[51] set out to simulate thermally driven flows and the associated chemical reactions in deep fryers. They demonstrated a strong spatial localization of radical oxidation reactions: Hydroperoxides of unsaturated fatty esters are generated at the interface, which are then advected into the bulk by heated plumes. This study could help with reducing toxic compounds by understanding the underlying processes and optimizing the equipment design.

VII. KITCHEN EDUCATION

Science can teach us how to make better food, but food can also teach us about science.[7] Moreover, science can be made more accessible by using the kitchen at home, instead of having to find a lab.[52,53] With this in mind, Nelson[54] started the "Soft Matter Kitchen" project to teach students about rheology and soft matter physics. For this project, a number of engaging demonstrations were developed and presented in a series of elegant online videos. Moreover, for each demonstration, detailed instructions are provided that can be used freely by other teachers around the world. The first demo highlighted in the article compares the properties of honey and whipped cream to explain what it means for a material to be "complex;" the notion that its properties depend on how we probe it. The second demo uses cheesecake to show that food can change completely without changing the ingredients or chemical composition, by changing its microstructure with purely mechanical processes. All the other demos and materials are available in Ref. 55. Try them all!

Because fluid mechanics is so common everywhere around us, it is likely that students already have a lot of experience with the subject before entering the classroom. However, many of these preconceptions turn out to be misconceptions. A classical example is the false notion that the pressure in a pipe constriction increases. Kaye and Ogle[56] aim to tackle these misconceptions using a new pedagogical approach grounded in active learning. They developed a series of short, low-cost activities that address specific problems in fluid mechanics. The activities have a five-step structure: First, the instructor describes the activity. Second, the students are asked to make a prediction. Third, they test the concept with a hands-on activity. Fourth, the students are asked to reflect on their findings. Finally, the instructor analyzes the problem. The feedback obtained from student evaluations shows they found this approach truly helpful.

Having expensive equipment does not always make your science better. During the shelter-in-place orders of the COVID-19 pandemic, Hossain and Ewoldt[57] could no longer teach their course with laboratory rheometers, so they overhauled their class and asked students to perform "do-it-yourself (DIY) rheometry" at home. First, the students are asked to describe their material of choice in an interesting way, to keep the reader interested. Second, they have to demonstrate its non-Newtonian properties qualitatively, by taking photos or videos. Third, they use readily accessible flow scenarios to quantitatively measure viscoelastic material properties, such as measuring the yield stress of buttercream using a compression test. Fourth, a discussion is started to see how the material microstructure could explain the observed rheological behaviors. The learning outcomes were so positive that they continued this implementation even after access to the lab was recovered. The notion of reducing complexity and cost does not only apply to teaching, but also to research: Frugal science is successfully transforming research methods to achieve more with fewer resources.[58]

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

G. G. Fuller, M. Lisicki, A. J. T. M. Mathijssen, E. J. L. Mossige, R. Pasquino, Vivek N. Prakash, and L. Ramos contributed equally to this work.

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