

Ostwald ripening in evaporating respiratory breath figuresJoseph J. Kilbride *School of Physics and Astronomy, [University of Edinburgh](#), Edinburgh EH9 3FD, United Kingdom*F. Fouzia Ouali *School of Science and Technology, [Nottingham Trent University](#), Nottingham NG11 8NS, United Kingdom*David J. Fairhurst *School of Physics and Astronomy, [University of Edinburgh](#), Edinburgh EH9 3FD, United Kingdom*

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Understanding collective evaporation of micron-sized breath droplets can enhance modeling of clouds and inform strategies to limit virus transmission. In this work, we analyze thousands of micron-sized droplets within human and pure water breath figures, identifying two regimes. First, during coarsening, whilst the entire array is evaporating, larger droplets grow at the expense of smaller ones, driven by differences in equilibrium vapor concentration as low as 0.02%, arising from varying interfacial curvature. In this regime, the temporal distribution of droplet radii behaves according to classic Ostwald ripening theory, a mechanism which is usually considered only for submicron droplets. We then use a mean field model to connect droplet evaporation theory with Ostwald ripening, and predict individual droplet dynamics, showing how the accuracy depends on droplet coverage fraction. Finally, we show how the Coarsening regime is terminated by an edge regime, in which all remaining droplets evaporate rapidly.

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Introduction. Ostwald ripening (OR) is a well-known mechanism for material redistribution between solid particles [1], bubbles [2,3], or droplets [4,5] dispersed in a continuous phase. Due to the energy cost associated with the interfacial area, the larger particles grow at the expense of the smaller ones. The redistribution process requires dissolution (or evaporation) from the small particles, diffusion through the matrix, and then condensation onto the larger particles. For liquid droplets in air, diffusion is driven by differences in the equilibrium vapor concentration c at the interface of droplets, historically described by the Kelvin effect [6], which captures the increase in c above a droplet (with radius r), compared to a flat interface c_∞ ($r \rightarrow \infty$) of the same liquid. The ratio of these two concentrations ϕ_{sat} is given by the Ostwald-Freundlich form of the Kelvin equation,

$$\phi_{\text{sat}} = \frac{c(r)}{c_\infty} = \exp\left(\frac{r_k}{r}\right), \quad (1)$$

where $r_k = 2\gamma V_m/RT$ is the Kelvin radius, which depends on the molar volume (V_m), temperature (T), and surface tension (γ) with R the ideal gas constant. For water evaporating in air at 21 °C, $r_k \sim 1$ nm so this effect is typically dismissed for micron-sized droplets, considered relevant only

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for nanoscale aerosols. Lifshitz, Slyozov, and Wagner (LSW) [7,8] modeled how this difference in concentration leads to diffusion-limited OR, showing that the radius of each droplet should grow or shrink in time t , according to

$$\frac{dr}{dt} = \frac{-Dc_\infty}{\rho r} \left(1 + \frac{r_k}{r} - \phi \right), \quad (2)$$

where ϕ is the fractional relative humidity, D is the diffusion coefficient, ρ is the liquid density, and the term $1 + r_k/r$ approximates Eq. (1) for the equilibrium vapor concentration ϕ_{sat} . LSW used asymptotic analysis of the long time limit ($t \rightarrow \infty$) to make predictions of the evolution of OR particles. They derived that for spherical particles the size distribution is self-similar about the average radius ($\bar{r}$), which itself increases as $t^{1/3}$ [7,8]. Experiments using a microscope to image and measure the $\bar{r}$ of ripening cobalt grains in a fixed volume of liquid copper have confirmed this growth law at different temperatures [9].

The same predictions also apply to the evolution of droplets in clouds [10], often referred to as Köhler theory [11], leading to the formation of rain. In previous studies of clouds, OR had to be isolated from other more significant effects such as coalescence [12], growth due to externally forced over-saturation, and the presence of solutes [13].

Schäfle *et al.* [14] were the first to observe droplets coarsening on surfaces, discovering an instability in monodisperse arrays of sub-micron diethylene glycol. Despite this, the importance of curvature for the dynamics of micron droplets (1000 times larger than the Kelvin radius) is overlooked [12,13,15–18] or dismissed as insignificant in many studies [19,20]. Quoting Krischer and Kast, Hansen states, “since deviations resulting from surface curvature are negligible as long as the radii of curvature are larger than about 10^{-6} cm” [21,22]. Sokuler *et al.* [23] showed that condensing droplets on cooled surfaces follow the LSW growth law, $\bar{r} \propto t^{1/3}$. In addition, the interplay between the overall evaporation dynamics and the specific droplet ripening has not been explored.

By analyzing tens of thousands of breath droplets on surfaces (commonly known as breath figures, BF), we show that the differences in interfacial curvature between micron-sized droplets lead to tiny differences in vapor concentration, as low as 0.02%. The resulting gradients in the vapor are the mechanism behind the coarsening regime, and exploring this is the main focus of this work. By making comparisons to LSW theory, we are able to show that this coarsening is consistent with OR. The characteristic self-similar distributions and linear growth of the cubed average radius observed in previous OR systems are found. We go beyond previous experimental studies by making further comparisons of LSW theory to individual droplets by implementing a mean field (MF) model.

After the coarsening regime, we identify an edge regime in which the droplets evaporate rapidly, governed by the dynamics of the edge of the BF. We also show that these two regimes are consistent across 19 separate human BFs taken in a relatively uncontrolled public setting, as well as pure water artificial BFs taken in the laboratory.

Because the size of the droplets studied is comparable to those exhaled/coughed, coarsening should be considered when modeling the period over which virus-laden respiratory droplets are contagious [24–26]. The coarsening is also a mechanism in which droplets can grow in volume and should also be considered when modeling the initiation of precipitation in clouds [10,11].

Methods. To generate human BFs, we recruited 19 participants during a ‘Curious Rebels’ outreach residency at Nottingham Castle. Volunteers breathed directly onto the lid of a new 90 mm diameter polystyrene Petri dish before quickly closing it, with duration and speed of breath varying between participants. The drop-wise condensation (on defects which act as nucleation sites [27]), as well as the possibility of droplets being ejected directly from the mouth and landing directly on the surface, led to different polydisperse distributions. The Petri dish lid was placed upside-down on its base with the droplets in a pendant geometry, attached to the upper surface. The lid formed a partial seal, slowing evaporation and extending droplet lifetimes from seconds to minutes. Artificial BFs were generated in the laboratory by holding the inside of a Petri dish lid above a bath of 60°C

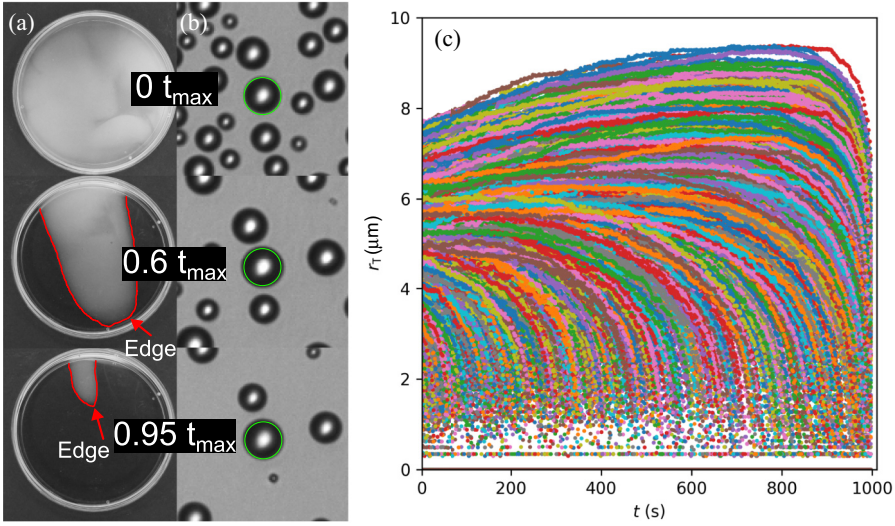


FIG. 1. Series of images of (a) macroscopic view of the breath figure inside a 90 mm Petri dish, (b) corresponding microscope images ($63.2 \times 63.2 \mu\text{m}$) of coarsening droplets in the center of the breath figure. The green ring indicates the largest droplet's initial radius of $7.4 \mu\text{m}$. (c) The extracted and tracked radii (r_T) as a function of time (t) for each droplet in the full microscope FOV, showing smaller droplets shrinking and larger ones growing.

deionized water for up to 1 minute, generating different droplet size distributions. Images with field of view (FOV) $793 \times 634 \mu\text{m}$, representing approximately 0.01% of the total BF area, are taken at least every 2 seconds using an optical microscope (Olympus BX50) with a $\times 10$ objective, focused on the contact line of the pendant droplets near the center. With this upright microscope, we image the droplets in a pendant orientation so that the contact line is never obscured by bulging droplets with contact angles greater than 90 degrees. For this reason, pendant droplets are preferred, noting that the shape of micron droplets is unaffected by gravity. The experiments were carried out at a range of external ambient humidities 30 to 60%, with humidity changing by $< 1\%$ during each experiment. The range of ambient temperatures were 19 to 24 $^{\circ}\text{C}$, with $< 1^{\circ}\text{C}$ variation during each experiment.

The radii (a) of all droplets in the breath figure image are extracted using FIJI ImageJ by first thresholding and then using the Analyze Particles tool to find the size and location of the features (droplets) in each image. During evaporation, the positions of the droplets' center of mass move slightly, and so each droplet is tracked between frames by finding the closest detected droplet in the next image. If no droplet is within the initial radius of the droplet, it is considered to have evaporated.

Results. Macroscopically, the breath figure appears as a 'fogged up' patch which covers most of the (90 mm diameter) Petri dish surface in Fig. 1(a). Over time, the patch shrinks (red line on left-hand panel) as the vapor escapes through the gap between the base and lid. The microscope images in Fig. 1(b) show an enlarged region ($63.2 \times 63.2 \mu\text{m}$) of the microscope images showing droplets initially at the center of the BF. The series shows three corresponding images with respect to $t_{\max}$, defined separately in both microscopic and macroscopic images, as the time at which all visible droplets have evaporated. In Fig. 1(b), the largest droplet grows over time: its initial radius is indicated by the $7.4 \mu\text{m}$ green ring, and after $0.6 t_{\max}$ has noticeably increased (by 18%). In addition, a number of smaller droplets have disappeared, indicating a size dependence on the droplets' behavior. The radii of all $N = 2307$ droplets within the full FOV have been tracked and plotted against time in Fig. 1(c), with the colors distinguishing between droplets. The radius dependence of the droplets in the BF is consistent across the entire FOV for any given time. Initially ($t = 0$), the

radii of the larger droplets (approximately $>5\text{ }\mu\text{m}$, for this breath figure) are increasing whilst radii of the smaller droplets ($<5\text{ }\mu\text{m}$) are decreasing. At later times, the radius defining which droplets grow/shrink increases, and the number of growing droplets decreases. This behavior is typical of many experiments. We identify this as the coarsening regime, in which, despite the overall BF losing around 33% volume through evaporation, some droplets increase in volume.

After several minutes, the edge of the BF [red line in Fig. 1(a)] reaches the microscope FOV and consequently the local humidity decreases. The coarsening stops and all remaining droplets evaporate very rapidly, which we name the edge regime. At $0.95t_{\text{max}}$ the edge regime has caused the highlighted droplet to decrease to its initial size, before evaporating completely at $t_{\text{max}} = 1010\text{ s}$. In Fig. 1(c) at $t \approx 800\text{ s}$, all droplets are decreasing in size, indicating the onset of this edge regime. The Supplemental Material video [28] of the full microscope FOV ($793 \times 634\text{ }\mu\text{m}$), which is close to the center of the breath figures, shows the temporal evolution of the droplets through the coarsening and edge regimes. In summary, 33% of the volume is lost during coarsening, which lasts 80% of the drying time; the remaining 66% is lost in the edge regime (final 20% of the drying time). Below, we focus on exploring the possible mechanisms for the coarsening regime before making quantitative comparisons to OR predictions.

Droplet coarsening requires water vapor transport from smaller droplets onto the larger droplets, down a sustained concentration gradient. We explore three potential mechanisms for this gradient: temperature effects, solute concentration, and interfacial curvature. We conclude that interfacial curvature is the only viable explanation for our observations. First, the equilibrium vapour concentration of water increases with temperature. If the diffusive gradients transporting liquid from small toward large droplets were due to temperature differences, the larger ones would have to be colder. This is, however, not expected as the smaller droplets evaporate faster, losing heat through evaporative cooling, in addition to having a lower thermal mass. As such, temperature effects would be expected to stabilise droplet sizes, rather than lead to coarsening.

Alternatively, higher concentrations of nonvolatile solutes (either naturally present in the liquid or from contamination) will generally lower a droplet's equilibrium vapor concentration, known as the Raoult effect [29]. For this to initiate coarsening, the larger droplets must have a higher concentration of solute. If greater amounts of solute from contaminants on the substrate promote nucleation of the bigger droplets, they would have a higher solute concentration initially, but continued growth would reduce this, and droplets of different sizes would again stabilise with equal solute concentration. For human BFs, natural solute could also be transferred by ejected droplets landing directly on the substrate; however, this would not systematically ensure higher solute concentrations in larger droplets. Neither source of solute would create the very specific initial concentrations required to explain the coarsening. Given the consistency of the dynamics across both artificial and human BFs, we rule out solute as being responsible for coarsening.

Finally, we consider how curvature (the Kelvin effect) can lead to coarsening. The vapor concentration over the polydisperse droplets in a BF varies spatially because droplets have varying interfacial curvatures. The Kelvin effect predicts that ϕ_{sat} will be greater for smaller droplets, leading to a concentration gradient toward larger droplets. The resulting diffusive fluxes would then cause bigger droplets to grow at the expense of their smaller neighbours. Whether an individual droplet grows or shrinks is then determined by the net flux it receives from its neighbours. Using Eq. (1), we estimate the difference in ϕ_{sat} between the minimum ($\approx 3.1\text{ }\mu\text{m}$) and maximum ($r = 8.1\text{ }\mu\text{m}$) droplet radius at $t = 0$ in Fig. 1 to be only 0.02%. This leads to the conclusion that surprisingly small gradients can drive significant redistribution. In previously studied OR systems, such as platinum nanoparticles on a planar silicon dioxide support [30], the difference in concentration is much larger, around $\approx 30\%$.

a. Comparing to Ostwald ripening theory. To establish if the Kelvin effect is the mechanism for coarsening, we quantitatively compare our experimental data to LSW predictions for OR. First, LSW theory predicts that the average droplet radius ($\bar{r}$) of the BF should increase above its initial value ($\bar{r}_0$) over time as $\bar{r}^3 - \bar{r}_0^3 = Kt$ where $K = 0.44\rho^{-1}Dc_{\infty}r_k$ is known as the rate constant. In Fig. 2, we plot $\bar{r}^3 - \bar{r}_0^3$ against t for the coarsening BFs with initially increasing $\bar{r}$. We smooth the

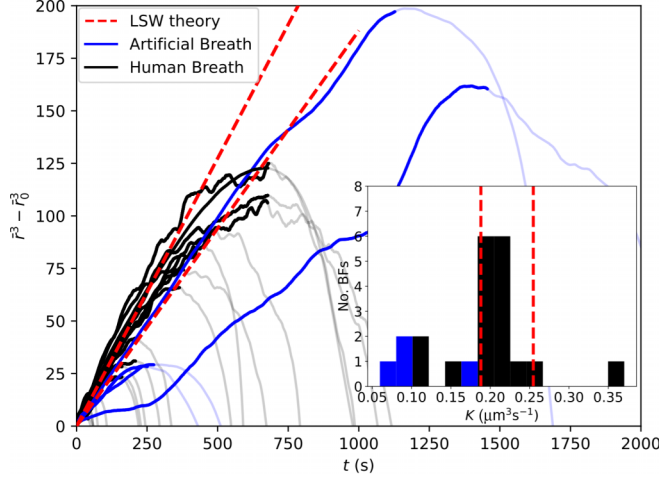


FIG. 2. The increase in the cube of the average droplet radius ($\bar{r}$) over time (t) for different breath figures. The curves become paler when $\bar{r}$ reaches its maximum value, and the BF enters its edge regime. The red dashed lines depict the range of predicted rate constants (K) by LSW theory. The inset shows a stacked histogram of the experimental values of K , with red dashed lines again showing the LSW prediction.

data to reduce scatter and improve the clarity between adjacent lines. We find approximately linear growth of $\bar{r}^3$ during the coarsening regime. After this, the value of $\bar{r}$ plateaus before quickly reducing to zero, which is due to the edge regime causing a rapid decrease in ambient humidity, as the edge of the BF reaches the camera's FOV. The dynamics in the edge regime are not modelled by the LSW theory, and consequently, for clarity, the data is plotted with a paler color beyond the maximum value, to highlight just the coarsening regimes. We find that most of the data initially grows between the range of rate constants predicted by LSW theory for different temperatures measured across the experiments (19 to 24 °C), using appropriate liquid and gas constants with no free fit parameters (red dashed lines on main plot and inset). The BFs with lower-than-predicted rate constants are likely to be initially influenced by the edge. The BF is growing much faster than predicted, as seen in the histogram is a very short experiment, making it difficult to see in the main panel. However, the reasons for its faster growth are unknown, although other authors [31] have suggested an additional dependence of K on the droplet coverage fraction.

In general, the fastest increases in the average radius come from the human BFs. This is because human BFs tend to form denser droplet packings, which we attribute to the formation of additional nucleation sites by ejected droplets within the exhaled breath. This closer packing promotes additional growth.

We observed no systematic difference between the evaporation of human and artificial breath, indicating that any additional volatile organic compounds, proteins, or saliva in human breath do not significantly influence the coarsening and evaporation process.

A second prediction of LSW theory is that the distribution of droplet radii should be self-similar in time when normalized by $\bar{r}$. In Fig. 3, we plot rescaled histograms for BFs at different initial coverage fractions 21.9, 23.5, 36.1 and 44.8%, for a series of times during the coarsening regime, where N is the number of droplets with a given size and N_{max} is the total number of droplets at time t . Each panel shows good self-similarity up to $0.6t_{\text{max}}$ (during the coarsening regime), consistent with LSW theory. The predicted shape of the histogram is given by

$$\frac{N}{N_{\text{max}}} = 0.561 \left(\frac{r}{\bar{r}} \right)^2 \left(\frac{3}{3 + \frac{r}{\bar{r}}} \right)^{\frac{7}{3}} \left(\frac{1.5}{1.5 - \frac{r}{\bar{r}}} \right)^{\frac{11}{3}} \exp \left(\frac{1.5}{\frac{r}{\bar{r}} - 1.5} \right), \quad (3)$$

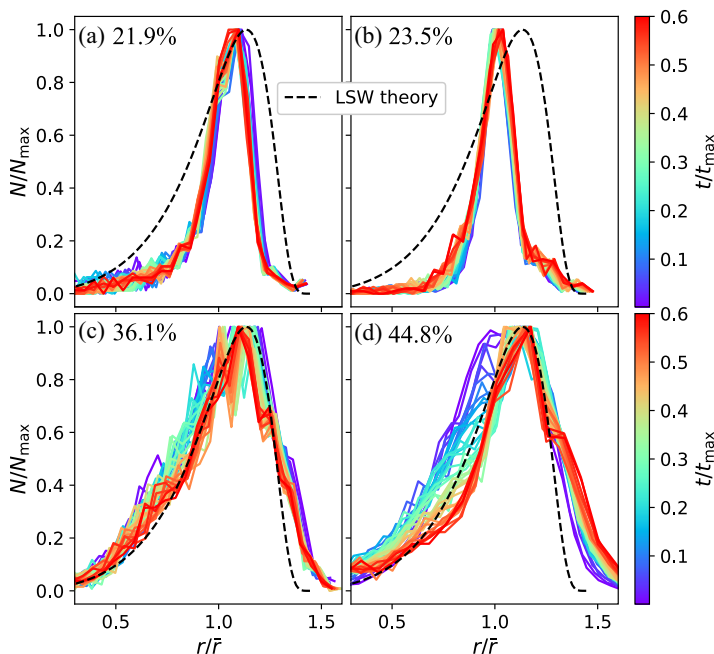


FIG. 3. Histogram of radius (r) normalized by the average ($\bar{r}$) at different times (indicated by the colorbar) for the evaporation of BFs at different initial coverage fractions (a) 21.9% (artificial), (b) 23.5% (artificial), (c) 36.1% (human), and (d) 44.8% (artificial). The number of droplets, N , is normalized by its maximum, $N_{\max}$ at each time. The black dashed curve is the form predicted by LSW theory.

which is plotted as the black dashed line in each panel. We find mixed agreement with this predicted distribution shape. The weaker agreement in panels (a) and (b) have narrower-than-predicted histograms, whereas the higher coverage fractions in (c) and (d) have broader distributions and are more consistent with Eq. (3). The reason for these differences is unknown, although previous studies have reported that this distribution does not always accurately capture the experimental data, indicating limitations of the theory as stated by Voorhees, “Soon after the publication of the LSW papers, many experimentalists rushed to test the veracity of the theory. Experiments have confirmed the prediction of self-similar coarsening behavior at long times; however, virtually none of the reported distributions are of the form predicted by LSW” [32]. Despite this, the data does exhibit the predicted self-similarity in Fig. 3, and in addition to the agreement with the $t^{1/3}$ law in Fig. 2, we conclude that the coarsening regime is Ostwald ripening driven by the Kelvin effect arising from differences in droplet curvature.

The asymptotic LSW theory provides long-term predictions for statistical quantities that describe the entire BF, namely the distribution shape and average droplet radius. At shorter times, there are no simple theoretical predictions.

b. Mean field modelling. To accurately investigate the evolution of individual droplets on surfaces from early times, we combine the mean field implementation of LSW theory [32,33] with existing diffusive droplet evaporation theory [34], predicting the mass flux of a single sessile/pendent droplet

$$\frac{dm}{dt} = -a\pi Dc_{\infty}(\phi_{\text{sat}}(r) - \phi)f(\theta). \quad (4)$$

Here, a is the droplet base radius (related to the radius of curvature via $a = r \sin \theta$). Equation (4) is equivalent to Eq. (2), but with the additional term $f(\theta) \approx 2/\sqrt{1 + \cos \theta}$, which is a known approximation of how the contact angle θ affects the flux [35]. Typically, in theories considering

droplets on surfaces, the Kelvin effect is ignored. However, as we have argued earlier, for the small droplets in our BFs, the Kelvin effect is essential to capture the droplet dynamics. Consequently, our expression for $\phi_{\text{sat}}(r)$ depends on interfacial curvature and is given by the Kelvin equation [Eq. (1)] discussed previously. Whether this value is larger or smaller than the fractional relative humidity in the surrounding gas ϕ , determines whether a droplet evaporates or grows via condensation. Equation (4) is, however, for a single droplet in a homogeneous ϕ and the BF is a multiple droplet system. The ambient humidity around any given droplet will vary spatially, depending on the curvatures and positions of the surrounding droplets and whether they are evaporating or condensing. In our mean field approach, we replace the spatially dependent vapor concentration with a mean field ϕ^* (or equivalently an effective ambient humidity), which is connected to the size distribution of droplets in the BF.

According to LSW theory, ϕ^* is set by the equilibrium vapor concentration of the average particle radius ($\bar{r}$) [32]. Therefore, for a known distribution of droplet radii, $\bar{r}$ can be calculated and the LSW mean field concentration can be determined using Eq. (1) as $\phi^*(t) = \exp(r_k/\bar{r})$. Because $\bar{r}(t)$ varies in time as droplets coarsen, ϕ^* is also time dependent, calculated from the instantaneous distribution of droplets present. The value of $\bar{r}$ can be seen as a critical droplet radius, above which droplets grow and below which they shrink, resulting in a size-dependent coarsening. The evaporation rate of any particular droplet in the BF is determined by Eq. (4), given by how its radius-dependent $\phi_{\text{sat}}(r)$ compares to the mean field concentration ϕ^* . For example, from Fig. 1(c), initially the average radius can be approximated by reading off the size of droplets which have $dr/dt = 0$, which is at $r \approx 5 \mu\text{m}$. Comparing this to the largest droplet ($r \approx 7.75 \mu\text{m}$), the rate this droplet grows can be calculated by substituting $\phi_{\text{sat}}(r = 7.75 \mu\text{m}) - \phi_{\text{sat}}(\bar{r} = 5 \mu\text{m})$ into Eq. (4). Other OR systems, such as platinum particles sintering on a silicon dioxide support [30], have found good agreement, using a similar mean field approach.

The mean field approximation assumes that local effects are small and cancel out across the array. This becomes more valid when droplets are well separated and the BFs have a lower coverage fraction. In applying the model, we must also assume that the FOV is representative of neighboring regions.

Numerically, we iterate Eq. (4) with $\phi = \phi^*$ in time using a fourth-order Runge-Kutta method to simulate the radius of each droplet. A further series of experiments was conducted, accurately imaging the droplet contact lines. These images were then processed, and the radius of each droplet was extracted and tracked in time (as described in the Methods section). The numerical iteration was initialized with the same starting distribution as each experiment, with as many as $N = 2307$ droplets. The experimental evolution of the droplet radii was compared to the theoretical predictions. The liquid is assumed to be pure water with a density of $\rho = 997 \text{ kg m}^{-3}$ and a surface tension of $\gamma = 72.75 \times 10^{-3} \text{ N m}^{-1}$. The droplets are assumed to evaporate with a constant contact angle of $\theta = 90^\circ$. The values of $c_\infty = 0.0193 \text{ kg m}^{-3}$ and $D = 2.446 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ were calculated corresponding to the ambient temperature of $T \approx 22^\circ\text{C}$. A timestep of 0.1 s ($\approx 1\%$ of the lifetime of the smallest droplets) was found to be sufficiently fine for the dynamics to be independent of further refinement. Figure 4 shows the radius predicted by the MF model for each droplet (r_{MFT}) against its experimentally tracked radius (r_{exp}) extracted from the images just before the start of the edge regime. We find that each dataset scatters about the $r_{\text{MFT}} = r_{\text{exp}}$ solid black line. In general, the MF model appears to slightly overpredict the droplet radius, which we attribute to uncertainties in the values for the gas and liquid constants, as well as the uncertainty in radii extracted from the images. There are no fitting parameters in this calculation. The inset shows the absolute residual ($\delta = |r_{\text{MFT}} - r_{\text{exp}}|$) averaged over all the droplets, capturing the width of the scatter in each series. Plotting against the BF's initial coverage fraction shows an overall increase in δ , demonstrating that the MFT performs worse when droplets are very densely packed. For the red, green, and orange series ($<25\%$), the average divergence of the MFT is $\delta < 0.2 \mu\text{m}$, indicating very good agreement. At 36.1% (blue) $\delta \approx 0.5 \mu\text{m}$ and the MFT model becomes much less accurate. The reason for the increase in overall scatter about the $r_{\text{MFT}} = r_{\text{exp}}$ line with coverage fraction is likely due to the increasing significance of local effects with droplet packing density. For example, a large growing

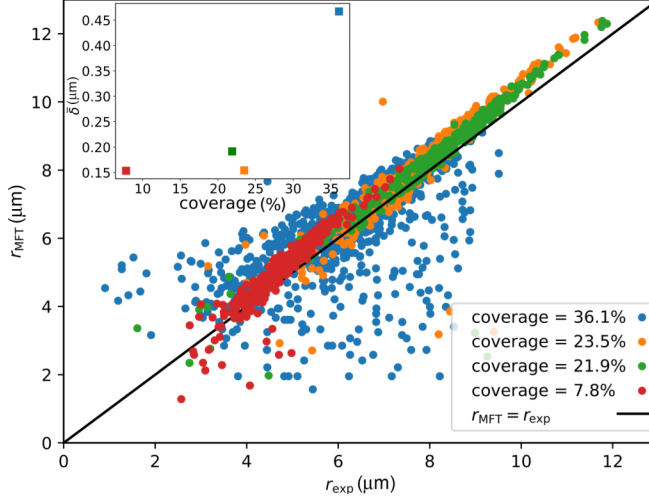


FIG. 4. Mean field droplet radii (r_{MFT}) after $t = 0.5t_{\text{max}}$ against the experimental tracked radii (r_{exp}). The legend indicates each experiment's initial coverage fraction. The black line along $r_{\text{MFT}} = r_{\text{exp}}$ represents perfect agreement. The inset presents the absolute residual ($\delta = |r_{\text{MFT}} - r_{\text{exp}}|$) averaged over all the droplets ($\bar{\delta}$) against the initial coverage fraction.

droplet might grow more quickly than predicted if it is surrounded by more small droplets than is predicted on average. This could result in this droplet growing quicker than another droplet in a different location with initially the same radius. The MFT does not account for these local effects and would predict that the two droplets would grow at the same rate. Furthermore, there is additional scatter in the blue series because at high packing fractions, droplets can grow sufficiently to touch and coalesce, which is also not accounted for.

Conclusion. In this paper, the evaporation of human and artificial breath figures on surfaces was studied. Experimental images were analysed to extract the transient behavior of thousands of droplets. In both cases a period of material redistribution (coarsening regime) was observed during which larger droplets were seen to grow, even as the entire array was evaporating, followed by bulk evaporation (edge regime). By comparing to existing Ostwald ripening theory, it was shown that the coarsening dynamics of the droplets is curvature dependent, an effect that is often overlooked for micron-sized droplets. A mean field diffusion-limited model of the evaporation is found to predict the overall dynamics not only for the BF as a whole but even for individual droplet radii. Divergence from the model is found when the coverage fraction of the droplets is very high (around $>30\%$) when local effects and coalescence become significant. This model is computationally inexpensive, only requiring a single calculation for each droplet (N calculations) at each timestep. Future work to improve the agreement for very dense breath figures by implicitly accounting for local effects could be made using the work of Fabrikant [36], Wray *et al.* [37], and Masoud *et al.* [38], as has previously been done for arrays of larger droplets [39–41]. However, given the number of droplets in the entire breath figure, this would be computationally challenging, requiring N^2 calculations at each timestep to take account of all the pairwise interactions between droplets. Additionally, assumptions about the droplet distribution outside the camera's FOV would be required.

Our findings will be very useful when modeling micron droplet systems such as clouds, breath, and condensation, which naturally contain thousands or even millions of droplets. Accounting for droplet curvature in this way could improve the modeling of viral transmission, as it is possible that Ostwald ripening prolongs the lifetime of large droplets, enhancing their opportunity to transmit viruses [24–26,42]. We note that on surfaces, Ostwald ripening can be suppressed if the substrate has high wettability, as the droplets' radius of curvature would be much larger.

Finally, our approach could be implemented in cloud-resolving meteorological models [43] to aid in the parametrisation of much larger climate and weather models, improving their predictions of cloud evolution and precipitation.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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- [1] W. Ostwald, Studien über die bildung und umwandlung fester körper, *Z. Phys. Chem.* **22U**, 289 (1897).
 - [2] S. Maheshwari, M. van der Hoef, J. Rodríguez Rodríguez, and D. Lohse, Leakiness of pinned neighboring surface nanobubbles induced by strong gas–surface interaction, *ACS Nano* **12**, 2603 (2018).
 - [3] X. Zhu, R. Verzicco, X. Zhang, and D. Lohse, Diffusive interaction of multiple surface nanobubbles: shrinkage, growth, and coarsening, *Soft Matter* **14**, 2006 (2018).
 - [4] Y. Li, S. L. Maux, H. Xiao, and D. J. McClements, Emulsion-based delivery systems for tributyrin, a potential colon cancer preventative agent, *J. Agric. Food. Chem.* **57**, 9243 (2009).
 - [5] M. Usui, F. Harusawa, T. Sakai, T. Yamashita, H. Sakai, and M. Abe, Dynamic light scattering studies on Ostwald ripening and composition ripening of oil droplets in oil-in-water emulsion systems, *J. Oleo Sci.* **53**, 611 (2004).
 - [6] W. Thomson, On the equilibrium of vapour at a curved surface of liquid, *Proc. R. Soc. Edinburgh* **7**, 63 (1872).
 - [7] I. M. Lifshitz and V. V. Slyozov, The kinetics of precipitation from supersaturated solid solutions, *J. Phys. Chem. Solids* **19**, 35 (1961).
 - [8] C. Wagner, Theorie der alterung von niederschlägen durch umlösen (Ostwald-Reifung), *Z. Elektrochem. Ber. Bunsen. Phys. Chem.* **65**, 581 (1961).
 - [9] C. H. Kang and D. N. Yoon, Coarsening of cobalt grains dispersed in liquid copper matrix, *Metall. Trans. A* **12**, 65 (1981).
 - [10] F. Yang, P. Kollias, R. A. Shaw, and A. M. Vogelmann, Cloud droplet size distribution broadening during diffusional growth: Ripening amplified by deactivation and reactivation, *Atmos. Chem. Phys.* **18**, 7313 (2018).
 - [11] R. E. L. West, Estimation of the indirect radiative effects of aerosol on climate using a general circulation model Ph.D. thesis, University of Oxford, 2012.
 - [12] H. Gau and S. Herminghaus, Ripening of ordered breath figures, *Phys. Rev. Lett.* **84**, 4156 (2000).
 - [13] J. Guadarrama-Cetina, R. D. Narhe, D. A. Beysens, and W. González-Viñas, Droplet pattern and condensation gradient around a humidity sink, *Phys. Rev. E* **89**, 012402 (2014).
 - [14] C. Schäfle, C. Bechinger, B. Rinn, C. David, and P. Leiderer, Cooperative evaporation in ordered arrays of volatile droplets, *Phys. Rev. Lett.* **83**, 5302 (1999).
 - [15] I. O. Ucar and H. Y. Erbil, Use of diffusion controlled drop evaporation equations for dropwise condensation during dew formation and effect of neighboring droplets, *Colloids Surf. A: Physicochem. Eng. Asp.* **411**, 60 (2012).
 - [16] C. S. Ng, K. L. Chong, R. Yang, M. Li, R. Verzicco, and D. Lohse, Growth of respiratory droplets in cold and humid air, *Phys. Rev. Fluids* **6**, 054303 (2021).
 - [17] C. Seyfert, J. Rodríguez-Rodríguez, D. Lohse, and A. Marin, Stability of respiratory-like droplets under evaporation, *Phys. Rev. Fluids* **7**, 023603 (2022).
 - [18] A. Bouillant, J. H. Snoeijer, and B. Andreotti, Collective effects in breath figures, *Phys. Rev. Fluids*, **10**, 053605 (2025).

- [19] R. N. Leach, F. Stevens, S. C. Langford, and J. T. Dickinson, Dropwise condensation: Experiments and simulations of nucleation and growth of water drops in a cooling system, *Langmuir* **22**, 8864 (2006).
- [20] M. Stiti, G. Castanet, A. Corber, M. Alden, and E. Berrocal, Transition from saliva droplets to solid aerosols in the context of Covid-19 spreading, *Environ. Res.* **204**, 112072 (2022).
- [21] O. Krischer and W. Kast, *Die Wissenschaftlichen Grundlagen der Trocknungstechnik. Dritte Auflage* (Springer-Verlag, London, England, 1978).
- [22] E. B. Hansen, On drying of laundry, *SIAM J. Appl. Math.* **52**, 1360 (1992).
- [23] M. Sokuler, G. K. Auernhammer, C. Liu, E. Bonaccorso, and H.-J. Butt, Dynamics of condensation and evaporation: Effect of inter-drop spacing, *Europhys. Lett.* **89**, 36004 (2010).
- [24] V. Stadnytskyi, C. E. Bax, A. Bax, and P. Anfinrud, The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission, *Proc. Natl. Acad. Sci. USA* **117**, 11875 (2020).
- [25] Z. He, S. Shao, J. Li, S. S. Kumar, J. B. Sokoloff, and J. Hong, Droplet evaporation residue indicating SARS-CoV-2 survivability on surfaces, *Phys. Fluids* **33**, 013309 (2021).
- [26] D. E. Corpet, Why does SARS-CoV-2 survive longer on plastic than on paper? *Med. Hypotheses* **146**, 110429 (2021).
- [27] T. S. B. Quang, F. Y. Leong, H. An, B. H. Tan, and C. D. Ohl, Growth and wetting of water droplet condensed between micron-sized particles and substrate, *Sci. Rep.* **6**, 30989 (2016).
- [28] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/6vms-ljj5> for microscope video of Ostwald ripening droplets in an evaporating breath figure.
- [29] F.-M. Raoult, Loi générale des tensions de vapeur des dissolvants, *CR Hebd. Seances Acad. Sci.* **104**, 1430 (1887).
- [30] S. B. Simonsen, I. Chorkendorff, S. Dahl, M. Skoglundh, J. Sehested, and S. Helveg, Ostwald ripening in a Pt/SiO₂ model catalyst studied by *in situ* TEM, *J. Catal.* **281**, 147 (2011).
- [31] J. A. Marqusee and J. Ross, Theory of Ostwald ripening: Competitive growth and its dependence on volume fraction, *J. Chem. Phys.* **80**, 536 (1984).
- [32] P. W. Voorhees, The theory of Ostwald ripening, *J. Stat. Phys.* **38**, 231 (1985).
- [33] C. F. Clement, Mean field theory for condensation on aerosols and application to multi-component organic vapours, *J. Aerosol Sci.* **34**, 27 (2003).
- [34] R. Picknett and R. Bexon, The evaporation of sessile or pendant drops in still air, *J. Colloid Interface Sci.* **61**, 336 (1977).
- [35] D. Hu, H. Wu, and Z. Liu, Effect of liquid-vapor interface area on the evaporation rate of small sessile droplets, *Int. J. Therm. Sci.* **84**, 300 (2014).
- [36] V. I. Fabrikant, On the potential flow through membranes, *Z. Angew Math. Phys.* **36**, 616 (1985).
- [37] A. W. Wray, B. R. Duffy, and S. K. Wilson, Competitive evaporation of multiple sessile droplets, *J. Fluid Mech.* **884**, A45 (2019).
- [38] H. Masoud, P. D. Howell, and H. A. Stone, Evaporation of multiple droplets, *J. Fluid Mech.* **927**, R4 (2021).
- [39] A. M. Edwards, J. Cater, J. J. Kilbride, P. Le Minter, C. V. Brown, D. J. Fairhurst, and F. F. Ouali, Interferometric measurement of co-operative evaporation in 2D droplet arrays, *Appl. Phys. Lett.* **119**, 151601 (2021).
- [40] A. Iqtidar, J. J. Kilbride, F. F. Ouali, D. J. Fairhurst, H. A. Stone, and H. Masoud, Drying dynamics of sessile-droplet arrays, *Phys. Rev. Fluids* **8**, 013602 (2023).
- [41] J. J. Kilbride, K. E. Fagg, F. F. Ouali, and D. J. Fairhurst, Pattern-distortion technique: Using liquid-lens magnification to extract volumes of individual droplets or bubbles within evaporating two-dimensional arrays, *Phys. Rev. Appl.* **19**, 044030 (2023).
- [42] B. J. Cowling, D. K. M. Ip, V. J. Fang, P. Suntarattiwong, S. J. Olsen, J. Levy, T. M. Uyeki, G. M. Leung, J. S. Malik Peiris, T. Chotpitayasunondh *et al.*, Aerosol transmission is an important mode of influenza A virus spread, *Nat. Commun.* **4**, 1935 (2013).
- [43] Y. Sato, D. Goto, T. Michibata, K. Suzuki, T. Takemura, H. Tomita, and T. Nakajima, Aerosol effects on cloud water amounts were successfully simulated by a global cloud-system resolving model, *Nat. Commun.* **9**, 985 (2018).