



Time-resolved 3D reconstruction of an early-stage condensing microdroplet using digital holographic microscopy

Sangmin Song¹ · Il Woong Park¹ · Carlos Alberto Dorao² · Maria Fernandino²

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Abstract

Early-stage condensation droplets set initial conditions for subsequent growth, coalescence, and surface re-exposure, yet their time-resolved three-dimensional morphology at the microscale remains difficult to measure using conventional two-dimensional imaging techniques. Here, digital holographic microscopy (DHM) was used to reconstruct time-resolved height fields of an individual condensing microdroplet on a silane-coated glass surface, with lateral and temporal resolutions of 0.83 μm and 66 ms, respectively. The reconstructed phase fields were converted into droplet height maps, from which maximum height, footprint-equivalent diameter, integrated volume, and projected-boundary descriptors were quantified. For the representative droplet analyzed in this study, early growth departed from uniform spherical-cap-like enlargement. Vertical growth was more pronounced than lateral footprint expansion during an early growth interval, while projected-boundary analysis showed that the initially less regular footprint became more circular as growth proceeded. At three selected growth stages, threshold-aligned spherical-cap cross-estimates underestimated the DHM-measured maximum height by 10.47–17.29% and the projected-footprint area by 9.00–27.74%, while overestimating the integrated volume by 9.84–28.53%. These observations indicate that the early lateral development of the analyzed droplet did not occur through uniform self-similar expansion, but through non-uniform morphological evolution involving coupled height growth, footprint development, volume accumulation, and boundary regularization. Together, the coupled temporal measurements and direct geometric comparison demonstrate that DHM can quantify non-uniform three-dimensional morphological evolution and assess the limitations of simplified droplet geometries during early-stage condensation.

1 Introduction

Condensation is a liquid–vapor phase-change process central to thermal management, energy conversion, desalination, and air-conditioning systems (Wen et al. 2018; Zheng et al. 2021). On cooled surfaces, condensate forms in filmwise or dropwise modes depending on surface wettability. Dropwise condensation can provide high heat-transfer performance because droplet nucleation, growth, coalescence, and departure repeatedly renew the exposed surface (Schmidt et al. 1930; Rose 2002; Tanasawa 1991; Zheng et al. 2021). There-

fore, its performance is governed by the growth, interaction, and removal of individual droplets.

Within this process, the early stage of dropwise condensation sets the initial conditions for subsequent droplet growth, coalescence, surface re-exposure, and population development (Graham and Griffith 1973; Ma et al. 2010; Beyens 2006; Zheng et al. 2021; Guo et al. 2023). Microscale droplets that appear immediately after nucleation are small, rapidly evolving, and sensitive to surface wettability, contact-line pinning, and local heterogeneity. Their height, footprint area, volume, and projected-boundary geometry can influence subsequent droplet-population and condensation-pattern development. Quantifying these early geometric changes is therefore necessary for linking individual-droplet growth to the subsequent evolution of dropwise condensation.

Previous studies have examined early-stage condensation in terms of nucleation, growth, coalescence, droplet-size distributions, wetting state, and pattern formation. Coalescence has been shown to govern growth laws and self-similar pat-

✉ Il Woong Park
ilwoongpark@inha.ac.kr

✉ Maria Fernandino
maria.fernandino@ntnu.no

¹ Department of Mechanical Engineering, Inha University, 100 Inha-ro, Michuhol-gu, Incheon, Republic of Korea

² Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

tern formation (Beysens 2006), while wettability gradients, contact-angle hysteresis, and contact-line pinning can drive transitions from spherical droplets to nonspherical structures (Zhao and Beysens 1995). Transient droplet-population evolution and the effects of surface structure and wetting state on footprint growth have also been investigated (Leach et al. 2006; Ma et al. 2010; Rykaczewski and Scott 2011; Rykaczewski et al. 2012; Miljkovic et al. 2012). These studies establish the importance of coalescence, wettability, surface structure, and contact-line effects in early condensation, but they mainly provide population-level, projected, or surface-specific observations rather than time-resolved quantitative height-field measurements of individual microscale droplets.

Despite these advances, most experimental studies have relied on planar imaging, side-view observations, environmental scanning electron microscopy (ESEM)-based visualization, or droplet-population statistics, which provide projected, indirect, or partial information about droplet geometry. Consequently, key quantities such as droplet height, volume, footprint evolution, and projected-boundary morphology are often not measured directly or simultaneously and must be inferred using simplified assumptions, including spherical-cap geometry and axisymmetric droplet shapes. Such geometric assumptions are also used in theoretical and numerical models of dropwise condensation to describe droplet growth, coalescence, departure, and heat-transfer behavior (Kim and Kim 2011; Zheng et al. 2021; Guo et al. 2023). While useful for modeling droplet populations and estimating heat-transfer trends, these approximations do not directly reveal how height, volume, footprint, and boundary shape evolve together in individual microscale droplets, especially during the early stage when droplet shapes may be non-axisymmetric and their projected boundaries may evolve non-uniformly.

These limitations also arise from the measurement constraints of existing techniques. Conventional optical contact-angle measurements and side-view observations provide projected or optically inferred droplet geometry rather than quantitative height fields, making non-axisymmetric droplets and irregular projected boundaries difficult to characterize in three dimensions (Allain et al. 1985; Zhang and Chao 2002). Confocal microscopy, ESEM, and atomic force microscopy can provide three-dimensional or micro- and nanoscale information, but axial scanning, image-stack acquisition, fluorescent labeling, viewing constraints, beam-sample interactions, and probe-liquid effects can limit their application to transient liquid interfaces (Sundberg et al. 2007; Chesna et al. 2016; Rykaczewski and Scott 2011; Bhushan and Jung 2008). Accordingly, time-resolved analysis of early-stage condensing droplets requires a non-contact, non-scanning method that provides quantitative height-field information with adequate spatial and temporal resolution.

Digital holographic microscopy (DHM) can address this measurement need by converting the optical phase delay induced by transparent droplets into quantitative height fields, providing non-contact access to interfacial geometry from a single hologram without mechanical axial scanning (Kim 2010; Katz and Sheng 2010). This single-hologram height-field reconstruction is well suited to transient microscale droplets, for which height, footprint evolution, volume, and projected-boundary morphology must be obtained from the same time-resolved dataset. DHM has been applied to fluid-mechanics and droplet-related problems, including particle tracking, droplet evaporation, internal flow measurements, and surface analysis of evaporating droplets (Lee et al. 2014; Marié et al. 2017; Asl et al. 2023). However, DHM-based height-field measurements of individual droplets during the earliest stages of condensation remain scarce, particularly for resolving how these geometric quantities evolve together in time.

In this study, DHM was used to directly resolve the transient three-dimensional geometry of an individual microscale droplet during the earliest measurable stages of condensation. The objective was to simultaneously quantify the time evolution of droplet height, volume, footprint, and projected-boundary morphology using DHM-based height-field reconstruction. Because theoretical and numerical models of dropwise condensation often represent droplets as uniform, axisymmetric spherical caps, direct height-field measurements are needed to evaluate how early condensing droplets depart from these idealized geometric descriptions. The corresponding geometric quantities were therefore extracted from the DHM-reconstructed height fields to examine how vertical growth, lateral development, volume accumulation, and changes in projected-boundary shape are coupled during early growth within a single time-resolved three-dimensional dataset. This approach provides a quantitative basis for assessing the applicability and limitations of simplified geometric assumptions in describing early-stage microscale condensation droplets and demonstrates how DHM can resolve stage-dependent relationships between vertical growth and projected-footprint evolution.

2 Methodology

2.1 Sample preparation

To quantitatively analyze early-stage droplet growth and geometric evolution during condensation, experiments were conducted on silane-coated glass substrates. The silane-coated glass surface was selected as a partially wetting model substrate suitable for transmission-mode DHM measurements because it allowed stable observation of microscale droplet formation and growth while maintaining a reproducible wet-

ting condition. Before each experiment, the specimen was cleaned with ethanol, rinsed with deionized water, and thoroughly dried using nitrogen gas. The deionized-water rinsing step was included to remove residual solvent and water-soluble contaminants that could remain on the surface after ethanol cleaning. In preliminary tests, when this cleaning procedure was omitted, droplets were observed to nucleate repeatedly at similar locations. Therefore, the same cleaning and drying procedure was applied before every experiment to minimize the influence of residual contamination and to improve experimental reproducibility.

2.2 Experimental setup and condensation conditions

A schematic of the experimental setup is shown in Fig. 1. The condensation process was observed in real time using a transmission-mode digital holographic microscope (T-1000, Lyncée Tec). The optical system was equipped with a 20 $\times$ objective lens with a numerical aperture of 0.40. The reconstructed field of view used for analysis was approximately 285 μm $\times$ 285 μm , with a lateral pixel spacing of approximately 0.286 $\mu\text{m}/\text{pixel}$ and an optical lateral resolution of 0.83 μm . Holographic images were acquired at 15 frames per second, corresponding to a temporal resolution of approximately 66 ms.

The entire DHM system, including the microscope, cooling stage, and sample, was placed inside a humid chamber to maintain a controlled ambient condition during condensation measurements. The relative humidity inside the chamber was adjusted using a temperature-controlled water bath, in which the water temperature was varied to control the vapor supply for humidification. To prevent warm, humid air from directly reaching the specimen and cooling stage, a baffle was installed between the humidification source and the stage, allowing the humid air to rise and disperse throughout the chamber. The relative humidity and ambient air temperature inside the chamber were monitored using a humidity and temperature meter (RH820W, Omega Engineering, USA). The sensor was positioned near the specimen region to measure

the local ambient condition as accurately as possible without interfering with the optical path.

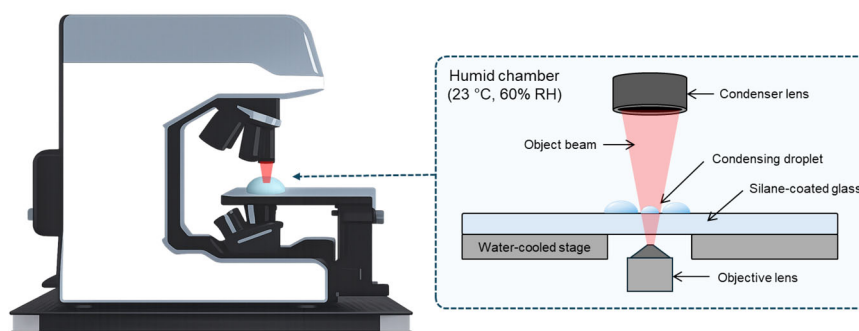
Condensation was induced using a water-cooled temperature-controlled stage from Linkam Scientific Instruments. During the experiments, the ambient air temperature and relative humidity near the specimen were maintained at 23.0 $^{\circ}\text{C}$ and 60% RH, respectively. Under these ambient conditions, the estimated dew-point temperature was approximately 15 $^{\circ}\text{C}$. The cooling-stage setpoint was therefore set to 10 $^{\circ}\text{C}$, below the estimated dew point, to induce condensation on the silane-coated surface. This configuration enabled stable cooling of the sample region while maintaining compatibility with transmission-mode DHM measurements.

2.3 Principle of DHM-based height reconstruction

Digital holographic microscopy (DHM) is based on the interference between two coherent optical paths: a reference beam and an object beam. The object beam passes through the specimen and is optically modulated by the condensed droplets, whereas the reference beam remains unaffected by the specimen. When the two beams are recombined, an interference pattern, or hologram, is formed. This hologram contains phase information associated with the optical path length difference introduced by the droplets. Unlike conventional optical microscopy, which mainly records intensity-based image contrast, DHM provides quantitative phase information and enables three-dimensional height-field analysis of microscopic droplets from a single hologram without mechanical axial scanning.

In the numerical reconstruction process, the recorded holograms were converted into quantitative phase maps. The reconstructed phase difference represents the optical path length variation caused by the refractive-index difference between the condensed water droplet and the surrounding air. Based on this phase information, the droplet height field can be reconstructed in terms of physical height. The measured phase difference, $\Delta\phi$, was converted into the relative physical height difference, Δh , using

Fig. 1 Schematic of the experimental setup



$$\Delta h = \frac{\lambda \Delta \phi}{2\pi(n_2 - n_1)} \quad (1)$$

where λ is the laser wavelength, n_2 is the refractive index of water, and n_1 is the refractive index of air. In the present study, $\lambda = 666 \text{ nm}$, a nominal water refractive index of $n_2 = 1.333$, and a nominal air refractive index of $n_1 = 1.000$ were used for phase-to-height conversion. A sensitivity analysis was performed using water refractive indices corresponding to the cooling-stage temperature of 10°C and the chamber temperature of 23°C as bounding conditions, while the air refractive index was fixed at $n_1 = 1.000$. The first-detection time was unchanged among the three water-refractive-index conditions, and the maximum absolute relative differences in the extracted metrics were below 1.5%. Detailed results are presented in Supplementary Fig. S1. The reconstructed height fields provided the basis for subsequent extraction of droplet height, footprint size, volume, and boundary-level geometric parameters during the initial condensation stage.

2.4 Condensation experiment procedure

For each experiment, a cleaned silane-coated glass substrate was mounted on the water-cooled cooling stage integrated with the transmission-mode DHM system. After the specimen was installed, the relative humidity inside the chamber was adjusted to 60% and allowed to stabilize for 5 min while maintaining the chamber temperature at 23.0°C . This stabilization period was introduced to ensure that the ambient condition was sufficiently steady before initiating cooling of the sample surface.

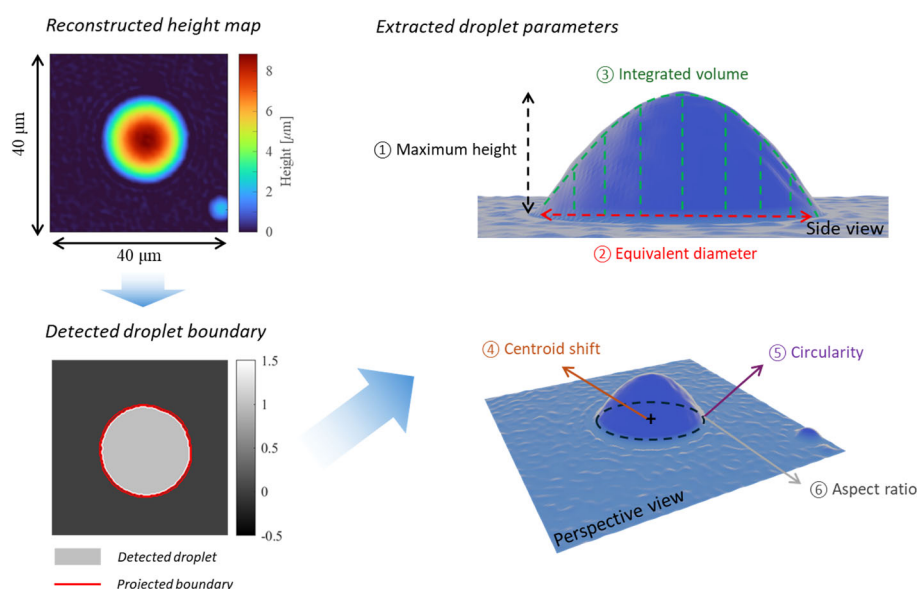
After humidity stabilization, holograms were recorded for 30 s during the initial dry-reference period to obtain the dry-surface reference state. Subsequently, cooling was initiated by setting the stage temperature to 10°C , which is below the dew-point temperature under the given chamber conditions. After cooling initiation, holograms were continuously recorded for 100 s. Therefore, the total recording duration for each experiment was 130 s, including the initial dry-reference period and the post-cooling recording period. All frames acquired during this sequence were saved as phase maps for later quantitative analysis. This procedure made it possible to track the transition from the initial non-condensing surface condition to the early stage of droplet formation and growth under controlled environmental conditions.

2.5 DHM-based data extraction and post-processing

Figure 2 shows the data extraction and post-processing procedure used to obtain quantitative droplet parameters from the DHM measurements. The reconstructed phase maps were converted into relative height fields and analyzed using an in-house MATLAB-based post-processing script. First, the dry-surface frames recorded during the initial 30 s dry-reference period were used to define the dry-reference height field. Based on this dry reference, the background height offset and overall tilt were removed to reduce the influence of slight substrate inclination, optical background variation, and frame-to-frame baseline differences. The influence of dry-reference selection on the extracted droplet metrics is presented in Supplementary Fig. S2.

In the corrected height fields, pixels with local relative heights greater than $0.089 \mu\text{m}$ relative to the dry-reference

Fig. 2 Schematic of the DHM-based extraction of droplet geometric parameters



surface were classified as droplet pixels. This operational threshold was established based on the height variation measured during the 0–30 s dry-reference period, and the basis for its selection is presented in Supplementary Fig. S3. The same height threshold was applied consistently to all frames. For each detected droplet, the projected footprint area was calculated from these droplet pixels, and the outer contour of this area was defined as the projected droplet boundary for subsequent footprint and projected-boundary analysis.

Based on the extracted droplet regions, the maximum height $H_{\max}$, projected footprint area A , footprint-equivalent diameter D_{eq} , and volume V were calculated. The maximum height was defined as the maximum relative height value within the detected droplet region. To separately quantify lateral footprint development and volumetric accumulation, D_{eq} was defined as the diameter of a circle having the same area as the projected footprint area of the detected droplet:

$$D_{\text{eq}} = \sqrt{\frac{4A}{\pi}} \quad (2)$$

where A is the projected footprint area of the droplet. The droplet volume was then obtained from the same detected footprint region by integrating the local relative height over the projected footprint area:

$$V = \iint_A h(x, y) dA \quad (3)$$

where $h(x, y)$ is the local relative height within the droplet region after dry-reference correction. This procedure allowed the temporal evolution of droplet height, footprint size, and volume to be quantitatively tracked from the DHM-reconstructed height fields.

To characterize the projected boundary morphology of the droplet, additional descriptors were calculated from the detected outer boundary. The boundary perimeter P , circularity C , aspect ratio AR , and centroid position (x_c, y_c) were obtained for each frame. The circularity was defined as

$$C = \frac{4\pi A}{P^2} \quad (4)$$

where A and P are the area enclosed by the detected projected boundary and the corresponding boundary perimeter, respectively. A circularity value close to unity indicates a nearly circular projected footprint, whereas lower values indicate a more irregular or elongated boundary. The aspect ratio was defined as $AR = L_{\text{major}}/L_{\text{minor}}$, where L_{major} and L_{minor} were obtained from a principal-component analysis of the detected projected-boundary coordinates. Here,

(x_c, y_c) denotes the geometric centroid of the detected projected footprint rather than the center of mass of the entire droplet.

The centroid displacement was evaluated relative to the centroid position at the initial detected frame:

$$\Delta r_c(t) = \sqrt{[x_c(t) - x_c(t_0)]^2 + [y_c(t) - y_c(t_0)]^2} \quad (5)$$

where t_0 denotes the first frame in which the droplet was detected. These projected-boundary-based descriptors were used to quantify the temporal evolution of footprint shape, boundary circularity, boundary elongation, and projected-footprint centroid position during the early stage of condensation.

This post-processing approach enabled simultaneous extraction of height-based and projected-boundary-based droplet parameters without assuming an ideal spherical-cap geometry. Therefore, the reconstructed DHM height fields provide a quantitative basis for evaluating the coupled evolution of vertical growth, lateral footprint development, volume accumulation, and projected-boundary morphology during early-stage condensation.

2.6 Detection criterion and analysis range

The optical configuration defines the range over which the reconstructed droplet interface can be interpreted reliably. Transmission-mode DHM is most suitable for transparent or semi-transparent specimens and for droplet interfaces whose local slope remains within the light-collection capability of the objective. For high-contact-angle droplets or strongly hydrophobic surfaces, steep interfacial regions may direct light outside the receiving optics, producing poorly reconstructed or dark regions. Therefore, the present study used a partially wetting silane-coated glass surface and a 20× objective lens. According to the manufacturer specification for the 20× DHM-T configuration, the maximum measurable slope is approximately 60.4°. The reconstructed droplet interfaces were therefore interpreted within the optical measurement range of the DHM configuration used in this study.

The droplet-detection criterion was defined from the dry-reference-corrected height field to suppress spurious detections near the onset of condensation. The frame-wise standard deviation of the dry-reference height field, averaged over the 0–30 s dry-reference period, was approximately 0.013 μm. An operational height threshold of $h_{\text{thr}} = 0.089$ μm was applied in this study, corresponding to approximately 6.9 times the standard deviation of the dry-reference height fluctuation. This threshold was selected to provide sufficient separation from the measured dry-reference height variation while retaining reliable detection of the droplet at the earliest measurable stage.

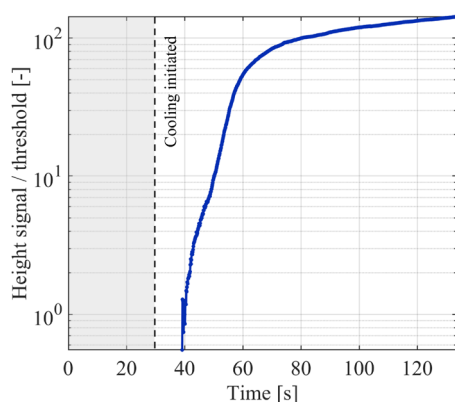


Fig. 3 Operational droplet-detection criterion based on the normalized maximum-height signal

The droplet footprint was defined as the top-view area occupied by pixels whose relative height exceeded h_{thr} , and the projected boundary was defined as the outer contour of this area. This threshold should be interpreted as an operational vertical detection criterion for quantitative droplet identification, rather than as a lateral optical resolution limit.

To evaluate the influence of threshold selection, the analysis was performed using height thresholds of $0.059 \mu\text{m}$, $0.089 \mu\text{m}$, and $0.118 \mu\text{m}$. The threshold primarily affected the first-detection time, with a maximum difference of approximately 1.36 s, whereas the subsequent temporal trends of the principal droplet metrics were nearly identical. Detailed results for the full observation period and the early detection stage are presented in Supplementary Figs. S4 and S5, respectively.

Figure 3 shows the extracted maximum height signal normalized by h_{thr} . The signal remained close to the threshold only at the earliest detectable stage and increased rapidly thereafter, indicating that most of the subsequent growth analysis was performed above the operational detection limit.

The detailed analysis in the main text focused on one representative droplet that could be continuously tracked from first detection to the end of the observation period without apparent coalescence with neighboring droplets. Within the same experimental run, the same DHM-based analysis procedure was applied to three droplets at different nucleation sites, including the representative droplet, and their locations and comparison results are presented in Supplementary Figs. S6 and S7.

3 Results and discussion

The early-stage condensation process was examined using the DHM-reconstructed height fields described above. The results are first presented through time-resolved three-dimensional reconstructions of a representative condensing

droplet. This is followed by a quantitative analysis of key geometric parameters, including maximum height, equivalent diameter, and integrated volume. Finally, projected-boundary characteristics are evaluated to assess lateral footprint development during early growth.

3.1 Time-resolved height-field reconstruction of a condensing droplet

Figure 4 presents representative DHM-reconstructed height fields of a condensing droplet at selected times during the early stages of condensation. The upper row shows two-dimensional height maps obtained from phase reconstruction, while the lower row displays three-dimensional surface representations reconstructed from the same height fields. Together, these views provide spatially resolved quantitative information on the droplet interface and visualize its three-dimensional development over time.

At the earliest time shown in Fig. 4, the droplet appeared as a small height feature whose local relative height exceeded $0.089 \mu\text{m}$ with respect to the dry-reference surface. This feature represents an early measurable state of the condensing droplet in the DHM-reconstructed height field. The subsequent frames show that the same detected droplet continued to grow under the imposed condensation condition.

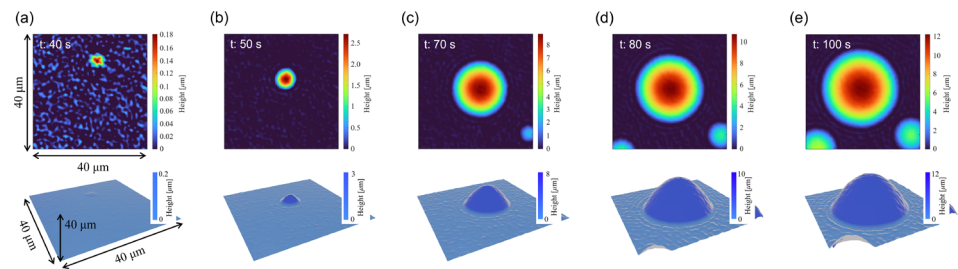
As condensation proceeded, the droplet exhibited a continuous increase in both maximum height and projected footprint. No apparent coalescence event was observed for the representative droplet within the observation window, allowing the development of the liquid–vapor interface of the same droplet to be followed over time. The successive height fields and three-dimensional renderings therefore show the growth of the representative droplet from its first measurable state to a clearly resolved microscale droplet structure.

This development indicates the progressive formation and growth of the liquid–vapor interface during the early stage of condensation. The height maps provide direct access to the spatial distribution of the droplet interface, enabling geometric parameters to be extracted without imposing an idealized droplet geometry. Overall, these reconstructed height fields provide a quantitative basis for evaluating the early growth behavior of the representative condensing droplet.

3.2 Growth dynamics of a condensing droplet

Figure 5 shows the temporal evolution and corresponding growth rates of the DHM-derived geometric parameters for the representative condensing droplet. The maximum relative height, equivalent diameter, and integrated volume were extracted directly from the reconstructed height fields. Cooling was initiated at $t = 30 \text{ s}$, and the droplet became detectable in the DHM-reconstructed height field approximately 8 s after cooling initiation. During the obser-

Fig. 4 Time-resolved DHM height fields and corresponding three-dimensional surface renderings of a representative condensing droplet: **a** 40 s, **b** 50 s, **c** 70 s, **d** 80 s, and **e** 100 s



vation period, $H_{\max}$ increased to approximately $13 \mu\text{m}$, D_{eq} increased to approximately $29 \mu\text{m}$, and the integrated volume reached approximately 4 pL .

Although all three parameters increased with time, their temporal behaviors differed. The maximum height increased gradually immediately after detection, then showed a more pronounced increase during the early growth interval, followed by a more gradual increase. The equivalent diameter also increased with time; however, during the early interval in which the increase in maximum height became pronounced, it showed only a relatively small change, followed by a more distinct increase at later times. The integrated volume remained low immediately after first detection and then exhibited an approximately linear increase over most of the post-detection period. These differences show that the analyzed representative droplet did not grow through self-similar enlargement of a fixed geometry. In other words, while the integrated volume increased approximately linearly, the maximum height and equivalent diameter exhibited different temporal variations, indicating that the early growth of the droplet cannot be described simply by the increase of a single geometric parameter.

The growth-rate curves in Fig. 5(d–f) further show that the three geometric parameters evolved at different rates. The height-growth rate increased markedly during the early growth interval and then decreased after reaching its peak. The equivalent-diameter growth rate showed a non-monotonic trend, increasing after droplet detection, decreasing during the early growth interval, and then increasing again. This result indicates that lateral footprint expansion did not proceed at a constant rate throughout the observation period. In comparison, the volume-growth rate increased after detection and then varied within a narrower range. Because derivative-based growth rates can be sensitive to frame-to-frame fluctuations and post-processing conditions, these curves are used here to compare relative temporal trends rather than to determine absolute instantaneous growth rates.

The nearly linear increase in integrated volume shows that the reconstructed droplet volume increased in a sustained manner over most of the post-detection period. Because V was obtained by integrating the local height field over the detected droplet footprint, this trend represents the temporal accumulation of reconstructed droplet volume within the

detected region. At the same time, $H_{\max}$ and D_{eq} did not show the same linear temporal behavior. This difference shows that the increase in reconstructed volume cannot be explained simply by the increase of either $H_{\max}$ or D_{eq} alone. In other words, although the volume increased approximately linearly, vertical growth and footprint expansion followed different temporal variations. Therefore, the early growth of the analyzed representative droplet appeared as a three-dimensional process in which vertical growth, lateral footprint expansion, and volume accumulation developed together but not in a geometrically uniform manner.

The log–log scaling analysis was performed to quantitatively characterize the interval-specific effective growth behavior observed for the representative droplet. Figure 6 shows D_{eq} and V as functions of the elapsed time after first detection, $\tau = t - t_{\text{detect}}$. The fitted curves were expressed as $y = y_0 + K\tau^m$, where τ is the elapsed time after first detection, K is the prefactor, m is the effective scaling exponent, and R^2 is the coefficient of determination. Fits were performed separately over the intervals $\tau < 20 \text{ s}$ and $\tau > 50 \text{ s}$, while the intermediate interval was treated as the region in which the growth behavior changed. This analysis was used to examine whether the post-detection growth of the droplet could be represented by a single offset power-law relationship and to identify changes in the effective growth behavior during the early stage. Accordingly, the fitted exponents were interpreted as effective descriptors of the interval-specific growth behavior of the representative droplet under the present experimental condition.

In the log–log plots, neither D_{eq} nor V followed a single straight trend over the entire observation period. For D_{eq} , the effective exponent was approximately 0.27 for $\tau < 20 \text{ s}$ and increased to approximately 0.52 for $\tau > 50 \text{ s}$. This change corresponds to the early growth interval in which the increase in $H_{\max}$ became pronounced, while the change in D_{eq} remained relatively limited. The increase in the effective exponent of D_{eq} indicates that lateral footprint development became more pronounced after the observed change in growth behavior than during the initial interval.

The integrated volume also showed different effective exponents between the two fitted intervals, decreasing from approximately 2.17 for $\tau < 20 \text{ s}$ to approximately 1.47 for $\tau > 50 \text{ s}$. Because V was calculated by integrating the recon-

Fig. 5 Temporal evolution and growth-rate analysis of DHM-derived droplet geometric parameters: **a** maximum relative height, **b** equivalent diameter, **c** integrated volume, **d** rate of maximum-height increase, **e** rate of equivalent-diameter increase, and **f** rate of volume increase

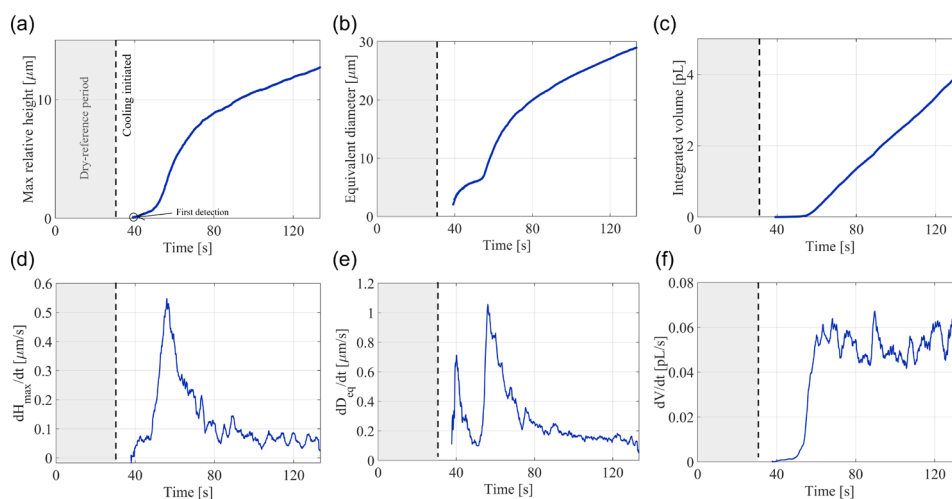
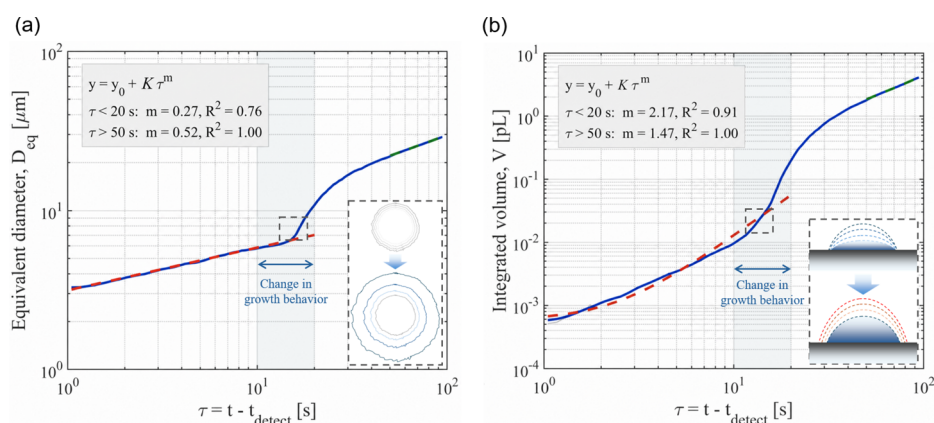


Fig. 6 Log-log scaling analysis of equivalent diameter and integrated volume after first detection: **a** D_{eq} as a function of elapsed time after first detection and **b** V as a function of elapsed time after first detection



structured height field over the detected droplet footprint, its variation reflects both footprint expansion and height-field development within the detected region. In the early interval, the low effective exponent of D_{eq} indicates that lateral footprint expansion was limited, whereas the relatively high effective exponent of V suggests that the volume increase was more closely associated with height-field development within the detected footprint. After the observed change in growth behavior, the effective exponent of D_{eq} increased, while that of V decreased, indicating that lateral footprint expansion became more clearly involved in the growth process. Accordingly, the observed change in growth behavior reflects a change in the relative development of the height field and lateral footprint expansion associated with volume accumulation in the representative droplet.

3.3 Projected-boundary evolution

Figure 7 presents the time-resolved evolution of the projected boundary of the representative condensing droplet. The projected boundary was defined as the outer contour of the top-view droplet area, where droplet pixels were identified by local relative heights greater than $0.089 \mu\text{m}$ relative

to the dry-reference surface. Therefore, the circularity and aspect ratio in Fig. 7 represent the temporal evolution of the projected footprint shape obtained using the same detection criterion. At the first detectable stage, the projected footprint was small and spatially non-uniform, with a non-circular shape. As condensation proceeded, the circularity increased to approximately 0.9, while the aspect ratio approached unity. These trends show that the initially non-circular footprint was reorganized toward a more regular and nearly circular projected boundary during growth.

When considered together with the growth analysis discussed above, the significance of this boundary evolution becomes clearer. As shown earlier, the change in D_{eq} was relatively limited during the early interval in which the increase in H_{max} became pronounced. However, Fig. 7 shows that, even during this interval of limited footprint-area growth, the projected boundary evolved from a spatially non-uniform, non-circular shape toward a more regular and nearly circular boundary. Thus, the moderate increase in D_{eq} coexisted with boundary redistribution and shape regularization without a large expansion of the footprint area. This boundary evolution is difficult to describe solely as uniform radial expansion

Fig. 7 Time-resolved projected-boundary evolution of the condensing droplet: **a** outer boundary evolution, **b** circularity index, and **c** footprint aspect ratio

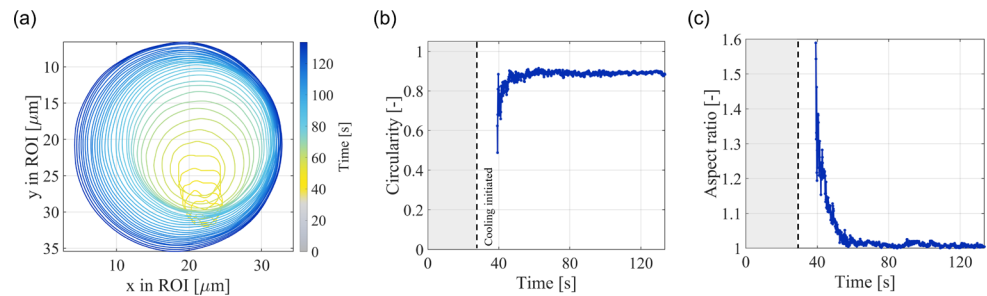
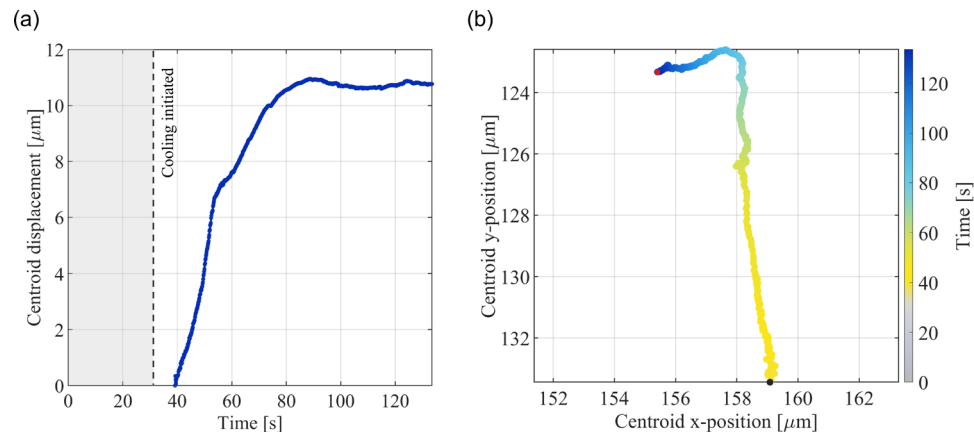


Fig. 8 Projected-footprint centroid-position change during droplet growth: **a** centroid displacement relative to the first detected boundary and **b** trajectory of the projected-footprint centroid in the x - y plane



and indicates that the footprint area and boundary shape followed different temporal variations during early growth.

Figure 8 quantifies the projected-footprint position change visible in the boundary contours of Fig. 7a by showing the centroid displacement and the corresponding x - y trajectory of the detected projected footprint. Here, the centroid represents the geometric center of the detected projected footprint rather than the center of mass of the entire droplet. In Fig. 8a, the projected-footprint centroid displacement increased during the early boundary-reorganization period and then approached a plateau value of approximately 10 μm to 11 μm . This indicates that the centroid-position change was concentrated during the interval in which the boundary shape changed most strongly, rather than increasing continuously throughout the entire observation period. In Fig. 8b, the x - y trajectory shows that the projected-footprint centroid-position change occurred mainly along a preferred direction rather than as random frame-to-frame fluctuation.

Taken together, Figs. 7 and 8 show that the early projected footprint did not evolve through uniform radial expansion around a fixed center. Instead, the footprint underwent boundary regularization together with a directional shift of the projected-footprint centroid during growth. Cha et al. (2025) reported that micro- and nanoscale surface heterogeneity can induce contact-line pinning, local depinning, and contact-line asymmetry, leading to microdroplet motion. In this context, the boundary regularization and projected-footprint

centroid shift observed here suggest that the early lateral development of the condensing droplet may have resulted from coupled height and boundary changes under spatially non-uniform contact-line conditions, rather than solely from uniform footprint-area expansion.

Although potential environmental disturbances were minimized through the chamber-control procedure, residual mechanical or optical drift cannot be completely excluded. Therefore, the centroid displacement is interpreted as a geometric descriptor of the positional evolution of the projected footprint rather than as direct evidence of physical translation of the entire droplet.

The detailed projected-boundary analysis in the main text focused on one representative droplet that could be continuously tracked without apparent coalescence during the observation period. Accordingly, the present results quantitatively demonstrate the change in growth behavior, projected-boundary regularization, and centroid-position evolution of an individual condensing microdroplet through DHM-based height-field measurements. Further clarification of early-stage droplet growth pathways and morphological-evolution mechanisms will require extending the present analysis framework to various condensation environments, operating conditions, and surface wettability conditions. The specific contributions of local contact-line constraints and surface heterogeneity to the observed morphological changes

should be clarified in future studies incorporating direct measurements of local wetting and contact-line behavior.

3.4 Geometric comparison with a spherical-cap-equivalent geometry

The preceding analysis showed that the maximum height, footprint-equivalent diameter, and integrated volume exhibited different temporal behaviors during droplet growth. To quantitatively examine the geometric relationship among these measurements, the DHM-measured geometry of the representative droplet was compared with a spherical-cap-equivalent geometry. Three comparison times were selected: 45 s, representing an early post-detection stage; 55 s, representing the interval in which height development became pronounced relative to footprint expansion; and 100 s, representing a later developed stage.

Figure 9 compares the radially averaged DHM height profile at each selected time with a spherical-cap-equivalent profile constructed using the measured maximum height and footprint-equivalent diameter. The footprint radius was defined as $a = D_{eq}/2$, and the effective cap height above the detection plane was defined as $h_{cap} = H_{max} - h_{thr}$. To apply the same height reference as that used for the DHM-integrated volume, the spherical-cap-equivalent volume was calculated as

$$V_{SC} = \frac{\pi h_{cap}}{6} (3a^2 + h_{cap}^2) + \pi a^2 h_{thr} \quad (6)$$

where the first term represents the spherical-cap volume above the detection plane and the second term accounts for

the height contribution associated with the detection threshold. The radially averaged profiles were used to visualize the mean cross-sectional geometry, whereas the quantitative errors were evaluated using the DHM measurements obtained from the complete detected footprint and its integrated height field.

The geometric consistency among the maximum height, projected-footprint area, and integrated volume was further evaluated by using two DHM-measured quantities to cross-estimate the remaining quantity through the threshold-aligned spherical-cap relationship. Specifically, the spherical-cap height was estimated from the measured footprint area and volume, the footprint area was estimated from the measured maximum height and volume, and the volume was estimated from the measured maximum height and footprint area. The signed relative error for each quantity was defined as

$$\varepsilon_X = \frac{X_{SC} - X_{DHM}}{X_{DHM}} \times 100 \quad (7)$$

where negative and positive values indicate underestimation and overestimation relative to the corresponding DHM measurement, respectively. The three cross-estimation results are not independent errors; rather, they represent different expressions of whether the DHM-measured maximum height, projected-footprint area, and integrated volume simultaneously satisfy a single spherical-cap relationship.

As summarized in Table 1, the maximum height obtained from the spherical-cap relationship was 10.47–17.29% lower than the DHM measurement, while the projected-footprint area was 9.00–27.74% lower. In contrast, the spherical-

Fig. 9 Comparison of the radially averaged DHM height profiles and spherical-cap-equivalent profiles at **a** 45 s, **b** 55 s, and **c** 100 s

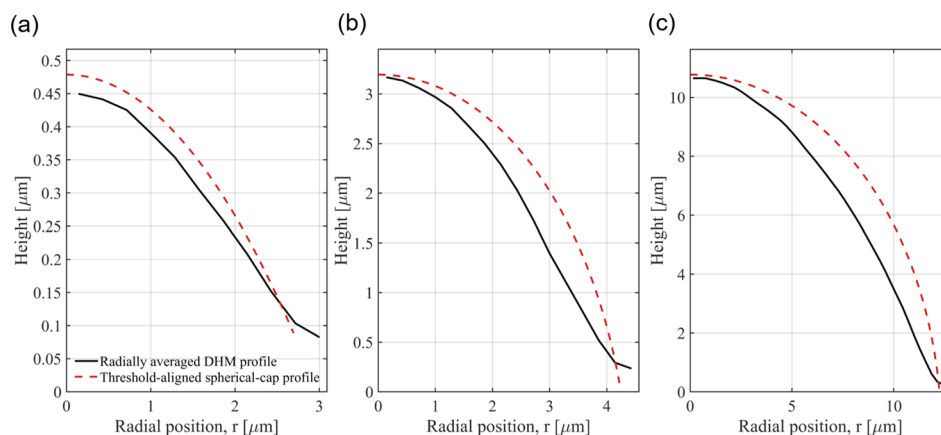


Table 1 Signed relative errors of the spherical-cap cross-estimates at the selected growth stages

Time (s)	Height error, ε_H (%)	Footprint-area error, ε_A (%)	Volume error, ε_V (%)
45	−10.47	−9.00	+9.84
55	−17.29	−24.40	+26.34
100	−17.07	−27.74	+28.53

cap volume calculated from the measured maximum height and footprint area was 9.84–28.53% higher than the DHM-integrated volume. For the droplet analyzed in this study, these results show that a spherical-cap-equivalent geometry constructed from two measured quantities did not simultaneously reproduce the remaining DHM-measured quantity.

4 Conclusions

In this study, digital holographic microscopy (DHM) was used to quantify the time-resolved three-dimensional geometry of an individual microscale droplet during the early stage of condensation on a silane-coated glass surface. The DHM-reconstructed phase fields were converted into quantitative height maps, from which maximum height, footprint-equivalent diameter, integrated volume, and projected-boundary descriptors were extracted.

The reconstructed height fields captured the development of the droplet from its first measurable state to a clearly resolved three-dimensional microscale structure. Growth analysis showed that the droplet did not evolve through uniform enlargement of a fixed geometry. Instead, maximum height, footprint-equivalent diameter, and integrated volume exhibited different temporal behaviors, indicating that early condensate accumulation was expressed through coupled vertical growth, lateral footprint development, and volume accumulation. The log–log scaling analysis further showed that D_{eq} and V did not follow a single effective scaling behavior over the full observation window. The change in the effective exponent of D_{eq} indicates that the relative contribution of lateral footprint growth varied during the early growth process, rather than remaining consistent with a single self-similar growth mode.

Projected-boundary analysis showed that the droplet footprint did not evolve as a self-similar circular footprint. The initially non-circular boundary became more regular during growth, and the geometric centroid of the projected footprint showed a directional position change in the x - y image plane. These results provide boundary-based evidence that early lateral footprint development proceeded non-uniformly, together with height-field development and volume accumulation.

At the three selected growth stages, the threshold-aligned spherical-cap relationship underestimated the DHM-measured maximum height by 10.47–17.29% and the projected-footprint area by 9.00–27.74%, while overestimating the integrated volume by 9.84–28.53%. These case-specific differences show that a single spherical-cap relationship did not simultaneously reproduce the maximum height, projected-footprint area, and integrated volume of the droplet analyzed in this study.

These results support the use of coupled three-dimensional growth descriptors for evaluating early-stage condensing microdroplet morphology and suggest that simplified projection-based geometric interpretations and uniform spherical-cap-like growth assumptions may not fully capture the non-uniform morphological evolution observed in the present case.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00348-026-04323-x>.

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Author contributions S.S. contributed to conceptualization, methodology, investigation, data curation, formal analysis, visualization, and writing—original draft. I.W.P. was involved in supervision, conceptualization, and writing—review and editing. M.F. contributed to supervision, methodology, and writing—review and editing. C.A.D. was involved in supervision, conceptualization, methodology, and writing—review and editing. All authors reviewed and approved the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Materials availability Not applicable.

Code Availability The analysis code used in this study is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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