

Quantitative high-speed imaging of ice-crystal impact, melting, and amalgamation into ice layers on an ice-cloud-immersed heated surface

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ABSTRACT

Using high-speed imaging and a custom image-processing framework, we reveal a non-monotonic effect of the heating ratio, Γ —which represents the ratio of imposed substrate heat flux to the thermal loading of the incoming ice cloud—on the late-stage evolution of an initiating ice accretion forming on a heated stagnating substrate, during which the surface transitions from dry to a fully developed quasi-one-dimensional ice layer. Specifically, increasing Γ initially accelerates areal spreading before further increases suppress it. This non-monotonic behavior is directly tied to a transition in accretion morphology with increasing heating: for $\Gamma \lesssim 0.1$, increases in heating shift the late-stage morphology away from predominantly solid ice crystals toward sprawling, relatively immobile, slush-like amalgamations that spread through the formation of liquid bridges. The extensive footprint and low mobility of these structures accelerate areal coverage and structure growth while simultaneously depleting structure number density through amalgamation. Conversely, for $\Gamma \gtrsim 0.1$, increasing heating promotes the formation of large liquid droplets that coalesce into areally compact structures, thereby suppressing areal coverage and structure growth while reducing the depletion rate of structure number density. These collective dynamics emerge only after the surface saturates with accreted structures; prior to saturation, accretion evolution remains governed primarily by isolated crystal impacts, with heating promoting adhesion but exerting little influence on areal coverage or structure growth. These findings demonstrate that heating influences initiation-phase ice-crystal accretion not only through its effect on individual crystal adhesion, but also through its control of the collective morphological evolution and interactions of accreted structures that ultimately govern the late-stage spreading of the nascent ice layer.

1. Introduction

Ice crystal icing (ICI), a process in which airborne ice crystals form accretions on cloud-immersed substrates, involves a complex interplay of ice-crystal advection, impact, melting, refreezing, and erosion. In the current literature, ICI narratively proceeds in four stages (Karpen et al., 2022; Hauk et al., 2015). First, ice crystals impact and adhere to a substrate, potentially cooling the surface if the surface is heated. The adhered crystals then form a wetted layer, either because they were partially melted while airborne or because melting occurs upon impact through heat transfer—typically from surface heating. As more crystals impinge, the wetted layer transitions into a mixed-phase

region in which newly arriving crystals absorb excess heat, liquid water is redistributed through the porous structure by capillary action, and ice in direct contact with the substrate may undergo further melting if the surface remains sufficiently warm. Ultimately, a quasi-steady-state accretion process can develop, in which adhesion of incoming crystals, liquid transport, and erosion reach a dynamic balance—sometimes even through periodic catastrophic shedding.

Numerous parameters have been investigated for their influence on this four-stage process, but four that exhibit particularly nuanced effects are the melt ratio, wet-bulb temperature, heating and particle size. The first three govern the liquid fraction within the ice layer, which in turn controls the ability of the oncoming ice crystals to stick and strongly adhere on the surface; while the final parameter controls the dynamics surrounding particle advection and impact. The melt ratio, defined as the liquid mass fraction of incoming crystals, initially correlates positively with the sticking efficiency, which represents the percentage of impacting particles that adhere to the surface. Specifically, the sticking efficiency increases with melt ratio until the melt ratio reaches 12 to 25%, beyond which it decreases due to enhanced erosion resulting from poor adhesion in overly wet layers (Currie and Fuleki, 2016; Bartkus et al., 2019; Struk et al., 2019). The wet-bulb temperature (T_{bulb}), defined as the ambient air temperature reached through evaporation until saturation at constant pressure, determines whether the accretion is: freeze-dominated ($T_{\text{bulb}} < \text{freezing point}$), producing well-adhered solid structures; or melt-dominated ($T_{\text{bulb}} > \text{freezing point}$), yielding mixed-phase, loosely adhered deposits (Currie et al., 2014; Löwe et al., 2016; Currie and Fuleki, 2016; Köbschall, 2023). In the case where the wet-bulb temperature is beneath the freezing point, heating becomes essential for the formation of ice, as the oncoming ice crystals fail to produce sufficient liquid to create an adhesive liquid layer (Hu et al., 2023; Malik et al., 2024a). Finally, like the previously described parameters, the effect of particle size is similarly non-monotonic: larger particles are more ballistic and in theory should accelerate accretion, yet their higher impact energy also promotes erosion, such that experiments indicate an intermediate size range most effectively supports ice buildup (Knezevici et al., 2012, 2013).

Most numerical tools for ice accretion are based on the Messinger model, which assumes a steady ice-growth rate and uniform temperature within the ice layer and any overlying runback water layer (Messinger, 1953). While the model is appropriate for supercooled droplet icing and offers simplifications to the mass and energy balances (Trontin et al., 2017), the model's assumptions break down for ice-crystal accretion on heated surfaces, where a thin liquid film can form between the substrate and ice, leading to a three-layer structure consisting of a substrate-adjacent liquid film, an ice layer, and a runback liquid film, with non-negligible temperature gradients. Extensions of the Messinger model address these limitations and can capture this three-layer configuration (Figure 1b) by solving steady heat conduction in each layer and allowing convective transport in the runback film (Trontin and Villedieu, 2018; Chauvin et al., 2018; Bucknell et al., 2019; Gallia et al., 2023). However, experiments suggest that ice-crystal accretion often forms a mixed-phase “mush” rather than a distinct ice layer (Malik et al., 2023, 2024a), motivating enthalpy-based (mixed-layer) approaches (Figure 1a) that determine local phase composition from the enthalpy field (Malik et al., 2023; Peters et al., 2024). While these methods accurately predict bulk ice growth, challenges re-

main in tracking layer-thickness evolution, particularly in surface-parallel dimensions where normalization, mesh deformation, or remeshing strategies are required (Chauvin et al., 2018; Peters et al., 2024). In both three-layer and mixed-layer formulations, the surface is discretized into elements that evolve through local phase change while exchanging mass and energy via convective fluxes in the exposed free-surface layer.

Although the aforementioned models can successfully predict ice-growth rates and temperatures, and thereby ice-layer topology during late-stage development, they do not, to the best of the authors' knowledge, capture the initiation phase of accretion—when a dry substrate transitions to a fully covered quasi-one-dimensional ice layer. Malik et al. (2023) describe this process (shown schematically in Figure 1c) as one in which impinging ice crystals stick or generate secondary fragments and residues that adhere to the surface and melt into micron-scale sessile droplets (Figure 1c-I). The sessile droplets are continually impacted by incoming crystals, causing splashing and growth (Figure 1c-II). The increasing volume of droplets can cause bridging events between droplets that then pulls them together through capillary action (Figure 1c-III). This process ends in the fully merged, semi-frozen, mixed-phase layer that coalesces into an ice deposit representative of the previous models (Figure 1b-IV). While the aforementioned enthalpy models neglect this short-lived regime, it governs the inception of adhesion, heat transfer, and layer morphology that ultimately control how the ice layer develops. The interactions among transient sessile droplets, melting residues, and incoming ice fragments determine the morphology of the substrate-adjacent film and the efficiency of heat transfer between the ice layer and substrate. Furthermore, these microscale processes set the initial thermal and geometric conditions for column-based accretion models, and understanding them is therefore essential for establishing physically consistent boundary conditions and improving the predictive accuracy of large-scale icing simulations. These concerns are not merely academic. Improved characterization of the initiation phase may help explain the differing delays in the onset of ice-layer growth reported across experiments, with some studies observing substantial delays before sustained growth begins (Malik et al., 2023, 2024a,b), while others report much shorter delays or none at all (Löwe et al., 2016; Hu et al., 2023). Improved understanding of this regime may also provide insight into the initial imbibition and transport of liquid within the nascent ice layer, processes that dominate early accretion growth yet remain challenging to model accurately (Bennani et al., 2026).

Aside from the qualitative description offered by Malik et al. (2023), quantitative experiments that characterize the initiation phase from a dry to a fully covered substrate do not exist. Instead, numerous investigations of isolated ice-crystal impacts over a broad range of Stokes numbers have been conducted for both normal and oblique collisions on dry, wetted, and heated surfaces. These studies primarily employ high-speed imaging, which reveal: different crystal fracture regimes, as well as fragment distributions that are well described by power-law or log-normal distributions that shift towards increasingly smaller particle sizes as momentum increases (Hauk et al., 2015; Reitter, 2023; Yang et al., 2024a); the positive effect that substrate heating has on sticking efficiency despite having no effect on particle distribution (Lausch et al., 2023; Yang et al., 2025); and splash dynamics on wetted surfaces (Yang et al., 2024b,c). Despite their valuable insights, studies of

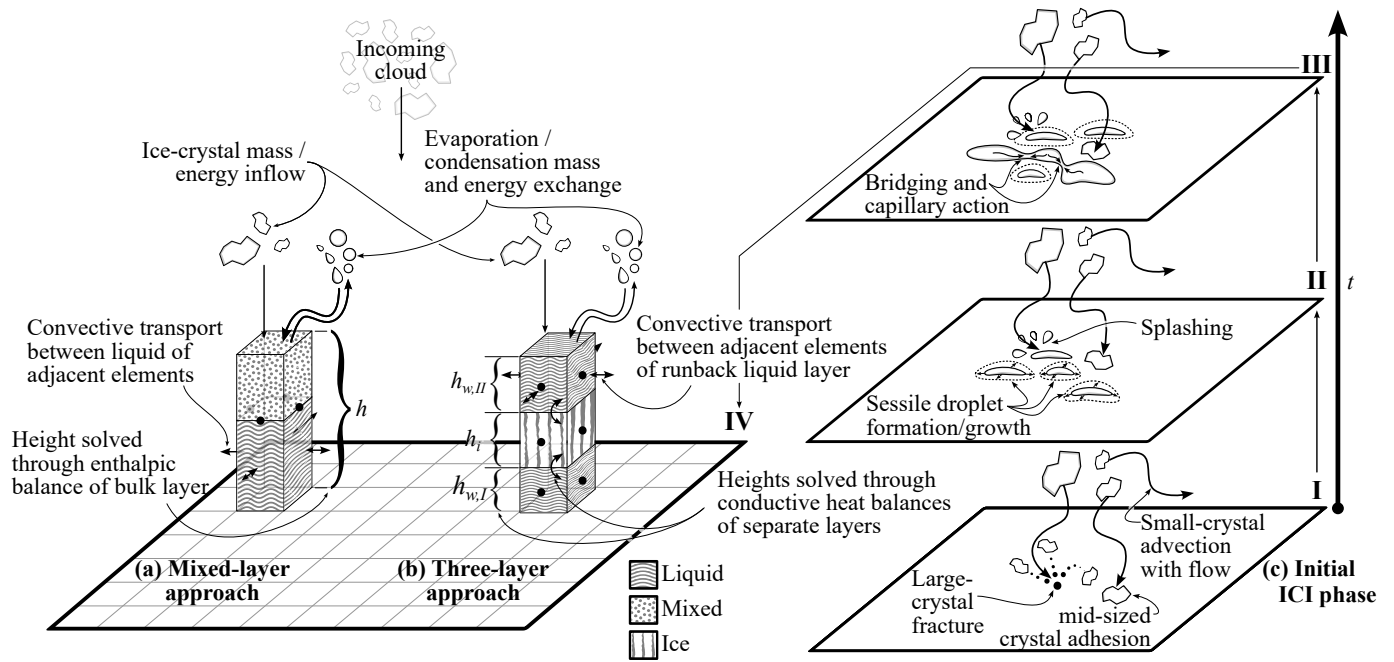


Figure 1. Despite differences, both the (a) mixed-layer; and (b) three-phase modeling approach represent the ice layer as columnar elements that exchange mass and energy with the substrate, the free-surface flow and adjacent ice-layer elements. (c) This representation, though accurate for a fully-developed ice layer (IV), may not capture the initiation phase where the substrate transitions from dry to fully covered (I - III).

isolated crystal impacts are far from representative of the initiation phase, in which a polydisperse cloud carried by an unsteady flow gradually forms an ice layer on the substrate through sessile droplet growth and inter-droplet bridging. In contrast, conventional ICI investigations perform camera imaging from various lateral perspectives to temporally quantify the accretion height along a vertical or spanwise dimension (Knezevici et al., 2013; Currie et al., 2014; Currie and Fuleki, 2016; Köbschall, 2023), pairing this with time-resolved surface temperature measurements (Löwe et al., 2016; Bartkus et al., 2019; Malik et al., 2023, 2024a) or even capacitance measurements (Currie and Fuleki, 2015; Köbschall, 2023) to determine bulk liquid fraction of the ice layer. However, the viewing perspectives employed in these measurements do not allow quantification of ice-layer spreading as the surface transitions from dry to fully wetted. Likewise, current temperature and capacitance measurements lack the spatial resolution needed to capture the microscale dynamics involved. Thus, high-speed imaging from a surface-normal perspective as performed in Malik et al. (2023) still remains as the most promising approach to quantifying the initiation phase.

Nonetheless, this experimental approach has notable limitations. Estimating the size of irregularly shaped impacting crystals from a surface-normal view and inferring phase change solely from image intensity are methods whose accuracy requires further evaluation. Moreover, as the surface becomes progressively wetted, high-speed imaging from this perspective becomes increasingly difficult, obscuring the impacts of incoming crystals. These limitations must be carefully considered to ensure proper interpretation of the observed ICI dynamics. The present study nonetheless employs surface-normal high-speed imaging and image processing to examine how impact, melt-

ing, and spreading interact during the initiation phase of ice-crystal accretion, and how these processes collectively govern the transition from a dry substrate to a fully developed ice layer, while also highlighting both the capabilities and limitations of this approach.

The following section first outlines the key parameters governing the initial ICI process and recasts them in non-dimensional form to identify the dominant dimensionless groups. The experimental setup is then described, including: the Braunschweig Icing Wind Tunnel (BIWT); the ice-crystal generation and seeding system; the test section and model; the high-speed imaging; and finally the capabilities of our surface-normal image-processing algorithm. The proposed test matrix is presented in both dimensional and non-dimensional form, followed by results obtained from high-speed imaging, which reveal non-monotonic trends in accretion spreading dynamics and in the evolution of accretion nucleation sites with increasing heat flux at the heated substrate. The implications of the results for the physical mechanisms governing the inception and early evolution of ice-crystal accretion are then discussed, and key findings are summarized.

1.1. Onset of ice crystal icing: significant parameters and non-dimensionalization

Figure 2 schematically illustrates the initiation phase of ICI for the specific case of fully frozen, subcooled ice crystals impacting a heated substrate. The ice and liquid phases are characterized by their densities ($\rho_{I,L}$), specific heat capacities ($c_{I,L}$), thermal conductivities ($k_{I,L}$), and latent heats of fusion and evaporation ($L_{I,L}$). A cloud with ice volume fraction α and freestream temperature T_∞ advects toward the submerged substrate at velocity U , delivering crystals of characteristic diameter D and mass $m_0 = \rho_I \frac{\pi}{6} D^3$ at a mass flux $\dot{G}_I = \alpha \rho_I U$. Only a fraction of these crystals impact and adhere to the surface, reducing the impingement mass flux to $\dot{G}_{\text{imp}} = \eta_{\text{wet/dry}} \dot{G}_I$, where $\eta_{\text{wet/dry}}$ denotes the sticking efficiency for dry or wetted conditions. The freezing point of liquid water is chosen as the zero reference for enthalpy. Consequently, because the freestream temperature T_∞ is below the freezing point T_f , incoming crystals arrive fully frozen and subcooled with specific enthalpy $H_I = -L_I - c_I(T_\infty - T_f) = -L_I - c_I \Delta T$. Upon impact and sticking to a dry surface, fully frozen crystals initially possess a melt state of $\lambda = 0$ and occupy an area characteristic of their size, i.e. $A_I = \frac{\pi}{4} D^2$. Over time, however, crystals melt toward a fully liquid state ($\lambda = 1$) due to the surface heat flux $\dot{q}$, transitioning to a footprint area of $A_L = \frac{\pi}{4} D_L^2$, where D_L represents the diameter of a spherical-cap droplet containing an equivalent mass of water with contact angle θ , determined by surface tension. As droplets grow and interact, neighboring droplets coalesce over a characteristic timescale given by the rate coefficient K_c^{-1} . These coupled phenomena gradually increase the covered area of the substrate, with the coverage fraction, Φ , asymptotically approaching unity.

It is assumed that the incoming cloud is fully saturated and never warmer than the plate, which is typical of atmospheric ice clouds under normal conditions, resulting in negligible evaporation and therefore rendering L_L unimportant. Furthermore, c_L is neglected because liquid sensible heating occurs only after meltwater has formed, whereas the dominant energetic cost governing the onset of surface coverage is warming and melting incoming subcooled ice, represented by $H_I = -L_I - c_I \Delta T$. Consequently, c_L primarily determines how surplus heat is stored in existing

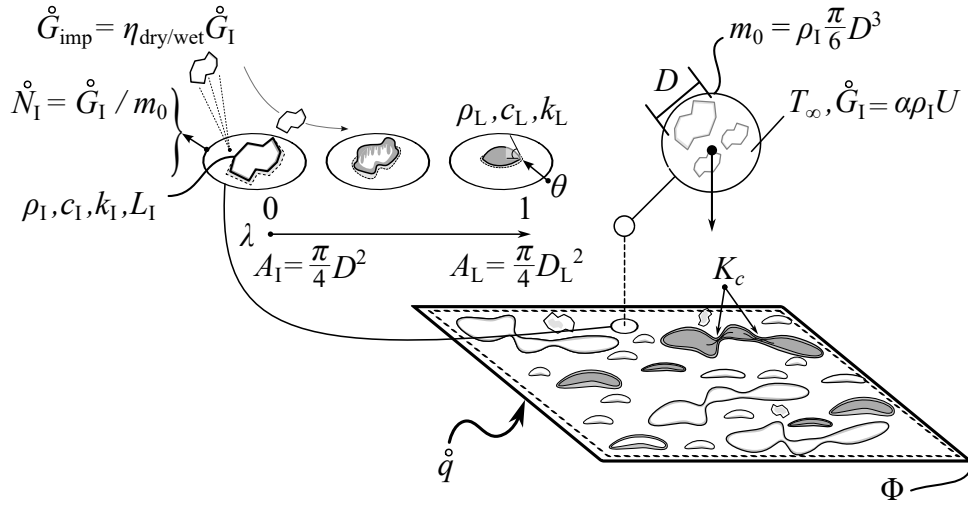


Figure 2. Schematic of the initiation phase of ICI illustrating the key dimensional parameters. A cloud with ice volume fraction α , velocity U , and freestream temperature T_∞ delivers fully frozen ice crystals of characteristic size D to a substrate subjected to a surface heat flux $\dot{q}$, with an incoming mass flux $\dot{G}_I$. Upon impact, crystals adhere to the surface at rates $\dot{G}_{\text{imp}} = \eta_{\text{dry}}\dot{G}_I$ or $\eta_{\text{wet}}\dot{G}_I$, depending on local wetted conditions. Material properties of the ice and liquid phases are characterized by densities $\rho_{I,L}$, heat capacities $c_{I,L}$, thermal conductivities $k_{I,L}$, and latent heats $L_{I,L}$. Following impact, crystals initially occupy a characteristic area A_I , which transitions through melting to a liquid footprint A_L , defined by a spherical-cap geometry with contact angle θ , collectively contributing to a surface coverage fraction Φ .

meltwater and is expected to be a higher-order correction relative to the imposed wall heat flux $\dot{q}$, which controls the primary rate of melting and coverage growth. During the initial sparse-coverage phase, the accretion thickness—and thus internal thermal gradients—remain on the order of the crystal size itself, resulting in conductive timescales that are negligible relative to melting and deposition timescales. We therefore adopt a lumped thermal treatment and neglect conductivity effects (k_I). Additional simplifications arise where certain parameters determine more significant quantities but are not otherwise independent: T_∞ and c_I define H_I ; α and U determine $\dot{G}_I$; and θ determines A_L . Consequently, the process is controlled by eight dimensional parameters— ρ_I , ρ_L , A_I , A_L , K_c , $\dot{q}$, $\dot{G}_I = \alpha\rho_I U$, and $H_I = -L_I - c_I\Delta T$ —as well as two sticking efficiencies, η_{dry} and η_{wet} , yielding a total of six dimensionless groups governing Φ . These groups are shown below:

$$\eta_{\text{dry}}, \quad \eta_{\text{wet}}, \quad R = \frac{\rho_I}{\rho_L}, \quad \beta = \frac{A_L}{A_I}, \quad \hat{K}_c = \frac{2K_c D}{3\alpha U}, \quad \Gamma = \frac{\dot{q}}{\alpha\rho_I U(L_I + c_I T_\infty)}. \quad (1)$$

In the above groups, the absolute value of H_I is used for convenience. The sticking efficiencies, η_{wet} and η_{dry} , have been measured experimentally for stagnating surfaces and shown to be on the order of $O(10^{-1})$ and $O(10^{-2})$, respectively (Malik et al., 2024b; Yang et al., 2024a). Using standard values for the densities of ice and liquid water yields $R \approx 1$, while adopting a broad range of wetting angles gives an area ratio of $2 \lesssim \beta \lesssim 4$. The parameter $\hat{K}_c$, alternatively expressed as $K_c/(\dot{G}_I A_I)$, represents the ratio between the characteristic timescales of coalescence and areal coverage.

In the case of Γ , multiplying the numerator and denominator by $D/(k_L \Delta T)$ and introducing a

representative sticking efficiency, η , allows Γ to be reexpressed as

$$\Gamma_\eta = \frac{\Gamma}{\eta} = \frac{\dot{q}D/k_L\Delta T}{\eta \left(c_1 \dot{G}_1 D / k_L \right) (L_1/c_1\Delta T + 1)} = \frac{\Pi_{\dot{q}}}{\eta \text{Pe}_{\text{imp}}(\Lambda + 1)}, \quad (2)$$

which, following the energy-balance framework of Peters et al. (2024) for an isothermal substrate but modified here for a constant heat-flux boundary condition, may be interpreted as a simplified ratio of energy supplied at the substrate to the thermal load of the incoming ice cloud for a one-dimensionally growing accretion layer. Within the present framework, the sticking efficiencies are prescribed by the impact geometry and wetting conditions, while R , β , are determined by liquid properties. Upon prescribing Γ , and given the limitations of our experiment to vary D from a single size distribution, K_c^* is also practically fixed. Consequently, in this simplified formulation, Γ emerges as the sole independent dimensionless parameter governing the problem and is therefore systematically varied throughout the experiments. For consistency with our previous work, we adopt Γ_η , with a value of $\eta = 0.3$, which has been measured in past experiments (Malik et al., 2024b).

An additional parameter governing the problem, which has thus far not been considered, is time, t . We adopt an accumulation-based normalization of the form:

$$\hat{t}_{\dot{G}} = t \cdot \frac{\rho_I \alpha U}{\rho_A D}, \quad (3)$$

which ensures that equal values of $\hat{t}_{\dot{G}}$ correspond to equal accumulated incoming ice mass fluxes across disparate experimental conditions.

2. Methods

The following section first describes the crystal-generation system and the icing-wind-tunnel facility used in the experiments. We then detail the test-section setup, including the shielding system that prevents premature accretion while the icing cloud stabilizes; the plate obstruction that establishes the stagnation flow and its associated heating system; and the temperature sensors and high-speed-camera arrangement used to image the substrate-normal plane. This is followed by a description of our processing workflow for images captured normal to the plate surface, used to characterize the initial ice accretion phase. Finally, we present the test matrix for the measurement campaign—first in nominal terms of freestream velocity, plate heat flux, wet-bulb temperature, and ice-water content, and then in non-dimensional form using Γ and $\hat{K}_c$.

2.1. Icing wind tunnel & crystal generation system

ICI tests are performed in the Braunschweig Icing Wind Tunnel (BIWT), a facility specifically designed for controlled studies of supercooled droplet and ICI phenomena. The main components of the facility—including the tunnel and test section, the refrigeration system, and the ice-crystal-generation system—are shown in Figure 3. The tunnel is a Göttingen-style recirculating wind tunnel capable of airspeeds up to 40m/s within its 50cm $\times$ 50cm test section (Figure 3.3). Air

is cooled by a refrigeration system (Figure 3.4), which maintains the recirculating flow at temperatures between -25°C and 30°C . During ICI tests, ice crystals are injected upstream of the tunnel contraction from the ice-crystal-generation system (IGS, Figure 3.8) through a vertical feed tube (Figure 3.14) into the airflow. The IGS produces crystals by injecting warm, saturated air into large balloons placed in a subzero environment, initiating ice-crystal nucleation and mimicking atmospheric crystal formation. The generated crystals exhibit representative morphologies of atmospheric crystals, and possess a characteristic mean volumetric diameter and bulk density of $\text{MVD} = 80\mu\text{m}$ and $\bar{\rho} = 919\text{kg/m}^3$, respectively. Before entering the tunnel, the crystals pass through a dosing device (Figure 3.13), where they are conveyed by a screw pump and sieved to minimize agglomerates. This process yields a homogeneous and repeatable ice cloud with ice-water contents up to 20g/m^3 . The crystal properties generated in the BIWT have been validated against in-flight measurements in tropical convective systems, as documented in Bansmer et al. (2018).

2.2. Heated-plate model, high-speed imaging, and temperature instrumentation

The fully assembled experimental setup in the BIWT test section, including the model and all instrumentation, is shown in Figure 4(a). A flat plate with a chord length of $c = 105\text{mm}$ is positioned at the mid-height of the $500\text{mm} \times 500\text{mm}$ test section and aligned normal to the incoming flow. The flow advects an ice cloud with an ice-water content of $4\text{g/m}^3 \leq \rho_I \alpha \leq 13\text{g/m}^3$ at mean velocities of $U = 20$ and 40m/s . The thickness and spanwise length of the plate are $0.1c$ and $4.7c$, respectively, allowing for the plate to be treated as thin and two-dimensional, while achieving a blockage ratio of 20% within the tunnel.

At a distance of $10c$ upstream of the flat plate, a semicircular ice shield is positioned to prevent the impingement of ice crystals on the plate until the ice cloud stabilizes. Upon stabilization of the cloud, the ice shield is retracted from the test section. This initiates the formation of an ice layer on a clear borosilicate glass inset placed at the center of the model, as well as automatically triggering the acquisition of surface-temperature measurements and high-speed recordings from the sensors and cameras integrated into the setup. A schematic of the glass inset is shown in Figure 4(b). The inset has a height and span of 60mm and 250mm , respectively, and a thickness of 2.75mm . The inset is coated with indium tin oxide (ITO), which distributes electrical power uniformly along its span, ensuring homogeneous heating across the entire glass surface. Infrared imaging of the glass plate at full heating under standard conditions in ambient air reveal a surface-temperature standard deviation of 1%, verifying heating homogeneity.

During the icing process, a high-speed camera (Phantom v711) was positioned to view the substrate-normal plane through the sidewall of the wind tunnel. The camera captured $512\text{px} \times 512\text{px}$ images of the evolving ice layer through the transparent substrate, using a mirror oriented at 45° to the surface to obtain a reflected view of the accretion area. This camera was illuminated by a non-strobing blue-light LED (Takey) positioned at roughly 150° relative to the camera's line of sight, producing backlit shadows of the incoming ice crystals and enabling measurement of the areal growth and amalgamation of nucleation sites of the accretion. The camera was equipped with a

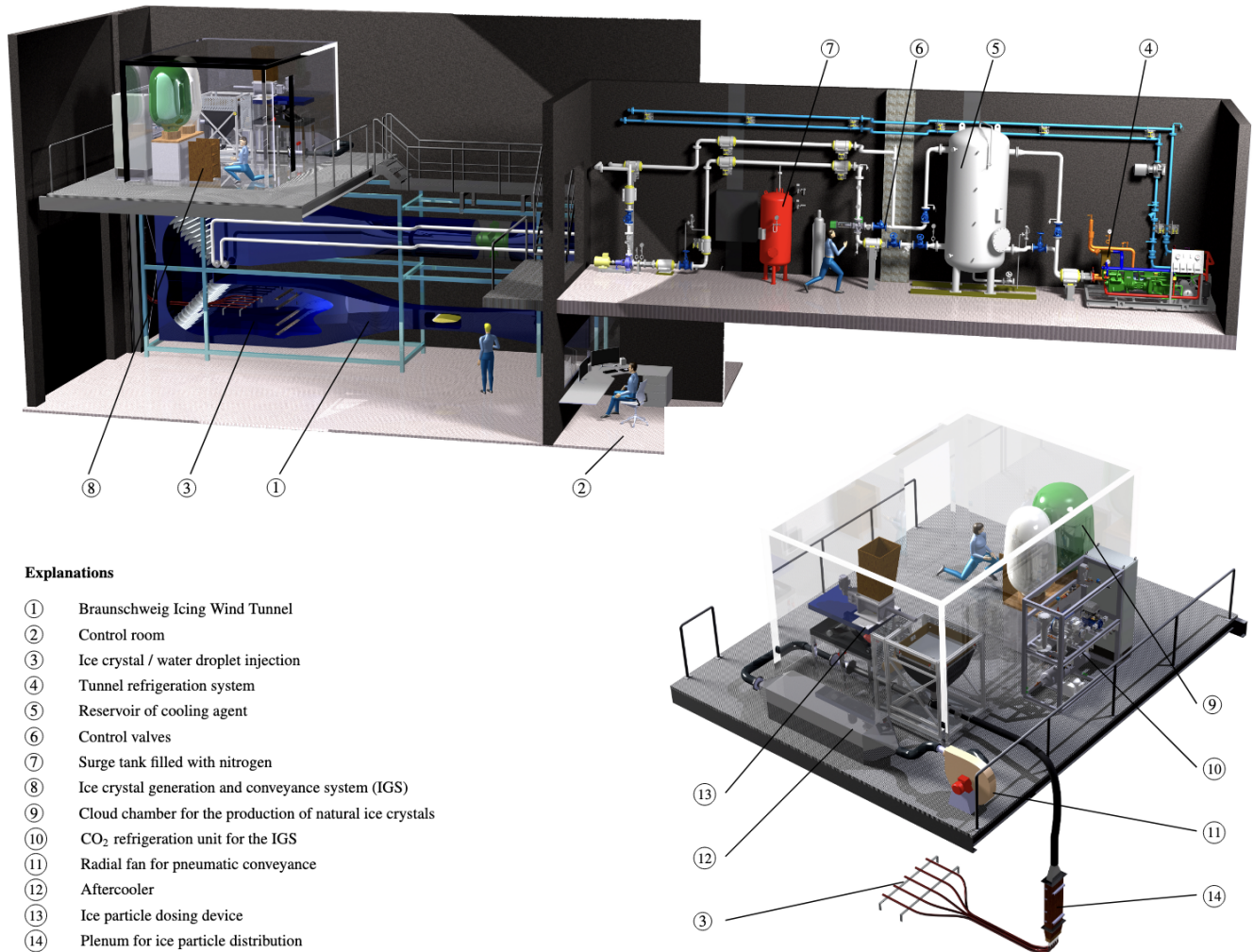


Figure 3. The Braunschweig Icing Wind Tunnel (BIWT) facility. The test section, refrigeration system, and ice generation system (IGS) are shown in the top left, top right and bottom right of the figure, with annotations indicating major components.

Scheimpflug adapter to correct for focus distortions. The resulting surface-normal field of view is centered on the stagnation point and extends 7mm in both the vertical and spanwise directions, yielding a spatial resolution of 14 μ m/px. The camera is equipped with a band-pass filter, minimizing ambient light contamination within its measurement. Simultaneously with these image sequences, three temperature sensors (PT1000) record measurements at three locations on the rear surface of the glass. One sensor was positioned along the vertical centreline approximately 10mm above the surface field of view to quantify the temperature at the imaged plane. The other two sensors are mounted along the horizontal centreline, spaced approximately 170mm apart. The temperatures measurements verified a thermal homogeneity of 1% on the plate and a variability in the decay time constant of roughly 10% between runs, and demonstrated that the removal of the shield representative a step increase in the heat transfer coefficient of 2.5 times.

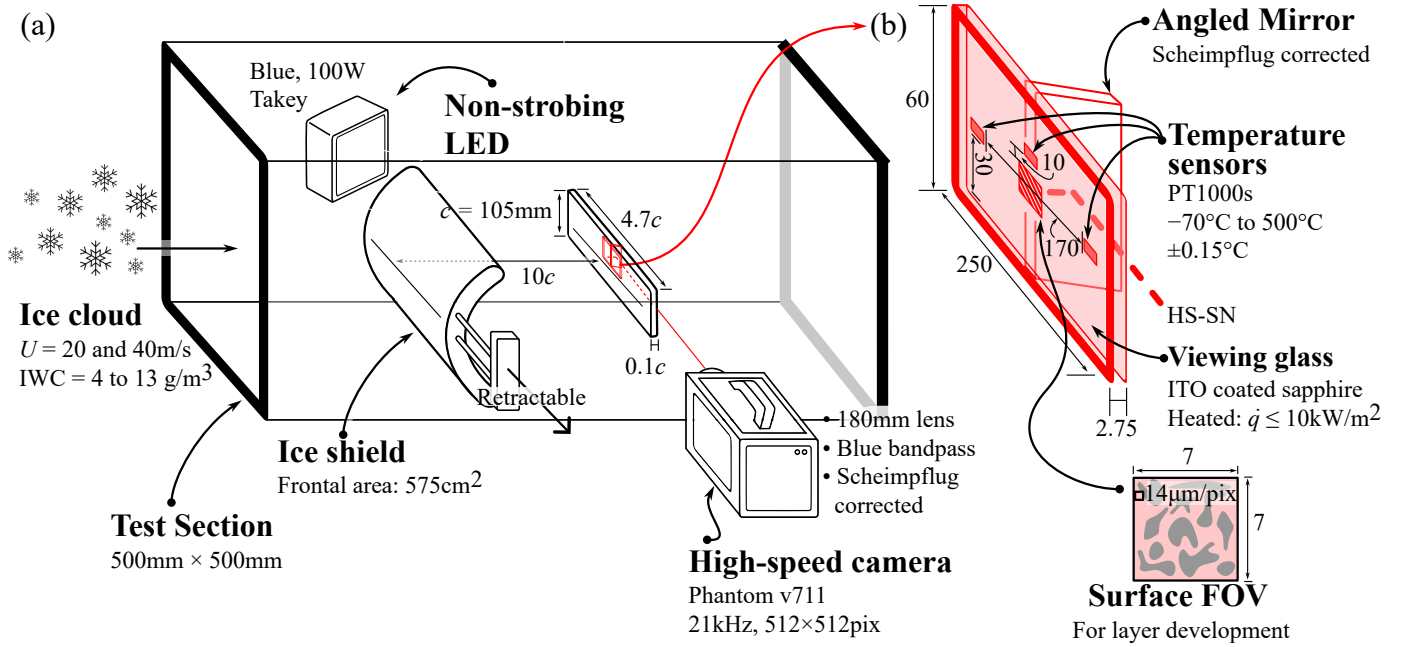


Figure 4. (a) Schematic of the test section equipped with the heated-plate model, ice shield, and imaging setup, with relevant geometries indicated. (b) Close-up of the heated-glass inset embedded within the flat plate, showing the glass-plate geometry, temperature-sensor locations, and the resulting surface-oriented field of view.

2.3. Image processing and quantification of areal coverage

The high-speed backlit shadowgraph recordings were processed with a custom routine implemented in Python using the OpenCV and NumPy libraries. In the shadowgraph projection the ice crystals appear as dark regions against a bright, approximately uniform background, so the analysis reduces to three steps: segmenting the dark regions in each image, measuring their projected area, and expressing that area as a fraction of the field of view. The principal quantity reported in this work is the temporal evolution of the areal coverage of the heated surface; the same segmentation additionally yields the number of detected objects and their object size distribution. The processing chain is described below and is illustrated step by step in Figure 5.

2.3.1. Spatial calibration and temporal averaging

Each frame is a 512×512 pixel, 16-bit grayscale image spanning a 7×7 mm field of view, which yields an isotropic spatial calibration with a pixel pitch of $s = 13.7 \mu\text{m px}^{-1}$ and a physical pixel area of $a_p = s^2 \approx 187 \mu\text{m}^2 \text{px}^{-1}$. All areas in the following are obtained in pixels and converted to physical units through a_p . A 10-pixel border is excluded from every image before analysis to suppress boundary artifacts, so coverage is evaluated over the interior 492×492 pixel region. To mitigate high frequency noise, the images are processed in non-overlapping groups of 10 consecutive frames. Each group is reduced to a single mean image, which function as input frames for all subsequent steps (Figure 5a). The instant assigned to each group is that of its fifth frame, $t = n_5/f$, where n_5 is the fifth frame's index and f the acquisition rate. Recordings were respectively ac-

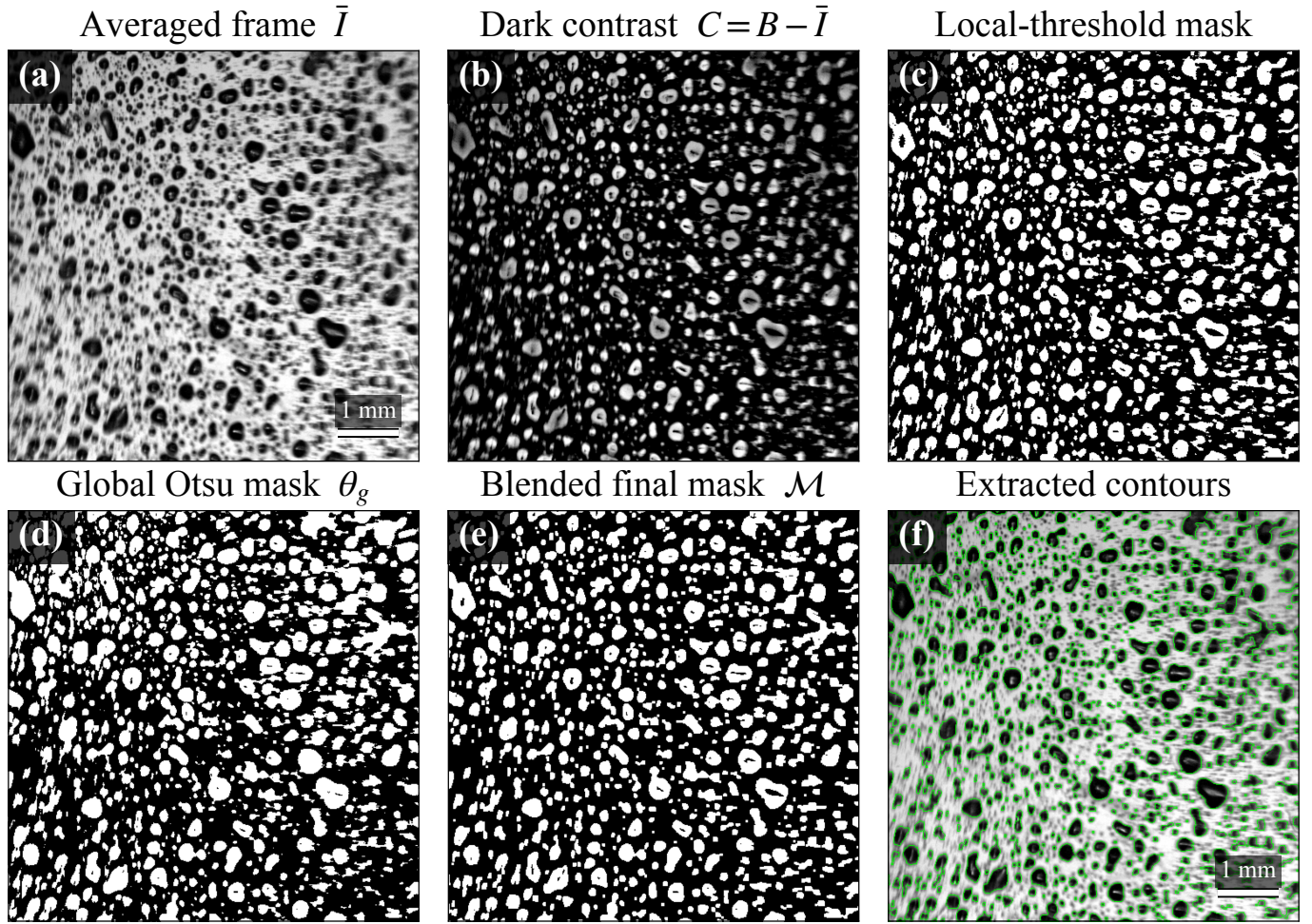


Figure 5. The averaged shadowgraph (a) is converted to a local dark-contrast field (b) and segmented both by a local threshold (c) and by a global Otsu threshold (d); the two thresholds are blended according to the prevailing object size and cleaned by a morphological opening to yield the final crystal-shadow mask (e), whose retained contours give the projected areas used for the areal-coverage measurement (f).

quired $f = 21,000$ and $10,500$ fps for tunnel wind speeds of 40 and 20m/s , resulting in respective temporal resolutions of 0.48 ms and 0.95 ms.

2.3.2. Segmentation of crystal shadows

Robust segmentation throughout an impact event is challenging because the characteristic size of the crystal shadows changes substantially over time. During the onset of coverage, the field contains sparse, small, and low-contrast crystal shadows. At later stages, the shadows become much larger, corresponding to larger mixed-phase structures, and may occupy a substantial fraction of the field of view. Consequently, no single intensity threshold performs well across the full range of observed scales. To address this, two complementary thresholding methods are combined: one optimized for the detection of small structures and the other for large structures. Their relative contribution is adjusted according to the characteristic object size present in each image.

The first thresholding we consider is a local adaptive thresholding method. Here, a spatially varying background intensity of B is estimated from a moving average over a 31×31 pixel window. A pixel is classified as part of a covered-area shadow when the local intensity $\bar{I}$ lies beneath this local background by a contrast difference of δ , such that $\bar{I} < B - \delta$. The contrast offset δ is determined automatically for each local window within the image: an Otsu threshold τ_{Otsu} is computed for each local window's contrast field ($C = \max(B - \bar{I}, 0)$, see Figure 5b) and then halved, but subject to a fixed lower threshold bound of 150 counts, such that $\delta = \max(150 \text{ counts}, \frac{1}{2} \tau_{\text{Otsu}}(C))$. The 150 count floor (approximately 0.2% of the 16-bit intensity range) prevents spurious detections in low-contrast frames. Since this method only operates within local windows, it is sensitive to intensity fluctuations in its immediate neighborhood, and therefore can detect small and faint features, resulting in early-stage detection masks, such as that shown in Figure 5c.

The local thresholding method described above is adept at small features but struggles to accurately capture large features, making it a poor approach during the later stages of areal coverage. Thus, a global thresholding method, in which a single intensity threshold τ_g is obtained for the whole image via a 16-bit adapted Otsu-method algorithm is obtained. Specifically, τ_g is determined by maximizing the between-class variance of the intensity histogram,

$$\tau_g = \arg \max_{\tau} \omega_0(\tau) \omega_1(\tau) [\mu_0(\tau) - \mu_1(\tau)]^2, \quad (4)$$

where ω and μ respectively represent population fractions and pixelar intensity means, while the subscripts 0 and 1 denote populations beneath and above τ . Thresholding the frame at τ_g yields the detection mask in Figure 5(d). Global thresholding is more reliable when the objects are large and the histogram of the entire image is strongly bimodal, whereas the local thresholding method degrades because as the averaging windows becomes filled entirely by the objects themselves, thereby causing the local contrasting to collapse. As such, global thresholding excels at later stages of areal coverage, but performs poorly at identifying small features in the earlier stages.

Both methods—local thresholding and global thresholding—needed to be applied seamlessly through-

out an image series using objective, non-arbitrary selection criteria informed both by the characterized performance of each method and by information extracted from the current image. The criterion selected here was the characteristic area size of objects within the current image. The performance of either method with characteristic object area size was assessed from synthetic images: local thresholding was found to be most reliable for objects up to a projected area of roughly $A_1 = 60 \text{ px}^2$, and global thresholding was found to be reliable for objects larger than roughly $A_2 = 150 \text{ px}^2$. With the present calibration these limits correspond to area-equivalent circular diameters, $d_{\text{eq}} = 2\sqrt{A/\pi}$, of roughly 120 and 190 μm , respectively.

The two thresholds are seamlessly blended on the basis of the characteristic object size in each averaged image. To avoid a circular dependence between the segmentation result and the choice of method, the object size that controls the blend is taken from an independent, preliminary segmentation that uses the local thresholding alone: the mean projected area $\bar{A}$ of the objects detected in this preliminary pass is used then calculate a blend. A smoothstep weighting function is then calculated, defined below, is then applied:

$$u = \text{clamp}\left(\frac{\bar{A} - A_1}{A_2 - A_1}, 0, 1\right), \quad w_g = 3u^2 - 2u^3, \quad w_l = 1 - w_g. \quad (5)$$

Thus, the local threshold is used exclusively when $\bar{A} \leq A_1$, the global threshold is used exclusively when $\bar{A} \geq A_2$, and a continuous combination of the two is employed in between. The thresholds are combined into a single spatially varying threshold field,

$$T(x, y) = w_l [B(x, y) - \delta] + w_g \tau_g, \quad (6)$$

and the final binary mask of crystal shadows is

$$\mathcal{M} = \{(x, y) : \bar{I}(x, y) < T(x, y)\}. \quad (7)$$

The weighting is evaluated once per averaged image, so a single, image-wide blend is selected from the mean size of the objects present at that instant.

2.3.3. Morphological refinement and object extraction

The binary mask is cleaned with a morphological opening using a 3×3 structuring element, which removes isolated single-pixel detections while leaving the shape of genuine shadows essentially unchanged; the resulting mask is shown in Figure 5(e). Connected components are then extracted as external contours, and any contour with a projected area below 2 px^2 is discarded as residual noise. Each retained contour represents the projected shadow of a crystal or a mixed-phase blob, and its area A_k is taken as the corresponding projected area. The full set of retained contours is shown overlaid on the averaged frame in Figure 5(f).

2.3.4. Areal coverage and size statistics

The primary quantity reported in this work is the areal coverage ratio, defined as the fraction of the interior field of view occupied by ice mass, either in the form of ice crystals or mixed-phase blobs,

$$\Phi(t) = \frac{\sum_k A_k}{A}, \quad (8)$$

where the sum operates over all retained objects in the averaged image and A is the area of the field of view. In addition to $\Phi(t)$, the analysis yields N , the total number of detected objects within the field of view. We report this quantity as the dimensionless object density ND^2/A , which may be interpreted as the average number of objects contained within an area equal to the projected area of a crystal with diameter D . We also report the normalized mean object area, $\overline{A^*} = 4\overline{A}/\pi D^2$, which represents the average object size normalized by the projected area of a crystal of diameter D . In the following analysis, we examine the temporal evolution of these parameters and their rates of change with respect to $\hat{t}_{\hat{c}}$ across cases spanning Γ_η and $\hat{K}_c$. Combined with the corresponding high-speed imagery, these measurements provide a mechanistic interpretation of the areal-coverage trends observed across the test matrix.

2.4. Test matrix

The test matrix for the measurement campaign is summarized in nominal form in Table 1. Four dimensional parameters were controlled throughout the campaign: the surface heat flux ($\dot{q}$), the freestream temperature (T_∞), the ice water content ($\text{IWC} = \rho_I \alpha$), and the freestream velocity (U). For all test cases, T_∞ was held fixed at -5°C . The matrix was divided into two sets of cases: a high-speed set and a low-speed set, with freestream velocities of 40 and 20 m/s and ice water contents ranges of 4 to 7 and 12 to 13 g/m³, respectively. Within the high-speed set, the surface heat flux was varied from 440 to 5340 W/m² in increments of approximately 540 W/m², while in the low-speed set it was varied from 1090 to 2150 W/m² using the same approximate increment.

Table 2 presents the nominal test matrix recast in terms of the two relevant non-dimensional groups introduced previously: the coalescence ratio, $\hat{K}_c$, and the heating ratio, Γ_η . In constructing this matrix, standard thermophysical values were adopted, with the latent heat of melting and specific heat capacity of ice taken as $L_I = 3.34 \times 10^5 \text{ J kg}^{-1}$ and $c_I = 2100 \text{ J kg}^{-1} \text{ K}^{-1}$, respectively. The densities of liquid water and ice were taken as $\rho_L = 1000$ and $\rho_I = 919 \text{ kg m}^{-3}$, respectively. The coalescence time was estimated from reported numerical visualizations of contacting droplets, which exhibit relaxation to a single droplet over a timescale of $t \sim 10^{-4} \text{ s}$. Assuming this timescale is representative of post-contact droplet merging yields an effective coalescence rate coefficient of $K_c \sim 10^4 \text{ s}^{-1}$ (Adhikari and Rattner, 2018). Within the range of coalescence ratios explored, no consistent dependence of the measured accretion metrics on $\hat{K}_c$ was observed. As such, the results presented throughout this work focus on mean trends with respect to heating ratio, Γ , which was found to be the dominant parameter governing the observed behavior, while the mean coalescence ratio, $\overline{\hat{K}_c}$, is used throughout the results to delineate between the low and high-speed data sets.

Case set	Surface heat flux ($\dot{q}$, W/m ²)	Freestream temperature (T_∞ , °C)	Ice water content ($\rho_I \alpha$, g/m ³)	Freestream velocity (U , m/s)
High-speed (10)	400 : 550 : 5340	-5	4 to 7	40
Low-speed (3)	1070 : 560 : 2200	-5	12 to 13	20

Table 1. Nominal test matrix summary. The bracketed number appearing next to each case-set name indicates the number of cases contained within that set. Entries separated by commas denote single tested values, whereas entries of the form “ $a : b : c$ ” represent ranges spanning from a to c in increments of b .

Case set	Coalescence ratio ($\hat{K}_c \times 10^{-3}$)	Heating ratio ($\Gamma_\eta \times 10^2$)
High-speed (10)	1.9 to 3.2 (2.3)	2.57 to 25.2
Low-speed (3)	1.9 to 2.0 (1.9)	4.2 to 6.3

Table 2. Test matrix expressed in terms of the non-dimensional coalescence ratio, $\hat{K}_c$, and heating ratio, Γ_η , with mean values presented in brackets. Values of $\hat{K}_c$ were estimated assuming a representative coalescence rate coefficient of $K_c \sim 10^4 \text{ s}^{-1}$ based on reported droplet-merging timescales (Adhikari and Rattner, 2018). Values of Γ_η were calculated using an assumed sticking efficiency of $\eta = 0.3$.

3. Results

This section begins by comparing trends in integral area coverage, Φ , on the heated substrate with representative plate images at selected times and conditions. These comparisons provide a mechanistic explanation for how the area-coverage behavior changes with heating ratio, Γ . This interpretation is further supported by trends in the object number density, ND^2/A , and the mean object area, $\bar{A}^* = 4A/\pi D^2$, discussed later. Finally, we examine early- and late-stage growth rates, with the stages delineated by trends in number density. These rates reveal growth behaviors that reinforce the proposed mechanism and quantify its dependence on Γ .

4. Evolution in coverage, density and mean size: non-monotonic dependence on heating

The areal coverage, Φ , is first examined across all tested conditions to assess the effect of heating on the evolution of the nascent ice layer. Figure 6 presents the median development of Φ for $0 \leq \hat{t}_{\hat{G}} \leq 3250$, with traces colored by heating ratio, Γ . Figures 6a and b respectively show cases with $\Gamma < 0.10$ and $\Gamma > 0.10$. Considering Figure 6a first, the growth of area coverage generally accelerates with increasing Γ . The lowest- Γ cases reach $\Phi \approx 0.3$, whereas the highest- Γ cases attain values approaching $\Phi \approx 0.9$. This initial increase in coverage with heating is consistent with single-particle impact studies, which have shown that increasing either substrate temperature or particle temperature promotes melting upon impact. The resulting liquid phase improves adhesion to the surface and generates lubrication and water trails that increase the areal footprint of deposited particles (Reitter, 2023; Yang et al., 2025; Yan, 2016). Although not directly analogous, a similar

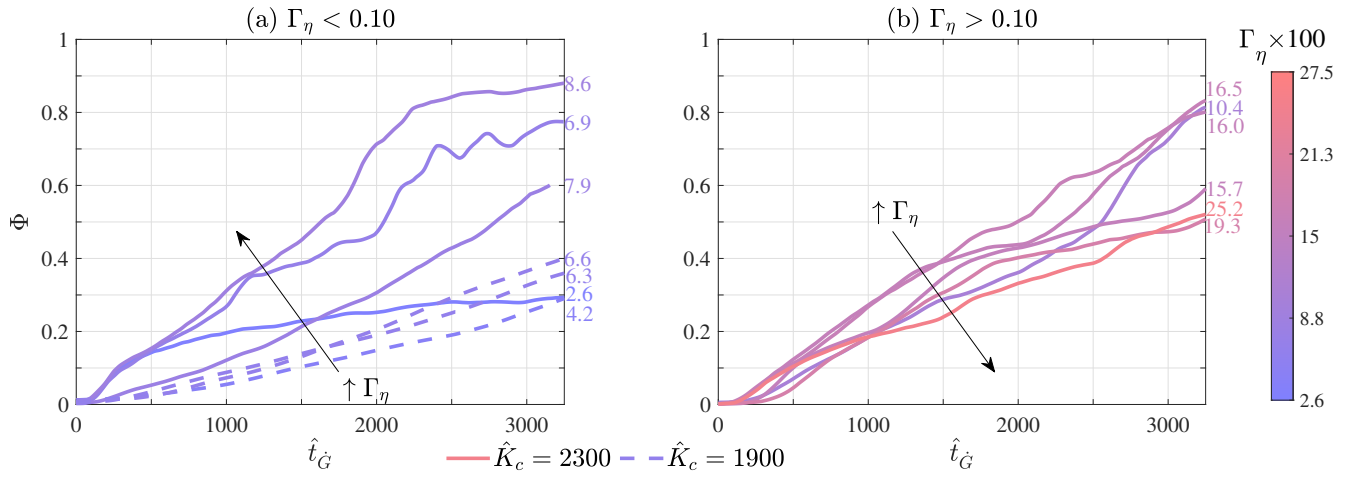


Figure 6. Areal coverage ratio, Φ , as a function of the accretion-based dimensionless time, $\hat{t}_{\dot{G}}$. Time traces are colored according to the heating ratio, Γ , as indicated by the color bar. Solid and dashed lines denote coalescence ratios of $\hat{K}_c = 2300$ and 1900 , respectively. The growth rate of Φ initially increases with Γ , but becomes non-monotonic at higher heating ratios.

trend has been observed during the later stages of ice-crystal icing, where heating promotes liquid production on the substrate, thereby improving crystal adhesion and sticking efficiency and accelerating the development of the accreted layer (Hauk, 2016; Hu et al., 2023; Malik et al., 2024a). In contrast, Figure 6b shows that further increases in Γ reverse this trend, leading to a reduction in the growth rate of Φ . Such a reversal is not clearly documented in the existing literature. Across the full temperature range investigated by Yang et al. (2024a) (20°C–160°C), the adhered volume fraction of impacting ice crystals increased monotonically with temperature, while Yan (2016) observed no clear trend in the ratio of projected to adhered particle area. Studies of later-stage accretion have suggested that excessive heating can reduce areal growth (Currie et al., 2014; Malik et al., 2024a); however, the proposed mechanism is accretion erosion resulting from poor adhesion of the growing deposit. Given the stagnation-flow configuration examined here, together with the early stage of accretion under consideration, erosion is unlikely to be the primary cause of the observed reduction in coverage growth.

The mechanism underlying this non-monotonic behavior in area-coverage growth becomes apparent when examining representative accretion images across the range of heating ratios tested. Figure 7 presents snapshots of the developing accretion over the interval $750 \leq \hat{t}_{\dot{G}} \leq 3000$ for heating ratios spanning $2 \leq \Gamma \leq 16$, where darker regions indicate accreted material. At the lowest heating ratio ($\Gamma \approx 2$, Figures 7a–d), the substrate is progressively covered by incoming ice crystals that remain predominantly as singular particles or loosely connected agglomerates. This behavior indicates insufficient heating to induce substantial melting and subsequent coalescence into larger structures. As the heating ratio is increased ($\Gamma = 6.6$ and 8.6 , Figures 7e–h and i–l, respectively), the crystals undergo significant melting, forming sessile droplets with enhanced mobility and an increased tendency to merge with neighboring particles. As these agglomerations grow, the heating remains insufficient to maintain a fully melted state, resulting in the formation of extensive

limited-mobility slush-like structures interconnected by thin bridges that result in a large areal footprint. At still higher heating ratios ($\Gamma = 12.5$ and 15.4 , Figures 7m–p and q–t, respectively), accretion proceeds through a similar sequence of melting and coalescence. However, the elevated heating maintains the droplets in a substantially more liquid state. Consequently, the growing agglomerates retain a degree of mobility not present at lower Γ , allowing them to reorganize into more compact structures. Rather than forming extended slush-like networks, the accreted material preferentially collects into larger spherical-cap-like deposits that occupy the substrate more efficiently and therefore produce a smaller areal footprint for a given volume of accreted material. Several examples can be observed in the high- Γ cases where neighboring droplets attract and merge in an amoeba-like manner, producing larger and more compact structures. Such events occur only infrequently at lower heating ratios.

The two limiting morphologies observed with increasing Γ —bridge-connected, slush-like agglomerates at intermediate heating ratios and large, predominantly liquid, rapidly coalescing droplets at high heating ratios—are reminiscent of two well-studied phenomena: liquid-bridge-mediated agglomeration in granular suspensions and the coalescence of pure-liquid droplets. Indeed, the trends in Φ observed here bear qualitative similarities to both processes. At intermediate heating ratios, partial melting introduces a modest liquid fraction into the accretion, promoting the formation of liquid bridges between neighboring crystals and the development of extensive, interconnected agglomerates with limited mobility. A similar response is observed in wet granular materials, where the introduction of small amounts of liquid leads to the formation of capillary bridges between particles, substantially increasing cohesion, yield stress, and tensile strength, a phenomena that could be interpreted as a form of reduced mobility, with these effects often strengthening as liquid volume fraction approaches roughly 10% (Kohonen et al., 2004; Scheel et al., 2008). Interestingly, the upward trend in cohesion then reverses with increased liquid volume fraction, somewhat analogous to the reversal in agglomeration mobility observed here. At the other extreme, at higher heating ratios, the accreted material remains sufficiently liquid and therefore mobile for neighboring droplets to merge and form larger structures. In contrast to the extended slush-like agglomerates observed at intermediate heating ratios, these merged droplets adopt more compact morphologies and therefore occupy a smaller projected area on the substrate. Similar coalescence-driven restructuring towards more areally compact has been widely observed in sessile liquid droplets (Meakin, 1992).

These two limiting dynamics—bridge-mediated spreading of mixed-phase agglomerates at low Γ and the formation of compact, coalescing droplets at high Γ —can be further examined through the evolution of object number density (ND^2/A) and mean object size ($\overline{A^*}$) on the substrate. Object number density quantifies the abundance of discrete accreted structures, whereas mean object size reflects the extent of their growth and coalescence. These quantities are presented in Figures 8 and 9, respectively, in a manner analogous to the areal coverage results of Figure 6.

For both ND^2/A and $\overline{A^*}$, non-monotonic behavior is observed that mirrors the trends in areal coverage. Across all heating ratios, ND^2/A initially increases before reaching a maximum value of

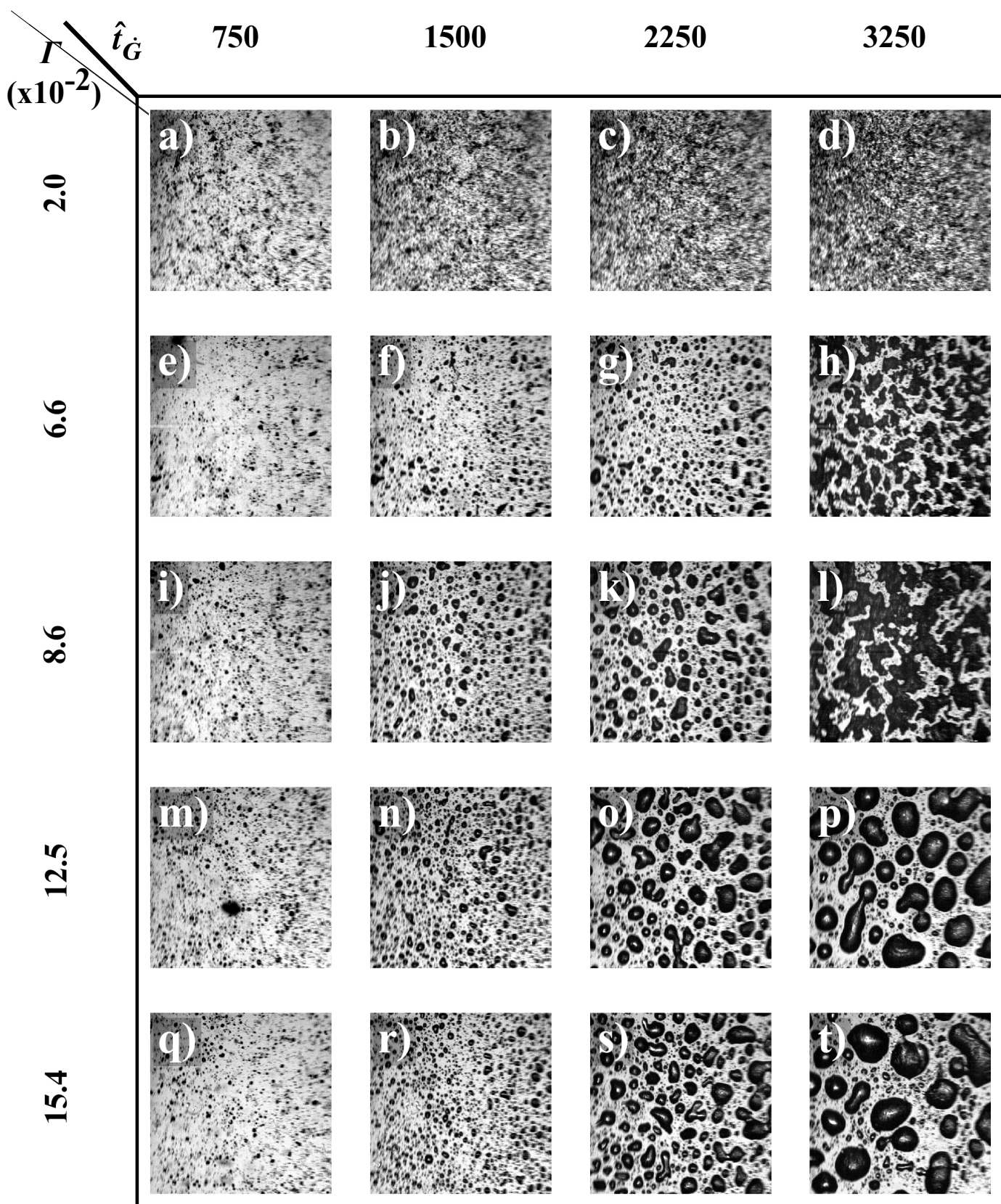


Figure 7. Representative instances of areal coverage on the plate at four accretion-based dimensionless times, $\hat{t}_{\hat{G}}$, indicated by the column headers, and for five heating ratios, Γ , indicated by the row labels.

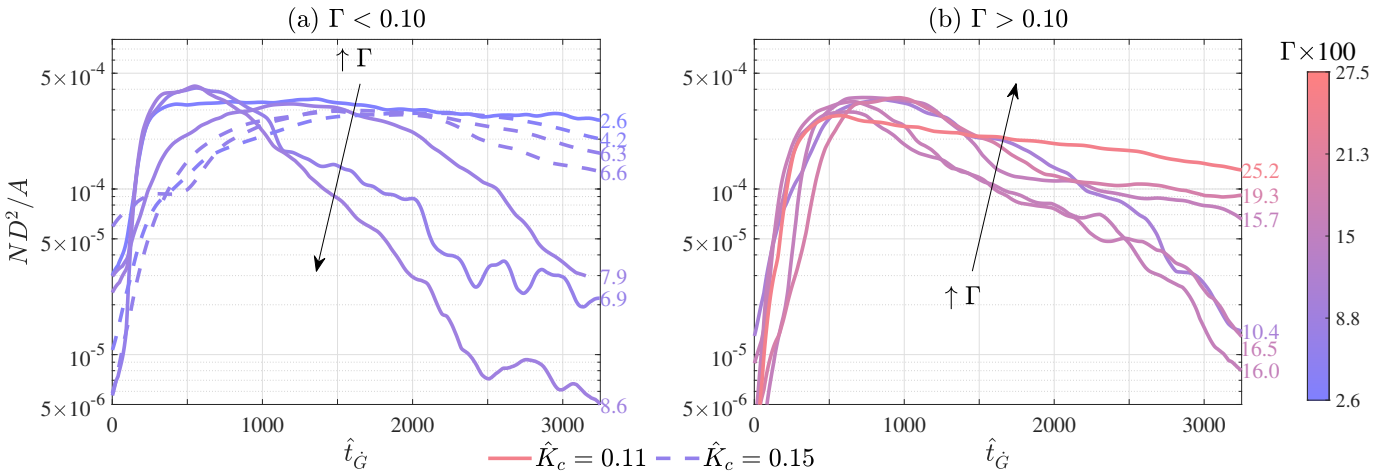


Figure 8. Normalized object number density, ND^2/A , as a function of accretion-based dimensionless time, $\hat{t}_{\dot{G}}$, presented in a manner analogous to Figure 6. Across all heating ratios, the number density initially increases before reaching a maximum of approximately 5×10^{-4} , after which object depletion dominates. The depletion rate exhibits a non-monotonic dependence on Γ , increasing for $\Gamma < 0.1$ (a) and decreasing for $\Gamma > 0.1$ (b).

$O(10^{-4})$, after which the trend reverses and the number density decreases. For $\Gamma \lesssim 0.1$, (Figure 8a) increasing Γ causes this peak to occur earlier and increases the subsequent rate of object depletion. Considering the first three rows of representative accretion images shown in Figure 7, this enhanced depletion is consistent with increased bridging between neighboring accreted structures, causing initially discrete objects to merge into larger interconnected agglomerates. This interpretation is further supported by the corresponding rate increase in $\overline{A}^*$ (Figure 8a), indicating that the reduction in object number density results not from diminished accretion, but rather from the accelerated amalgamation and continued growth of existing structures.

By comparison, once $\Gamma \gtrsim 0.1$ (Figure 8b), these trends reverse. Increasing Γ reduces the rate of object depletion while simultaneously decreasing the growth rate of the mean object size (Figures 8b and 9b, respectively). This reversal is consistent with the representative accretion images at higher heating ratios (final two rows of Figure 7). Unlike the large bridge-mediated superstructures observed at lower Γ , the compact morphology of the predominantly liquid droplets leaves substantial regions of the substrate unoccupied. These interstitial regions can then be populated by newly impinging crystals or smaller sessile droplets, maintaining a higher object number density while limiting the growth of the mean object size. Consequently, although coalescence remains active at high Γ , it proceeds through the formation of compact droplets rather than extensive interconnected networks, thereby reducing the efficiency with which accreted material increases areal coverage. Consequently, a greater fraction of the accreted material is concentrated within compact droplets, reducing the projected area gained per unit accreted mass and thereby limiting the growth of Φ . The combined trends in number density and mean object size therefore further reinforce a transition from bridge-mediated spreading to coalescence-driven compaction as the dominant growth mechanism. This transition provides a natural explanation for the reversal in areal coverage growth rate observed at elevated heating ratios.

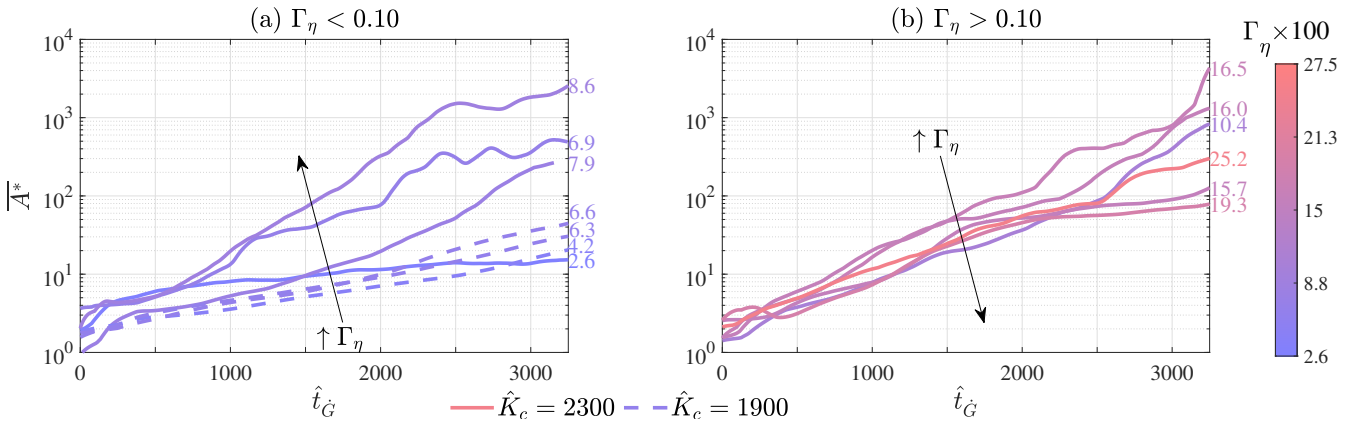


Figure 9. Normalized mean object area, $A^* = 4A/\pi D^2$, as a function of accretion-based dimensionless time, $\hat{t}_{\dot{G}}$, presented in a manner analogous to Figure 6. Object sizes initiate on the order of individual crystals, $O(1)$, and then grow at a rate that initially increases with $\Gamma < 0.1$, reaching sizes on the order of $O(10^3)$ (a). Upon Γ increasing beyond 0.1, the growth rate reduces, with objects reaching sizes of only $O(10^2)$ (b).

Whereas the number-depletion rate and mean object area exhibit a non-monotonic dependence on Γ , the saturation time, $(\hat{t}_{\dot{G}, |, \max(ND^2/A)})$, defined as the time at which the object number density reaches its maximum before beginning to decline, does not. Instead, for low heating ratios, the saturation time decreases with increasing Γ , falling from approximately $\hat{t}_{\dot{G}} \approx 2000$ to $\hat{t}_{\dot{G}} \approx 750$. Beyond this point, further increases in Γ produce little change, and the saturation time remains approximately constant at $\hat{t}_{\dot{G}} \approx 750$ for $\Gamma \gtrsim 0.1$. This behavior is summarized in Figure 10, which presents the saturation time as a function of Γ . Insight into this trend can be obtained by considering the early stages of accretion shown in Figure 7. At these times, the substrate remains only sparsely covered, and interactions between deposited crystals are limited. Consequently, the accretion dynamics should more closely resemble those of isolated particle impacts on heated surfaces. The observed reduction in saturation time with increasing Γ therefore suggests that heating promotes the initial retention of incoming crystals on the relatively clean substrate in a manner consistent with the impact-induced melting and enhanced adhesion mechanisms for isolated-crystal impacts discussed earlier. However, once the number density saturates and interactions between deposited structures become frequent, the governing dynamics transitions away from those of isolated impacts, and towards one controlled primarily by collective interactions between deposited structures, either through the formation of slush-like bridge-mediated agglomerates at low Γ or through the coalescence of large, predominantly liquid droplets at high Γ . These collective dynamics ultimately govern the subsequent evolution of areal coverage on the plate, as per our observed non-monotonic behavior.

The saturation time presents a natural transition point between a regime dominated by isolated crystal dynamics and one governed by collective interactions between accreted structures. Thus, as a final form of analysis, we assess the growth rates of areal coverage, mean object area, and number density, namely $d\Phi/d\hat{t}_{\dot{G}}$, $d\bar{A}^*/d\hat{t}_{\dot{G}}$, and $d(\log_{10}(ND^2/A))/d\hat{t}_{\dot{G}}$, both prior to and following saturation, which are referred to here as the early- and late-stage regimes, respectively. In the case of number density, the time derivative of its base-10 logarithm is considered to better rep-

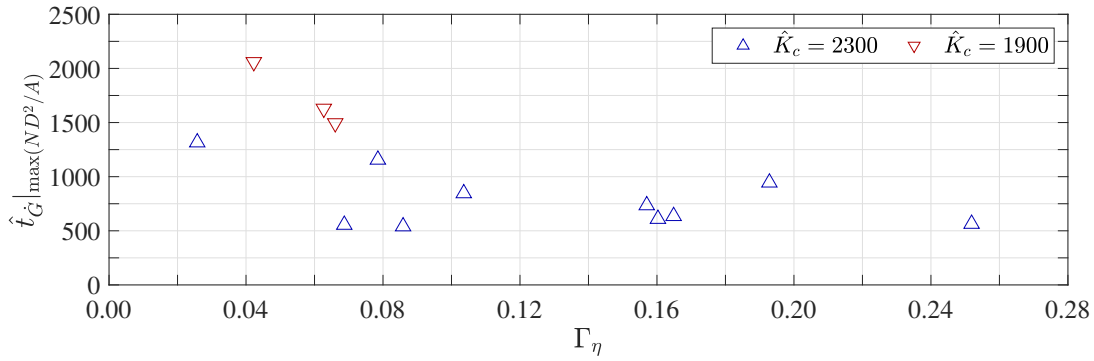


Figure 10. Time of object number saturation (in accretion time units) on the plate ($\hat{t}_{\dot{G}}|_{\max(ND^2/A)}$), defined here as the instant the number density reaches a maximum as a function of Γ . The plate saturates with objects at $\Gamma \approx 0.1$, stabilizing at a value of ≈ 750 .

resent the approximately exponential growth observed in Figure 8. Furthermore, the late-stage number-density growth rate is multiplied by negative one to account for its consistently depleting behavior and to facilitate direct comparison with the other growth-rate metrics. As functions of Γ , the early-stage growth rates of areal coverage, mean object area, and number density are presented in Figure 11(a), (c), and (e), respectively, while the corresponding late-stage growth rates are presented in Figure 11(b), (d), and (f).

Generally, the early-stage growth rates exhibit only a weak dependence on Γ . The areal coverage growth rate remains near 2.5×10^{-4} , while the mean object area growth rate remains approximately constant at $O(10^{-2})$. In contrast, the logarithmic number-density growth rate steadily increases through the 10^{-2} decade. This result suggests that, aside from promoting particle adhesion—as evidenced by the increase in number-density growth rate and consistent with observations from single-crystal impact studies—increasing Γ has little influence on the subsequent progression of the accretion during the early stage. The growth of the initial nucleation sites appears largely unaffected by heating ratio, and consequently the areal coverage growth rate remains approximately constant as well.

Conversely, the late-stage growth rates exhibit a strong dependence on Γ , consistent with the trends observed in the time traces. Both the areal coverage and mean object area growth rates increase rapidly as Γ approaches approximately 0.1, with $d\Phi/d\hat{t}_{\dot{G}}$ reaching a maximum of roughly 3×10^{-4} and $d\bar{A}^*/d\hat{t}_{\dot{G}}$ entering the $O(10^0)$ decade. Beyond this point, both quantities decrease with increasing Γ , reaching values of approximately 1.5×10^{-4} and $O(10^{-1})$, respectively. Correspondingly, the logarithmic number-density depletion rate increases to approximately 10^{-3} as Γ approaches 0.1, after which it decreases toward 10^{-4} with further increases in heating ratio.

The late-stage results again coincide with the observations made from the representative instances of areal coverage and the resulting time traces. At low Γ , increasing heating transitions the late-stage accretion progression from one governed by the individual impingement of largely solid crystals that progressively cover the substrate to one accelerated by the formation of slush-like, relatively immobile structures that connect through liquid bridges. This transition increases both the

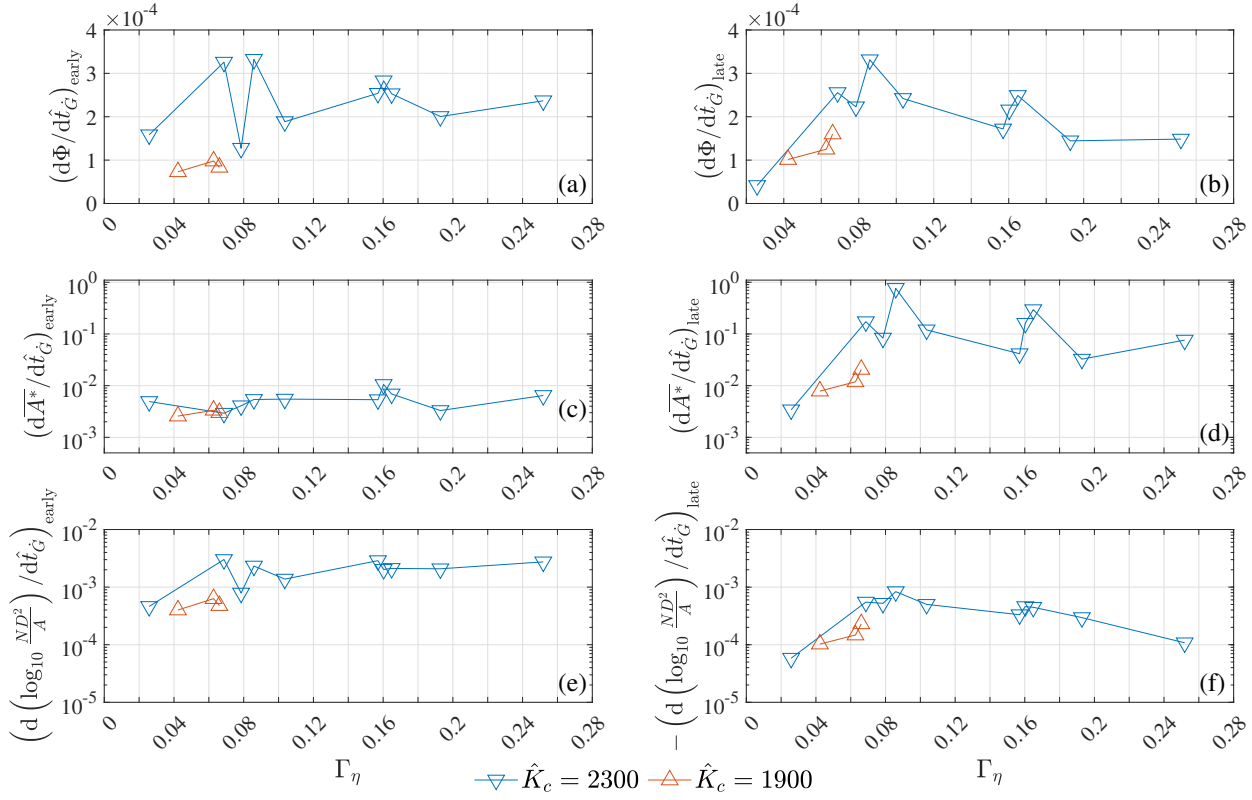


Figure 11. Growth rates of areal coverage, mean object area, and number density separated into early- and late-stage regimes defined by the saturation time of the number density. Panels (a), (c), and (e) present the early-stage growth rates of areal coverage, mean object area, and logarithmic number density, respectively, while panels (b), (d), and (f) present the corresponding late-stage growth rates. Early-stage growth rates exhibit only a weak dependence on heating ratio, Γ , whereas the late-stage growth rates display a pronounced non-monotonic dependence, with areal coverage and mean object area growth rates maximizing near $\Gamma \approx 0.1$ and the logarithmic number-density depletion rate exhibiting a corresponding peak.

growth rate of the mean object area and the depletion rate of number density as neighboring structures amalgamate into large interconnected superstructures. Upon Γ increasing beyond approximately 0.1, the governing dynamics transition from bridge-mediated agglomeration to droplet coalescence. In this regime, droplets remain sufficiently liquid to reorganize into more areally compact structures, reducing the growth rate of mean object area despite continued coalescence. Simultaneously, the compact occupancy of these larger droplets leaves greater portions of the substrate available for newly impinging crystals and smaller droplets, thereby reducing the depletion rate of number density.

Taken together, these results indicate that heating influences the accretion process through two distinct mechanisms operating at different stages of development. During the early stage, increasing Γ primarily promotes the retention of incoming crystals through impact-induced melting, leading to a modest increase in the number-density growth rate but having little influence on the subsequent growth of coverage or structure size. Once the accretion becomes sufficiently developed for interactions between deposited structures to occur, the governing dynamics transition to a col-

lective regime. In this regime, moderate heating promotes the formation of liquid bridges and extensive slush-like agglomerates, accelerating the growth of both areal coverage and structure size. At higher heating ratios, however, continued melting favors droplet mobility and coalescence, producing more compact morphologies that reduce the projected area gained per unit accreted material. The resulting transition from bridge-mediated spreading to coalescence-driven compaction provides a unified explanation for the observed non-monotonic dependence of areal coverage on heating ratio.

5. Conclusions & outlook

Through the use of high-speed imaging and subsequent image processing, the present work revealed a non-monotonic relationship between heating and ice-crystal accretion during the initiation phase, as the accretion transitions from a dry substrate to a fully developed quasi-one-dimensional ice layer. This behavior was identified through trends in areal coverage and complementary structure-derived metrics, which together revealed distinct heat-driven mechanisms governing the development and spreading of the accretion. Specifically, while the early-stage evolution is governed primarily by single-crystal impingement and melting, the later stages transition toward collective behavior, first through bridge-mediated spreading of relatively immobile, predominantly slush-like agglomerates at moderate heating, and subsequently through droplet-coalescence-driven compaction at elevated heating. The former accelerates areal spreading, whereas the latter suppresses it.

This was achieved through experiments performed on a heated stagnation-point glass substrate subjected to a step change in convection and ice-cloud exposure, spanning two mean coalescence ratios, $\overline{K}_c = 1900$ and 2300 , and heating ratios of $2.57 \leq \Gamma \leq 25.2$. An image-processing algorithm was developed that extracts and tracks accreted structures from substrate-normal high-speed imagery, enabling quantitative measurement of areal coverage, structure number density, and mean structure size throughout the initiation phase of ice-crystal accretion. Using this algorithm, the areal coverage ratio Φ , the crystal-normalized mean structure size $4A/\pi D^2$, and the crystal-normalized structure number density ND^2/A were extracted. Combined with the corresponding high-speed imagery, these measurements revealed a non-monotonic transition with heating in accretion spreading behavior during the later part of the initiation phase of ice-crystal icing. Within the range of coalescence ratios explored here, no systematic dependence of the measured accretion metrics on $\hat{K}_c$ was observed, indicating that heating ratio was the dominant parameter governing the observed transition. Consequently, the results presented throughout this work focus primarily on the influence of Γ .

Our results revealed a divergence in behavior between the early and late stages of accretion development, separated by a saturation time defined as the instance at which the structure number density reaches its maximum. Early-stage growth was governed primarily by isolated single-crystal dynamics, as evidenced by the high-speed imagery and growth-rate analysis. Within this stage, increasing Γ promoted adhesion and accelerated the approach to saturation, consistent with observations from previous studies of isolated crystal impacts. However, the growth rates of areal

coverage and mean structure size remained largely independent of heating ratio, suggesting that heating exerts only a limited influence on the overall evolution of the accretion during the early stage.

During late-stage development, i.e. following saturation, the evolution of the accretion transitions away from a regime governed by single-crystal dynamics to one governed by the collective interactions of the agglomerates forming on the plate, and it is the evolution in agglomerate morphology with increasing heating that mediates the non-monotonic behavior observed here. At low Γ , increasing heating promotes the transition from dry crystals to slush-like, relatively immobile agglomerates that spread through the formation of liquid bridges. As heating increases further, these structures evolve into predominantly liquid droplets that coalesce into areally compact morphologies, with the transition occurring near $\Gamma \approx 0.1$. Consequently, moderate heating promotes rapid spreading and structure growth through bridge-mediated amalgamation, whereas elevated heating suppresses spreading through droplet-coalescence-driven compaction.

Thus, our results reveal a non-monotonic effect of heating on the evolution of the ice layer during the initiation phase, first accelerating and then decelerating its development. This behavior arises directly from the transition in morphology from bridge-mediated slush-like agglomerates to large coalescing droplets that occupy the substrate more compactly. These findings help reconcile disparate observations reported in studies of initiation-phase ice-crystal icing, including differences in the onset of height growth and early accretion rates. They also provide insight into the development of improved initiation-stage models, where the evolution of the nascent ice layer remains challenging to predict owing to the coupled effects of liquid production, transport, and redistribution.

Despite the significance of these findings, the present study is limited to a single sub-zero wet-bulb temperature and a hydrophilic glass substrate. Future work should investigate the influence of mixed-phase conditions, substrate wettability, and substrate thermal properties on the observed transition. The image-processing framework developed here additionally provides a pathway for tracking the nucleation, growth, motion, and merger histories of individual accreted structures, enabling direct quantification of bridge formation, coalescence frequency, and structure-growth statistics. More broadly, the present results demonstrate that the initiation phase of ice-crystal icing is governed not only by crystal adhesion, but also by the emergence of collective interactions between accreted structures, whose evolution ultimately determines the rate at which a heated surface becomes covered by ice.

Acknowledgements

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Nomenclature

Roman symbols

A	Area
A_I	Projected area of an ice crystal
A_L	Footprint area of an equivalent liquid droplet
$\overline{A}^*$	Crystal-normalized mean object area, $4\overline{A}/\pi D^2$
c_I	Specific heat capacity of ice
c_L	Specific heat capacity of liquid water
D	Characteristic crystal diameter (MVD)
d_{eq}	Equivalent circular diameter
f	Camera acquisition frequency
H_I	Specific enthalpy of incoming ice crystal
K_c	Coalescence rate coefficient
L_I	Latent heat of fusion of ice
L_L	Latent heat of evaporation of water
m_0	Characteristic crystal mass
N	Number of detected structures
$\dot{q}$	Imposed substrate heat flux
s	Spatial calibration (pixel pitch)
t	Time
T	Temperature
T_f	Freezing temperature
T_∞	Freestream temperature
U	Freestream velocity

Greek symbols

α	Ice volume fraction in cloud
β	Area ratio, A_L/A_I
Γ	Heating ratio
Γ_η	Heating ratio including sticking efficiency
δ	Local threshold contrast offset
η	Representative sticking efficiency
η_{dry}	Dry sticking efficiency
η_{wet}	Wetted sticking efficiency
θ	Contact angle
λ	Melt fraction
μ	Mean image intensity
ρ_I	Density of ice
ρ_L	Density of liquid water
τ_g	Global threshold intensity
τ_{Otsu}	Otsu threshold intensity
Φ	Areal coverage fraction

Dimensionless groups

$\hat{K}_c$	Coalescence ratio, $2K_c D/(3\alpha U)$
$\hat{t}_{\dot{G}}$	Accretion-based dimensionless time
ND^2/A	Crystal-normalized structure number density
R	Density ratio, ρ_I/ρ_L

Subscripts

A	Air
I	Ice
L	Liquid
imp	Impingement
surf	Surface
wet	Wetted condition
dry	Dry condition

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