

Experimental Investigation of Air-Water Bubbly Flow Characteristics under Motion Conditions Using Synchronized Wire-Mesh Sensor and High-Speed Camera

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1. Introduction

Floating nuclear power plants (FNPPs) have gained significant attention as a solution for electricity supply to remote areas. Russia has operated Akademik Lomonosov, the world's first floating nuclear power unit, since 2019 [1], and Korea is pursuing its own FNPP development through the BANDI project [2].

FNPPs in the marine environment are continuously subject to ocean motions such as rolling and heaving. The resulting changes in acceleration can significantly affect thermal-hydraulic characteristics such as flow regime transitions and critical heat flux. Therefore, analyzing thermal-hydraulic behavior under motion conditions is essential for FNPP safety assessment.

Seoul National University has been conducting thermal-hydraulic experiments on motion platforms simulating rolling and inclination. Flow boiling experiments on these platforms confirmed that a direct understanding of bubble behavior is essential for analyzing thermal-hydraulic phenomena under motion conditions.

To this end, wire-mesh sensors (WMS) were introduced. WMS measures cross-sectional void fraction with high temporal and spatial resolution (up to 10,000 fps) and allows estimation of bubble-wise characteristics. The previous adiabatic air-water experiments under inclined and rolling conditions using WMS identified void fraction reduction due to inclination-induced bubble coalescence, and periodic void fraction fluctuation driven by rolling motion.

To cross-validate the void fraction measurements and to acquire axial (z-direction) information on bubble dynamics, the present study additionally employs a high-speed camera (HSC). HSC enables direct optical observation of bubble morphology and measurement of rise velocity through image processing, compensating for the intrusive nature of WMS. A similar cross-comparison between WMS and high-speed imaging was performed under vertical conditions by Prasser et al. [3].

In this study, WMS and HSC were operated simultaneously to directly observe and phenomenologically analyze air-water bubbly flow under inclined and rolling conditions. Each system was synchronized via a hardware trigger, and image processing was applied to the HSC images for quantitative data acquisition. WMS data were used to support the development of the HSC image processing methodology.

2. Experimental Methods

2.1 Experimental Setup

Experiments were conducted on YEOUL-R (Fig. 1), a compact rolling motion platform developed at Seoul National University. It can simulate rolling motion up to 45° amplitude with a minimum period of 6 s. The resulting acceleration range acting on the test section is $-0.3g$ to $+0.05g$ (axial) and $-0.7g$ to $+0.7g$ (lateral).

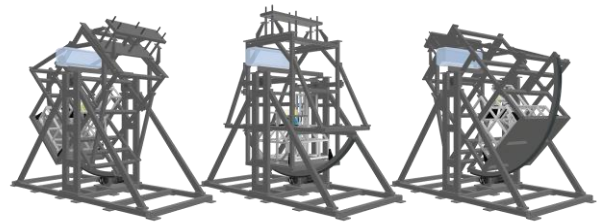


Fig. 1. Compact rolling motion platform (YEOUL-R)

The test loop consists of a water supply system, an air supply system, and a vertical test section mounted on the rolling platform (Fig. 2). Water is circulated in a closed loop with the flow rate measured by a Coriolis flow meter, and compressed air is supplied through a multi-stage drying and filtration system followed by a mass flow controller. The air is injected through a porous nozzle installed at the inlet to generate uniformly sized bubbles (Fig. 3). The test section is an acrylic pipe with an inner diameter of 13 mm and a total length of 865 mm ($L/D \approx 66$). The test-section mount and configuration are shown in Fig. 4. Flexible hose connections accommodate the platform motion, and flow rate fluctuations due to rolling were confirmed to remain below 1%.

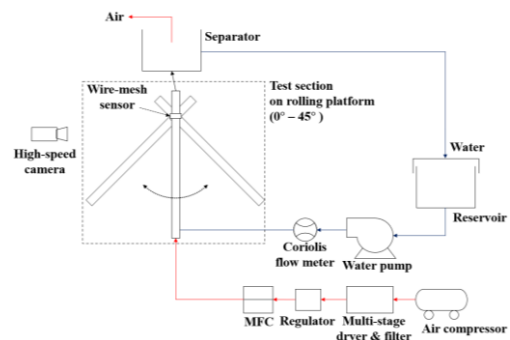


Fig. 2. Schematic of the two-phase flow test loop

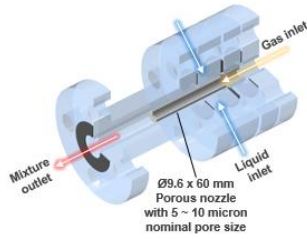


Fig. 3. Inlet module with porous nozzle

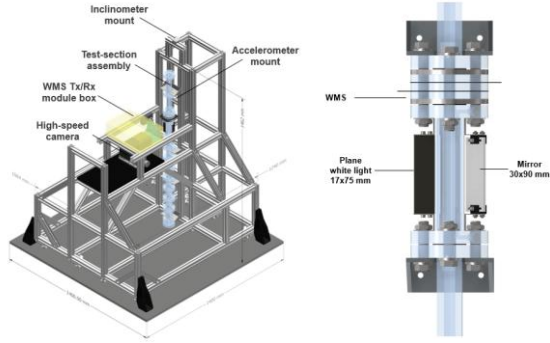


Fig. 4. Test-section mount and components configuration

The motion conditions are summarized in Table I. All conditions were conducted at atmospheric pressure and room temperature. The liquid flow rate was 5 lpm ($j_L = 0.63$ m/s). The gas flow rates were 200 and 500 mlpm ($j_G = 0.022$ and 0.053 m/s, respectively), corresponding to the bubbly flow regime.

Table I: Motion conditions

Condition	Amplitude [deg]	Period [s]
VT, IN	0, 15, 30, 45	—
RO	30, 45	6, 12

* VT : vertical, IN : static inclined, RO : rolling motion

An IDT Y4-S2 high-speed camera is used for bubble visualization, operated at 600 fps with a resolution of $1,024 \times 720$ pixels. The field of view is centered 105 mm upstream of the WMS sensor plane (Fig. 5). Two LED panels provide uniform back-illumination from two orthogonal directions: one behind the test section for the direct view, and one on the left side for the reflected view by an approximately 45° flat mirror mounted on the right side of the test section. This configuration enables two perpendicular projections of each bubble to be captured simultaneously in a single frame (Fig. 6).

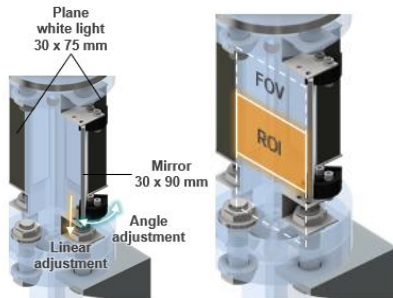


Fig. 5. (a) Scheme of the HSC optical configuration (b) HSC record area

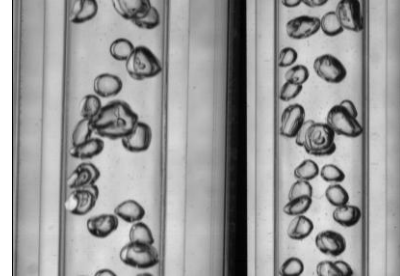


Fig. 6. Representative HSC frame showing simultaneous direct view (left) and mirror-reflected view (right)

The wire-mesh sensor (WMS) measures the electrical conductivity of the two-phase mixture at each wire crossing point; since the gas phase has a negligibly small conductivity compared to the liquid phase (water of approximately $80 \mu\text{S/cm}$), the local void fraction can be determined from the conductivity contrast. The WMS is a conductivity-type double-stacked configuration (12×12 electrodes, wire diameter $100 \mu\text{m}$, pitch 1.073 mm, axial spacing 10 mm) manufactured by HZDR Innovation GmbH, operated at 8,000 fps (Fig. 7). Each run records 24 s, covering at least two rolling cycles at the maximum period.

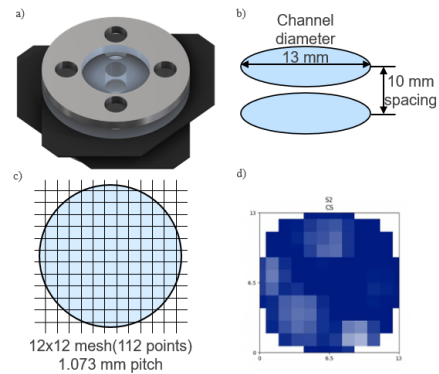


Fig. 7. (a) WMS assembly, (b) double-stacked sensor configuration, (c) electrode grid layout, (d) cross-sectional void fraction distribution

2.2 Data Processing

HSC image processing follows four main stages: preprocessing, bubble detection, 3D reconstruction, and void fraction estimation. In the preprocessing stage, a background image was estimated from the temporal intensity average and subtracted from each frame. The subtracted images were contrast-enhanced and inverted to produce the input for bubble detection (Fig. 8).

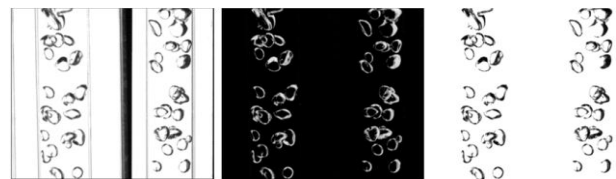


Fig. 8. Preprocessing stage (a) raw frame (b) background subtraction (c) contrast-enhanced

Bubble detection follows the deep-learning framework of Hessenkemper et al. [4], with Cellpose [5]. A UNetL3 generates a binary bubble mask, and Cellpose segments individual bubble instances. An ellipse is then fitted to the non-occluded contour points of each instance. This reconstructs overlapping bubbles and gives the centroid position and projected equivalent diameter (Fig. 9).



Fig. 9. Bubble detection stage (a) UNetL3 (b) Cellpose (c) ellipse fitting

The bubbles detected in the direct and mirror views were matched and reconstructed in three dimensions. The cross-sectional void fraction was then evaluated at the axial mid-plane of the field of view. For each bubble crossing this plane, its cross-section was projected onto the plane as ellipse defined by the horizontal extents in the two views. Instantaneous void fraction was obtained as sum of elliptical bubble region divided by the cross-sectional area of test section.

WMS data processing extracts the local void fraction and individual bubble characteristics from the raw signals (Fig. 10). Bubbles were identified as connected regions in the spatiotemporal void fraction field. The axial velocity was obtained from cross-correlation between the two sensor planes. WMS, HSC, and DAQ were synchronized through a hardware trigger, with the WMS trigger signal relayed to the HSC via the DAQ. The DAQ also recorded the process and platform variables, including flow rates, pressures, accelerations, and roll angles.

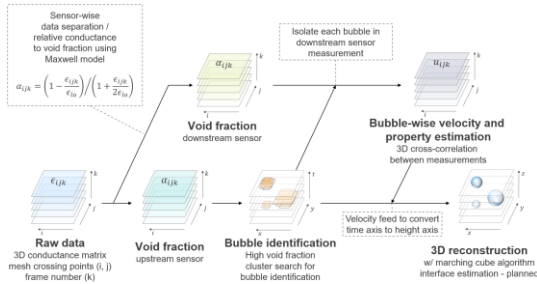


Fig. 10. Scheme of WMS data processing method

3. Results and Discussion

3.1 Bubble Behavior under Stationary Conditions

Fig. 11. presents HSC detection results alongside WMS 3D reconstructions for the vertical (VT) and inclined (IN15, IN30, IN45) conditions. Under vertical condition, bubbles are distributed throughout the pipe cross-section without preferential wall accumulation.

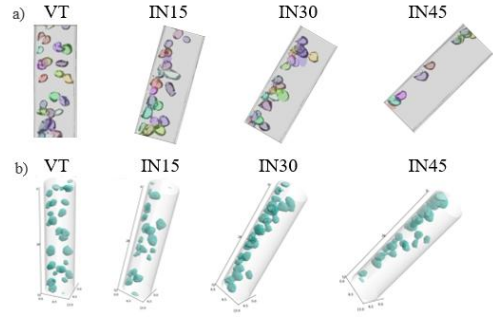


Fig. 11. a) HSC bubble detection results and b) WMS 3D reconstructions under stationary conditions

Fig. 12. compares the time-averaged cross-sectional void fraction distributions under the vertical condition. The HSC result shows the same wall-peaking structure as the WMS, and the cross-sectional averages agree closely.

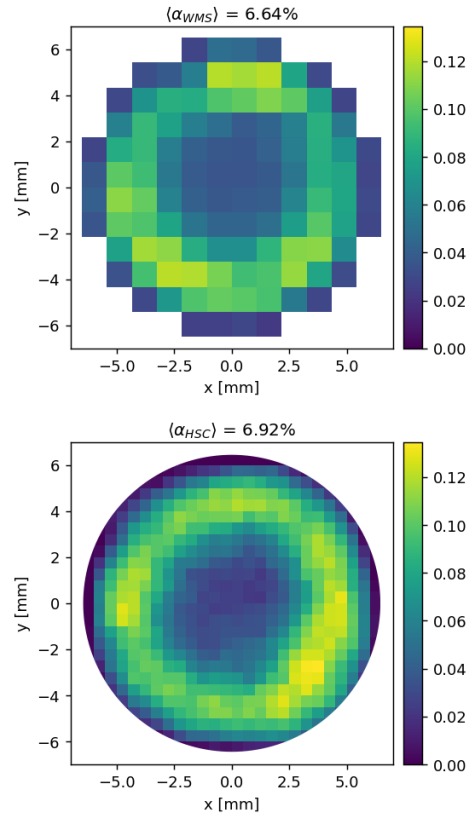


Fig. 12. Time-averaged cross-sectional void fraction under vertical condition (top: WMS, bottom: HSC)

With increasing inclination, bubbles progressively migrate toward the upper wall, and increasingly large bubble ellipses appear in the upper region, indicating enhanced coalescence. At near 45°, all detected bubbles are concentrated near the upper wall.

Fig. 13. shows the same comparison under the 45° inclined condition. Both instruments identify the bubble concentration near the upper wall. However, the HSC underestimates the void fraction in the wall region, where bubble detection becomes unstable due to overlapping bubbles along the line of sight.

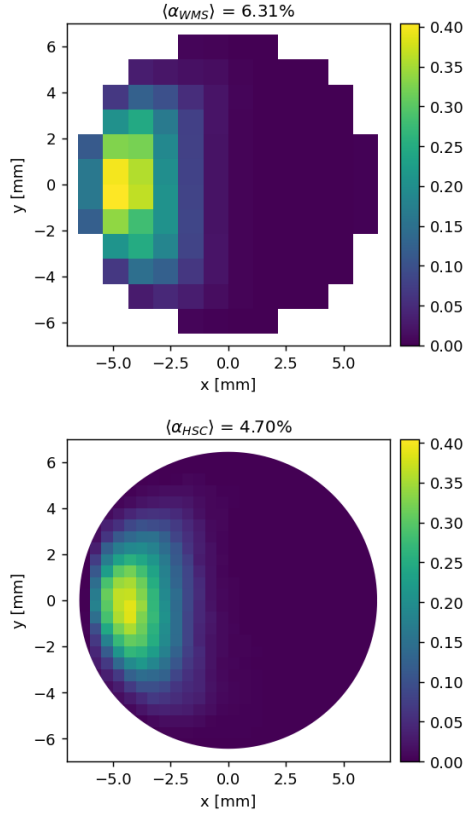


Fig. 13. Time-averaged cross-sectional void fraction under 45°-12 s rolling condition (top: WMS, bottom: HSC)

3.3 Bubble Behavior under Rolling Conditions

Four rolling cases were examined, combining two amplitudes ($\theta_{max} = 30^\circ, 45^\circ$) with two periods ($T = 6$ s and 12 s). Within each cycle the decreasing-inclination portion is termed the "roll-down" phase, and the opposite portion, the "roll-up" phase.

Fig. 13 compares HSC detection results during the roll-down phase of the 45°-12s rolling condition at selected instantaneous inclinations with the corresponding stationary cases. The rolling distributions broadly follow the stationary ones at the same instantaneous angle, but with a visible delay: some bubbles remain spread toward the center during roll-down, and near 0° a slight bias toward the side that formed the upper wall in the preceding phase persists. The instantaneous distribution therefore reflects the recent orientation history as well as the current inclination.

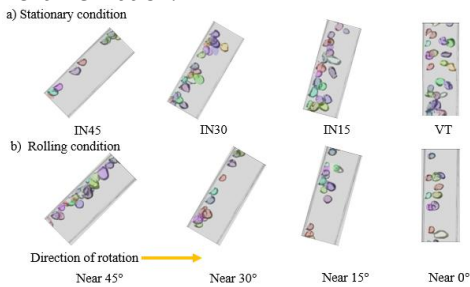


Fig. 13. HSC bubble detection results under a) stationary conditions and b) the roll-down phase of 45°-12s rolling condition at matching inclinations

Phase-resolved HSC snapshots for the 45°-12 s rolling cases are presented in Fig. 14. The distributions evolve smoothly with the orientation change. At the extreme angles they are close to the corresponding stationary cases, and near 0° they become nearly symmetric with only a slight residual bias, consistent with a small phase lag between bubble redistribution and the orientation change.

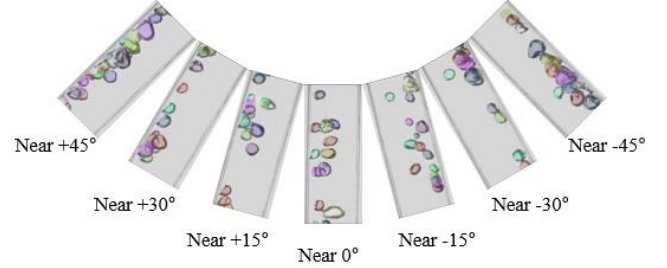


Fig. 14. HSC bubble detection results under the rolling condition ($\theta_{max} = 45^\circ, T = 12$ s)

Fig. 15 compares the time-averaged void fraction under the rolling condition ($\theta_{max} = 45^\circ, T = 12$ s). Unlike the inclined conditions, where bubbles accumulate along a single wall, the rolling motion carries the bubble back and forth between the two side walls, so the time-averaged void fraction distribution shows symmetric bubble concentration near both walls and low void fraction in the core region. This pattern is consistent between both measurements, and the underestimation of the HSC near the wall remains as in the inclined conditions.

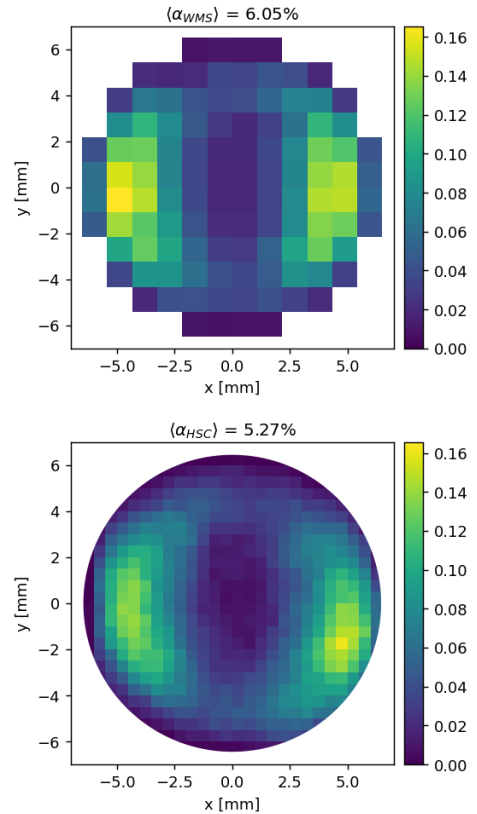


Fig. 15. Time-averaged cross-sectional void fraction under 45°-12s rolling condition (top: WMS, bottom: HSC)

Under the shorter period ($T = 6$ s, Fig. 16), the distributions differ markedly from the stationary cases. Bubbles are concentrated closer to the upper wall at the extreme angles, while at the intermediate angles they spread over a wide portion of the cross section, reflecting the limited time available for redistribution. Near 0° , a clear asymmetry toward the side that formed the upper wall in the preceding phase persists. These features are pronounced in the range of angles where the angular velocity is large, suggesting that the fast orientation change alters the redistribution beyond a simple phase lag.

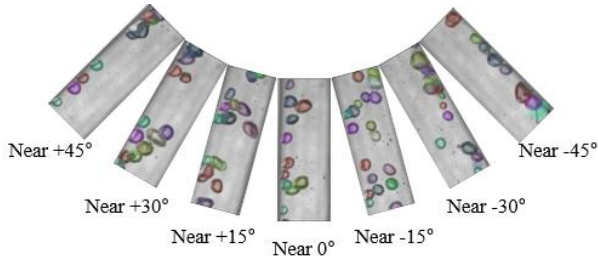


Fig. 16. HSC bubble detection results under the rolling condition ($\theta_{max} = 45^\circ$, $T = 6$ s)

Fig. 17 compares the time-averaged void fraction for 45° -6 s rolling condition. Although the instantaneous distributions depend strongly on the rolling direction, the time-averaged distribution is nearly unchanged from the 12 s case and the two instruments remain consistent, as the direction-dependent redistribution in Fig. 16 is averaged out.

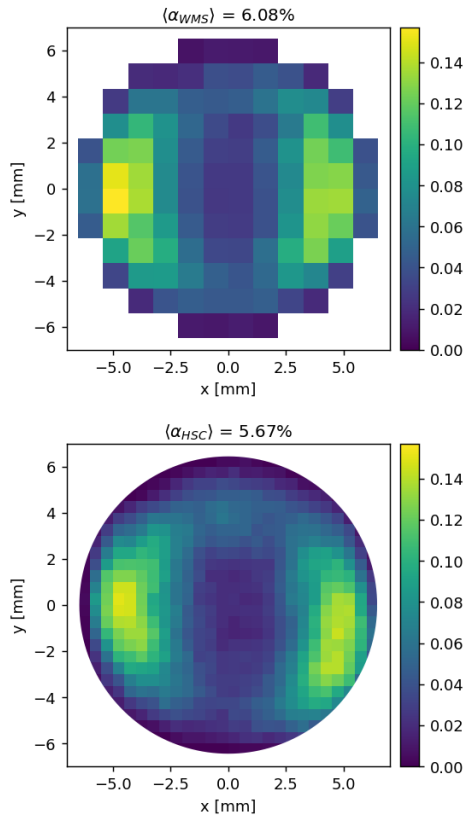


Fig. 17. Time-averaged cross-sectional void fraction under 45° -6s rolling condition (top: WMS, bottom: HSC)

4. Conclusion

A simultaneous WMS and HSC measurement system was established to analyze air-water bubbly flow under inclined and rolling conditions. The main findings are as follows.

The time-averaged cross-sectional void fraction estimated from the HSC images agreed with the WMS measurement within $\pm 30\%$ over all 16 conditions without any tuning parameter, underpredicting the stationary conditions and overpredicting the rolling conditions.

A hardware-triggered system was successfully built, and HSC detection results and the WMS measurements showed consistent void fraction distributions under all stationary conditions, capturing the progressive bubble migration toward the upper wall with increasing inclination angle. The largest deviations were confined to the wall region, where overlapping bubbles make optical detection unstable.

Under rolling conditions, the time-averaged distributions of the two instruments also agreed, showing symmetric bubble concentration near both side walls regardless of the rolling period. The phase-resolved snapshots, in contrast, revealed the effect of the period: under the longer period the instantaneous distributions follow the orientation change with only a small phase lag, whereas under the shorter period features beyond a simple phase lag emerge, including closer wall attachment at the extreme angles and persistent asymmetry near the vertical phase.

The established platform thus provides both quantitative cross-validation of the void fraction and phase-resolved visualization of the bubble behavior, forming the basis for subsequent bubble-by-bubble analysis under rolling conditions.

REFERENCES

- [1] Belyaev, V.M., Bol'shukhin, M.A., Pakhomov, A.N. et al. The World's First Floating NPP: Origination and Direction of Future Development. *At Energy* 129, 27–34 (2020).
- [2] Han Ok Kang, Byung Jin Lee, Sang Gyu Lim, Light water SMR development status in Korea, *Nuclear Engineering and Design*, Volume 419, 2024, 112966.
- [3] H.-M. Prasser, D. Scholz, C. Zippe, Bubble size measurement using wire-mesh sensors, *Flow Measurement and Instrumentation*, Volume 12, Issue 4, 2001, Pages 299-312.
- [4] Hendrik Hessenkemper, Lantian Wang, Dirk Lucas, Shiyong Tan, Rui Ni, Tian Ma, 3D detection and tracking of deformable bubbles in swarms with the aid of deep learning models, *International Journal of Multiphase Flow*, Volume 179, 2024, 104932.
- [5] Stringer, C., Wang, T., Michaelos, M. et al. Cellpose: a generalist algorithm for cellular segmentation. *Nat Methods* 18, 100–106 (2021).