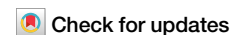




Generation and stability of nanobubbles under microgravity conditions: unlocking a new horizon



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Nanobubbles (NBs) have attracted considerable interest for applications in gas-limited systems, environmental processes, and enhanced mass transfer. However, their existence and functionality under microgravity conditions remain unverified, limiting their potential for space-related applications. Here, we evaluate the stability, generation, and gas-transfer properties of air, oxygen, and carbon dioxide NBs under microgravity conditions achieved during parabolic flights. By exposing NBs generated under terrestrial atmospheric conditions to microgravity, we observe negligible changes in NBs concentration and size distribution, even when varying the headspace of NBs storage systems. When NBs are generated directly under microgravity, nanoparticle tracking analysis reveals a statistically significant increase in NBs concentration relative to the background signal, demonstrating their formation and stabilization in the absence of gravity. This behavior is further confirmed under dynamic gravity conditions (~0–1.8 g), where a continuous increase in NBs concentration is observed. Consistent with NBs generation trends, gas-transfer performance is assessed through dissolved oxygen and pH variations for oxygen and carbon dioxide NBs, respectively. These results enabled elucidating fundamental mechanistics of NBs formation, establish the viability of NBs under microgravity, and highlight their potential to enable new strategies for overcoming gas–liquid mass transfer limitations in space environments.

Gas/liquid systems are integral to life-support, propulsion, and chemical processes in both terrestrial and extraterrestrial environments^{1–3}. However, the absence of buoyancy forces in spaceflight fundamentally alters fluid dynamics, as without gravitational separation, bubbles do not rise or detach as on Earth, leading to gas accumulation, unstable interfaces, and limited mass transfer efficiency^{4–6}. These phenomena impede the reliability of reactors, heat exchangers, and oxygenation systems designed for microgravity, making the management of multiphase flows one of the most persistent engineering challenges for space exploration^{7,8}. Current strategies, ranging from centrifugal separation and capillary-driven designs to mechanical phase control, remain complex, energy-intensive, and scale-limited. Therefore, the research of techniques capable of maintaining efficient gas/liquid exchange independent of gravity represents a paradigm shift for space-based technologies^{9–13}.

Nanobubbles (NBs), or ultrafine bubbles (diameter < 500 nm), have emerged as a compelling alternative to conventional gas injection methods. Unlike micro- and macrobubbles, NBs exhibit exceptionally large specific surface area, uniform size distributions, and long lifetimes under supersaturating conditions^{14–17}. Their unexpected stability, contradicting classical dissolution models such as Epstein-Plesset, is now understood to result from electrostatic stabilization and interfacial phenomena governed by the Young-Laplace relationship^{18–21}. The formation of an electrical double layer on the NBs surface prevents their coalescence and confers colloidal-like behavior^{22–24}. On Earth, these mechanisms enable NBs to persist for days to weeks without buoyant rise, demonstrating promise in applications including water treatment, catalysis, and agriculture^{25–28}. Despite extensive progress in NBs generation and characterization^{17,29–33}, their behavior under microgravity and variable-gravity environments remains entirely unknown.

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Although they exhibit negligible buoyancy, gravity may still influence critical processes involved in their formation and persistence, including nucleation dynamics, bubble detachment from surfaces, gas/liquid stratification, and headspace equilibration. Determining whether these stabilization mechanisms are gravity-independent is critical both for understanding interfacial physics and for unlocking NBs-based gas management in space exploration.

Here, this study presents the first experimental evaluation of NBs behavior under microgravity and alternating gravity conditions, conducted during zero-gravity parabolic flight campaigns and framed around three fundamental research questions:

- (i) Are NBs generated under standard Earth gravity and pressure conditions stable when exposed to microgravity?
- (ii) Can NBs be directly generated under microgravity?
- (iii) Does NBs generation persist during continuous transitions between microgravity (~ 0 g) and hypergravity (~ 1.8 g)?

Three gravitational regimes were evaluated: (i) NBs generated on ground and subsequently exposed to repeated microgravity and hypergravity cycles, (ii) in situ NBs generation performed exclusively during microgravity intervals (20–25 s), and (iii) continuous generation across alternating gravity levels. For each tested gas (air, O₂, CO₂), NBs concentration, size distribution, headspace effects, and gas/liquid mass transfer were quantified using nanoparticle tracking analysis (NTA) and dissolved gas measurements. This framework enabled a direct assessment of whether NBs stability and generation are governed by gravity or by interfacial and electrostatic interactions alone.

This work provides the first empirical evidence that NBs are agnostic to gravity, establishing them as a scalable and energy-efficient gas/liquid platform for use beyond the scope of Earth applications. The demonstrated stability and continuous generation of NBs under variable gravitational accelerations redefine the fundamentals of multiphase systems in space and open new pathways for controlled gas delivery, mass transfer, and resource utilization in extraterrestrial environments for a wide range of applications in space missions.

Results and discussion

Nanobubble stability overcomes gravity variations under quiescent conditions

A substantial body of work conducted under standard Earth gravity conditions (i.e., 1 g) has established that NBs generation consistently exhibits size distributions below 500 nm¹⁷. The extremely small size of NBs results in negligible buoyancy, which, together with their negative surface charge, allows NBs to remain suspended in the liquid instead of coalescing, rising, and bursting at the surface. This behavior represents a key advantage over micro- and macrobubbles. In microgravity, buoyancy becomes effectively null for bubbles of any size, but macro- and microbubble coalescence and their inefficient mixing make gas dissolution dramatically difficult. Conventional sparging approaches in microgravity often generate bubbles that are too large, with broad size distributions and sensitivity to small residual accelerations. Under these conditions, bubbles tend to persist, collide, and coalesce, leading to unstable bubble accumulation near injection points, in regions of frequent collisions, or throughout the bulk as natural convection ceases^{5,6}. This inhibits effective gas/liquid mixing under microgravity and reduces the active area of the gas/liquid interface, negatively impacting mass transfer and fluid dynamics. Herein, is where the unique nanoscale properties of NBs can arise as a game-changing technology for gas delivery systems under microgravity. Extending these considerations to the nanoscale and understanding the stability of NBs under variable-gravity environments is critical for enabling transformative applications during launch and spaceflight.

The stability of NBs was evaluated and monitored in real time under alternating gravitational accelerations, ranging from hypergravity (~ 1.8 g) to microgravity (~ 0 g). Different NBs solutions of air, O₂, and CO₂ were prepared on the ground one day before flight and sealed in thermally

insulated glass containers with two distinct headspace (HS) volumes: no-headspace ($<1\%$ volume, denoted as 0% HS) and high (50% HS). Containers holding the pre-generated NBs suspensions were securely mounted within the payload to minimize thermal and mechanical perturbations and were evaluated alongside parallel samples that were maintained on the ground. This experimental design enabled evaluation of gas/liquid equilibrium effects on NBs under variable-gravity conditions in a quiescent state and provided a direct benchmark against previously reported responses under standard laboratory conditions on Earth¹⁷.

The variation in NBs concentration relative to the initial stock solutions is summarized in Fig. 1a–c. Under 0% HS, air NBs decreased to 79.8% in ground and 80.5% in flight of the initial concentration. Similarly, O₂ NBs decreased to 80.1% and 78.5%, while CO₂ NBs decreased to 66.7% and 69.4% under the same respective conditions. By contrast, samples stored with 50% HS exhibited greater losses: air NBs decreased to 70.8% (ground) and 68.2% (flight), O₂ NBs to 66.8% and 68.5%, and CO₂ NBs to 51.5% and 53.7%. These results confirm that headspace volume impact NBs lifetime via gas/liquid equilibrium and demonstrate that this mechanism is largely unaffected by transient gravity variations. No statistically significant differences were observed between ground and flight samples for all gas species tested. Across all gases, NBs were more stable under 0% HS than under 50% HS, underscoring the dominant role of HS, and consequently liquid supersaturation, in governing NBs persistence. The extent of NBs concentration loss is followed by the order CO₂ > O₂ > air, consistent with relative gas partial pressures in the HS, which are independent of gravity. Gas/liquid equilibria are governed by Henry's law, where partial pressure determines gas solubility. Thus, while agnostic to gravity changes, the supersaturation conditions led to a faster return to equilibrium for gases with lower partial pressure in the headspace, such as CO₂. In addition to NBs concentration, the size distribution provides a critical insight into whether NBs undergo growth or coalescence in a quiescent state. Figure 1d–f shows the NBs size distribution measured by NTA before and after storage under both ground and alternating gravity conditions. In both environments, and across all the gases tested (air, O₂ and CO₂), distributions remained below 400 nm, with no discernible deviations relative to initial stock solutions or between HS conditions (0% HS vs. 50% HS). These results demonstrate that, although total NBs concentration may decrease due to headspace equilibria, this does not necessarily correspond to measurable shifts in size distribution. The mean diameter, representing the dominant population peak, consistently remained near 100 nm and was independent of gas species. These observations indicate that NBs diameter is primarily determined by the nucleation and generation process, in which shear-driven formation at interfaces and rapid gas oversaturation define the initial bubble size. These mechanisms appear largely unaffected by gravity variations. This behavior is consistent with classical capillarity theory, which predicts that although buoyancy-driven phenomena are suppressed under microgravity, the thermodynamic principles governing curved gas–liquid interfaces, including surface tension, interface curvature, Laplace pressure, and Kelvin effects, remain unchanged and continue to govern bubble stability³⁴.

The observed agnostic behavior of NBs to transient gravity conditions in a quiescent state can be further rationalized by considering the underlying physics of buoyant forces. Under standard Earth gravity, a bubble experiences an upward buoyant force (δ) opposing its weight, which scales with the product of liquid density and gravitational acceleration, and can be expressed in simplified form as Eq. (1).

$$\delta = \sqrt{\frac{\rho g R_m}{(p_{amb} - p_v)}} \quad (1)$$

where ρ is the liquid density, g is the gravitational acceleration, R_m the maximum bubble radius, p_{amb} the ambient pressure, and p_v the saturated vapor pressure. The buoyant force determines the rising velocity and hence the persistence of a bubble in the solution. At 1 g, R_m is the only tunable parameter; decreasing the size reduces the rising velocity accordingly. The

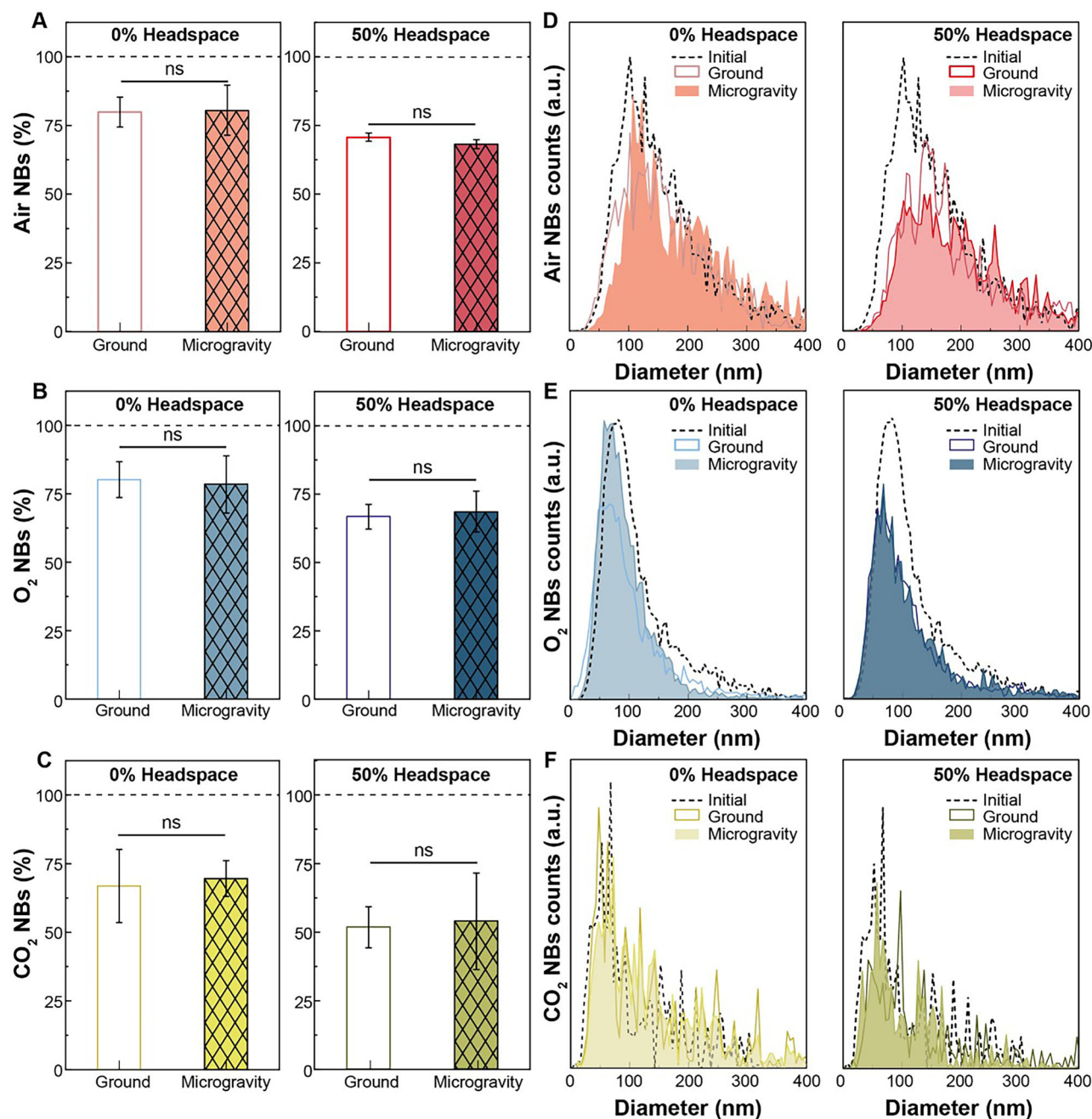


Fig. 1 | Nanobubbles stability analysis under different gravitational and headspace storage conditions. A–C Variation in NBs concentration. Percentage (%) of remaining NBs relative to initial stock (dashed line) after ground-control conditions (1 g) and alternating gravitational conditions (~0–1.8 g) for **A** air, **B** O₂, and **C** CO₂ NBs. **D–F** Size distribution of NBs under different gravitational and headspace

storage conditions. Diameter (nm) of NBs in stock solution (dashed line), ground-control, and alternating gravitational conditions samples for **D** air, **E** O₂, and **F** CO₂ NBs. Data were shown for 0 and 50% headspace. Statistical significance is indicated as follows: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$, and ns not significant, relative to the corresponding ground-control group.

negligible buoyancy effect on NBs, therefore, arises from their nanoscale radius. When pre-generated NBs of a given diameter are exposed to alternating gravity, their observed NBs stability indicates that changes in g are insufficient to produce measurable variations in NBs size or concentration. Even at 1.8 g, approximately double terrestrial acceleration, no significant variation was observed, consistent with the weak or negligible buoyancy at the nanoscale.

In the absence of buoyancy forces, particle dynamics are governed by interfacial and Brownian forces (Fig. 2a, b). As a result, NBs are not only gas/liquid interfaces but also behave like colloid dispersions, potentially exhibiting processes such as creaming, sedimentation, and/or random thermal

motion³⁵. According to Stokes' law, the settling (creaming) velocity (v_s) of a colloidal particle inside a liquid is given by Eq. (2).

$$v_s = \frac{2r^2(\rho_p - \rho_l)g}{9\mu} \quad (2)$$

where r is particle radius, ρ_p and ρ_l are particle and liquid densities, respectively, g is the gravitational acceleration, and μ is liquid viscosity. Under microgravity (~0 g), $v_s \rightarrow 0$, effectively eliminating creaming and sedimentation. In this environment, random thermal fluctuations dominate

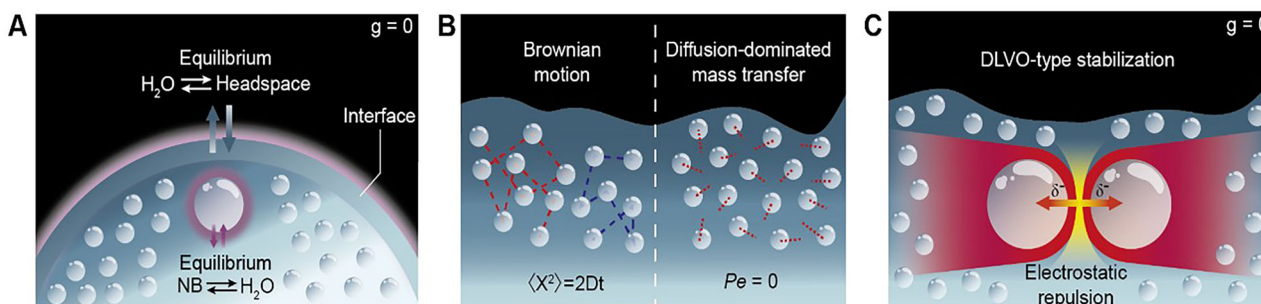


Fig. 2 | Driving forces governing nanobubble stability under microgravity. **A** Gas/liquid equilibrium at the interfaces. **B** DLVO-type stabilization (Derjaguin–Landau–Verwey–Overbeek). **C** Brownian forces and diffusion-controlled transport.

trajectories, and NBs behave as diffusive colloids governed solely by Brownian motion in a quiescent state.

To quantify the relative contribution of diffusion and gravity-driven transport, the Peclet number (Pe) is introduced. This dimensionless parameter compares the rates of advective (gravitational) and diffusive motion, see Eq. (3).

$$Pe = \frac{v_s r}{D} \quad (3)$$

where D is the Stokes–Einstein diffusivity. When $v_s = 0$ under microgravity, $Pe = 0$, indicating purely diffusive dynamics. Diffusion-controlled transport suppresses orthokinetic collisions and favors perikinetic interactions, promoting uniform dispersion and enhancing NBs stability (Fig. 2b).

Furthermore, while gravity influences macroscopic transport, the persistence of NBs is ultimately governed by nanoscale interfacial forces. According to the Derjaguin–Landau–Verwey–Overbeek (DLVO) framework³⁶, the total interaction energy (V_T) is the sum of electrostatic double-layer repulsion (V_{EDL}) and van der Waals attraction (V_{vdW}), as shown in Eq. (4).

$$V_T(h) = V_{EDL}(h) + V_{vdW}(h) \quad (4)$$

where h is interparticle surface separation. Although direct application of DLVO theory to NBs is still being refined, the consistently negative zeta potential and long-term stability reported for NBs support strong repulsion forces in existence, as it is consistent with DLVO-type stabilization (Fig. 2c).

These results explain the insignificant differences in NBs concentration and size distribution between flight and ground controls for pre-generated NBs under storage. Hypergravity experiments extend current understanding by demonstrating that NBs stability persists even under elevated accelerations, whereas microgravity provides an even more favorable regime for long-term preservation. Consequently, NBs dispersions represent robust, self-stabilizing gas/liquid systems ideally suited for space-based operations, where conventional micro- or macrobubbles approaches are hindered by coalescence. The observed persistence of NBs under both terrestrial and microgravity conditions does not necessarily imply that individual nanobubbles are indefinitely stable. A possible alternative hypothesis presented in the literature suggests a possible dynamic equilibrium where Laplace pressure-driven gas outflux is compensated by continuous gas influx, allowing a persistent nanobubble population to be maintained under nonequilibrium conditions³⁷. Accordingly, our results demonstrate that a solution with NBs of air, O_2 and CO_2 generated under standard Earth gravity conditions can be stored, loaded and subsequently used in space-flight applications, providing an effective means to enhance gas/liquid interactions and gas availability. For example, incorporating O_2 NBs into liquid propellants could potentially provide localized O_2 enrichment, enhance combustion kinetics, boost thrust efficiency, and cut propellant

weight (reduced vehicle mass), potentially improving overall rocket propulsion performance².

Nanobubbles can be generated under microgravity conditions

Building on evidence that NBs remain stable under alternating gravity regimes, an outstanding question is whether NBs can be generated in microgravity rather than merely maintained after formation on Earth. Earlier quiescent experiments, conducted without flow or recirculation, were inherently diffusion-limited and dominated by Brownian dynamics. By contrast, NBs generation systems driven by external forces (e.g., inlet/outlet flows, liquid recirculation, and pressurized gas sparging) introduce measurable velocities and thus forced convection, even in microgravity. Such a configuration more closely resembles terrestrial generation systems, enabling the simultaneous action of convective and diffusive mass transfer processes. Nanobubble technology can become a paradigm shift for the effective operation of gas starving systems under microgravity conditions, where gas/liquid mixing is extremely inefficient. Despite the technological relevance, the direct generation of NBs under microgravity has yet to be demonstrated, limiting their potential deployment in space-related applications. The generation of NBs under a microgravity environment were conducted in the atmosphere of the Earth by using the designed payload (Fig. 3a, b). Parabolic flight maneuvers conducted variations in altitude and speed that result in different acceleration profiles in which microgravity is produced for an interval of 15–25 s (Fig. 3c, d).

In order to assess the effective generation of NBs in microgravity equivalent conditions, gas injection events for NBs generation were performed exclusively during microgravity acceleration intervals, as depicted by the gray segments in the schematics of Fig. 4a for each parabola set (usually containing 5 parabolas). Note that hypergravity regions ($\sim 1.8 g$) were inactive phases of the experiment, during which no gas injection occurred.

Figure 4b–d showcase NBs concentration measured after successive parabolic cycles for different gases, where gas injection and subsequent NBs generation exclusively occurred during 15–25 s microgravity intervals within each 75 s parabola (i.e., ~ 20 s at $\sim 0 g$ and 40–50 s at $\sim 1.8 g$). Control measurements consisting of only water circulation yielded background counts of $0.183 \pm 0.017 \times 10^7$ particles mL^{-1} , confirming that the observed increases originated from NBs generation during microgravity. Similar background counts were observed for macrobubbles gas injection, demonstrating the lack of debris or particulates when injected from gas canisters into solution. Regardless of gas type, NBs were effectively generated under microgravity conditions, reaching values greater than 10×10^7 particles mL^{-1} , i.e., two orders of magnitude higher than control readings. For air NBs (Fig. 4b), concentrations increased from 5.4×10^7 particles mL^{-1} after the first parabola up to 9.9×10^7 particles mL^{-1} after the third. For O_2 NBs (Fig. 4c), the concentration rose from 9.2×10^7 after the first parabola to 15.5×10^7 particles mL^{-1} after five parabolas, while CO_2 NBs (Fig. 4d) increased from 7.7×10^7 to 13.8×10^7 particles mL^{-1} over the same number of cycles.

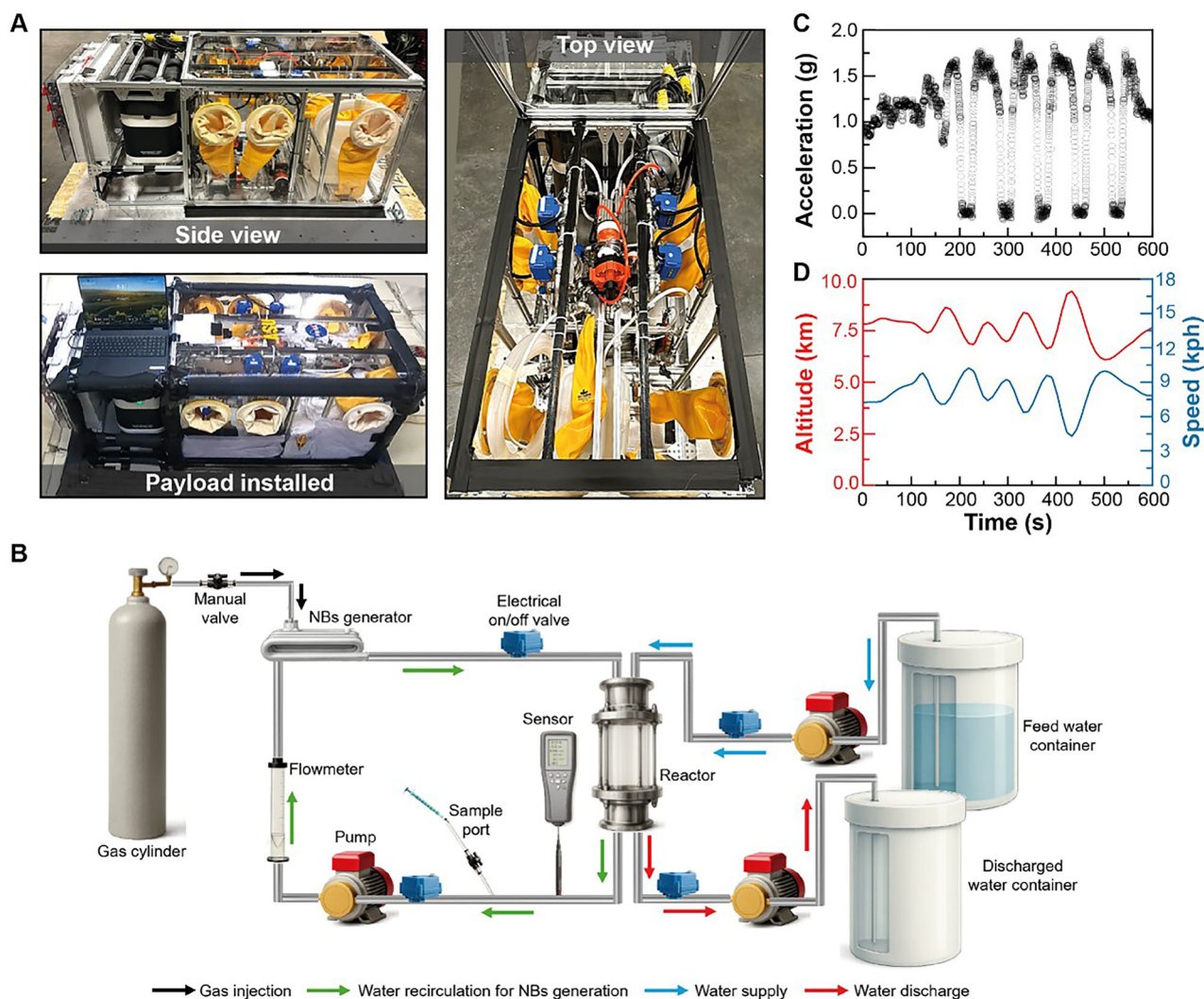


Fig. 3 | Experimental setup and operating conditions for nanobubbles generation under microgravity. **A** Payload used for nanobubbles generation under variable gravity. Principal components: two identical circuits of NBs generation isolated inside an acrylic box, a nanoparticle tracking analyzer (NTA) for in situ NBs characterization, electrical control panel. **B** Scheme of the circuit of nanobubbles

generation. Water containers are made of polystyrene, meanwhile the hydraulic connections of stainless steel. Arrows represent the flow direction of liquid and gas. **C, D** zero-gravity flight conditions. Variation of acceleration (g-force), altitude and speed of the flight during a set of parabolas.

The NBs generator used for these experiments enabled rapid formation and stabilization of NBs through a diffuser and static mixer operating under continuous water recirculation (3 L min^{-1}) and pressurized gas injection (30 psig). Unlike micro- and macrobubbles sparging methods, NBs dissolve almost immediately upon nucleation, delivering gas efficiently to the solution, and remaining stable within the liquid phase once gas supersaturation is achieved. In this configuration, both pressure and liquid flow contribute to convective transport, producing a coupled convection-diffusion mass transfer regime. The temporal and spatial distribution of NBs in the liquid under supersaturated conditions can be described by the convection-diffusion Eq. (5).

$$\frac{\partial C_{NB}}{\partial t} + \nabla \cdot (C_{NB} u) = D_{NB} \nabla^2 C_{NB} \quad (5)$$

where C_{NB} is NBs concentration, t is time, u is the liquid velocity, and D_{NB} is the NBs diffusivity determined by Brownian motion. Beyond bulk transport, interfacial effects also contribute to NBs distribution. Marangoni forces, which are fluid flows triggered by surface tension along a gas/liquid interface, drive motion from regions of low surface tension towards regions

of high surface tension, generating interfacial shear and bulk circulation. Under microgravity, where buoyancy-driven convection is absent, solutal Marangoni forces arising from concentration gradients become particularly significant. These forces facilitate the lateral dispersion of newly formed NBs and help suppress coalescence after generation. In addition, NBs acquire a negative ζ -potential upon nucleation, and the resulting electrostatic repulsion further prevents coalesce, a mechanism that remains effective under microgravity conditions.

Limited and inefficient gas/liquid mass transfer in microgravity is one of the most fundamental constraints in space systems, and a pitfall for many essential technologies. Because buoyancy is nearly nonexistent under microgravity, bubbles do not rise, and fluids do not stratify, demoting gas delivery into liquids as inefficient or impossible. As a result of this limitation, many technologies that rely on efficient gas/liquid exchange on Earth become restricted or inoperative in space, such as algae bioreactors, microbial bioreactors, food production systems that need plant root-zone aeration, water treatment processes, CO_2 reduction systems, H_2O_2 electrogeneration technologies, or propellant management, among others. The integration of NBs technology can become a massive breakthrough and a

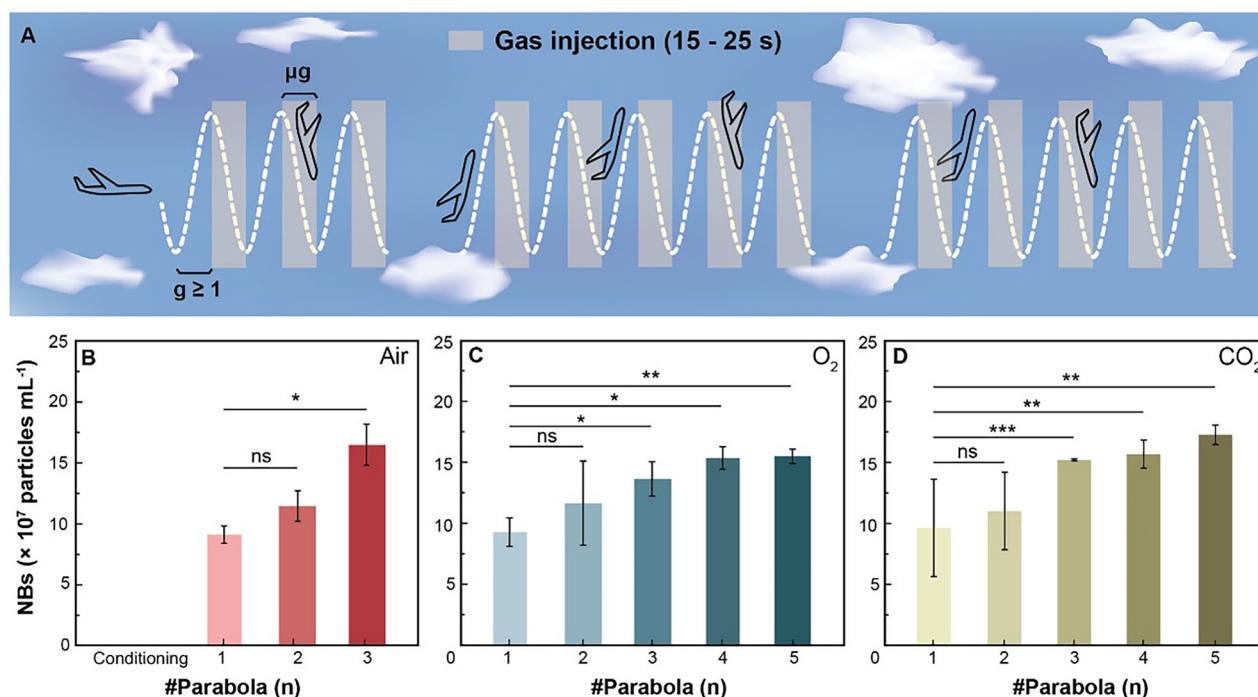


Fig. 4 | Generation of nanobubbles under microgravity. A Schematic of the parabolic flight profile showing gray zones corresponding to gas injection during microgravity intervals. B–D NBs concentration measured after successive parabolas

for B air ($n = 3$), C O₂ ($n = 5$), and D CO₂ ($n = 5$). Statistical significance relative to parabola 1 of each group is indicated as follows: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$, and ns not significant.

game changer for these extremely needed technologies to advance space exploration goals.

After establishing that NBs can be directly generated under microgravity, the next objective was to assess whether their gas/liquid mass transfer performance remains comparable to ground operation. This question is particularly relevant for gas-limited systems, where mass transfer is often constrained by insufficient renewal of the liquid boundary layer, a key challenge for multiphase reactors that conventionally rely on turbulence to sustain mass exchange. The volumetric mass-transfer coefficient ($k_L a$) typically decreases under reduced gravity because turbulence is diminished. Indeed, modeling studies of multiphase unit operations predict $k_L a$ reduction to 0.64 and 0.79 times the terrestrial value for lunar and Martian gravity, respectively³⁸.

To evaluate mass-transfer performance under microgravity conditions, dissolved oxygen (DO) and pH were monitored in real time during O₂ and CO₂ NBs generation, respectively. In each case, the $k_L a$ was determined and compared to a ground-control experiment performed under identical operating conditions at standard Earth gravity (1 g). On the ground, DO increased to ~40 mg L⁻¹ within 2 min, corresponding to $k_L a = 0.108$ s⁻¹. Whereas under microgravity conditions, DO followed a nearly identical trajectory, yielding $k_L a = 0.125$ s⁻¹ (Fig. 5a). Similarly, for CO₂ NBs, $k_L a$ values were 1.3×10^{-3} and 1.9×10^{-3} s⁻¹ on the ground and microgravity conditions, respectively (Fig. 5b). The nearly identical evolution of DO and pH under both gravity conditions demonstrates that gas dissolution and NB generation are governed by cumulative gas injection rather than transient changes in gravity during experiments. Accordingly, the progressive decrease in pH during CO₂ injection at two time intervals and the corresponding increase in NB concentration (see Fig. 4) confirm that the accumulation of NBs resulted from repeated gas injection, while microgravity does not significantly alter the generation process. These results demonstrate that NBs can be effectively generated in microgravity (Fig. 5c, d) with mass-transfer performance comparable to and even slightly exceeding terrestrial benchmarks. This behavior can be attributed to the constancy of hydrodynamic conditions ($Re_{1g} = Re_{0g}$), which maintains equivalent

interfacial renewal rates and therefore similar $k_L a$ values during NBs generation (Fig. 5e). Limited and inefficient gas/liquid mass transfer in microgravity is a fundamental constraint in space systems and a major bottleneck for numerous essential technologies. Gas-starved systems, including algae and microbial bioreactors that require sustained gas exchange³⁹, proper for plant root-zone aeration for food production^{40,41}, propellant management², water treatment⁴², and emerging technologies such as CO₂ storage and revitalization^{43,44} or sustainable H₂O₂ electrogeneration⁴⁵, rely on efficient gas/liquid exchange and become severely restricted or inoperative in space due to the limitations of conventional sparging methods. The demonstration of efficient gas supersaturation, beyond mere NB persistence, therefore, represents a potential breakthrough with the capacity to transform these critical technologies and advance space exploration objectives. The results presented here establish, for the first time, NBs as a suitable platform for gas/liquid processes in space.

Nanobubbles can be generated during variable-gravity conditions

The parabolic flight profiles of our experimental conditions provided a unique opportunity to assess the capacity of current technology to produce NBs under continuous transitions between microgravity and hypergravity. This condition is representative of real spaceflight environments during launching, where fluctuating gravitational accelerations are inevitable. Evaluating NBs generation under such variable-gravity conditions is therefore essential to determine their robustness and applicability for space technologies.

To this end, experiments were conducted in which gas injection was maintained through the entire parabolic maneuvers ($n = 5$), allowing NBs generation across both microgravity and hypergravity conditions. Figure 6a shows a representative parabolic flight profile, with the gray zone indicating continuous gas injection throughout parabolic transitions. Under these conditions, NBs concentrations of air, O₂ and CO₂ increased steadily across parabolas until reaching steady-state concentrations (Fig. 6b–d), as is usually observed during NBs generation. Although the number of parabolas

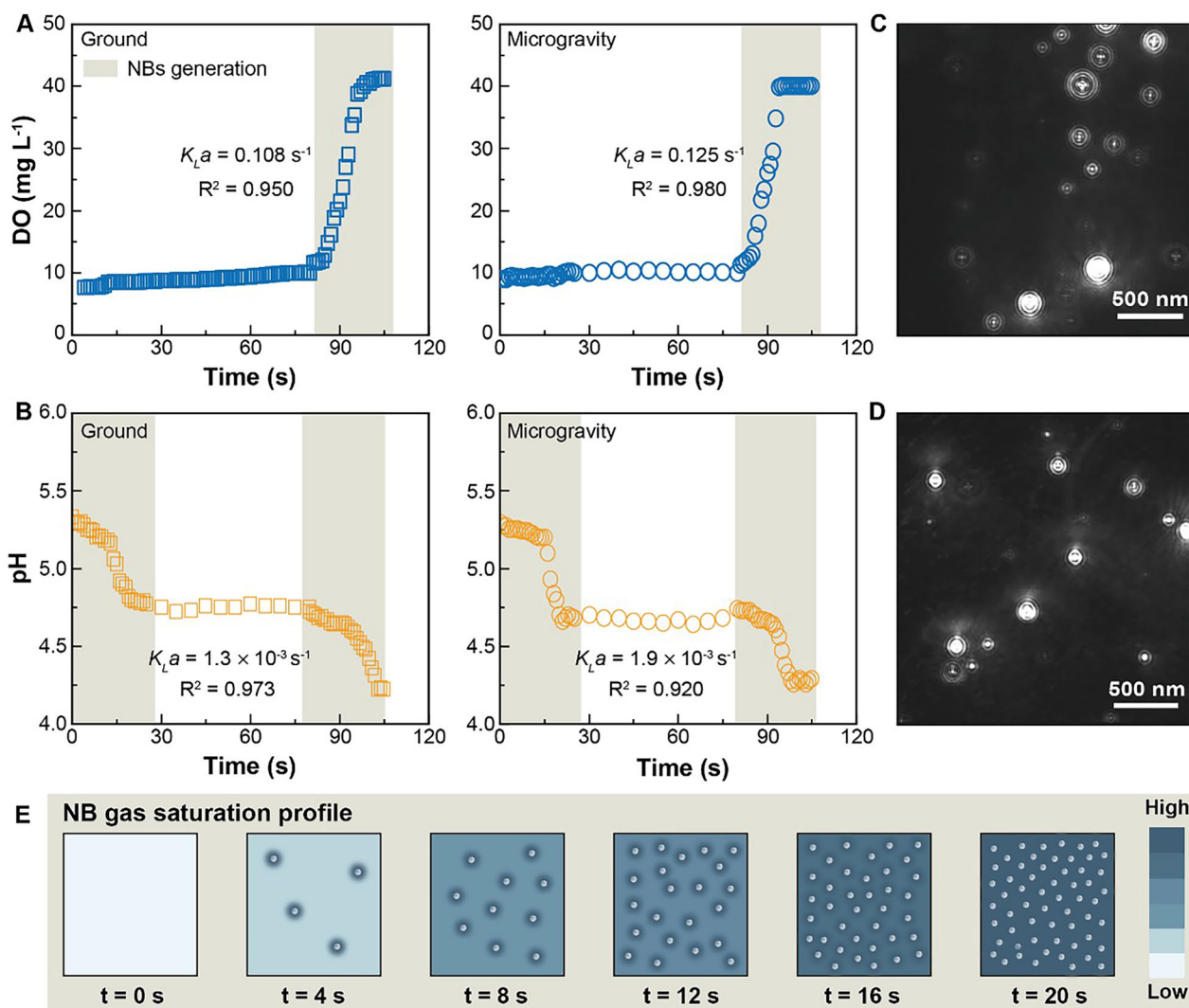


Fig. 5 | Volumetric mass-transfer coefficients of nanobubbles under microgravity. **A** Dissolved oxygen (DO, mg L^{-1}) profiles during O_2 NBs generation under ground-control conditions and microgravity. **B** Variation of pH during CO_2 NBs generation under ground-control conditions and microgravity. Values of mass

transfer coefficient ($K_L a$) with corresponding R^2 values for each condition tested. **C**, **D** Nanoparticles Tracking Analysis (NTA) images of **C** O_2 and **D** CO_2 NBs generated under microgravity after the first set of parabolas. **E** Scheme of gas saturation and NBs profile during the generation of NBs under microgravity.

tested for each gas varied due to flight-path constraints, statistically significant differences were observed between the 1st, 2nd, and 3rd parabolas ($p < 0.01$), reflecting rapid gas supersaturation ($< 5 \text{ min}$) and continuous NBs formation.

The continuous increase in NBs concentration despite alternating g -force levels indicates that the controlling mechanisms are largely independent of gravitational acceleration, buoyancy, or hydrostatic effects. Instead, gas dissolution and shear-induced breakup dominate the NBs generation, with bubble stability governed by Henry's law and local hydrodynamics within the static mixer. This suggests a two-step mechanism during continuous generation under variable gravity. First, gas was dissolved into liquid according to Henry's law, saturating local volumes and forming transient micro-nanobubbles, and second, shear and pressure gradients generated within the static mixer further fragmented these bubbles into stable and persistent NBs. Because both steps depend on interfacial physics rather than gravity, NBs generation proceeds unaffected by g -force fluctuations, explaining the consistent increase throughout the parabolic sequence. It is important to note that alternative NBs generation systems, based on mechanisms such as cavitation⁴⁶, membrane sparging⁴⁷, or electrochemical gas evolution⁴⁸, may exhibit different sensitivities to gravitational variation and warrant further investigation.

Implications of present experiments

Gas/liquid mass transfer remains a central challenge for spacecrafts operations and space exploration, as transport phenomena differ markedly between terrestrial conditions. Systems that depend on efficient gas/liquid contacting designed for Earth often exhibit reduced performance, longer operational times, or fail entirely in microgravity. NBs offer a promising solution due to their nanoscale size, high interfacial area, rapid gas dissolution, and resistance to coalescence, yet experimental evidence for their generation and stability in space-relevant environments has been lacking.

Here, we provide the first integrated evaluation of air, O_2 , and CO_2 NBs under microgravity simulated by parabolic flights through three-regime experimental framework: (i) stability of ground generated NBs to microgravity and hypergravity, (ii) direct NBs generation during microgravity, and (iii) continuous generation under alternating gravitational acceleration. NBs generated on Earth remained stable across variable gravity (from ~ 0 to $\sim 1.8 \text{ g}$) and headspace volumes (0% or 50%), confirming that their persistence is governed by gas/liquid equilibrium rather than gravity. Their mean diameter ($\sim 100 \text{ nm}$) and long-term stability are dictated by interfacial physics and electrostatic repulsion, consistent with DLVO-type colloidal behavior.

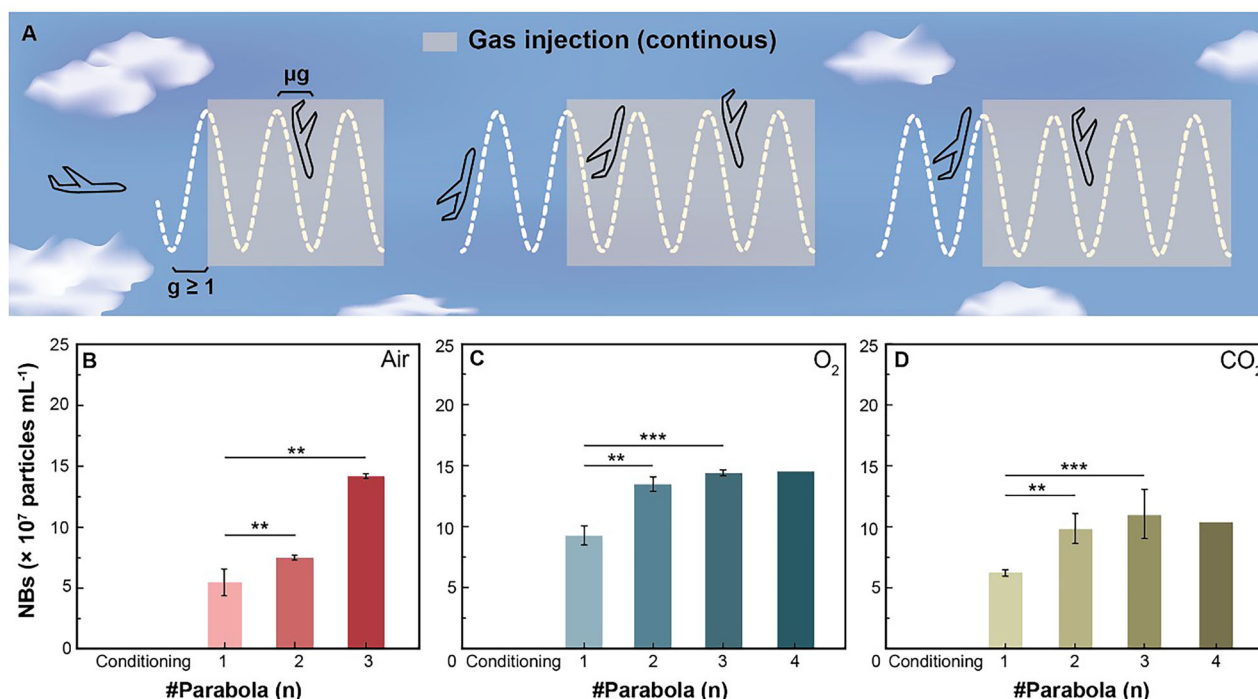


Fig. 6 | Generation of nanobubbles under variable gravity. A Schematic of parabolic maneuvers flight profile showing gray zones corresponding to gas injection during microgravity intervals. B–D NBs concentration measured after successive

parabolas for **B** air ($n = 3$), **C** O₂ ($n = 4$), and **D** CO₂ ($n = 4$). Statistical significance relative to parabola #1 of each group is indicated as follows: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$, and ns not significant.

We demonstrate for the first time direct NBs generation under microgravity, with concentrations increasing steadily across successive parabolas volumetric mass-transfer coefficient ($k_L a$) comparable to standard Earth gravity benchmarks. Sustained NBs generation under variable-gravity conditions confirmed that NBs formation in static mixers is primarily governed by rapid gas dissolution and shear-induced fragmentation, independent of g -force.

This work establishes NBs as a gravity-agnostic platform for space applications, enabling efficient gas/liquid contacting and dissolution. The demonstrated stability, generation, and performance of simple NB generators, driven by shear and turbulence, under microgravity, hypergravity, and variable-gravity conditions highlight their robustness. These findings open new opportunities for implementing NBs technologies in life-support systems, bioreactors, and interfacial chemistry for future space missions, and redefine design principles for gas/liquid systems in reduced-gravity environments, enabling compact, efficient, and reliable operation beyond Earth.

Methods

Chemicals

Ultrapure distilled water was used as a liquid matrix for the generation of NBs. The gases injected into the system were supplied by MESA Specialty Gases and Equipment (US). Cylinders of 103 L at 1000 psig were used: Air zero (99.99%), HP Oxygen (O₂ 99.99%), and carbon dioxide (CO₂ 10% balanced with N₂).

Payload design

The payload was designed to contain two independent NBs generation lines for duplicate testing, the electrical control circuit and the analytical equipment for NBs in situ quantification (Fig. 3a). The assembly of the NBs generation system was based on previously optimized set-ups at lab scale. The system was assembled within a secondary containment to provide a physical barrier to capture any leaked liquid, preventing it from escaping into the spacecraft cabin during parabolic flight testing. The secondary

containment was built as a glovebox-like enclosure, providing access for system operation, sample collection, and sample injection into the NTA. The entire payload assembly was affixed to an aluminum base plate, which was firmly bolted to the cabin structure to ensure mechanical stability during operation. Furthermore, the whole structure and assembly were designed to withstand g -loads of up to 9 g applied to the equipment's centers of gravity in all directions (i.e., forward, aft, down, lateral, and up).

The system schematics for NBs generation illustrated in Fig. 3b include three main subsequent processes: (1) feed of the ultrapure distilled water (~ 1 L) to the stainless-steel reactor, (2) NBs generation, and (3) discharge of the NBs solution into a waste container. Process (2) involved the recirculation of the water (3 L min⁻¹) between the reactor and the NBs generator (Gaia UFB), where the gas is injected (30 psig) by a diffuser to create microbubbles, which were then transported through the internal static mixer that converts them into NBs via shear forces. The system hydraulics were based on diaphragm pumps (SEAFLO SFDP1-050-070-56A) and electrically actuated on/off valves (US Solid USS-MSV00038), all controlled via an electrical panel equipped with action buttons for on, off and an emergency shut-down. Gas injection, sample withdrawal, and analysis injections were performed manually, resulting in a hands-on approach during ground and microgravity experiments.

Experimental procedures for nanobubble generation and stability assessment

The system was flushed several times with ultrapure distilled water on the ground to minimize background noise, achieving baseline concentration $< 10^7$ particles mL⁻¹. The NBs generation was then assessed under both ground and microgravity conditions. Each zero-gravity flight comprises several sets of parabolas performed by Zero-Gravity Corporation, with 4–6 parabolas per set depending on the aerospace flight conditions. Altitude, aircraft speed, and gravitational acceleration were monitored in real time, with microgravity intervals identified for each parabola set, as shown in Fig. 3c, d. Acceleration was tracked using an onboard accelerometer (WitMotion Model WT901BLECL), while altitude and speed were obtained from

FlightAware for flight VTS7773. During parabolas, acceleration rapidly fluctuated between microgravity (~ 0 g for ~ 25 s) and hypergravity (~ 1.8 g during 45 s). The NBs generation under microgravity was carried out in two groups: (i) restricted to the microgravity interval within each parabola, and (ii) continuous throughout the entire parabola set, encompassing transitions between micro- and hypergravity. In experimental group (i), the first parabola was critical, as it best emulates true space microgravity conditions and therefore is essential to isolating NBs generation under microgravity. Subsequent parabolas included varying g -levels. Experiments were performed in duplicate, with two sets of parabolas per group and three gases (air, O_2 and CO_2). Error bars represent standard deviation. Ground-level experiments were conducted under equivalent conditions for comparison.

A solution of NBs generated at ground level the day before the flight was used to assess their stability under microgravity conditions. Equal volumes of the solution were stored in glass containers (40 mL) with 0 and 50% of headspace (HS), hermetically sealed, and covered with thermal insulation foam to minimize the impact of temperature fluctuations. Two sets of identical samples were prepared for each HS condition, with three identical vials per set (triplicates). One set was stored on the ground, while the other accompanied the flight. NBs concentrations were measured one day before the flight and post-flight for both the ground-stored and microgravity-exposed samples. The stability of NBs was evaluated for all three gases tested, i.e., air, O_2 , and CO_2 .

Nanobubbles characterization and quantification

The short duration of microgravity conditions experiments (~ 25 s per parabola) dictated sample collection and measurement during flight. Samples from the NBs solution were taken during the microgravity interval of each parabola. In situ measurements conducted during microgravity yielded values similar to those obtained post-flight in underground conditions. Only measurements alternating between the two payload lines (A and B) were performed in microgravity conditions. Nevertheless, all samples were subsequently analyzed after the flight (including those measured in microgravity).

The NBs concentration and size distribution were measured using a Nanoparticle Track Analyzer (NTA, NanoSight Pro 300, Malvern Panalytical), which calculates NBs diameters in the 10–1000 nm range from Brownian motion. Concentration of NBs were quantified using the instrument's dynamic observation algorithm, suitable for 10^6 to 10^9 particles mL^{-1} . Quality control included ultrapure water as a negative control that represents particle-free liquid. Measurements were performed under optimized settings for camera level, threshold, brightness, and contrast.

Physical-chemical analysis of water samples

For O_2 and CO_2 NB generation, dissolved oxygen (DO) and pH were monitored as indicators of the gas saturation inside the bulk liquid. The DO was measured using a ProQuatro probe (YSI, Xylem Inc.), employing an electrochemical polarographic sensor comprising an anode and a cathode in an electrolyte solution (Na_2SO_4 , KCl, YSI formulation) separated from the sample by an oxygen-permeable membrane (YSI 5908). The pH was measured by a ProQuatro probe (YSI, Xylem Inc.) based on an ion-selective measurement mechanism.

Statistical analysis

Data were presented as mean values $\pm$ standard deviation (SD) from triplicate measurements of experiments conducted in duplicate. For stability assessment, the concentration of NBs was statistically compared to the corresponding initial concentrations using two-tailed unpaired t -tests assuming unequal variances, with significance defined at 95% ($\alpha = 0.95$).

Data availability

All data supporting the findings of this study are available within the paper.

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Competing interests

The authors declare no competing interests.

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