Supplementary material to: ”Effusive sedimentary volcanism experimentally reproduced under Martian-like conditions”

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1 Mud Ejection Ballistics Model

To simulate and quantify the potential distribution of liquid mud portions, from single droplets to larger effusions around the extrusion site, we employed a simple analytical-numerical model. The model consists of three levels. The first calculates the initial velocity based on Bernoulli's principle (Bernoulli, 1738; Kundu et al., 2024; NASA GRC, 2024; Milne-Thomson, 1973; Fuchs et al., 1965), modified for volcanic extrusions (Gonnermann, 2019; Jones et al., 2019; Petford et al., 1994). This velocity serves as the input for the second stage, the modeling ballistic trajectories using a simple ballistic model with drag. The third level is designed to estimate (in flight) cooling, and the state of the mud when impacting the substrate.

All experimental conditions and model calculations assume a surface pressure of 4.5 mbar (Mars-like), and the experimental approach is not designed to operate at Earth atmospheric pressure (does not allow pressurization of the mud reservoir) — standard pressure prevents the pressure-driven mud ejections from occurring. The Earth-gravity cases (Cases 1–2; experiments Exp1 and Exp2) therefore represent experiments conducted at 4.5 mbar in the Earth laboratory ($g = 9.81\ m/s^2$), while the Mars-gravity cases (Cases 3–4, no experimental counterpart) represent corresponding conditions under the Martian gravity ($g = 3.71\ m/s^2$).

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The velocity calculation, based on Bernoulli's principle, incorporates parameters of mud properties, gravity, and surface pressure but neglects phase changes. It assumes only the pressure difference in the conduit and uses an effective density parameter, which accounts for voids present and void-induced volumetric expansion. We did not simulate any droplet interactions above the conduit or their fragmentation, keeping the calculations as simple as possible.

The ballistics model uses the calculated velocity as input and investigates size fractions of ejected mud droplets in the range of 0.5 to 40 mm. Droplets sized 0.5 to 5 mm are assumed to represent the explosive (Strombolian) stage when the conduit is open (estimated optically from experiments). Larger droplet sizes, 10 to 40 mm, correspond to the effusive (or transient) stage, in which pressure stabilizes and mud is extruded in a more Hawaiian-like eruption style (also evidenced from experiments). Ballistic trajectories are calculated for the full range of ejection angles and specifically visualized for 15°, 45°, and 85°.

An important parameter in this model is the velocity attenuation factor, which empirically scales the initial velocity to match the observed maximum trajectory amplitude (0.5–1 m above the tray; given by limiting size of the chamber). Our implementation also allows this factor to be disabled, yielding the unscaled solution in which ballistic paths develop in unconstrained free space.

Finally, the impact density zones are calculated for initial ejection angles ranging from 5° to 85°.

Governing Equations

Bernoulli Equation for Ejection Velocity

The initial ejection velocity is derived from Bernoulli's principle along a streamline:

$$v_0 = \sqrt{\frac{2\Delta P}{\rho_{\text{eff}}}}, \quad \rho_{\text{eff}} = (1-\alpha_{\text{void}})\rho_{\text{mud}} + \alpha_{\text{void}}\rho_{\text{gas}} \tag{1}$$

where $\Delta P \approx 1 \times 10^5$ Pa (more precisely, $10^5 - 450 \approx 9.96 \times 10^4$ Pa) is the pressure difference between the mud reservoir — sealed at approximately atmospheric pressure during sample preparation — and the surface pressure of 4.5 mbar (450 Pa) inside the vacuum chamber; $\rho_{\text{mud}} = 1020\,\text{kg/m}^3$; $\alpha_{\text{void}} = 0.7$ is the void fraction; and $\rho_{\text{gas}} = 0.01\,\text{kg/m}^3$ to $0.001\,\text{kg/m}^3$ (CO_2 vs. water vapour). The ρ_{gas} term is negligible relative to $(1-\alpha_{\text{void}})\rho_{\text{mud}}$ and is retained only for completeness. The high void fraction reflects the foam-like state of the mud–gas mixture resulting from rapid boiling and vigorous degassing upon exposure to 4.5 mbar surface pressure, as directly observed in post-experimental snapshots. Because $v_0 \propto (1-\alpha_{\text{void}})^{-1/2}$, varying α_{void} over the plausible range 0.5–0.8 changes v_0 (and hence the tabulated ranges) by roughly −25% to +22% relative to the nominal value of 0.7; the qualitative conclusions on Mars-vs-Earth scaling are unaffected. We assume the reservoir remains at 1 atm at the moment of conduit opening, because the ice crust acts as a near-impermeable seal on the relevant (second-scale) timescale of conduit opening.

Empirical scaling yields the following stage-specific velocities: explosive stage $v_{\text{stage1}} = At \cdot v_0 = 2.6\,\text{m/s}$–$3.8\,\text{m/s}$; effusive stage $v_{\text{stage2}} = At \cdot v_0 = 1.3\,\text{m/s}$. Here, the attenuation factor At is defined as

$$At = \frac{h_{\text{observed}}}{h_{\max}},$$

where $h_{\max}$ is the theoretical maximum height derived from the Bernoulli velocity assuming ideal ejection conditions, and h_{observed} is the maximum experimentally observed trajectory height of a 1 mm diameter droplet ejected at approximately 85° (explosive phase: $At = 0.10$–0.15; effusive phase: $At = 0.05$). The velocities are thus scaled to match observed features in the experiments, constraining the ballistic trajectories to remain relevant within the experimental tray.

We emphasise that At is a lumped empirical correction that absorbs (i) unmodelled drag in the small-droplet (low-Re) regime, (ii) departures of the mud–gas foam from the idealised effective density, (iii) conduit-geometry losses, and (iv) any non-Bernoulli effects. It is not a pure drag factor.

We note that while our workflow and scripts are configured for the specific conditions of the experiments performed, the method is readily adaptable to broader theoretical modelling based purely on Bernoulli's principle (by disabling the factor At) and to parametric studies spanning a wide range of reservoir and conduit conditions.

Ballistic Trajectory ODE with Drag

The droplet trajectory $\mathbf{r}(t) = (x(t), y(t))$ is governed by the second-order ODE, integrated numerically as a first-order system in `ode45`:

$$\frac{d^2\mathbf{r}}{dt^2} = \mathbf{g} - \frac{1}{2} C_d \rho_{\text{air}} \frac{A}{m} v^2 \hat{\mathbf{v}}, \quad \begin{array}{l} A = \pi \left(\dfrac{d}{2}\right)^2, \quad m = \dfrac{4}{3}\pi \left(\dfrac{d}{2}\right)^3 \rho_{\text{mud}} \\ \mathbf{v} = [v_x, v_y], \quad v = |\mathbf{v}|, \quad \hat{\mathbf{v}} = \mathbf{v}/v \end{array} \tag{2}$$

The system is integrated from initial conditions $\mathbf{r}(0) = (0.22,\ 0.22)$ m and $\mathbf{v}(0) = v_s(\cos\theta,\ \sin\theta)$, where $v_s = v_{\text{stage1}}$ or v_{stage2} is the attenuated initial velocity for the relevant eruption stage and θ is the ejection angle. The origin corresponds to the position of the conduit opening above the experimental tray. The remaining parameters are: $C_d = 0.47$, the drag coefficient for a smooth sphere in the non-turbulent regime; A, the droplet cross-sectional area [m^2]; d, the droplet diameter [m], varied as an input parameter under the simplifying assumption that it remains constant during flight (i.e. no modification by wind, evaporative cooling, or other factors); m, the droplet mass [kg]; $\rho_{\text{air}} \approx 0.0085\,\text{kg/m}^3$ (CO_2 at 4.5 mbar, $T \approx 281\,\text{K}$; see Eq. 10); and $g_{\text{Earth}} = 9.81\,\text{m/s}^2$, $g_{\text{Mars}} = 3.71\,\text{m/s}^2$. Integration proceeds via `ode45` with an event function that terminates integration at ground impact ($y = 0$).

We note that at 4.5 mbar ($\rho_{\text{air}} \approx 0.0085$ kg/m^3), aerodynamic drag forces are small relative to gravity for all droplet sizes considered: drag deceleration is less than 2% of g for $d \geq 5$ mm. For the smallest droplet fractions, where Re ~ 1–12 and the physical drag coefficient would exceed 0.47, the empirical attenuation factor At — calibrated to observed trajectory heights — implicitly compensates for any drag-model sensitivity. The choice of C_d therefore does not materially affect the computed trajectories.

Impact Density Field

For full-circle envelopes around the extrusion site $(x_0, y_0) = (0.22, 0.22)$ m we adopt a Gaussian envelope as a smooth and radially symmetric approximation to the probability density of impact. Each (θ, d) channel contributes a normalized kernel centered on the source, with width set by its ballistic range $r_{\max}(\ theta, d)$:

$$\rho_{\text{impact}}(\mathbf{r}) = \sum_{\theta,d} \exp\left(-\frac{r^2}{2r_{\max}(\theta, d)^2}\right) \mathbb{1}_{r \le r_{\max}} \tag{3}$$

where $r = |\mathbf{r} - \mathbf{r}_0|$, $r_{\max}(\theta, d)$ from the ballistic range, $\theta \in [5°, 85°]$.

Computational Algorithm

The mud impact zones are computed through the following mathematical procedure (applied in MatLab 2024a environment):

1. **Bernoulli velocity computation**:

$$v_0 = \sqrt{\frac{2\Delta P}{\rho_{\text{eff}}}}, \quad v_{\text{stage1}} = At_1 v_0, \quad v_{\text{stage2}} = At_2 v_0 \tag{4}$$

2. **Full angular sweep** over four conditions $C_k = (g_k, v_k, D_k)$, $k = 1, 2, 3, 4$:

$$\begin{aligned} g_1 = g_2 = 9.81 \text{ m/s}^2 \quad (\text{Earth}), \quad g_3 = g_4 = 3.71 \text{ m/s}^2 \quad (\text{Mars}) \\ D_1 = D_3 = \{0.5, 5\} \text{ mm} \quad (\text{Explosive}), \quad D_2 = D_4 = \{10, 40\} \text{ mm} \quad (\text{Effusive}) \end{aligned} \tag{5}$$

3. **Ballistic range field** for each $(d, \theta) \in D_k \times [5°, 85°]$:

$$r_{\max}(d, \theta) = \min\left(0.45, \max\left[\mathbf{y}_{\text{traj}}(d, \theta, g_k, v_k)\right]\right) \tag{6}$$

where $\mathbf{y}_{\text{traj}}$ solves Eq. (2) with $\mathbf{y}_0 = [0, v_k \cos\theta, 0, v_k \sin\theta]$.

4. **Impact density field** on 90×45 grid $\Omega = [0, 0.9] \times [0, 0.45]$ m:

$$\rho_k(x, y) = \sum_{d \in D_k} \sum_{\theta=5°}^{85°} \exp\left(-\frac{r(x, y)^2}{2r_{\max}(d, \theta)^2}\right) \mathbb{1}_{r \le r_{\max}} \tag{7}$$

with $r(x, y) = \sqrt{(x - x_0)^2 + (y - y_0)^2}$, $(x_0, y_0) = (0.22, 0.22)$ m.

5. **Normalized visualization**: $\tilde{\rho}_k = \rho_k / \max(\rho_k)$, plotted by $\texttt{contourf}(\tilde{\rho}_k, 12)$.

The four resulting impact density fields $\tilde{\rho}_k$ $(k = 1, 2, 3, 4)$ quantify the spatial distribution of mud deposition around the extrusion site for each physical condition.

Model Parameters and Results

Table 1: Input Parameters

Parameter	Value	Description
ΔP	10^5	Pressure drop between reservoir and chamber surface (Pa)
ρ_{mud}	1020	Mud density (kg/m^3)
ρ_{air}	0.0085	Mars atmosphere, CO_2 at 4.5 mbar (kg/m^3)
C_d	0.47	Drag coefficient (sphere)
α_{void}	0.7	Void fraction
(x_0, y_0)	(0.22,0.22)	Extrusion site (m)
Domain	0.9×0.45	Topography view

Table 2: Tested Conditions (4 Cases)

Case	Gravity (m/s^2)	Stage	v_0 (m/s)	Fractions (mm)	Angles
1	9.81	Explosive	3.8	0.5, 5	5°-85°
2	9.81	Effusive	1.3	10, 40	5°-85°
3	3.71	Explosive	3.8	0.5, 5	5°-85°
4	3.71	Effusive	1.3	10, 40	5°-85°

* The initial velocities are shown after the modification by the attenuation factor A_t. Full (Bernoulli-principle calculated) velocity is $\sim 25\ m.s^{-1}$.

Table 3: Expected Maximum Ranges

Condition	$r_{\max}$ (m) Small fraction	Large fraction	Avg. Spread[a](m)	Max. Distance[b](m)
Earth Explosive	0.35	0.25	0.40	0.65
Earth Effusive	0.15	0.10	0.20	0.17
Mars Explosive	0.60	0.45	0.65	1.62
Mars Effusive	0.25	0.18	0.30	0.47

[a] Mean radial extent of the 50% impact density contour.
[b] Furthest landing point at optimal ejection angle.
[c] Explosive $v_0 = 3.8$ m/s is the upper bound of the calibrated range (2.6–3.8 m/ s); it maximises TOF and hence gives the most conservative (largest) cooling estimate in Section 2.

Both the velocity and ballistics calculations are available to be reproduced by the attached scripts (`ballistics_model` and `radial_distribution`).

2 Mud Droplet Cooling During Ballistic Ejection (4.5 mbar)

As the next stage, we applied a simple thermal model(s) to estimate if the mud droplets are able to cool down and freeze before touching the sand surface. We assume initial temperature to be 8 °C which is in a correspondence to measurements from mud reservoir before melting and conduit opening to 4.5 mbar atmosphere. Model is a simplified approximation based on works of Siegel (2002); Renksizbulut and Yuen (1983); Ranz and Marshall (1952) or technical literature (NASA, 1988; Incropera et al., 2011; Dombrovsky, 2011).

Our model is lumped-capacitance, single-particle approximation using the total time of flight from the ballistic model. That approach is chosen because droplet fragmentation and detailed drag evolution are unknown.

In the first place, we focus on convective and radiative estimates which describe the bulk heat loss. However, the expected and most dominant (low-pressure)-induced evaporative cooling is treated as an addition to this simple model. Due to simplifications made due to uncertainties in complexity of droplet shape and evaporative response, we provide only a brief estimation at the end of this chapter.

Input Parameters

Table 4: Thermal model settings - simplified estimation

Parameter	Value	Unit	Description
ρ_{mud}	1020	kg/m^3	Mud density
T_0	8	°C	Initial temperature
P	4.5	mbar	Ambient pressure
T_{amb}	-50	°C	Ambient temperature
$c_{p,\text{mud}}$	4200	J/kg·K	Specific heat capacity
k_{air}	0.015	W/m·K	Thermal conductivity
v_{stage1}	3.8	m/s	Explosive velocity
v_{stage2}	1.3	m/s	Effusive velocity
g_{Earth}	9.81	m/s^2	Earth gravity
g_{Mars}	3.71	m/s^2	Mars gravity
d_{small}	1	mm	Small droplet diameter
d_{large}	20	mm	Large droplet diameter

Convective cooling model

Governing Equations

Equations use the calculated TOF (Time Of Flight) of the mud droplets, allowing to use the full or simplified (bellow case) ballistic calculations without drag. Further, the thermal response in thin atmosphere is approximated first through the purely convection model, followed by radiation cooling extension (see below). The effects of the evaporative cooling are discussed at the end of this section.

1. Time of Flight ($45°$ maximum range, no drag, upper bound)

$$t_f = \frac{2v_0\,At\sin\theta}{g} \overset{\theta=45°}{=} \frac{\sqrt{2}\,v_0\,At}{g} \approx 1.414\,\frac{v_0\,At}{g} \tag{8}$$

where the At is the velocity attenuation factor, v_0 is the initial velocity calculated by Bernoulli's principle, g is the gravitational acceleration, and θ is the angle of the droplet ejection.

Equation (8) gives the drag-free time of flight at the range-maximising angle ($\theta = 45°$) and serves as an analytic upper bound. In the tabulated cooling estimates (Tables 5–6) we instead use the time of flight returned by the full ballistic solver (Eq. 2), which integrates each trajectory over the 5°–85° angular sweep with aerodynamic drag included and selects the range-maximising path. At 4.5 mbar the two differ by at most a few percent (drag decelerations $< 2\%$ of g for $d \geq 5$ mm; Section 1), so Eq. (8) reproduces the solver t_f to within the precision relevant here. The drag-free bound is reported here only because it maximises t_f and therefore the cooling, consistent with the conservative framing adopted throughout.

2. Range ($45°$ maximum range, no drag)

In following steps we again simplified problem to exclude drag factor and using modified velocity from ballistic calculations ($v_0 \leftarrow v_0 \cdot At$). We restricted problem to show results for the near maximum ballistic trajectories (45°).

$$R = \frac{v_0^2\sin 2\theta}{g} = \frac{v_0^2}{g} \tag{9}$$

Note that Eqs. 8–9 neglect aerodynamic drag, which is justified at 4.5 mbar where drag decelerations are $< 2\%$ of gravity for d $\geq$ 5 mm (see ballistic model). The resulting TOF represents an upper bound, making the cooling estimates conservative. Bellow tabulated ranges derive from the solver on (Eq. 2) and coincide with drag-free analytic form to within a few percent at 4.5 mbar.

As next, the steps 3 and 4 are used to calculate air density for Mars atmosphere and to determine convective transfer coefficient for the laminar flow (no drag).

3. Air density (ideal gas, CO_2 Mars-like)

$$\rho_{\text{air}} = \frac{P}{R_{\text{CO2}}T_0} = \frac{4.5\times10^2}{188.9\times281.15} \approx 0.0085\ \text{kg/m}^3 \tag{10}$$

where R_{CO_2} is the specific gas constant for carbon dioxide $[J/(kgK)]$; $R_{CO_2} = \frac{M_{\text{universal}}}{M_{\text{CO2}}} = \frac{8314.5}{44.01} \approx 188.9\ J/(kgK)$ (derivation from the universal gas constant and molar mass), and T_0 is the initial mud/vapour temperature $[K]$; $T_0 = 281.15K$ (≈ 8 °C, measured at the beginning of the experiment) - assumed here for the ambient atmosphere temperature of the neighborhood around mud droplets (distant temperatures can be assumed in the range 223 - 293 K; see discussion and the end of the document).

4. Convective heat transfer coefficient (Nu=2, laminar sphere)

$$h = \frac{\mathrm{Nu} \cdot k_{\mathrm{air}}}{d} = \frac{2 \cdot 0.015}{d} = \frac{0.03}{d} \tag{11}$$

$$\mathrm{Nu} = \frac{hd}{k_{\mathrm{air}}} = 2.0 \tag{12}$$

where k_{air} is the air conductivity; $k_{\mathrm{air}} = 0.015\ W/(m \cdot K)$, d is the diameter of the droplet $[m]$ and h is the coefficient of convective heat transfer $[W/(m^2 \cdot K)]$.

Justification for the Nusselt number (Nu = 2): At 4.5 mbar ($\rho_{\mathrm{air}} \approx 0.0085\ \mathrm{kg\,m^{-3}}$) the particle Reynolds numbers lie in the range 1–16, placing the flow firmly in the laminar regime. In this regime the Ranz–Marshall correlation, $\mathrm{Nu} = 2 + 0.6\,\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}$, yields $\mathrm{Nu} \approx 2.8$–4.2, while its zero-Reynolds limit recovers the stagnant-fluid value Nu = 2 — the exact analytical solution for conductive heat transfer from an isolated sphere into a quiescent medium (Incropera et al., 2011). Because our conclusion is that convective cooling is small, the conservative test is to *maximise* the cooling: we therefore verify the result against the full Ranz–Marshall coefficient, which raises Nu — and hence $h = \mathrm{Nu}\,k_{\mathrm{air}}/d$ and the predicted temperature drop — by ∼40–110% over the Nu = 2 case. Even under this cooling-maximising estimate the bulk temperature drop remains far below that required for freezing, so the non-freezing conclusion holds.

We nonetheless report Nu = 2 as the baseline value for three reasons. First, it is the rigorous low-Reynolds limit appropriate to our conditions: the Ranz–Marshall enhancement is a forced-convection correction that is only marginally activated at $\mathrm{Re} \sim 1$–16 (the $0.6\,\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}$ term contributes less than the leading 2), and it formally requires a steady relative wind that the droplet does not maintain — near the top of its ballistic arc the relative velocity, and with it the forced-convection enhancement, falls to zero. Second, Nu = 2 is the standard reference value for heat transfer from spheres as $\mathrm{Re} \to 0$ and makes the baseline calculation transparent and reproducible without invoking an empirical correlation. Third, because Nu = 2 is the *lower* bound on convective cooling, any conclusion of negligible cooling drawn from it is strengthened, not weakened, by the larger Ranz–Marshall coefficient established above. The two choices therefore bracket the convective term from below (Nu = 2, reported) and above (Ranz–Marshall, sensitivity check), and the non-freezing result is robust across the full range.

5. Initial cooling rate

$$\left.\frac{dT}{dt}\right|_0 = -\frac{hA(T_0 - T_{\mathrm{amb}})}{mc_p} \tag{13}$$

where A is the surface area of the droplet $[m^2]$; $A = \pi d^2$, T_0 is the initial temperature of the mud/droplet $[K]$, C_p is the specific heat (for low viscosity mud approximated similar as for pure water (4200 $J/(kgK)$), and T_{amb} is the ambient air temperature inside the chamber (estimated as -50 °C at 4.5 mbar). We were also inspired by liquid-phase models for fuel droplet heating by (Sazhin et al., 2006) but in a reverse meaning.

The small offset between $T_{\mathrm{amb}} = 223\,\mathrm{K}$ (chamber/atmosphere) and $T_{\mathrm{sky}} \approx 220\,\mathrm{K}$ reflects the distinction between local gas temperature and the effective radiative background; its impact on ΔT is well below 1%.

6. Temperature drop over flight (constant h approximation)

$$\Delta T \approx \left.\frac{dT}{dt}\right|_0 \cdot t_f \tag{14}$$

Summary of thermal (convection cooling) calculations for ballistic model

The time of flight t_f used here is taken from the ballistic trajectory solver (full 5°–85° angular sweep, aerodynamic drag included; Eq. 2), evaluated at the range-maximising trajectory for each (d, θ). The analytic expression in Eq. (8) is the drag-free 45° closed form and provides an upper bound on t_f; because drag decelerations are $< 2\%$ of gravity at 4.5 mbar (Section 1), the solver and analytic values agree to within a few percent, and the small differences do not affect the cooling estimates.

Table 5: Cooling estimates for 0.1–3 m ballistic trajectories at 4.5 mbar. Small droplets ($d = 1$ mm) show measurable cooling; large droplets ($d = 20$ mm) negligible.

Case	**TOF (s)**	**Range (m)**	dT/dt_0 **(K/s)**	ΔT **(K)**
Earth Explosive (small)	0.55	1.47	−2.437	1.3400
Earth Effusive (large)	0.26	0.33	−0.006	0.0016
Mars Explosive (small)	1.54	4.13	−2.437	3.7530
Mars Effusive (large)	0.73	0.93	−0.006	0.0044

Key Findings

Small droplets cool ∼1.3–3.8 K during flight due to high surface-to-volume ratio and $h \approx 30$ W/m^{2}K. Large droplets experience negligible cooling (< 0.005 K) due to low hA/m. Values are valid for 0–3 m ranges within our assumption for restricted initial velocities, scaled by maximum trajectory height.

Including aerodynamic drag would modestly shorten TOF relative to the drag-free bound used here, further reducing the temperature drop and thus strengthening the non-freezing conclusion.

Radiative Cooling of Mud Droplets (4.5 mbar) – Extension of cooling model

7. Net radiative flux (Stefan-Boltzmann, gray body)

$$q_{\text{rad}} = \varepsilon\sigma(T^4 - T_{\text{sky}}^4) \tag{15}$$

This equation calculates the net radiative heat flux emitted by the mud droplet as a gray body. ε is the emissivity of the mud surface, approximately 0.95, indicating it emits 95% of the radiation of an ideal black body. $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is the Stefan-Boltzmann constant, fundamental for radiative heat transfer of black bodies. T is the absolute temperature of the droplet surface, and T_{sky} is the effective temperature of the surroundings (the cold sky environment at about 220 K on Mars). This difference $(T^4 - T_{\text{sky}}^4)$ drives the net radiative loss from the droplet to the atmosphere.

8. Initial radiative flux ($\mathbf{T}_0 = 281$ K)

$$q_{\text{rad},0} = 0.95 \times 5.67 \times 10^{-8} \times (281^4 - 220^4) \approx 210\,\text{W/m}^2 \tag{16}$$

This evaluates the radiative flux at the initial temperature T_0 of the mud droplet. The calculated value quantifies the initial rate at which the droplet radiatively loses heat to the colder sky, determining the baseline radiative cooling strength when the droplet just leaves the reservoir.

9. Radiative cooling rate

$$\left.\frac{dT}{dt}\right|_{\text{rad},0} = -\frac{q_{\text{rad},0}A}{mc_p} \tag{17}$$

The equation expresses the initial rate of temperature decrease of the droplet due to radiation. A is the surface area of the droplet, m is the mass of the droplet, and c_p is the specific heat capacity of the mud. The flux divided by thermal capacity scales how fast temperature drops, with the negative sign indicating cooling.

10. Total temperature drop (convection + radiation)

$$\left.\frac{dT}{dt}\right|_0 = -\frac{hA(T_0 - T_{\text{amb}}) + q_{\text{rad},0}A}{mc_p}, \qquad \Delta T_{\text{total}} \approx \left.\frac{dT}{dt}\right|_0 \cdot t_f. \tag{18}$$

Combining convective and radiative effects, the total initial cooling rate is given by the equation above where the first term on the numerator accounts for convective heat loss based on the convective heat transfer coefficient h, surface area A, and temperature difference between droplet T_0 and ambient T_{amb}. The second term adds the radiative heat loss $q_{\text{rad},0}A$. This total rate gives a combined view of how the droplet cools due to both mechanisms during flight.

Table 6: Total cooling including radiation. Small droplets (1 mm) cool by 1.5–4.2 K, of which radiation contributes ∼12%; large droplets (20 mm) show negligible cooling ($\Delta T < 0.02$ K).

Case	**TOF (s)**	$dT/dt_{\mathbf{conv}}$ **(K/s)**	$dT/dt_{\mathbf{rad}}$ **(K/s)**	$\Delta T_{\mathbf{total}}$ **(K)**
Earth Explosive (small)	0.55	−2.437	−0.295	1.5030
Earth Effusive (large)	0.26	−0.006	−0.015	0.0054
Mars Explosive (small)	1.54	−2.437	−0.295	4.2070
Mars Effusive (large)	0.73	−0.006	−0.015	0.0152

Complete Results with Radiation

Radiation Linearization

We operated with assumption that for a small ΔT, we can linearize Eq. (15):

$$q_{\text{rad}} \approx h_{\text{rad}}(T - T_{\text{sky}}), \quad h_{\text{rad}} = \varepsilon\sigma(T_0^2 + T_{\text{sky}}^2)(T_0 + T_{\text{sky}}) \approx 3.4\,\mathrm{W/m^2K} \tag{19}$$

Total $h_{\text{eff}} = h + h_{\text{rad}}$. For 1 mm droplets, the radiation is ∼<20% of convection for our conditions. With increasing size, the cooling contribution becomes more equivalent and is also negligible.

These convective and radiative estimates describe bulk heat loss only; the dominant low-pressure channel — evaporative cooling — is treated separately below.

Evaporative cooling and crust formation

Because the experiments operate below the triple point of water (611 Pa), liquid mud exposed at the vent is supersaturated with respect to its own vapour and evaporates rapidly. The droplet surface evaporates at the net Hertz–Knudsen–Schrage rate

$$J_{\text{net}} = \sqrt{\frac{M}{2\pi R}}\left(\alpha_e \frac{p_{\text{sat}}(T_s)}{\sqrt{T_s}} - \alpha_c \frac{p_v}{\sqrt{T_\infty}}\right), \tag{20}$$

where $M = 0.018$ kg mol^{-1} is the molar mass of water, $R = 8.314$ J mol^{-1} K^{-1} the universal gas constant, α_e, α_c the evaporation and condensation coefficients, $p_{\text{sat}}(T_s)$ the saturation vapour pressure of water evaluated at the droplet surface temperature T_s, p_v the water-vapour partial pressure in the surrounding atmosphere, and T_s, T_∞ the surface and far-field temperatures. Adopting the isothermal, single-coefficient limit ($T_s = T_\infty = T$, $\alpha_e = \alpha_c = \alpha$) reduces this to the net evaporative flux

$$J = \alpha\sqrt{\frac{M}{2\pi R T}}\left(p_{\text{sat}}(T) - p_v\right) = \alpha\,\frac{p_{\text{sat}}(T) - p_v}{\sqrt{2\pi R_v T}}, \tag{21}$$

with $R_v = R/M = 461.5$ J kg^{-1} K^{-1} the specific gas constant of water vapour and $\alpha \sim 0.1$–1 the evaporation coefficient. At the initial surface temperature $T = 281$ K, $p_{\text{sat}} \approx 1.07$ kPa. Because the chamber is not saturated in water vapour, we take $p_v \leq P_{\text{chamber}} = 0.45$ kPa as a conservative upper bound on the back-flux (minimising net evaporation), giving $J \approx \alpha \cdot 0.69\ \mathrm{kg\,m^{-2}\,s^{-1}}$. The corresponding heat flux $q_{\text{evap}} = L_v J \approx \alpha \cdot 1.7 \times 10^6\ \mathrm{W\,m^{-2}}$ ($L_v \approx 2.5 \times 10^6\ \mathrm{J\,kg^{-1}}$) exceeds the convective flux $h(T_0 - T_{\text{amb}}) \approx 1.7 \times 10^3\ \mathrm{W\,m^{-2}}$ and the radiative flux ($\sim 2 \times 10^2\ \mathrm{W\,m^{-2}}$) by two to three orders of magnitude even at $\alpha = 0.1$. Evaporation is thus the dominant heat-loss channel under these conditions (Ingersoll, 1970; Hecht, 2002).

This cooling is, however, surface-localised and self-limiting, so it does not drive bulk freezing during flight. An energy balance shows that removing the sensible heat required to bring the droplet to $0\,^\circ\mathrm{C}$ ($c_p \Delta T = 33.6\ \mathrm{kJ\,kg^{-1}}$) consumes evaporation of only $f = c_p \Delta T / L_v \approx 1.3\%$ of the droplet mass, whereas freezing the bulk additionally requires the fusion enthalpy ($L_f = 334\ \mathrm{kJ\,kg^{-1}}$), i.e. $f \approx 15\%$. As the surface cools, $p_{\text{sat}}(T)$ falls (Clausius–Clapeyron) toward the ambient vapour pressure; once $p_{\text{sat}}(T) \approx p_v$ — reached near the frost point at $T \sim 270$ K — the net flux collapses and a thin frozen crust forms within $\sim$ 10–100 ms. Further freezing is then limited by internal conduction: with a mud thermal diffusivity $\kappa_{\text{mud}} = k_{\text{mud}}/(\rho c_p) \approx 1.4 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$ ($k_{\text{mud}} \approx 0.6\ \mathrm{W\,m^{-1}\,K^{-1}}$), the equilibration time $\tau_{\text{cond}} = (d/2)^2/\kappa_{\text{mud}}$ is ~ 1.8 s for $d = 1$ mm (comparable to the Martian time of flight) and ~ 700 s for $d = 20$ mm (far exceeding it). The conductive growth of the frozen front over the flight is correspondingly limited to a skin of thickness $\delta \sim \sqrt{\kappa_{\text{mud}}\, t_f} \lesssim 0.3$ mm.

Evaporation therefore flash-forms a thin frozen crust on sub-second timescales while the droplet interior remains warm and liquid; complete in-flight freezing is restricted to the sub-millimetre fraction, and the $\gtrsim$mm droplets that dominate proximal accumulation and flow formation land crust-on with liquid cores. This is consistent with the progressive surface darkening-to-lightening recorded in the videos and with the persistence of mobile mud upon impact.

Conclusions

Applied to our mud droplets, bulk convective and radiative cooling is insufficient to freeze the interior during flight. Evaporative cooling, although the dominant heat-loss channel, is surface-localised and self-arresting (above): it forms a thin frozen crust within tens of milliseconds while the warm liquid core is preserved, so droplets land crust-on with mobile interiors. Only the sub-millimetre fraction may freeze through. This is consistent with the majority of impacts observed in the experimental videos, in which erupted mud appears dark (liquid) and progressively lightens as a surface crust develops.

Appendix: Internal consistency of temperature assumptions and sensitivity analysis

The convective cooling model requires specification of several temperature parameters whose values differ between the laboratory experiment and Mars. Here we summarise the choices made, demonstrate their internal consistency, and show that they collectively yield conservative (i.e. maximised) cooling estimates.

Gas temperature for density calculation. In the ideal-gas calculation (Eq. 10), we evaluate the atmospheric density at $T_0 = 281\,\mathrm{K}$, i.e. the same temperature as the mud at the moment of ejection. This choice is physically appropriate because the CO_2 immediately surrounding the droplet as it exits the reservoir is heated by contact with the warm mud. The resulting density, $\rho_{\mathrm{air}} \approx 0.0085\,\mathrm{kg/m^3}$, is lower than it would be if evaluated at the colder ambient temperature (223 K, which would give $\rho_{\mathrm{air}} \approx 0.0107\,\mathrm{kg/m^3}$). Because ρ_{air} does not appear in the convective heat-transfer equations — which depend only on Nu, k_{air}, d, and $(T_0 - T_{\mathrm{amb}})$ — the density choice does not affect the computed cooling rate directly. Were aerodynamic drag to be included in the trajectory calculation, the lower density would reduce drag, prolong the time of flight, and thus *increase* the total cooling — again the conservative direction.

Ambient temperature for convective cooling. Away from the reservoir, the chamber gas equilibrates to a substantially lower temperature. We adopt $T_{\mathrm{amb}} = 223\,\mathrm{K}$ as the convective sink in Eq. 13, corresponding to the equilibrium temperature of air (CO_2 for the Mars) at 4.5 mbar in the chamber far from the heated reservoir walls. This maximises the driving temperature difference $(T_0 - T_{\mathrm{amb}}) = 58\,\mathrm{K}$ and hence maximises the computed convective cooling. On Mars, near-surface atmospheric temperatures show large diurnal and seasonal variability. In-situ measurements from Viking through Curiosity span approximately 170–290 K depending on latitude, season, and time of day (Martínez et al., 2017). The average surface emission temperature is approximately 215 K (Haberle et al., 2017), while the InSight HP^3 thermal probe recorded a year-averaged subsurface temperature of $\sim$217.5 K at the landing site (Spohn et al., 2024). Theoretical radiative-equilibrium estimates place the mean surface temperature in the range 219–233 K (Catling and Kasting, 2017). Our adopted $T_{\mathrm{amb}} = 223\,\mathrm{K}$ falls within the cooler portion of this well-constrained range, consistent with conditions most favourable to cooling and thus conservative with respect to our conclusions.

Radiative background temperature. In the laboratory, the chamber walls are close to room temperature ($\sim$281 K), meaning that radiative exchange with a droplet at a similar temperature is negligible. On Mars, the effective radiative background seen by an airborne droplet would be colder. We adopt $T_{\mathrm{sky}} \approx 220\,\mathrm{K}$ for the Mars cases, reflecting the near-transparency of the thin CO_2 atmosphere to thermal infrared radiation (Haberle et al., 2017; Martínez et al., 2017). The small offset between T_{amb} and T_{sky} ($\sim$3 K) has a negligible impact on ΔT (well below 1%). Because the laboratory configuration omits this radiative contribution entirely, it underestimates total cooling relative to Mars, further supporting the conservative framing.

Sensitivity of the Nusselt number to gas-property temperature. Although we adopt the stagnant-fluid limit Nu = 2 for the baseline calculation, it is instructive to examine whether the choice of gas-property evaluation temperature affects the Ranz–Marshall Nusselt number (Ranz and Marshall, 1952):

$$\mathrm{Nu} = 2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}, \quad \mathrm{Re} = \frac{\rho_{\mathrm{air}}\,v\,d}{\mu} \tag{22}$$

where Pr is the Prandtl number and Re is the Reynolds number. The relevant CO_2 transport properties at 4.5 mbar are summarised in Table 7.

Table 7: CO_2 transport properties at 4.5 mbar for two gas-temperature assumptions, and resulting Nusselt numbers and convective heat-transfer coefficients from the Ranz–Marshall correlation at $v = 3.0\,\mathrm{m/s}$.

Property	281 K	223 K	Change
ρ_{air} [kg/m^3]	0.0085	0.0107	+26%
μ [Pa s]	1.4×10^{-5}	1.1×10^{-5}	−21%
k_{air} [W m^{-1} K^{-1}]	0.015	0.011	−27%
Pr	0.79	0.80	+1%
Droplet diameter $d = 1\,\mathrm{mm}$			
Re	1.8	2.9	+60%
Nu	2.7	3.0	+8%
h [W m^{-2} K^{-1}]	41.3	32.5	−**21**%
Droplet diameter $d = 5\,\mathrm{mm}$			
Re	9.1	14.6	+60%
Nu	3.7	4.1	+11%
h [W m^{-2} K^{-1}]	11.0	9.1	−**18**%
Droplet diameter $d = 10\,\mathrm{mm}$			
Re	18.2	29.1	+60%
Nu	4.4	5.0	+14%
h [W m^{-2} K^{-1}]	6.6	5.5	−**16**%

Switching from 281 K to 223 K gas properties increases Re (higher density, lower viscosity) and thus raises Nu by 8–14%. However, the thermal conductivity of CO_2 drops by $\sim$27% over the same temperature interval, and because $h = \mathrm{Nu} \cdot k_{\mathrm{air}}/d$, the net effect is a *decrease* in the convective heat-transfer coefficient by 16–21% across all droplet sizes. Evaluating transport properties at $T_0 = 281\,\mathrm{K}$ therefore overestimates convective cooling relative to a film-temperature or ambient-temperature evaluation, consistent with the conservative framing adopted throughout.

We note that in the full Ranz–Marshall formulation, Re depends on ρ_{air}, which would couple the density assumption back into the thermal model. This coupling is absent in our baseline (Nu = 2) calculation. The sensitivity check presented here confirms that even when this coupling is included, the 281 K property evaluation remains conservative.

Summary of conservative assumptions. The parameter combination adopted in this study — warm gas for density evaluation (low ρ_{air}, hence minimal drag and longest flight), cold ambient temperature for convective driving (maximum $T_0 - T_{\mathrm{amb}}$), warm-gas transport properties (maximum h), and neglect of wall radiation in the laboratory — collectively represents the scenario most favourable to cooling. If the computed ΔT remains small under these assumptions, it will be smaller still under any less conservative parameter choice. This ensures that the reported temperature drops during flight represent robust upper bounds applicable to both the laboratory experiments and Mars surface conditions.

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