# Sublimation of a dry ice sphere in a controlled ambient

## Visualization of density gradients at the phase-changing interface

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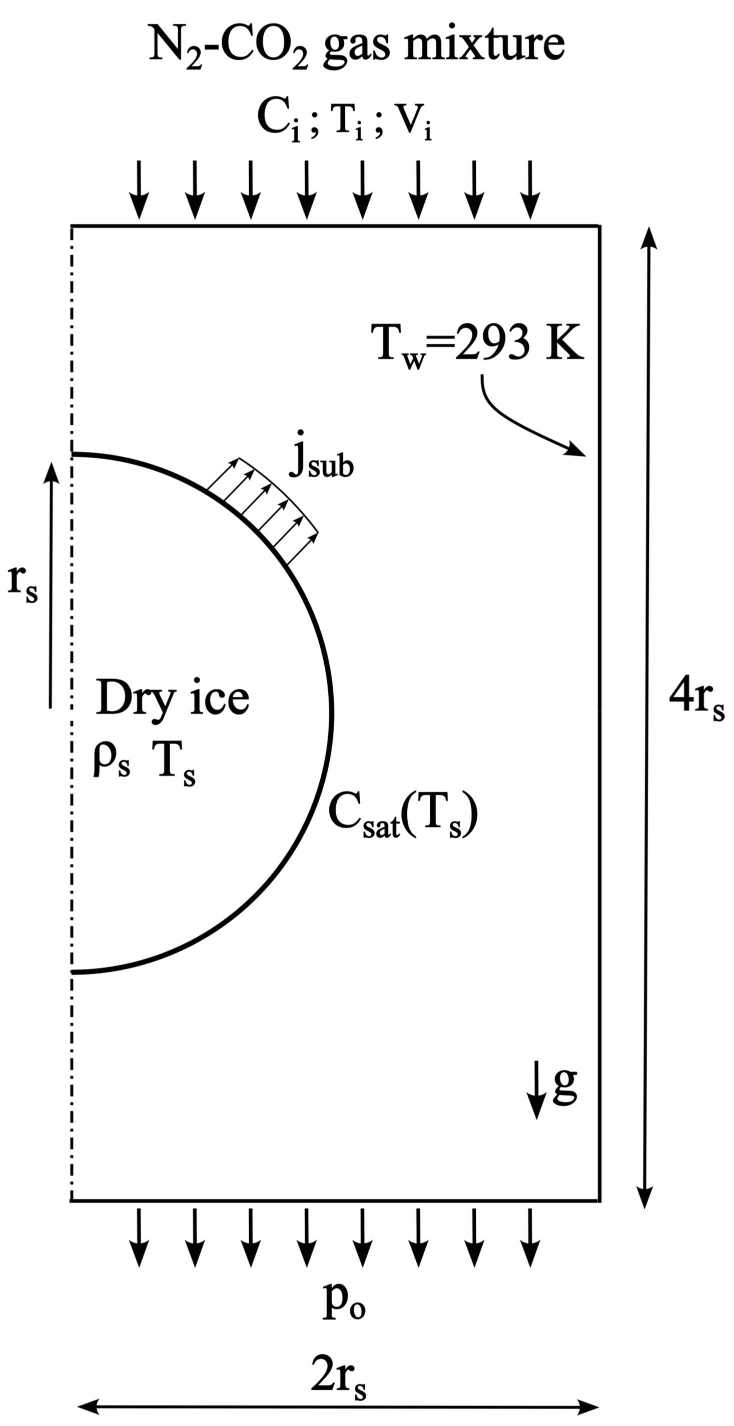
## Temperature and concentration gradient at phase-changing interface

Heat and mass transport in the case of an evaporating liquid droplet or a sublimating solid is driven by the strong temperature and concentration gradients that appear at the phase-changing interface in a medium with a discontinuous temperature and vapor concentration. Obtaining fundamental data regarding the factors that influence the rates of the transport phenomena is essential for applications such as spray cooling, machining, and food freezing. In this work, we employ the Schlieren imaging [1] technique to visualize the density gradients that arise due to temperature and concentration changes at the interface of a dry ice sphere and the surrounding gas medium, while simultaneously tracking the movement of the sublimating dry ice boundary. A qualitative comparison between experimental results and numerical results predicted using the commercial COMSOL Multiphysics software is presented.

## Phenomenological Model




Transient problem of coupled heat, momentum and mass transport from the dry ice surface to the surrounding gas medium is computed assuming:

- Axial symmetry of the problem.
- Negligible radiative heat transfer in gas domain.
- Velocity of dry ice surface depends on the local mass flux – $j_{sub}/\rho_s$.
- Inlet $CO_2$ concentration, $C_i$ is determined by the ideal gas law.
- Saturation concentration at the dry ice interface is obtained from Clausius-Clapeyron relation[2].

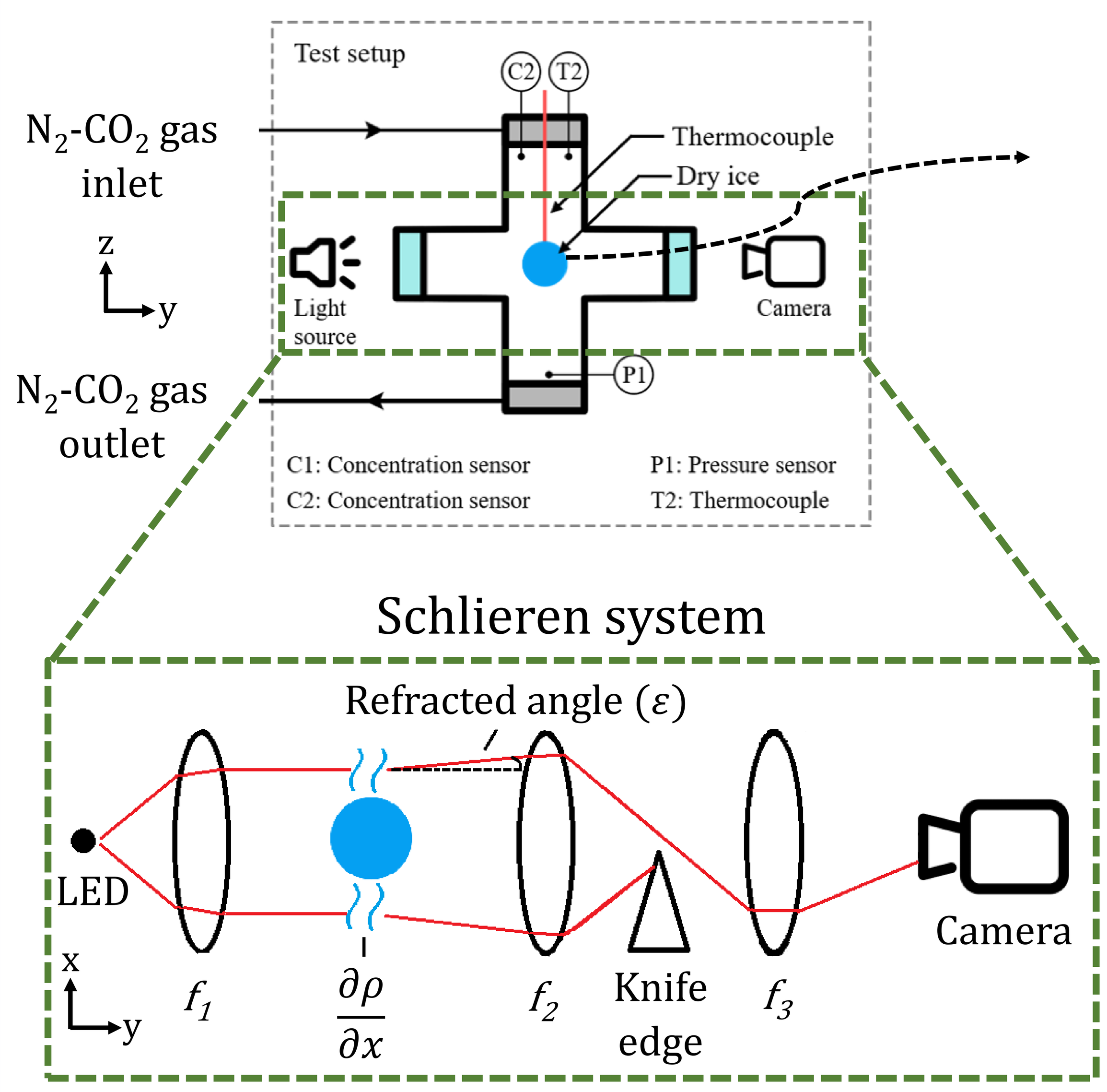
$$P_{sat} = 1\text{bar} * \exp -\frac{L_h}{R}\left(\frac{1}{T} - \frac{1}{T_{sub}}\right)$$

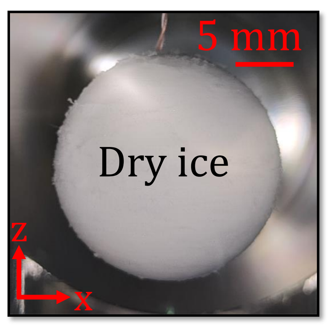
$$c_{sat} = \frac{P_{sat}}{RT}$$

- Laminar flow for the given geometry and flow conditions $80 < Re < 150$.

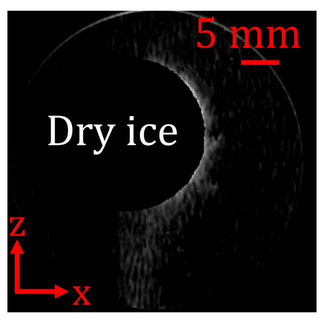
## Schlieren System

Test-section with ambient control [3]

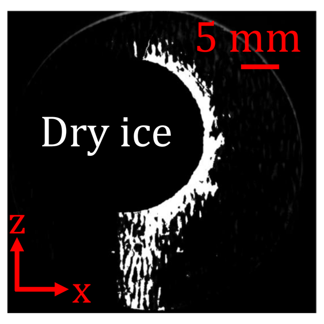



As seen by human eye



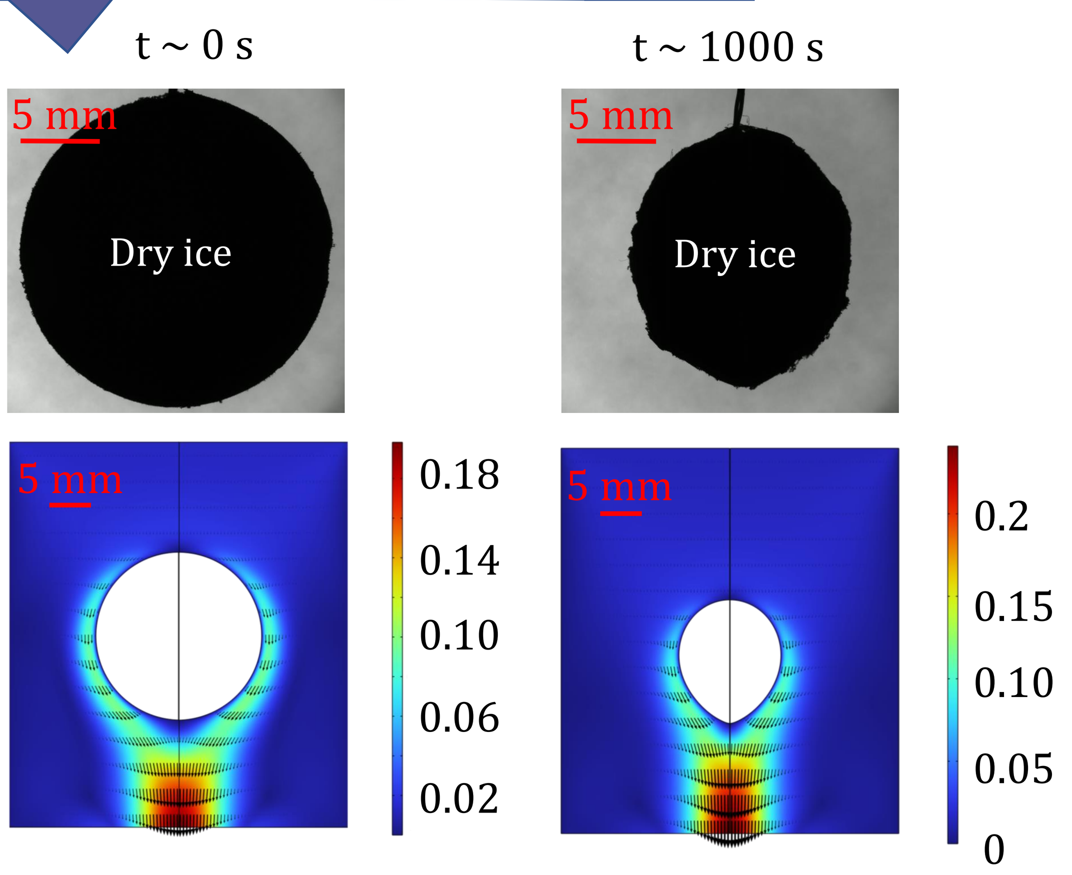

As captured by Schlieren




After image processing

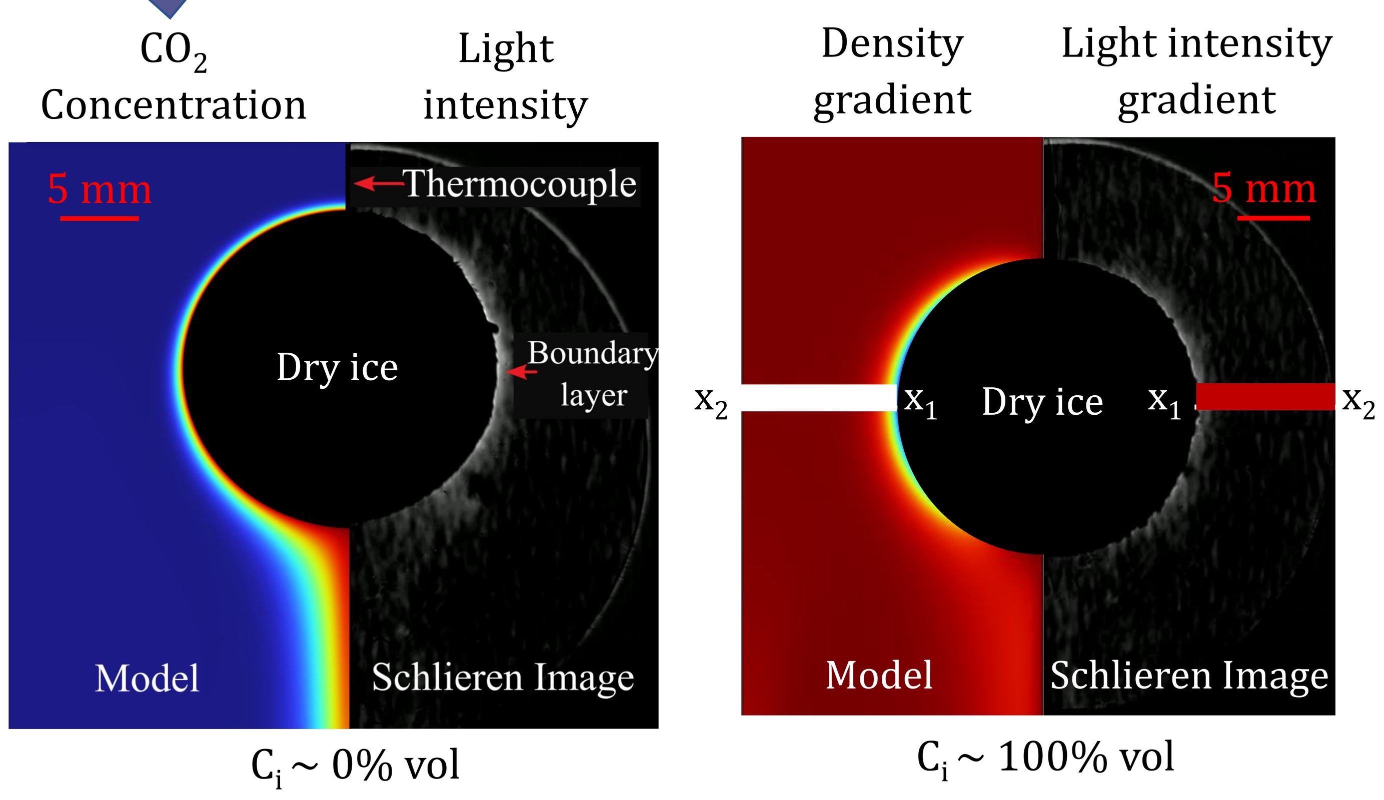
- Desired initial condition: Flush (1 liter/min) test-section with $N_2$-$CO_2$ gas mixture.
- Dry ice sphere (~ 3.5 g) is introduced in the test-section.
- Schlieren images captured for varying inlet CO2 concentrations – 0:20:100 Vol %.
- Pressure is maintained constant at ~ 1.01 bar.

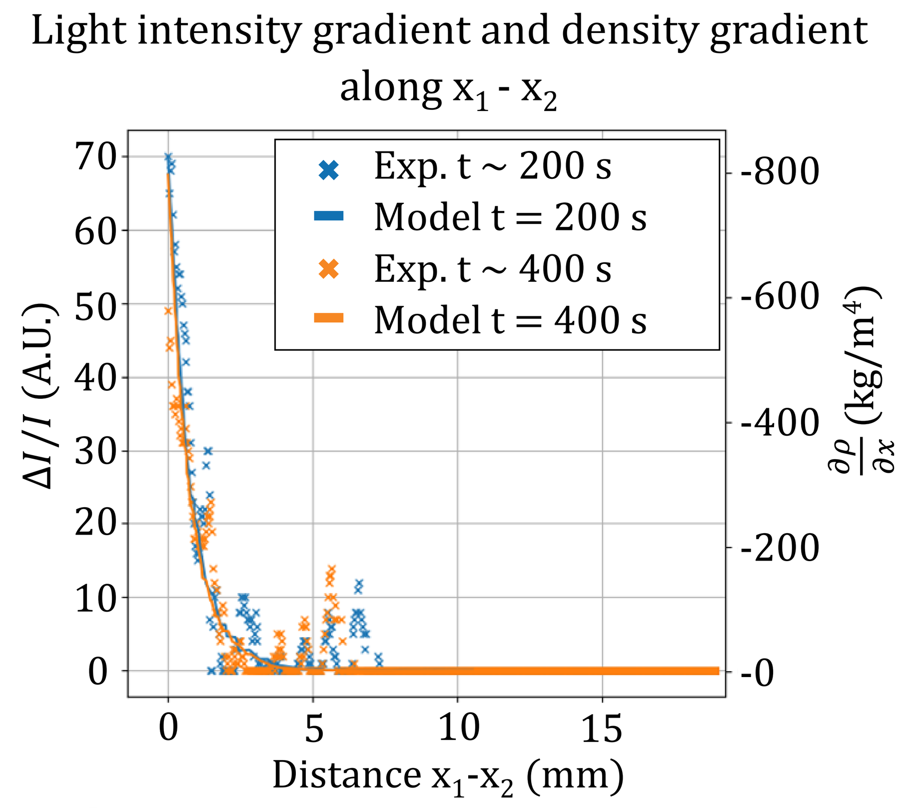
## Dry ice morphology




- Gas velocity accelerates and intensifies sublimation near sphere's lower part.
- Gradually adopting elliptical shape over time.

## $CO_2$ concentration and density gradient




- Bright region in Schlieren image ~ Large refractive index gradient.
- Refractive index gradient ~ Density gradient due to temperature and concentration variations.
- $\frac{\Delta I}{I} \sim \frac{\partial \rho}{\partial x} \sim \frac{\partial T}{\partial x}$ and/or $\frac{\partial c}{\partial x}$

## Conclusion and Outlook

- Model results and Schlieren images reveal alike density gradients around the dry ice sphere featuring distinct side gradients and elongated bottom gradient.
- Model's qualitative alignment with experiments is evident; however, further investigation, especially in quantifying Schlieren image density gradients, is necessary.

[1] Settles G S, Schlieren and shadowgraph techniques: Visualizing phenomena in transparent media, Springer-Verlag GmbH (2001)
[2] Schroeder D V An Introduction to Thermal Physics, Addison Wesley (2000)
[3] Purandare A, Verbruggen W, and Vanapalli S 2023 Experimental and theoretical investigation of the dry ice sublimation temperature for varying far-field pressure and CO2 concentration Preprint 10.2139/ssrn.4462700

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