

Resolving the Temperature Jump Paradox in Evaporating Droplets

Resolving the long-standing controversy surrounding positive and negative temperature jumps during evaporation.

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Introduction & Goals

Evaporation is a fundamental transport process in thermal management, energy systems, and advanced manufacturing. Interfacial temperature discontinuities arise from non-equilibrium molecular transport across the liquid-vapour interface. Although the existence of a temperature jump is widely accepted, its sign remains controversial, with both positive and negative values reported in the literature[1].

A 2D axisymmetric Young-Laplace profile-based sessile droplet evaporating in its own vapour is simulated in COMSOL Multiphysics® 6.3. A kinetic-continuum framework derived from the Boltzmann transport equation is implemented using a coupled kinetic-continuum model to investigate the mechanisms governing interfacial temperature-jump reversal during evaporation under varying substrate temperature conditions.

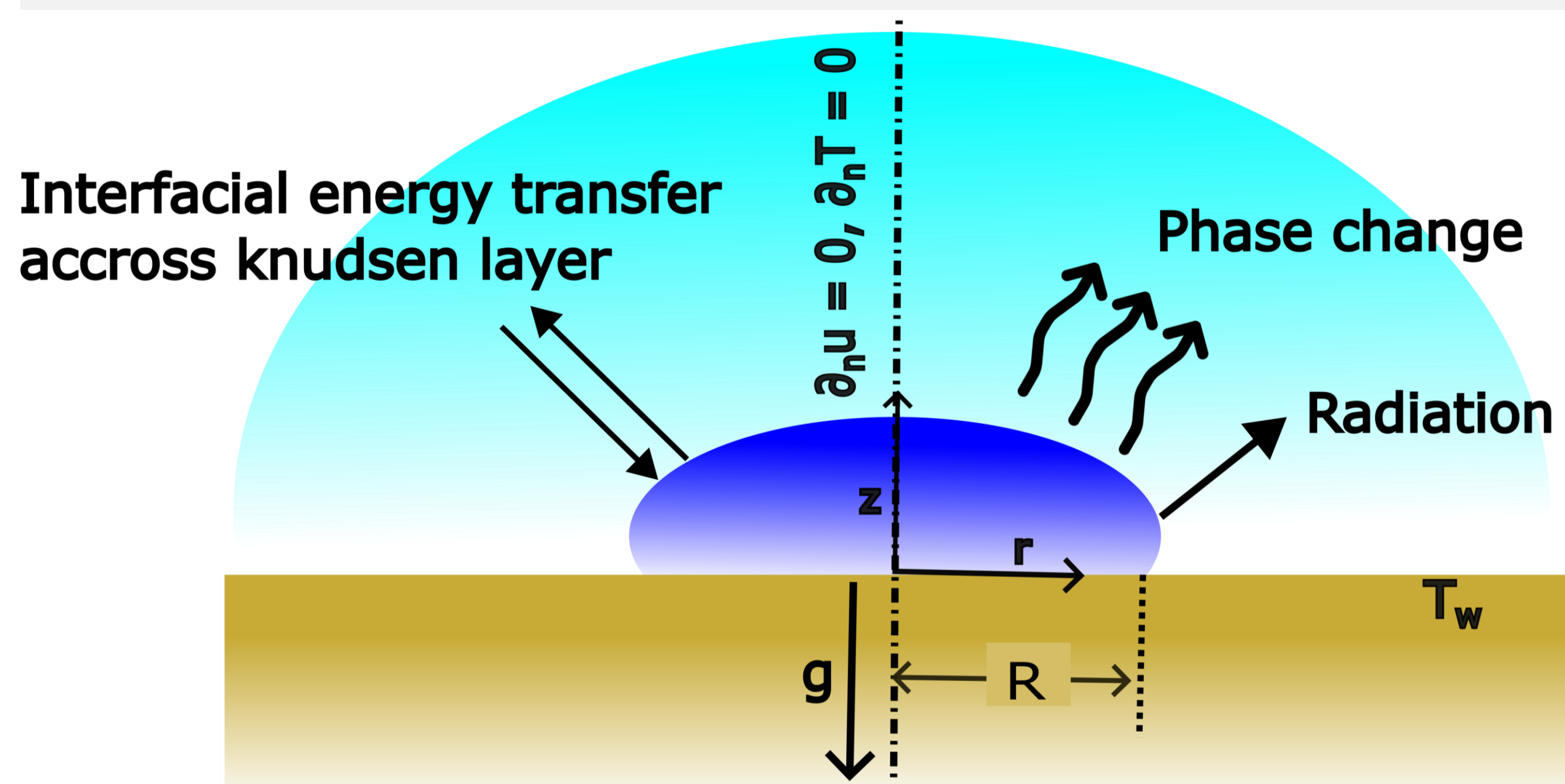


Figure 1: Computational domain and heat-transfer mechanisms during sessile droplet evaporation in its own vapour.

Methodology

The continuity, Navier-Stokes, and energy equations were solved in both liquid and vapour domains. Interfacial mass and heat transfer were coupled through Chen's kinetic-theory-based boundary conditions[2]. Simulations were performed under vacuum conditions for substrate temperatures ranging from 0°C to 35°C. The governing interfacial heat-flux relations are shown below.

$$n \cdot (-k_l \nabla T_l) = \dot{m}_{ev}'' h_{fg} + \sigma \epsilon (T_s^4 - T_{surr}^4) + \frac{2R_u T_s \dot{m}_{ev}''}{M} + \frac{2\alpha}{2-\alpha} \frac{R_u}{M} \sqrt{\frac{2R_u}{\pi M}} \rho_v \sqrt{T_v} (T_s - T_v)$$

$$n \cdot (k_v \nabla T_v) = \frac{2R_u T_s \dot{m}_{ev}''}{M} + \frac{2\alpha}{2-\alpha} \frac{R_u}{M} \sqrt{\frac{2R_u}{\pi M}} \rho_v \sqrt{T_v} (T_s - T_v) - \dot{m}_{ev}'' c_p T_v$$

Results

At low substrate temperatures, positive temperature jumps were observed due to reverse heat conduction from the vapour phase. As substrate temperature increased, the temperature jump changed sign and became negative because of enhanced evaporative cooling. The largest temperature discontinuities occurred near the three-phase contact line, where evaporation was strongest.

Evaporation increased with substrate temperature and reached a maximum near the contact line. A small condensation region developed near the droplet apex at higher temperatures because the local vapour density exceeded the saturation density corresponding to the interfacial temperature. Localized condensation and evaporation coexisted on the same droplet interface, while the net mass transport remained evaporation-dominated.

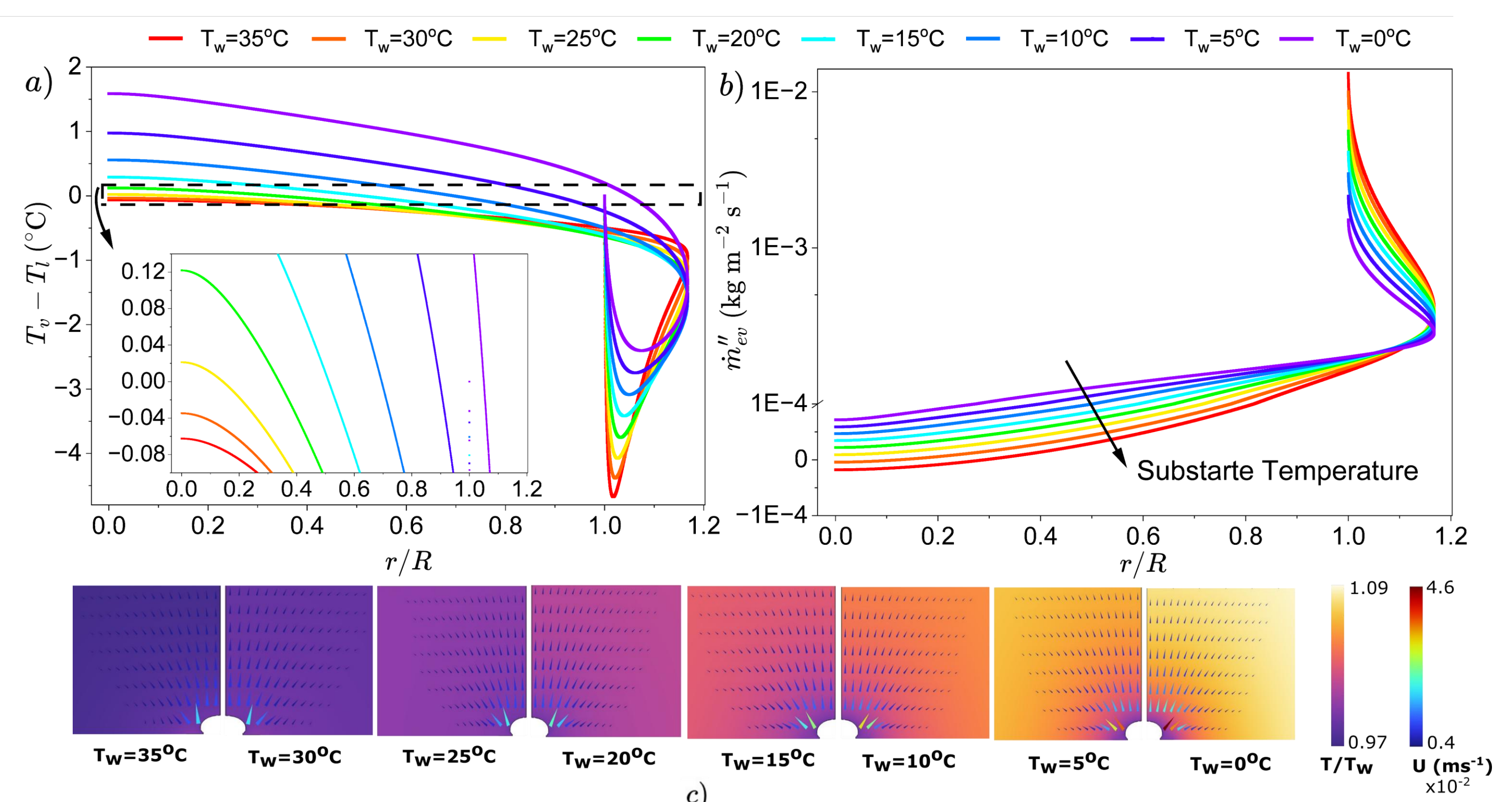


Figure 2: Variation of a) temperature jump, b) evaporation mass flux, and c) normalized temperature and velocity fields for different substrate temperatures.

REFERENCES

1. A. H. Persad and C. A. Ward. Expressions for the evaporation and condensation coefficients in the Hertz-Knudsen relation. Chem. Rev., 116(14):7727–7767, 2016.
2. G. Chen. Interfacial cooling and heating, temperature discontinuity and inversion in evaporation and condensation. Int. J. Heat Mass Transf., 218:124762, 2024.



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