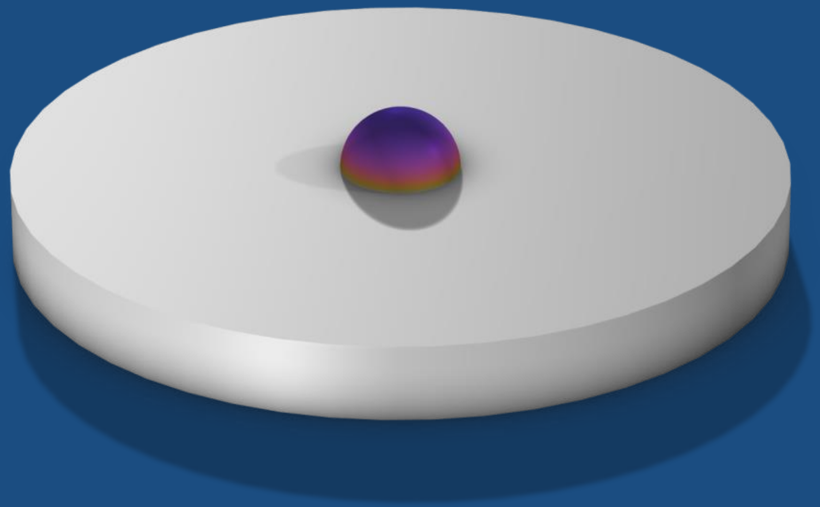


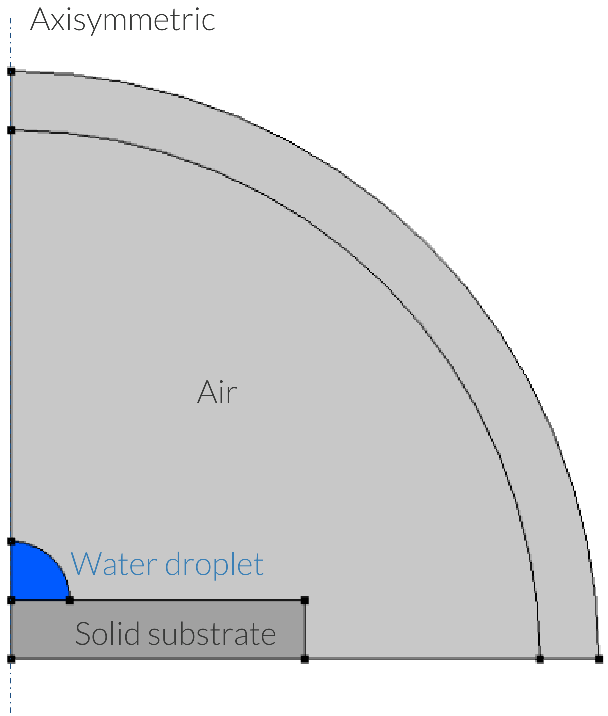
Droplet Evaporation on a Solid Substrate

Background

- Droplet evaporation is ubiquitous in everyday life and is essential in many industrial processes, such as inkjet printing, cleaning/coating of surfaces, and phase change heat transfer
- For a macroscopic droplet in quiescent atmospheric conditions, the rate-limiting step for evaporation is the diffusion of vapor in air (Ref. 1–4)
- The vapor concentration at the droplet interface is assumed to be in a local equilibrium given by the saturation vapor density, which depends on surface temperature

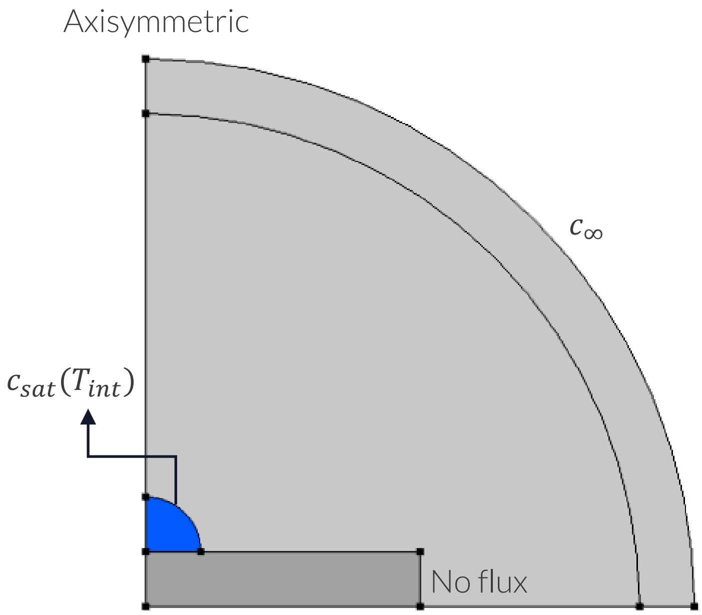
Physics Interfaces

- Two-Phase Laminar Flow
  - Moving mesh to track the water–air interface
  - Fluid–fluid interface that incorporates evaporative mass flux
- Transport of Diluted Species
  - Water vapor diffusion (and convection) through air, which predicts the evaporation rate
- Heat Transfer in Solids and Fluids
  - Nonisothermal flow
  - Temperature-dependent saturation vapor density at droplet interface
  - Latent heat of evaporation
  - Substrate heating effects

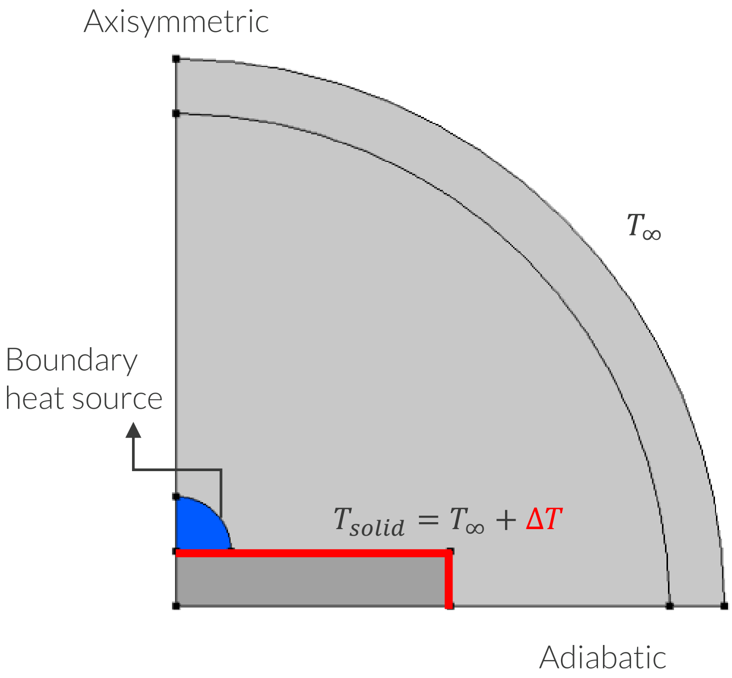


Boundary Conditions

Transport of Diluted Species



Heat Transfer in Solids and Fluids



Boundary Conditions

- The saturation vapor pressure is given by the Antoine equation (Ref. 5), and the saturation vapor density is given by the ideal gas law

$$\log_{10}(p_{sat}) = A - \frac{B}{C+T}, \qquad c_{sat} = \frac{p_{sat}}{R_s T M_w}$$

  where p_{sat} and c_{sat} are saturation vapor pressure and concentration, T is temperature, R_s is the specific gas constant, and M_w is the molecular weight

- The evaporative mass flux at the interface is given by diffusion of water vapor

$$J = M_w \boldsymbol{n} \cdot (-D\nabla c)$$

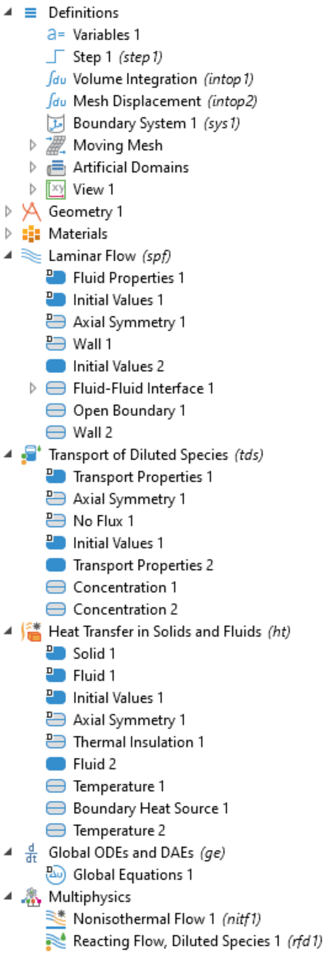
  where $\boldsymbol{n}$ is the surface normal and D is the diffusion constant of vapor in air

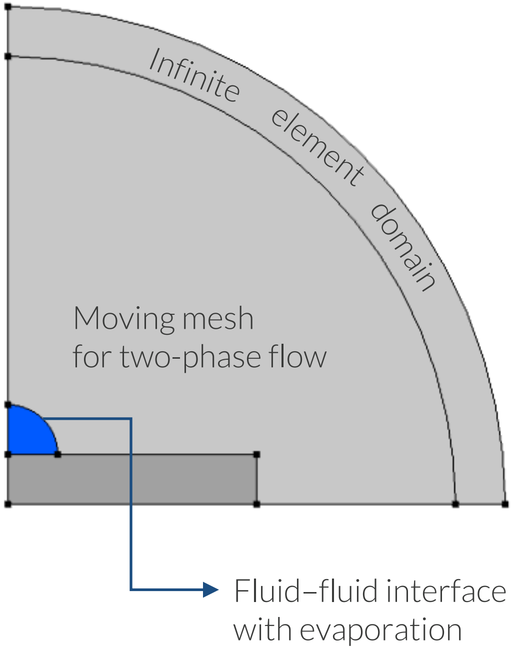
  The Lagrange multiplier is used for an accurate boundary flux, and a conditional statement is used to regularize singularity at r = 0

- The latent heat of evaporation $\mathcal{L}$ is incorporated as a boundary heat source $-J\mathcal{L}$ [W/m^2]

Implementation

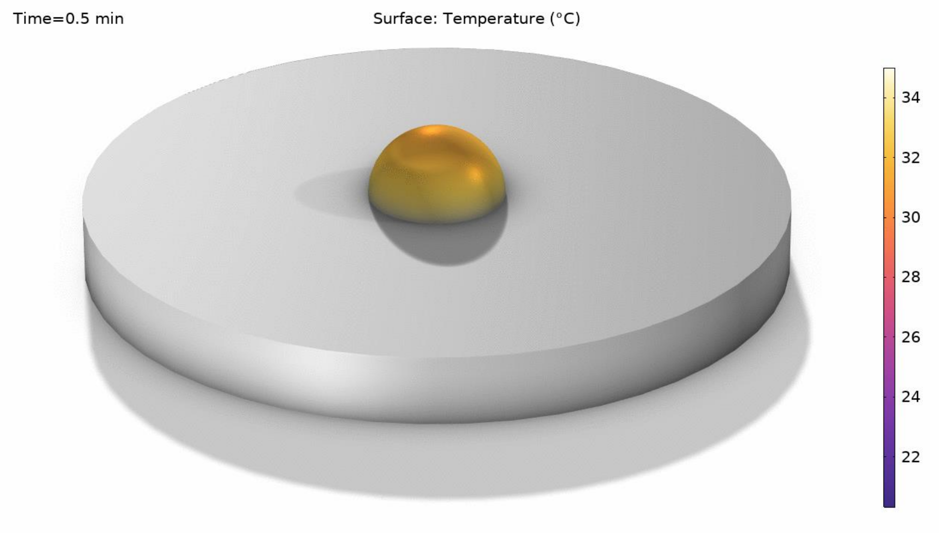
- Moving mesh with fluid–fluid interface is used to track the shrinking water droplet
- Mass transport at the fluid–fluid interface coupled to species transport
- Infinite element domain for specifying boundary conditions far away
- Navier-slip wall for moving contact line
- Boundary heat source to account for latent heat of evaporation
- Nonisothermal flow coupling between heat transfer and fluid flow





Results

The evaporation dynamics of a water droplet in air on a heated solid glass substrate can be predicted.



Verification: Isothermal Case

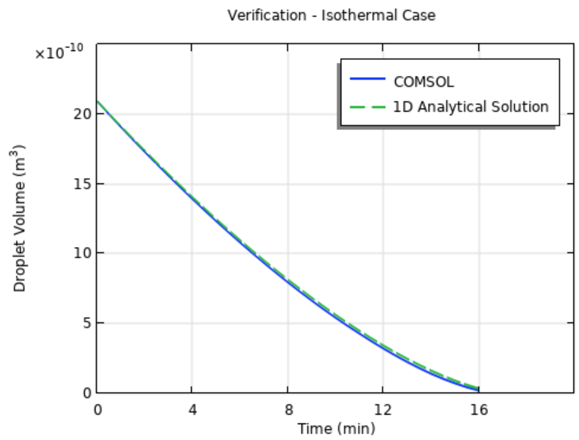
- Assuming the system is isothermal and evaporation is purely driven by diffusion, the evaporation rate of a hemispherical droplet is given by Ref. 4, where V is the volume, ρ_{sat} is the saturation vapor density, $\rho_\infty = 0$ is the vapor density far away, and ρ_L is the liquid density

$$\frac{dV}{dt} = -2\pi RD\frac{\rho_{sat} - \rho_\infty}{\rho_L}$$

- Integrating this ODE, we get the analytical solution of the droplet volume as a function of time,

$$V(t) = \frac{2\pi}{3}\left(\sqrt{R_0^2 - 2D\frac{\rho_{sat}}{\rho_L}t}\right)^3$$

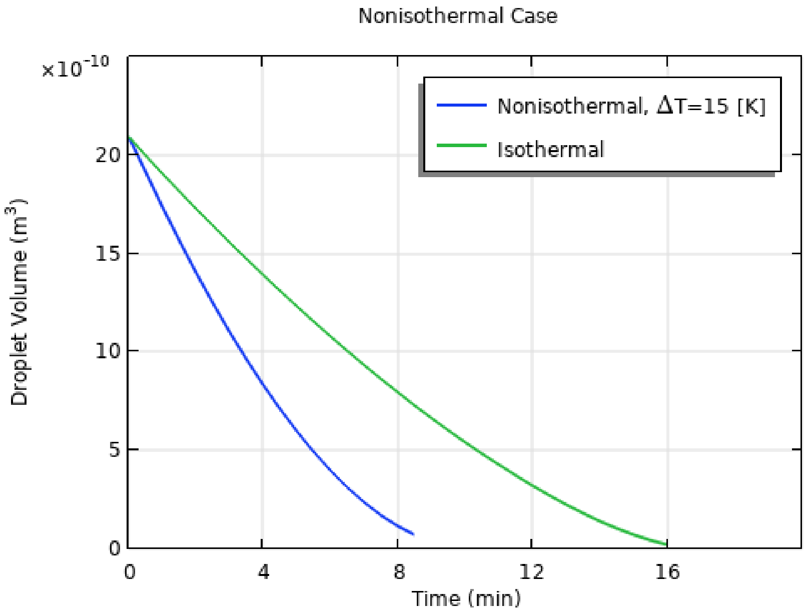
- We can then compare the volume of the droplet calculated using the expression above and COMSOL Multiphysics®, and a good agreement can be obtained



Droplet volume as a function of time, isothermal case

Nonisothermal Case

Heating the substrate will accelerate the evaporation of the water droplet.



Concluding Remarks

An example of how to model droplet evaporation on a solid substrate is presented. The evaporative flux is governed mostly by the diffusion of water vapor in ambient air. The model is verified against isothermal analytical solutions and is then extended to include nonisothermal effects.

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