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Assessment of Experimental Artifacts in Evaporation Tests on Isolated, Suspended Droplets

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ABSTRACT

The isolated droplet framework is commonly used to study liquid fuel evaporation and combustion. However, experimental measurements conducted in this configuration can be susceptible to different artifacts. This study explores their impact on experiments of butanol droplet evaporation conducted in a suspended droplet facility. The effects due to thermal radiation and fiber conduction are specifically addressed. Both experimental and modeling approaches are employed to assess the magnitude of each artifact. Results show that the conduction of heat through the fiber may significantly affect droplet evaporation, leading even to the onset of internal bubbling in some cases. Its impact diminishes with an increase in the initial droplet size to fiber diameter ratio. The absorption of thermal radiation from the environment was found to be less relevant for this specific setup, although its impact could be much more significant for cases where big-sized droplets are exposed to hot walls.

1. Experimental Methods (SDF and DCF)

Suspended droplet facility (SDF)
$\bar{T}_\infty$ = 1336 ± 50 K
d_0 = 350 µm ~ 850 µm
Very low Re (<0.5 for d_0 = 500 µm)
Radiation heat flux: Q_r = 23.5 kW/m^2
Suspension medium: 15µm Silicon Carbide and 25/50µm Platinum wire

Free-falling droplet facility (DCF)
$\bar{T}_\infty$ = 1730 K
d_0 = 145 µm
Very low Re (<0.4 for d_0 = 145 µm)
Radiation heat flux: Q_r = 20.6 ~ 29.4 kW/m^2
Suspension medium: -

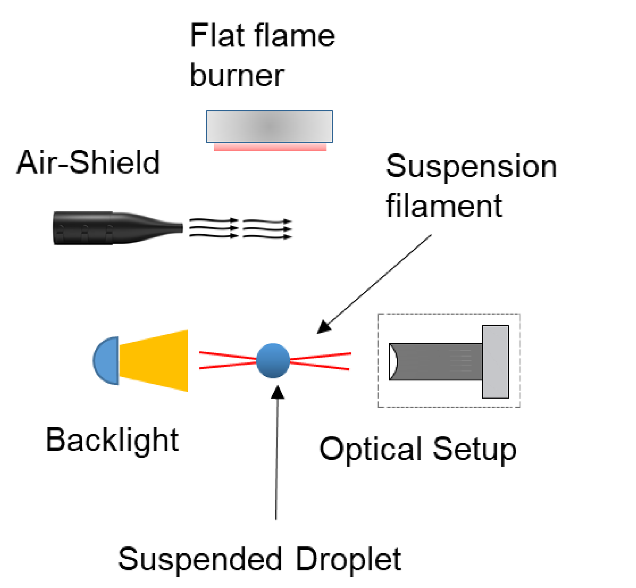


Figure 1. Suspended droplet facility (SDF)

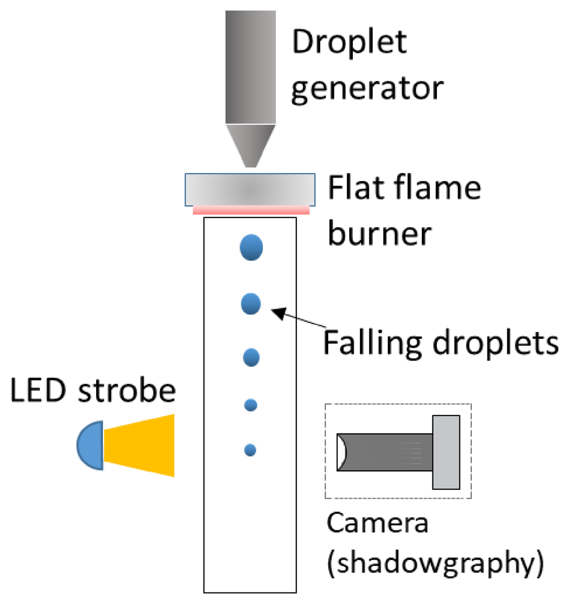


Figure 2. Droplet combustion facility (DCF)

2. Predictive Methods (droplet evaporation model)

A 1D evaporation model has been developed and successfully validated against experimental data obtained at DCF conditions for different alcohols (Butanol and Glycerin). To better emulate the actual droplet evaporation at SDF conditions, the fiber conduction and radiation absorption sub-models are added to this model. Figure 3, shows the general scheme of the contributing phenomena at SDF.

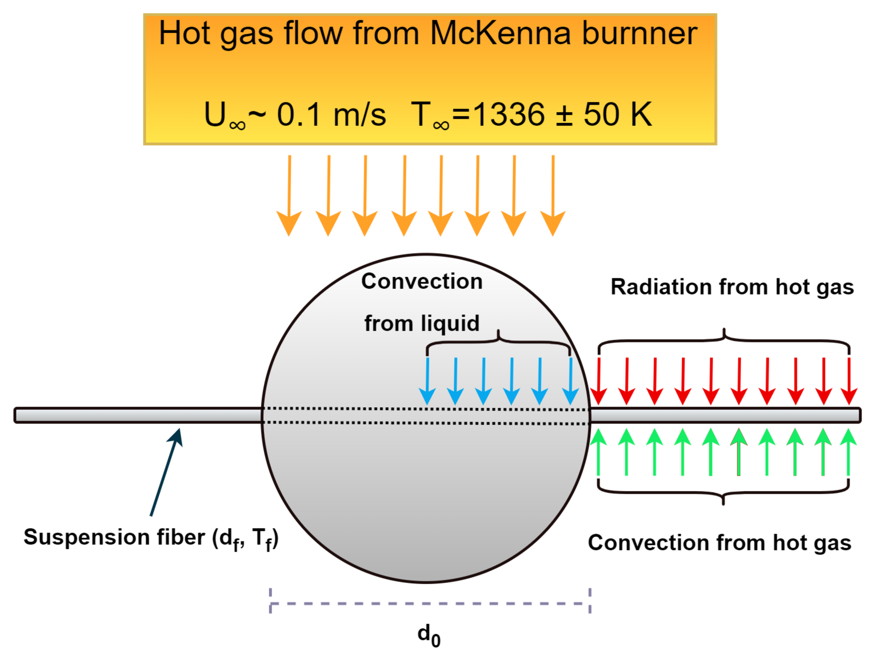


Figure 3. Evaporating fuel droplet suspended on fibers

Governing equations

Gas phase
$$\dot{m} = 2\pi\bar{\rho}_g\bar{D}_g r_s Sh^* ln(1+B_M)$$
$$\dot{q}_s = \dot{m}\left(\overline{Cp}_f(T_\infty - T_s)/B_T - Lv\right)$$

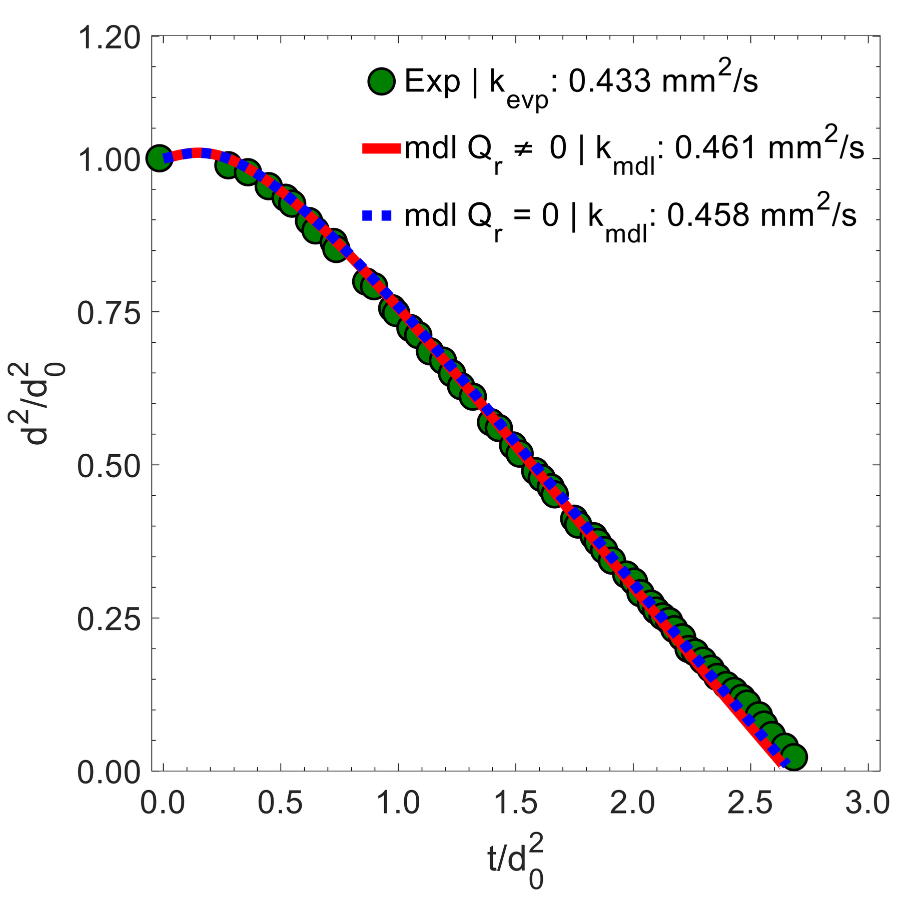
Liquid phase
$$\rho_l c_l \frac{\partial T_l}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\chi_T k_l r^2 \frac{\partial T_l}{\partial r}\right) + \dot{q}_f + \dot{q}_r$$

Fiber conduction
$$\rho_f c_f \frac{\partial T_f}{\partial t} = k_f \frac{\partial^2 T_f}{\partial r^2} + \frac{4h_\infty}{d_f}(T_g - T_f) - \frac{4\varepsilon_f}{d_f}\left(\sigma T_f^4 - \frac{1}{2}\dot{Q}_r\right)$$
$$\dot{q}_f = \left(\int_{x=-r}^{x=+r} h_l(x)\left(T_l(x) - T_f(x)\right)\pi d_f n_f dx\right)/\forall_d$$

Radiation heat
$$\dot{q}_r = \frac{1}{2}4\pi r_d^2 \sum_{i=1}^{N} x_{i,l}\bar{E}_{i,a}\dot{Q}_r / \forall_{net}$$

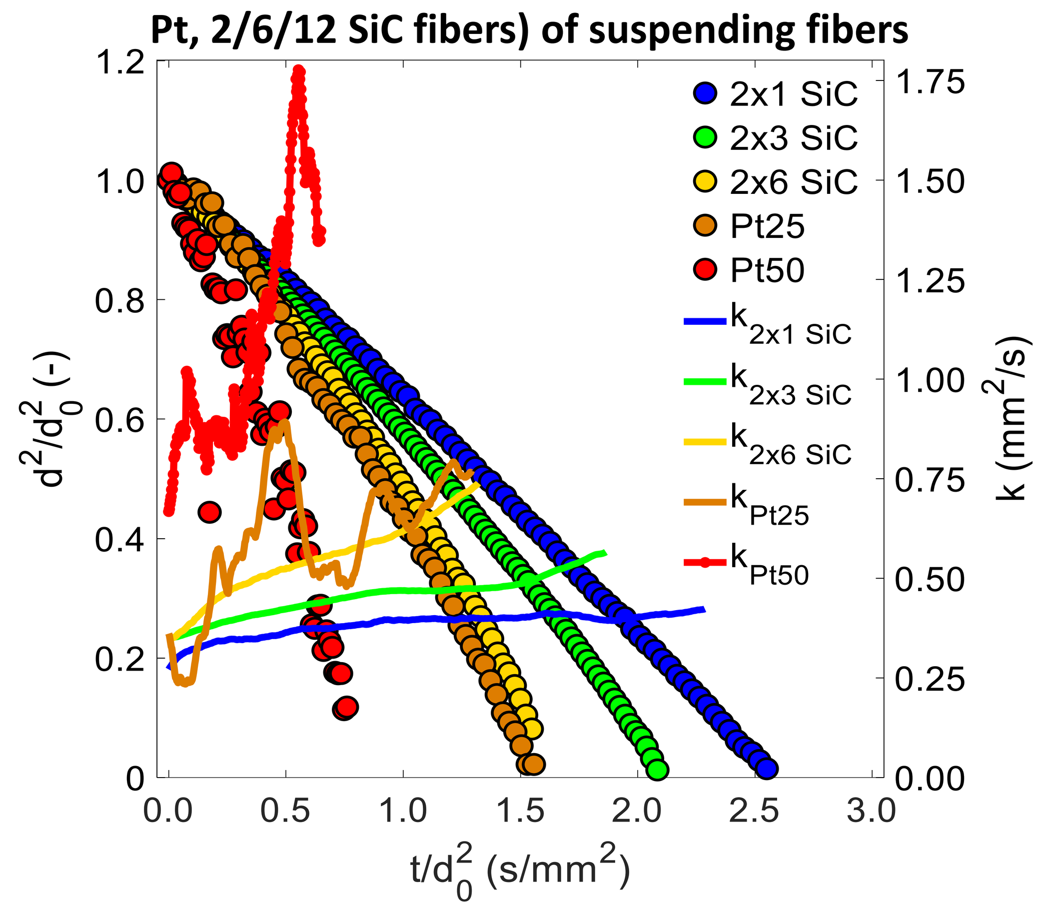
3. Results and discussion

DCF results: model validation for unsuspended droplets



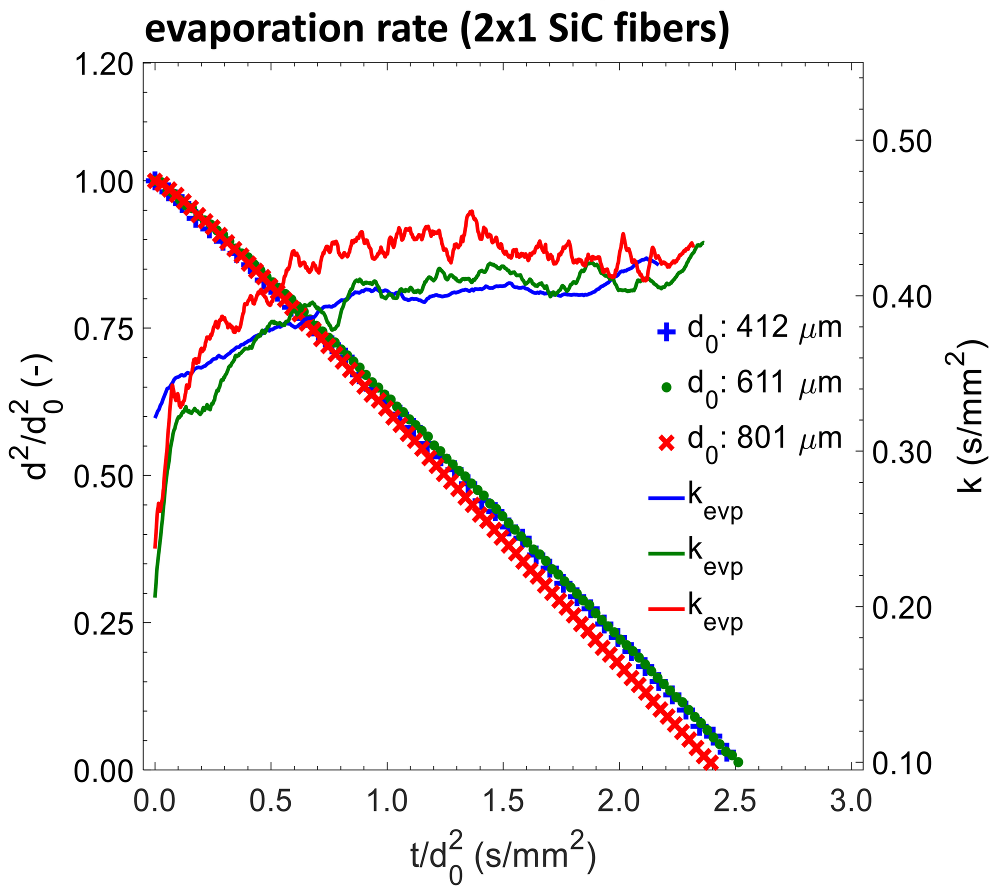
- Evaporation model successfully validated for unsupported droplets.
- Radiation effect only leads to a 0.6% difference in prediction of *k*. This can be due to small d_0 and low radiation heat flux at DCF condition.

SDF results: Effect of material (SiC, Pt) and size (25/50µm Pt, 2/6/12 SiC fibers) of suspending fibers



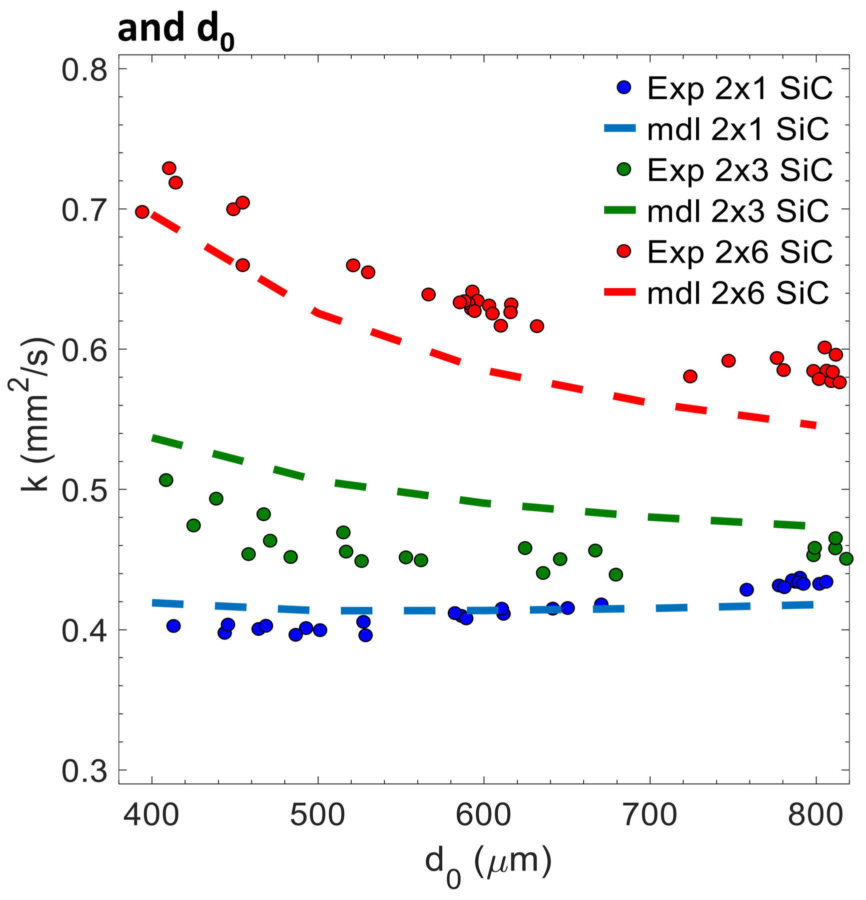
- k_{exp} drastically increases due to enhanced heat transfer, caused by fiber conduction.
- Butanol droplets suspended on Pt wires show puffing behaviors (that is the cause for the fluctuating' curves for Pt25 and Pt50)

SDF results: Effect of d_0 on butanol evaporation rate (2x1 SiC fibers)



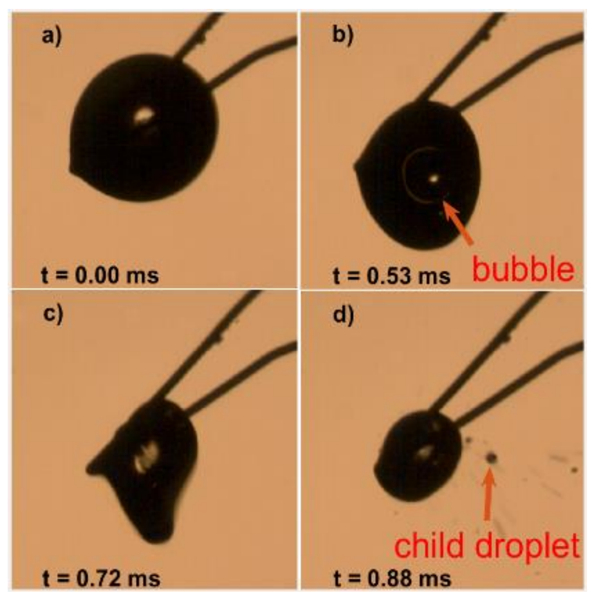
- The k_{exp} tends to slightly increase with the initial droplet size.
- This slight increase in k_{exp} along with d_0 is ascribed to the joint contribution of forced/natural convection and radiative heating.

SDF results: Combined effect of fiber and d_0



- For any fixed d_0, k_{exp} increases with the number of fibers as a result of the enhanced fiber conduction effect.
- For 2x3 and 2x6 arrangements, k_{exp} clearly decreases when d_0/d_f increases.

SDF results: Puffing of butanol droplet suspended on 50µm Pt wire

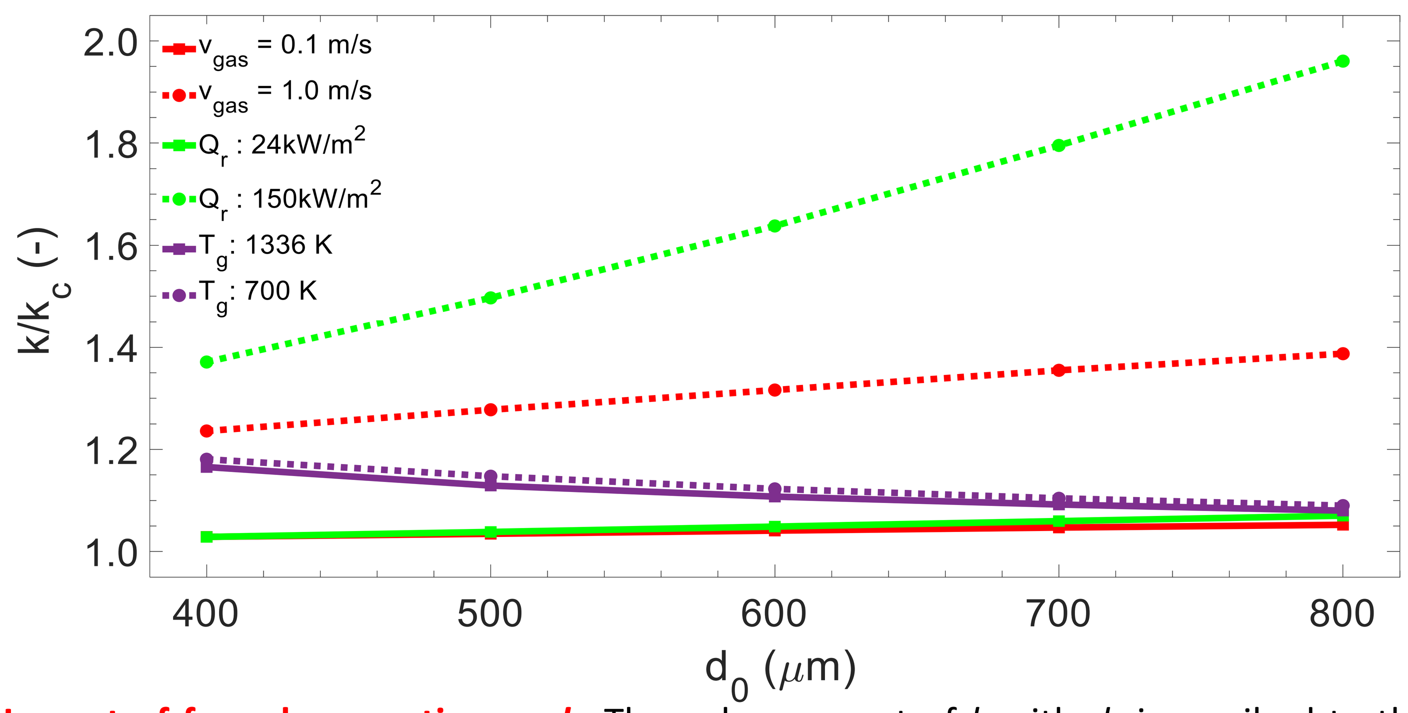


Hot fiber acts as an heterogeneous nucleation site, where butanol vapor bubbles can be produced.
Puffing sequence:

a) Steady evaporation.
b) Onset of bubble generation.
c) Droplet surface wrinkling.
d) Tiny child droplets are expelled with high velocity from the droplet surface.

Assessment of different artifacts on droplet evaporation

Deviation from canonical evaporation rate (k_c) for SDF test conditions (solid lines) and an additional case of interest (dashed lines).



- **Impact of forced convection on *k*:** The enhancement of *k* with d_0 is ascribed to the increase in *Re* (and therefore *Nu*) for larger droplets. Forced convection effect is negligible for SDF conditions.
- **Impact of radiation on *k*:** Its relevance also increases with d_0. Whereas its contribution is practically negligible for SDF conditions, due to the low Q_r, its impact would be quite large for 150 kW/m² (hot walls at 1400 K and ε=0.7).
- **Impact of fiber conduction on *k*:** Its impact decreases with d_0/d_f, since the heat absorbed from the suspension fibers reduces its relative importance when compared with the heat received through a larger droplet surface. The significance of this effect at the lower temperature (700 K), is about the same level of the higher temperature (1336 K).

Conclusions

- Two types of experimental setup and a modeling tool have been employed to assess the effect of experimental artifacts that can affect the isolated droplet evaporation.
- The Heat conduction through the fibers is found to be the most important mechanism that can enhance the *k*, leading even to puffing events for the case of Pt wire.
- The absorption of thermal radiation is less relevant for this specific setup, although it could have a large impact for setups where big droplets are surrounded by highly-emissive hot surfaces.

Acknowledgements

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