

# The effect of natural convection on the modeling of sessile and suspended evaporating drops

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## Introduction

Motivation: Analytical models commonly assume that the mass transfer from a liquid drop in a stagnant environment is a diffusion-driven phenomenon. In the presence of external body forces, like gravitation, natural convection arises affecting the drop evaporation.

Objective: To study the effect of natural convection on the evaporation of sessile and pendant drops, considering the buoyancy caused by the variation in the gas density due to the uneven distribution of the vapour concentration and temperature in the gas mixture.

## Materials and methods

The momentum, species and energy conservation equations are solved using ANSYS Fluent on 2D axis-symmetric grids, under steady-state conditions. The diffusive case is analytically modelled through the variable density model developed in [1, 2], applied to sessile and pendant droplets using the Picknett-Bexon correction [3] for spherical caps. Different values of the contact angle, drop size, drop and gas temperature and three different liquids were considered, see Table 1 for details.

Species	$\theta_c$ (°)	$R_{eq}$ (mm)	$T_d$ (°C)	$T_{inf}$ (°C)	$Gr$ (-)	$Sc$ (-)	$Mm$ (kg/kmol)
water	90	0.78-2.38	25	25	0.24-6.43	0.58	18
water	90	1.19	25-55	25-55	0.80-7.46	0.58-0.61	18
water	30-150	1.98	25	25	3.73	0.58	18
octane	90	0.634-1.59	20	20	0.49-7.59	2.28	114.23
octane	30-150	1.19	20	20	3.2	2.28	114.23
ethanol	90	0.634-1.59	25	25	0.50-7.76	1.15	46.07
ethanol	30-150	1.19	25	25	3.33	1.15	46.07

Table1. Test cases for the reported analysis

## Model verification and validation

The model predictions were first validated by a comparison to the predictions of the analytical model reported in [1,2], by setting to zero the gravitational acceleration in the simulation so to exclude buoyancy, since the analytical model accounts only for vapour diffusion and Stefan flow while external convection is excluded. The results, shown in figure 1, right) are in very good agreement and the model, under these conditions, can be considered verified.

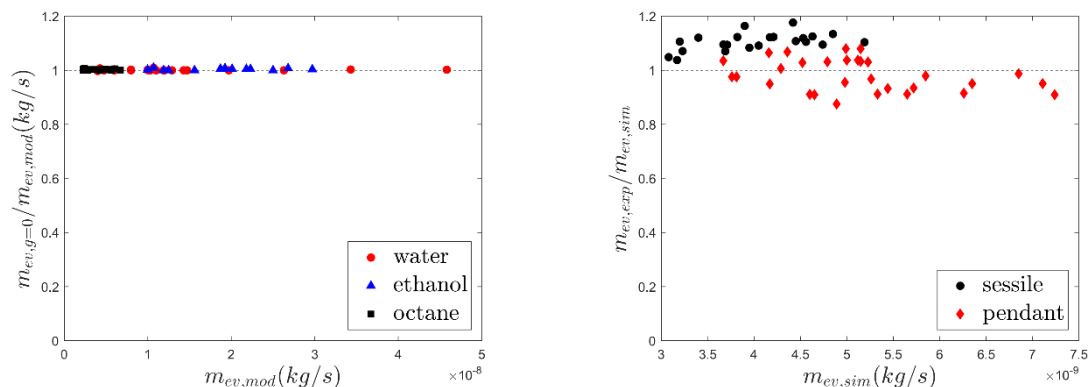
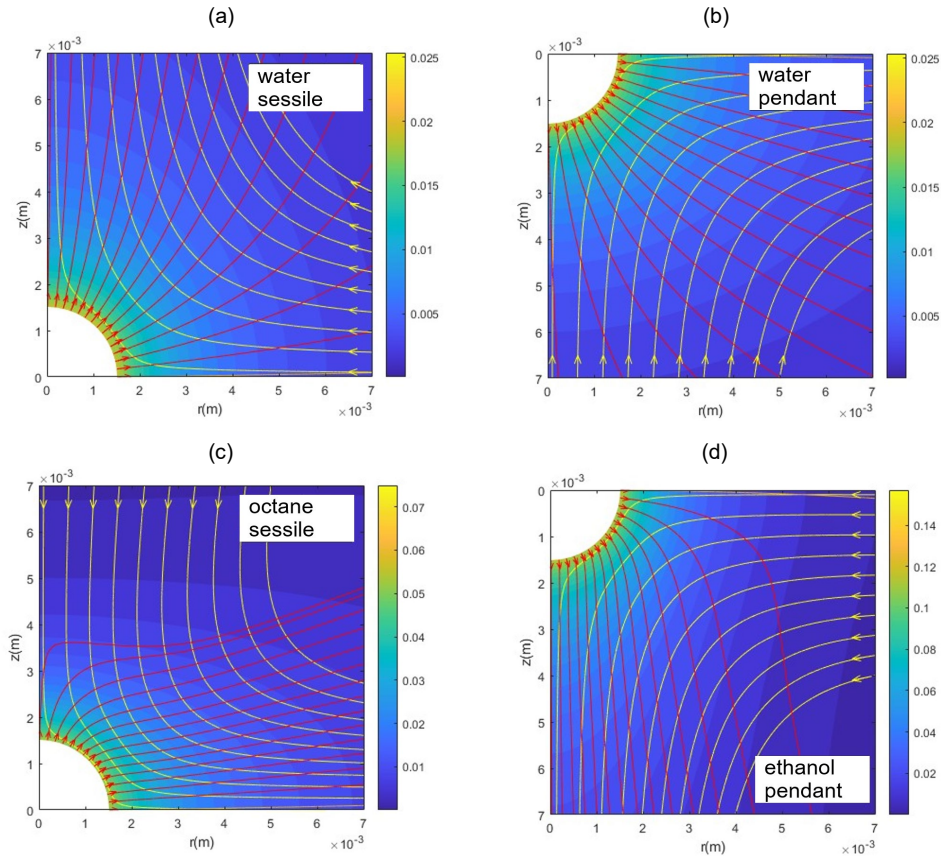


Figure 1. (Left) Comparison of the evaporation rate from the analytical model [1,2] predictions and from the numerical simulations with  $g=0$ ; (right) validation of the CFD results against experiments [4].

A model validation was also performed by comparison to the results from the experimental work as reported in [4]. The comparison shows acceptable consistency, with some overestimation for the pendant drop case (see figure 1, right).

## Results and Discussion

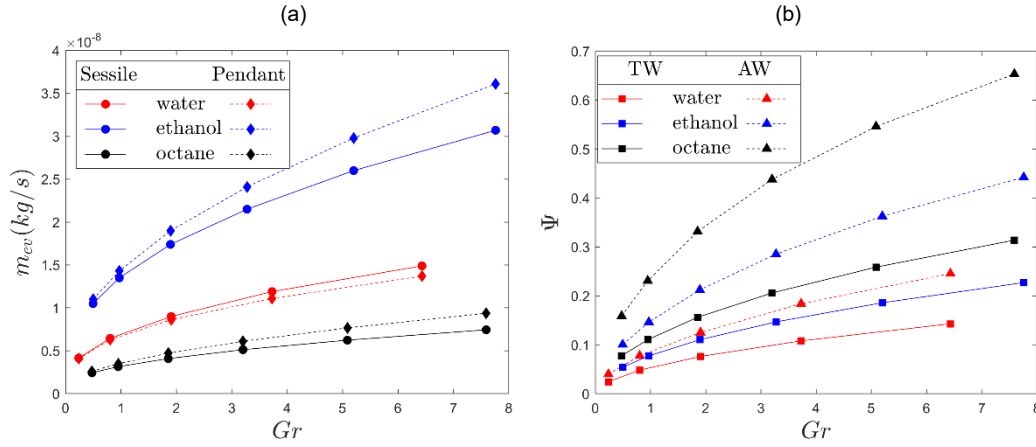
The flow field and vapour mass fraction around the evaporating drops are reported in figure 2 for four different cases. The buoyancy flow is directed as gravity in air/octane or air/ethanol gas mixture, supporting vapour convection with pendant drops (the flow is directed away from the wall, AW) and opposing it with sessile drops (the flow is directed towards the wall, TW). The contrary occurs with water drops. The effect is explained observing that water has a molar mass lower than that of air, then the gas flow is always directed in the direction opposite to the gravity acceleration, i.e. away from the wall for sessile drops and toward the wall for pendant drops. Octane and ethanol instead have molar mass larger than that of air and then the direction of the flow is the opposite: toward the wall for sessile drop and away from the wall for pendant drops.



**Figure 2.** Distribution of the vapour mass fraction and streamlines of gaseous mixture (yellow lines) and vapour (red lines) for drops with  $Re_{eq} = 1.19$  mm and  $\theta_c = 90^\circ$  made of: (a) water-sessile (TW), (b) water-pendant (AW), (c) octane-sessile (TW), (d) ethanol-pendant (AW).

This different flow behaviour with respect of the molar masses of the evaporating species explain why that sessile water drops show higher evaporation compared to suspended ones and the opposite occurring for ethanol and octane drops, with differences increasing with the Grashoff number as shown in figure 3(left). The re-classification of the results in term of flow direction (toward or away from the wall) instead of pendant or sessile geometry eliminates the apparent inconsistency seen in figure 3(right). Figure 3(right) reports the results using this classification, showing the quantity  $\Psi = m_{ev}/m_{ev}^0 - 1$  where  $m_{ev}$  is the evaporation rate in the presence of natural convection while  $m_{ev}^0$  is that in the absence of natural convection.

The substrate wettability has a small influence on the evaporation rate when the contact angle is comprised between 60 deg and 120 deg, while a non-negligible effect is observed for more hydrophilic and more hydrophobic substrates, up to about 24% and 29% with contact angles equal to  $30^\circ$  and  $150^\circ$ , respectively.

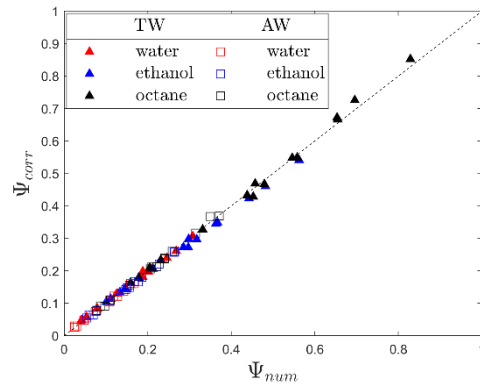


**Figure 3.** Effect of the Grashoff number on (left) the evaporation rate and on (right) relative difference of the evaporation rates with and without natural convection, predicted by the numerical model for pendant and sessile drops, and three liquids.  $\theta_c = 90^\circ$ .

In the attempt of correlating the results the quantity  $\Psi$  is written as a function of Grashoff and Schmidt numbers of the form:

$$\Psi = A Gr^m Sc^n \quad (1)$$

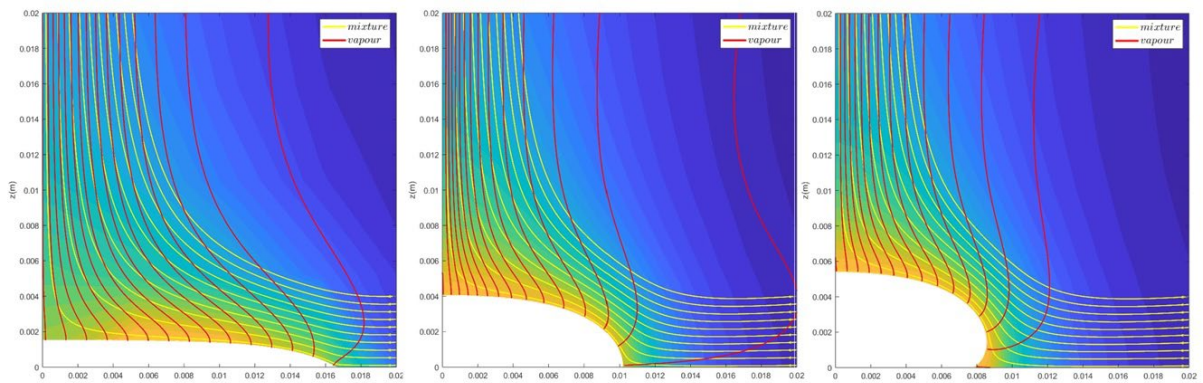
Figure 4 shows the first results by comparing the values obtained from the simulation,  $\Psi_{num}$ , to those predicted by the correlation,  $\Psi_{corr}$ . A better agreement is found by formulating two different correlations for the cases of flow directed toward the wall (TW) and away from the wall (AW).



**Figure 4.** Comparison of the non-dimensional evaporation rate predicted by the numerical model and by the empirical correlation, for all the tested operating conditions.

#### Work-in-progress: effect of drop deformation

The drop deformation induced by gravity seems to have a non-negligible effect on the evaporation in presence of natural convection when the drop size increases.



**Figure 5.** Distribution of the vapour mass fraction and streamlines of gaseous mixture (yellow lines) and vapour (red lines) for deformed water drops with  $R_{eq} = 6.102$  mm ( $Bo = 5$ ) and contact angle (a)  $\theta_c = 30^\circ$ , (b)  $\theta_c = 90^\circ$ , (c)  $\theta_c = 150^\circ$ .

Preliminary results obtained with water drops with Bond number about 5 (see figure 5 for the flow fields) suggest that the effect of natural convection on the evaporation rate, compared to the purely diffusive case, is about 133%, 94% and 89% for drops with contact angle equal to 30°, 90° and 150°, respectively.

### **Conclusions**

The effect of natural convection on the evaporation of sessile and pendant drops was studied in a range of Grashoff number up to 7.76, Schmidt number up to 2.28, and contact angle between 30° and 150°.

The comparison between the results from the numerical simulations assuming  $g=0$  and the analytical model shows an average difference of about 0.25%, while the discrepancies with the experiments are always lower than 20%. Buoyancy flow promotes the vapour convection with ethanol or octane pendant drops and the opposite with sessile drops. The contrary occurs with water drops.

The effect of wettability is lower than about 5% with contact angle between 60°- 120° respect to the case with 90°, up to 24-29% with contact angle of 30°.

The average discrepancy between the correlation and the numerical predictions is about 3.1% (about 3% for TW cases and 2.7% for AW).

### **References**

- [1] S. Tonini, G. Cossali, *Int. J. Therm. Sci.* 57, 45–53 (2012).
- [2] S. Tonini, G. Cossali, E. Shchepakina, V. Sobolev, S. Sazhin, *Phys. Fluids* 34, 073312 (2022).
- [3] R. Picknett, R. Bexon, *J. Colloid and Interface Science* 61, 336–350 (1977).
- [4] S. Tonini, P. Conti, G. Cossali, E. Starinskaya, N. Miskiv, A. Rodionov, S. Starinskiy, V. Terekhov, and S. Sazhin, *Phys. Fluids* 37