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Instability of axisymmetric flow in thermocapillary liquid bridges: Kinetic and thermal energy budgets for two-phase flow with temperature-dependent material properties – CORRIGENDUM

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1. Thermal energy

In [3] we have claimed to take into account *the temperature dependence of all thermophysical parameters*. However, in the temperature equation (3.1c) of [3] we have neglected the term describing the advection of c_p . Even though the advection of c_p has little effect (see below), we present the temperature equation which includes the advection of c_p , but still neglects the pressure variations. The correspondingly revised temperature equation reads

$$\partial_t (\rho c_p \hat{T}) + \nabla \cdot (\rho c_p \hat{\mathbf{U}} \hat{T}) = \nabla \cdot (\lambda \nabla \hat{T}) + \rho \hat{T} \frac{Dc_p}{Dt} \quad (3.1c)$$

or, equivalently [1],

$$\rho c_p \left(\partial_t + \hat{\mathbf{U}} \cdot \nabla \right) \hat{T} = \nabla \cdot (\lambda \nabla \hat{T}). \quad (3.1c)$$

As a result the equations (4.1)–(4.6) must be replaced by the following expressions, where we use the same equation numbering as in the original publication.

$$\rho c_p [\partial_t + (\mathbf{u}_0 + \mathbf{u}) \cdot \nabla] (T_0 + T) = \nabla \cdot (\lambda \nabla T_0) + \nabla \cdot (\lambda \nabla T). \quad (4.1)$$

$$\rho c_p (\partial_t T_0 + \partial_t T + \mathbf{u}_0 \cdot \nabla T_0 + \mathbf{u}_0 \cdot \nabla T + \mathbf{u} \cdot \nabla T_0) = \nabla \cdot (\lambda \nabla T_0) + \nabla \cdot (\lambda \nabla T). \quad (4.2)$$

$$\begin{aligned} \rho_0 c_{p0} \partial_t T_0 + (\rho_0 c'_p + \rho'_0 c_{p0}) T \partial_t T_0 + \rho_0 c_{p0} \partial_t T + [\rho_0 c_{p0} + (\rho_0 c'_{p0} + \rho'_0 c_{p0}) T] \mathbf{u}_0 \cdot \nabla T_0 \\ + \rho_0 c_{p0} (\mathbf{u}_0 \cdot \nabla T + \mathbf{u} \cdot \nabla T_0) = \nabla \cdot (\lambda_0 \nabla T_0) + \nabla \cdot (\lambda'_0 T \nabla T_0) + \nabla \cdot (\lambda_0 \nabla T). \end{aligned} \quad (4.3)$$

$$\rho_0 c_{p0} \mathbf{u}_0 \cdot \nabla T_0 = \nabla \cdot (\lambda_0 \nabla T_0). \quad (4.4)$$

$$\begin{aligned} \rho_0 c_{p0} \partial_t T + (\rho_0 c'_{p0} + \rho'_0 c_{p0}) T \mathbf{u}_0 \cdot \nabla T_0 + \rho_0 c_{p0} (\mathbf{u}_0 \cdot \nabla T + \mathbf{u} \cdot \nabla T_0) \\ = \nabla \cdot (\lambda'_0 T \nabla T_0) + \nabla \cdot (\lambda_0 \nabla T). \end{aligned} \quad (4.5)$$

$$\begin{aligned} \underbrace{\rho_0 c_{p0} T \partial_t T}_{T1} = & \underbrace{0}_{T2} - \underbrace{\rho'_0 c_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0}_{T3} - \underbrace{\rho_0 c'_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0}_{T4} \\ & - \underbrace{\rho_0 c_{p0} T \mathbf{u}_0 \cdot \nabla T}_{T5} - \underbrace{\rho_0 c_{p0} T \mathbf{u} \cdot \nabla T_0}_{T6} + \underbrace{T \nabla \cdot (\lambda'_0 T \nabla T_0)}_{T7} + \underbrace{T \nabla \cdot (\lambda_0 \nabla T)}_{T8}. \end{aligned} \quad (4.6)$$

As a result of the inclusions of the c_p -advection term, the term T2 in (4.6) of [3] vanishes and the terms T3 to T6 are modified. The rate of change of thermal energy (4.8) formally remains the same, but with the following meaning.

$$D_{\text{th}} = - \int_{V_i} (\text{part of T8}) \, dV = \int_{V_i} \lambda_0 (\nabla T)^2 \, dV, \quad (4.9a)$$

$$J = - \int_{V_i} \text{T6} \, dV = - \int_{V_i} \rho_0 c_{p0} T (u \partial_r T_0 + w \partial_z T_0) \, dV, \quad (4.9b)$$

$$H_{\text{fs}} = - \int_{V_i} (\text{part of T8}) \, dV = \alpha_i \int_{A_{\text{fs}}} \lambda_0 T \nabla T \cdot \mathbf{n} \, dS, \quad (4.9c)$$

$$K_{\text{G,th}} = - \int_{V_i} (\text{part of T5}) \, dV = - \frac{1 - \alpha_i}{4} \int_{A_{\text{out}}} \rho_0 c_{p0} T^2 w_0 \, dS, \quad (4.9d)$$

$$\Pi_\rho = - \int_{V_i} \text{T3} \, dV = - \int_{V_i} \rho'_0 c_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0 \, dV, \quad (4.9e)$$

$$\Pi_{c_p} = - \int_{V_i} (\text{T4} + \text{part of T5}) \, dV = - \frac{1}{2} \int_{V_i} \rho_0 c'_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0 \, dV, \quad (4.9f)$$

$$\Pi_\lambda = - \int_{V_i} \text{T7} \, dV = \alpha_i \int_{A_{\text{fs}}} \lambda'_0 T^2 \nabla T_0 \cdot \mathbf{n} \, dS - \frac{1}{2} \int_{V_i} \lambda'_0 \nabla T_0 \cdot \nabla T^2 \, dV, \quad (4.9g)$$

$$\partial_t E'_T = - \int_{V_i} \text{T2} \, dV = 0. \quad (4.9h)$$

For the sake of completeness we have specified all subequations of (4.9) of [3]. Note that equations (4.9a), (4.9c), (4.9d), (4.9g) and (4.9h) remain unchanged, while the subequations (4.9b), (4.9e), (4.9f) and (4.9h) are updated. The notation 'part of T#' in (4.9), # ∈ [5, 8], should indicate that only part of the respective term T# from (4.6) enters the integral in (4.9).

We note that the integral over T5 yields

$$\begin{aligned} \int_{V_i} \text{T5} \, dV &= \int_{V_i} \rho_0 c_{p0} T \mathbf{u}_0 \cdot \nabla T \, dV = \overbrace{\int_{A_{\text{out}}} \rho_0 c_{p0} T^2 \mathbf{u}_0 \cdot \mathbf{n} \, dS}^{:= -2K_{\text{G,th}}} - \int_{V_i} T \nabla \cdot (\rho_0 c_{p0} \mathbf{u}_0 T) \, dV \\ &= -2K_{\text{G,th}} - \int_{V_i} T \rho_0 \mathbf{u}_0 \cdot (c_{p0} \nabla T + T \nabla c_{p0}) \, dV \\ &= -2K_{\text{G,th}} - \int_{V_i} \rho_0 c_{p0} T \mathbf{u}_0 \cdot \nabla T \, dV - \int_{V_i} \rho_0 c'_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0 \, dV. \end{aligned}$$

From which one concludes

$$\int_{V_i} \rho_0 c_{p0} T \mathbf{u}_0 \cdot \nabla T \, dV = -K_{\text{G,th}} - \frac{1}{2} \int_{V_i} \rho_0 c'_{p0} T^2 \mathbf{u}_0 \cdot \nabla T_0 \, dV.$$

For a derivation of the remaining expressions in the revised equation (4.9) the Appendix A of [3] is not required anymore and should be dropped.

2. Effect of c_p advection on the linear stability boundary

To demonstrate the effect of c_p advection on the linear stability boundary, we supplement the linear stability boundaries from table 3 of [1] by critical Reynolds numbers (and temperature differences) obtained including the term $\rho \hat{T} Dc_p / Dt$, i.e. the effect of c_p advection (superscript 'adv'). Table 1 reveals that the advection of c_p reduces the critical Reynolds number in the full-temperature-dependence model (FTD) by 1.6%. Considering the deviations from the critical Reynolds number in the Oberbeck–Boussinesq (OB) model we find that the temperature dependence of c_p without c_p advection reduces the critical Reynolds number by 2.2%. From table 3 of [1] we note that the temperature dependence of ρ and λ (including advection of these quantities) individually reduce Re_c^{OB} by about 2%, while

Table 1. Critical temperature difference ΔT_c and critical Reynolds number $Re_c = \gamma \bar{\rho}_L \Delta T_c d / \bar{\mu}_L^2$ for a slender liquid bridge with $\Gamma = 0.66$ and $\mathcal{V} = 0.9$ made of 2-cSt silicone oil as in table 3 of [1]. The superscript 'adv' indicates results when the advection of c_p is included in the governing equations. For all models, the critical wave number is $m_c = 3$. The relative deviations $\epsilon_c^{FTD} := (Re_c - Re_c^{FTD})/Re_c^{FTD}$ and $\epsilon_c^{OB} := (Re_c - Re_c^{OB})/Re_c^{OB}$ are given in percent. For the definition of $\Delta^{(i)}Re_c$, please see the text

Approximation	ΔT_c [K]	Re_c	ϵ_c^{FTD} [%]	ϵ_c^{OB} [%]	$\Delta^{(i)}Re_c$
FTD	44.49	1471			
FTD ^{adv}	43.78	1448	−1.6	—	
OB	55.50	1835			
OB + $\rho(\hat{T})$	54.63	1806	—	−1.6	−29
OB + $\lambda(\hat{T})$	54.33	1797	—	−2.1	−38
OB + $c_p(\hat{T})$	54.28	1795	—	−2.2	
OB + $c_p^{\text{adv}}(\hat{T})$	53.11	1756	—	−4.3	−79
OB + $\mu(\hat{T})$	45.60	1509	—	−17.8	−326

individually taking into account $c_p(\hat{T})$ (including c_p advection) reduces Re_c^{OB} by to 4.3 percent, where the advection of c_p contributes about as much as the mere temperature dependence (without c_p advection) does. Therefore, among the three quantities ρ , λ and c_p , c_p has the largest share in reducing the critical Reynolds number relative to Re_c^{OB} . Of course, the temperature dependence of the viscosity μ alone dominates the reduction of the critical Reynolds number from Re_c^{OB} . The change of the critical Reynolds number $\Delta^{(i)}Re_c := Re_c^{(i)} - Re_c^{OB}$ due to the temperature dependence of each individual thermophysical parameter, where i symbolizes $i \in \{\text{OB} + \rho, \text{OB} + \mu, \text{OB} + c_p^{\text{adv}}, \text{OB} + \mu\}$ (including advection in all cases), is almost additive: For the case considered, the sum of the Reynolds number reductions amounts to $\sum_i \Delta^{(i)}Re_c = -473$ with the deviation $Re_c^{\text{FTD, adv}} - Re_c^{OB} = 1448 - 1835 = -387$. An updated version of the code `MaranStable` which includes the effect of c_p advection is available under <https://github.com/fromano88/MaranStable>. The driver file for the old version is 'main_v3d1.m', while the one for the new version is 'main_v3d2.m'.

3. Kinetic energy

Equation (B25) in [1] contains a sign error. The corrected equation (B25) reads

$$\begin{aligned}
 \int_{V_i} K7a \, dV &= \int_{V_i} \mu_0 u_l \partial_m \partial_m u_l \, dV \\
 &= \underbrace{\alpha_i \int_{A_{fs}} \mu_0 u_l n_m \partial_m u_l \, dS}_{:=M} - \int_{V_i} \mu_0 (\partial_m u_l)^2 \, dV - \int_{V_i} u_l (\partial_m \mu_0) (\partial_m u_l) \, dV \\
 &= - \int_{V_i} \mu_0 (\partial_m u_l)^2 \, dV + M - \int_{V_i} u_l (\partial_m u_l) (\partial_m \mu_0) \, dV \\
 &= - \int_{V_i} \mu_0 (\partial_m u_l)^2 \, dV + M_r + M_\varphi + M_z \\
 &\quad - \alpha_i \int_{A_{fs}} \mu_0 (h_0 w^2 h_{0zz} - v^2) \, d\varphi \, dz - \int_{V_i} \mu'_0 \mathbf{u} \cdot (\nabla \mathbf{u})^T \cdot \nabla T_0 \, dV.
 \end{aligned}$$

As a consequence (B26) must read

$$\int_{V_i} K7a \, dV = -D_{\text{kin}} + M_r + M_\varphi + M_z - \frac{1}{2} \int_{V_i} \mu'_0 \cdot (\nabla \mathbf{u}^2) \cdot \nabla T_0 \, dV,$$

Table 2. Critical Reynolds numbers Re_c and critical temperature differences ΔT_c for a liquid bridge volume ratio $\mathcal{V} = 0.88$ and different approximations of the transport equations. Shown are the results of [4] for the FTD, LTD and OB models (all exclusive of c_p advection) in comparison with the present results for the FDT^{adv} and LTD^{adv} models (both including the effect of c_p advection). The relative deviation $\epsilon_c = (Re_c - Re_c^{FTD})/Re_c^{FTD}$ is given in percent. All other parameters are identical to those for table 5 of [4]: Shin-Etsu silicone oil with $\nu(\hat{T} = 25^\circ\text{C}) = 2$ cSt, $\Gamma = 0.66$, $\mathcal{V} = 1$, $Bd = 0.363$

Approximation	Re_c	ΔT_c [K]	ϵ_c [%]
FTD	1679	50.79	0
FDT^{adv}	1659	50.17	−1.2
LTD	1572	47.53	−6.4
LTD^{adv}	1556	47.05	−7.3
OB	2263	68.45	34.8

and equation (5.8i) needs to be updated to

$$\begin{aligned} \Lambda_\mu = & \int_{V_i} \mu'_0 \mathbf{u} \cdot \nabla \mathbf{u} \cdot \nabla T_0 \, dV + \int_{V_i} (\mu'_0 + \mu''_0 T_0) \mathbf{u} \cdot [\mathcal{S}_0 + (\nabla \mathbf{u}_0)^T] \cdot \nabla T \, dV \\ & - \int_{V_i} \mu'_0 T (\nabla \mathbf{u}_0) : (\nabla \mathbf{u}) \, dV + \alpha_i \int_{A_{fs}} \mu'_0 w T (N^2 \partial_r w_0 - N^2 h_{0z} \partial_z w_0 - h_{0z}^2 h_{0zz} w_0) \, d\varphi \, dz. \end{aligned}$$

We apologize for the errors made.

4. Related publications

Publications [2] and [4] also considered the stability of the thermocapillary flow in liquid bridges when the specific heat $c_p(T)$ is temperature dependent. Similar as in table 1 above, we provide in table 2 the equivalent of table 5 of [4], here supplemented by the result when the advection of c_p is taken into account (superscript ‘adv’). Note that the deviations specified in the last column are taken relative to the full-temperature-dependence model (FTD) without c_p advection, as considered in [4].

Table 2 shows that the inclusion of c_p advection reduces the critical Reynolds number of the FTD model by 1.2%. In contrast, the linearization of the temperature dependence of all material properties yields a 6.4% reduction, mainly caused by the insufficient representation of $\mu(\hat{T})$ by a linear function of \hat{T} . The percentage change of the critical Reynolds number due to c_p advection is further corroborated by considering the critical data for the same liquid near the global maximum of Re_c from figures 5 (green square) and 9 (black square) of [4]. Table 3 shows the corresponding comparisons. In both cases considered the advection of c_p slightly decreases the critical Reynolds number by 1.9 % (case A) and 1.1 % (case B) which is compatible with the trend seen in table 2. In contrast, the critical frequency is slightly increased.

We have demonstrated that the advection of c_p affects the critical data presented in [2, 4] by reducing Re_c by 1 to 2 percent. This is much less than the effect a temperature dependent viscosity of 2 cSt silicone oil has on the critical Reynolds number. Nevertheless, the c_p advection influences the critical data about as much as the inclusion or neglect of the temperature dependence of the liquid’s density, its thermal conductivity or of c_p itself has.

In particular, the stability curves obtained by including $\rho \hat{T} D_{rc_p}$ in the governing equations are within a 2% tolerance level from the critical Reynolds numbers reported in [2, 4] for $\Delta T \leq 56$ K (see table 3). All conclusions drawn and discussions reported in [3, 4] still hold true when the c_p advection

Table 3. Critical Reynolds numbers Re_c near their extrema for a liquid bridge from 2 cSt silicone oil and selected cases of [4]. Case A: $\Gamma = 0.93$, $\mathcal{V} = 1$, $Bd = 0.721$, $Re_g = 0$. Case B: $\Gamma = 0.66$, $\mathcal{V} = 1$, $Bd = 0.363$, $Re_g = -500$. Values are given for the full-temperature-dependence model without (FTD) and with inclusion of c_p advection (FTD,adv). The relative deviation $\epsilon_c = (Re_c^{FTD,adv} - Re_c^{FTD})/Re_c^{FTD}$ is given in percent; correspondingly for the critical frequency ω_c

Case	Variable	FTD	FTD,adv	ϵ_c [%]
A	Re_c	1438	1411	-1.9
A	ΔT_c [K]	30.87	30.29	-1.9
A	ω_c	35.0	35.4	1.1
B	Re_c	1853	1833	-1.1
B	ΔT_c [K]	56.04	55.45	-1
B	ω_c	41.7	42.7	2.4

term $\rho \hat{T} D_t c_p$ is consistently included in the energy equation, except for small quantitative deviations discussed herein.

References

- [1] Bird, R. B., Stewart, W. E. & Lightfoot, E. N. (2001). *Transport Phenomena*. 2nd ed. J. Wiley, New York.
- [2] Stojanović, M., Romanò, F. & Kuhlmann, H. C. (2023) MaranStable: A linear stability solver for multiphase flows in canonical geometries. *Software X* **23**, 101405.
- [3] Stojanović, M., Romanò, F. & Kuhlmann, H. C. (2023) Instability of axisymmetric flow in thermocapillary liquid bridges: Kinetic and thermal energy budgets for two-phase flow with temperature-dependent material properties. *Eur. J. Appl. Math.* **35**(2), 267–293. DOI: [10.1017/S0956792523000189](https://doi.org/10.1017/S0956792523000189)
- [4] Stojanović, M., Romanò, F. & Kuhlmann, H. C. (2024) Flow instability in high-Prandtl-number liquid bridges with fully temperature-dependent thermophysical properties. *J. Fluid Mech* **978**, A17.