The effect of gas-phase transport on buoyancy-Marangoni convection in confined volatile binary fluids

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Keywords: Two-phase Flow, Phase Change, Evaporative Cooling, Buoyancy-Marangoni Convection, Thermocapillarity, Solutocapillarity

We consider convection in layers of volatile binary liquids with a free surface subjected to a horizontal temperature gradient, which is driven by a combination of three different forces: thermocapillarity, solutocapillarity, and buoyancy (for thick liquid layers). This problem has attracted increasing attentions recently due to its applications in thermal management devices that rely on evaporative cooling. In typical evaporative cooling devices, such as heat pipes, the sealed cavity is filled with volatile liquids and gases (vapors and noncondensables) separated by an interface, when the system is heated on one end and cooled on the other end, the heat is transported mostly due to the latent heat absorbed (released) near the heated (cooled) end, while the temperature gradient between the heated and cooled ends drives the system out of equilibrium and generates the flow.

For a single component coolant, surface tension typically decreases with increasing temperature, therefore, thermocapillary stresses drive the fluid away from the heated end of the heat pipe, which can cause dry-out, leading to a complete loss of evaporative cooling and a dramatic increase in the temperature of the hot end. Under certain conditions, however, solutocapillary stresses can oppose thermocapillary stresses. In particular, with a positive binary coolant \([1]\), the differential evaporation of the two components causes solutocapillary stresses towards, rather than away from, the hot end, hence delay the dry-out. Both thermo- and solutocapillary stresses depend sensitively on the local phase equilibrium at the liquid-gas interface. Furthermore, it is well known that the presence of noncondensable gases (such as air) could significantly affect the phase change and the heat transport. Therefore, flows in both phases, phase change, and the transport across the interface all have to be considered.

Hence we start with generalizing comprehensive two-sided (liquid/gas) transport model for binary fluids based on previous studies for simple fluids \([2-5]\), which is able to describe the two-phase convection in mixtures of an arbitrary number of miscible components with arbitrary composition. In particular, it provides a quantitative description of transport of heat, mass, and momentum in both the liquid and the gas phase, as well as across the liquid-gas interface \([6]\).

![Figure 2. Interfacial velocity at methanol concentration in the liquid \(Y_a = 0.6, \Delta T = 6\) K with different air concentration \(X_a\).](image-url)

The transport model has been numerically implemented, and numerical investigation are performed using the same geometry (cf. Figure 1), working fluid (water-methanol mixture), and working condition \((\Delta T = 6\) K) as in the experiments of Li and Yoda \([7]\). The numerical results successfully identified the flow regimes observed in the experiments, and reproduced the flow reversal at the interface as the air concentration \(X_a\) decreases (cf. Figure 2).

The presence of noncondensables and the mass transport in the gas phase is found to have significantly effect on the flow in both phases. At high \(X_a\) (\(= 0.91\)), thermocapillarity is dominant, as phase change and hence solutocapillarity is greatly suppressed. Therefore the flow is towards to the cold end \((u_i < 0)\) along the entire interface. As \(X_a\) reduces, differential phase change is enhanced, leading to stronger concentration gradient, hence a stronger solutocapillarity. Moreover, due to the latent heat associated with phase change, temperature gradient and hence thermocapillarity becomes weaker. As solutocapillarity exceeds thermocapillarity, the flow start to reverse \((u_i > 0)\) along the interface. At sufficiently low \(X_a\) (\(= 0.015\)), the flow reverses along the entire interface.

The fact that the mass transport in the gas phase could significantly affect the flow in both phases suggests that we should start with the gas phase transport if we plan to construct a simplified transport model. Since the mass transport in the gas phase is dominated by...
diffusion ($Pe_m \gg 1$), with the large aspect ratio in the direction of temperature gradient, the flow in the central region of gas phase can be approximated as one-dimensional, and the concentration in the gas phase can be described with a simplified analytical solution [8]

$$\tilde{X}_b = C_0 + C_1 e^{-Pe_m \chi},$$

where $\chi = x/d_g$, $Pe_m = |u_0|d_g/D_b$ is the mass Peclet number which corresponds to the mean flow $u_0$, and the constants $C_0$ and $C_1$ are determined by the boundary conditions at $\chi = 0$ and $\chi = L/d_g$.

Although the analytical solution in the bulk of liquid is difficult to obtain since the liquid phase is dominated by advection, we can estimate the temperature $T_i$, and the liquid concentration $Y_b$ along the interface with the help of local phase equilibrium (Raoult’s law and the Antoine equation), which relates them to the solution of the gas phase. Finally, the solutions of the temperature and concentration along the interface lead to the estimate the thermocapillary stresses $\Sigma_T$ and solutocapillary stresses $\Sigma_S$, and their relative strength.

As shown in Figure 3, the analytical solution predicts an increase in the ratio between the soluto- and thermocapillary stresses as $\tilde{X}_a$ decreases, which is consistent with the numerical results and experimental observation. In particular, the flow along the interface is towards the cold end when $\Sigma_S/\Sigma_T \gg 1$, starts to reverse when $\Sigma_S/\Sigma_T \approx 1$, and completely reverses when $\Sigma_S/\Sigma_T \ll 1$. Therefore, the analytical solutions could help us identify the critical value for air concentration $\tilde{X}_a$ below which the system reaches desired working condition (complete flow reversal along the interface).

In summary, we have developed a comprehensive two-sided transport model for confined two-phase buoyancy-Marangoni convection with volatile binary fluids. The numerical results suggest that the mass transport in the gas phase and the air concentration have a significant effect on the flow in both phases, and should not be neglected for modeling such systems. Moreover, we are able to construct a simplified analytical model by focusing on the gas phase transport. Despite the complex nature of this problem, the analytical solution was able to predict the flow reversal along the interface as $\tilde{X}_a$ decreases, which indicates that this simplified model captures the essential physics of the problem.

References


