Critical Point Dewetting: the role of the gravity and the long-range force

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Critical Point Dewetting:
the role of the gravity and the long-range force

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Near the critical temperature of a immiscible binary liquid system, a solid substrate is usually covered completely by one of the liquid phases. This phenomenon is called the "critical point wetting" which is predicted by Cahn in 1977 [1]. He argued that the complete wetting takes place inevitably in any three-phase system when the temperature is sufficiently close to the critical point. Indeed, the critical point wetting has been confirmed for many fluid systems experimentally [2].

On the other hand, it is suggested from a theoretical consideration that the critical point wetting does not necessarily takes place when both the long-range force between the substrate and the gravity are present [3]. For example, when a wetting film (phase 2) with thickness \( l \) is present between the bulk liquid phase (phase 1) and the solid substrate (phase s), a grand potential \( \Omega(l) \) per unit area can be written in the following form:

\[
\begin{align*}
\Omega(l) - \Omega(0) &= \sigma_{2s} - \sigma_{1s} + \sigma_{12} + W(l) + |\delta \rho g z| l, \\
\end{align*}
\]

where \( \sigma_{ij} \) are the surface tensions between i and j phases, \( \delta \rho \) is the difference of the mass density between the two liquid phases, \( g \) is the gravitational acceleration, \( z \) is the height from the bulk meniscus and \( W(l) \) is the free energy due to the long-range interaction per unit area of the wetting film. \( W(l) \) depends on \( l \) as \( W(l) \sim -H/12\pi l^2 \) for large \( l \) and \( W(l) \sim \sigma_{1s} - \sigma_{2s} - \sigma_{12} \) for \( l \to 0 \). Here, \( H < 0 \) is the Hamaker constant. This grand potential has two minima: one is located at \( l = 0 \) and the other is at \( l = l^* = (-H/6\pi|\delta \rho g z|)^{1/3} > 0 \). The former corresponds to the non-wetting state, and the latter to the wetting state. The difference of the grand potential between these two states can be written as

\[
\Omega(l^*) - \Omega(0) = \sigma_{2s} - \sigma_{1s} + \sigma_{12} + \frac{3}{2} (-H/6\pi)^{1/3} |\delta \rho g z|^{2/3}.
\]

When \( \Omega(l^*) - \Omega(0) \) is negative (positive), the wetting state is more stable (unstable) than the non-wetting state.

In the vicinity of the critical temperature \( T_c \) of the liquid-liquid phase separation, the variables in the equation (2) depend on the reduced temperature \( t = (T_c - T)/T_c \) as \( \sigma_{1s} - \sigma_{2s} \sim t^{\beta_1}, \sigma_{12} \sim t^{2\nu}, \) and \( -H \sim |\delta \rho| \sim t^{\beta} \), where \( \beta_1 \sim 0.8, 2\nu \sim 1.3 \) and \( \beta \sim 0.33 \) are critical exponents. Therefore, \( \Omega(l^*) - \Omega(0) \sim -At^{\beta_1} + Bt^{2\nu} + Ct^{\beta}|z|^{2/3} \), where \( A, B \) and \( C \) are positive proportional coefficients. If \( C = 0 \), which corresponds to the absence of the long-range interaction (i.e. \( H = 0 \)) or gravity (i.e. \( g|z| = 0 \)), \( \Omega(l^*) - \Omega(0) \) becomes negative for a sufficiently small \( t \) because \( \beta_1 < 2\nu \), and this coincides with the Cahn’s prediction. On the other hand, if \( C \neq 0 \), the \( Ct^{\beta}|z|^{2/3} \) term becomes dominant for \( t \to 0 \), and \( \Omega(l^*) - \Omega(0) \) becomes positive, indicating that the critical point dewetting takes place for the system with finite \( |z| \) and long-range force.

In the present work, we have studied the wetting phenomena of liquid Se-Tl system on a quartz substrate by photography and ellipsometry. Liquid Se-Tl system has a miscibility gap.
in the Se-rich region with a critical point at $T_c = 454^\circ$C and $X_c = 92.05$ at.% Se. Liquid Se-Tl is particularly interesting, because it is a unique system with combination of the large long-range force and the large mass density difference $\delta\rho$. In addition to the gravity, we introduced temperature difference $\Delta T$ between the internal temperature $T_{in}$ of the bulk sample and the wall temperature $T_{wall}$ as another external field to control the surface state of the system. $\Delta T$ can be used to shift the chemical potential near the surface from the twc liquid coexistence value, and this affects the wetting properties strongly. Details of the experimental set-up were described elsewhere [3].

We observed that the Se-Tl system does not show the critical-point wetting near the liquid-liquid critical point. On a contrary, when the temperature goes down from the critical point, a Se-rich wetting film intrudes between the Tl-rich bulk liquid and the silica wall. Namely, the "critical point dewetting" is observed. Furthermore, we observed that the wetting film disappears when the silica wall is slightly heated up relative to the bulk liquid sample. Figure 1 shows the observed wetting phase diagram on the $T_{in}$-$\Delta T$ plane. Below the phase boundary, the Se-rich wetting film covers the Tl-rich bulk liquid, while it disappears at high $\Delta T$ or at high $T_{in}$ region. The critical point ($T_{in} = T_c$ and $\Delta T = 0^\circ$C) is located in the non-wetting region.

Near the critical temperature $T_c$, it is observed that the height $\Delta h$ of the three-phase contact line measured from the bulk meniscus changes gradually with $\Delta T$, and this result suggests that downward spreading of the wetting film is blocked by the gravitational potential in this temperature region.

In order to interpret the observation, we constructed a model grand potential, incorporating the long-range interaction, the temperature difference and the gravity. We found that this grand potential reproduces the observed behavior qualitatively [3]. The apparent absence of the critical-point wetting has been qualitatively explained by taking the combined effects of gravity and long-range interaction [3].

References