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Horizontal capillary flow of a Newtonian liquid in a narrow gap between a plane wall and a sinusoidal wall

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Abstract

An experimental and theoretical study of the capillary flow of a Newtonian liquid (mineral oil) in a Hele-Shaw cell in which the gap varies sinusoidally in one coordinate direction, and flow takes place in the direction of constant channel cross-sectional area is reported. The geometric non-uniformity of the gap is observed to produce interface fingering. Finger length is observed to increase with decreasing spacing between plates of fixed shape, and with increasing gross penetration distance. In the regime of interest, finger length is observed to increase slowly with increasing interface advancement, motivating a quasi-steady model in which gross interface advancement is predicted by a Lucas–Washburn model and interface fingering is predicted by a Hele-Shaw model of steady flow. The steady interface velocity in the Hele-Shaw model is set equal to the instantaneous interface velocity predicted by the Lucas–Washburn model. Fingering predicted by the quasi-steady model matches the experimentally observed trends with regards to plate spacing and gross penetration distance.

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1. Introduction

1.1. Background and motivation

In the underfill process step in flip-chip electronics manufacturing, liquid epoxy fills (encapsulates) the narrow ($\sim 100\,\mu$m) gap between the chip and the printed circuit board by capillary action (Machuga et al., 1992). The epoxy contains a high volume fraction of silica particles, and is cured at elevated temperature once the gap is filled. The side length of the chip is typically ~ 10 mm. The chip and board are oriented horizontally with respect to gravity during the filling process. Epoxy is usually introduced along one or two edges of the chip. The gap between the chip and the board typically contains an array of solder ball electrical connections. Electrical trace lines may be found on the surface of the board. Geometrically, the solder balls resemble outward-bulging cylindrical posts and the trace lines resemble earthen dams.

Two aspects of the underfill process which many researchers seek to understand are the time rate of gap filling, and the occurrence of air bubbles in the filled gap. In some cases, distortion of the advancing air–liquid interface causes air bubble entrapment. Thus, interface shape in capillary flow is studied.

Typically, a plane channel populated by various arrangements of solderballs is the flow cell chosen for studying the underfill process. Fine et al. (2000) report an experimental study using commercial-type underfill fluid. Bogoyavlenskiy et al. (2004) carry out Hele-Shaw modeling of a Newtonian liquid advancing through an array of solder balls. So far, little attention has been given to the trace lines. To the best of the author's knowledge, Davidson et al. (2002) is the only publication associated with the underfill application which seeks to understand the effect of trace lines on the board. Davidson et al. (2002) report experimental observations of interface fingering in a Hele-Shaw cell composed of a flat glass plate and a printed circuit board with parallel trace lines; the advancing liquid is mineral oil.

In this work, we continue to study the experimental system introduced by Davidson et al. (2002). To review, we simplify the underfill flow process by replacing the epoxy–silica mixture with a Newtonian oil (mineral oil) of similar surface tension and viscosity, and simpler rheological behavior. We remove the solder balls from the gap, and populate the board with parallel arrays of trace lines. The trace lines impart a sinusoidal shape to the board. The silicon chip is represented by a flat glass plate. The resulting flow cell is shown in Fig. 1. The gravity vector is orientated in the negative z-direction. Flow is initiated in

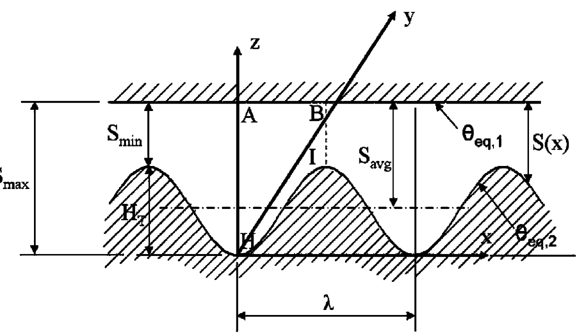

Fig. 1. Section view of the flow cell. The gap between the plates $S(x)$ is a sinusoidal function of coordinate x. S_{min} and S_{max} are the minimum and maximum of $S(x)$ with respect to x, and $S_{\text{avg}} = (1/\lambda)\int_0^{\lambda} S(x)\,\mathrm{d}x$. $H_{\text{T}} = S_{\text{max}} - S_{\text{min}}$. The static wetting angles of the advancing liquid on the plates are $\theta_{\text{eq},1}$ and $\theta_{\text{eq},2}$.