A MACH-ZEHNDER INTERFEROMETER-BASED STUDY OF EVAPORATION OF BINARY MIXTURES IN HELE-SHAW CELLS

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ABSTRACT: In this work, preliminary experiments on the evaporation of a water-ethanol mixture in a 2D Hele-Shaw cell are performed using a Mach-Zehnder interferometer. This showed that, as ethanol is preferentially evaporated, a boundary layer rich in water is formed near the interface. As this layer is heavier than the underlying mixture, hydrodynamic instabilities arise and water-rich tears fall down, leading to a complex dynamical process.

1 General Introduction

Heat transfer applications such as heat pipes, boilers and refrigerators use evaporation and condensation to evacuate the energy dissipated or stored in the system. To this end, pure liquids are primarily used as the use of mixtures leads to concentration gradients which generally lower the heat transfer coefficient. However, there are also reasons to expect that concentration gradients generated during evaporation may also trigger convective instabilities, possibly leading to increased heat (and mass) transfer [1]. Moreover, recent work [2] has shown that well-chosen mixtures can have special properties which can delay the onset of burn-out of heat pipes, also leading to an important enhancement of the maximum achievable heat transfer rate.

In this article, a mixture of water and ethanol is chosen as both liquids have a significantly different density, refractive index and surface tension. As a result, concentration changes that might occur in the mixture due to evaporation are likely to have a large effect, which can be measured by a Mach-Zehnder interferometer.

2 Experimental Setup

In this work, the evaporation of a water-ethanol mixture in a 2D Hele-Shaw cell is examined with a Mach-Zehnder interferometer. The general lay-out of the complete setup is shown in Fig. 1(a). The He-Ne laser beam (λ=632.8 nm) is cleaned using a spatial filter and expanded towards a first beamsplitter, which splits it into a reference beam and an object beam. The reference beam passes through the...
ambient air, while the object beam traverses the test cell. Finally, the two beams are recombined by a second beamsplitter and imaged on a CCD camera by a Micro-Nikkor objective with a focal length of 200mm.

![Diagram of Mach-Zehnder interferometer and Hele-Shaw cell](image)

**Fig. 1:** (a) Lay-out of the Mach-Zehnder interferometer (b) Sketch of the Hele-Shaw cell

The Hele-Shaw cell is constructed of two glass plates separated by a gap of 1mm. Inside this gap, an ethanol-water mixture is evaporating as a flow of Nitrogen gas passes over the surface (Fig. 1(b)). The location of the measurements is shown by the dashed rectangle.

### 3 Image Processing

Concentration changes inside the Hele-Shaw cell change the optical path of one of the laser lines, thus creating a visible phase shift $\Delta \phi$ of the fringes. Through the formula: $\Delta n = \lambda \Delta \phi / 2\pi t$, with $t$ being the thickness of the Hele-Shaw cell and $\lambda$ the wavelength of the laser, this phase difference can be transformed into a refractive index difference $\Delta n$. This, in turn, can be transformed through calibration into a concentration change of ethanol in our mixture, or in a temperature change.

The first step, however, is to extract the phase shifts from the interferograms. To this end, a Fourier transform based approach described by [3] is used. This method starts from a finite fringe interferogram as shown in (a). Upon inspection one notices that close to the surface (the gray band), all fringes are bent to the left. This corresponds to a negative phase shift, which itself corresponds to a decrease of the refractive index (for the used configuration of the mirrors). To extract this phase shift from the image, a 2D Fourier transform is first performed on the image (the corresponding power spectrum is seen in (b)). Next, everything is filtered out except a small region (the dashed rectangle) around the positive frequency peak. The size of the filter is chosen so as to eliminate some of the high frequency noise while trying to maintain the sharp borders of the formed instable structures. This zone is then re-centered around the origin and an inverse 2D Fourier transform generates a matrix of complex numbers. From these complex numbers, only the phase is extracted and this corresponds to the wanted phase shift shown in (c). A mathematical justification of this approach can be found in [3]. Note that in this figure, the phase is wrapped between 0 and $2\pi$ with 0 corresponding to black and $2\pi$ to white.

While the obtained map seems to work fine for the fringes in the water-ethanol mixture, the phase map in the nitrogen region above the interface shows a constant horizontal phase change. This is due to the fact that the re-centering of the frequency peak was not perfect for the nitrogen phase. To eliminate this sensitivity to the re-centering step and, perhaps even more importantly, to correct for imperfections in the optical setup of the equipment, a reference image is also taken. This is shown in (d). This image
was taken before the start of the test when the refractive index is expected to be uniform across the field of view. (f) shows that the obtained phase map is almost uniform in the water-ethanol mixture but a slight gradient still exists (from the top left to the bottom right). Note that this is not due to an inhomogeneity in the refractive index of the liquid itself but in the re-centering step of the algorithm. Now, this phase map is substracted from the obtained test result ((c)) to obtain the final result shown in (g). Important to note here is that the refractive index in the gas phase is homogeneous again after subtracation of the reference map, as it should be.

**Fig. 2: Fourier transform based extraction of phase shifts**

4 Experiments

4.1 8% Ethanol Mixture

In Fig. 3, one can see in the refractive index images shown at different instants after starting the injection of nitrogen, how tears of a lower refractive index are formed at the surface, and tumble down. Note that position 0 corresponds to the liquid-gas interface. Close to the interface, a boundary layer with a lower refractive index is visible, from which the tears originate. In order to try to understand the origin of this instability, the refractive index image is transformed into a map of the mass concentration of ethanol. To this end, the calibration curve shown in Fig. 4(a) is used [4]. This results in Fig. 4(b) for the last image in the sequence of Fig. 3. From this graph it is clear that both the falling tears and the boundary layer at the surface are richer in water. This is understandable as ethanol is preferentially evaporated, hence leaving a mixture rich in water behind.
The next step to understand the observed instability is to transform the obtained concentration map into a density map. From the curve in Fig. 5(a), which was obtained from [5], one can extract the vertical density profiles of Fig. 5(b) (corresponding to a horizontal position of 8mm in Fig. 3) at different instants in time. This shows that the boundary layer becomes richer and richer in water and consequently also heavier and heavier (25=>30). Then, the bottom region of the boundary layer breaks away and a tear is formed. This suggests that the formed instability is most likely a Rayleigh-Taylor instability caused by the density stratification.
4.2 Different Ethanol Concentrations

A second test was performed at 20.8% of ethanol under the same test conditions. A similar phenomenon was observed. After several seconds of evaporation, water-rich tears started falling. In order to compare the two test cases directly, Fig. 6 shows the concentration difference with respect to the starting ethanol concentration. This shows that in the case of the mixture with 20.8% of ethanol, up to 1.7% of ethanol is ‘lost’ in the tears, whereas less than half that amount is present in the case of the mixture with 8% of ethanol. Thus, the density stratification is approximately doubled as well.
5 Discussion

In the above derivation of the corresponding concentration and density plots, it was assumed that the temperature of the mixture remains constant. However, during evaporation this is certainly not the case, due to latent heat consumption at the interface. Therefore, as the refractive index also depends on the temperature, one could tentatively argue that there is no concentration change whatsoever, but only a temperature change. Using the temperature dependency of the refractive index of pure water, Fig. 7(b) is obtained for the evaporation of the mixture with 20.8% of ethanol. This inversion suggests that the falling tears have a temperature of up to 40° and even higher temperatures are obtained in the boundary layer. Using the refractive index dependency on temperature of pure ethanol, even higher temperatures are obtained. This is clearly not a physical result. During evaporation, the surface is cooled, which would increase its density and its refractive index. As this is the opposite of what is seen in the experiment, there must necessarily be concentration changes in the mixture, which have a more important and opposing influence on the refractive index. Thus, Fig. 7(a) corresponds indeed more closely to the reality, but due to the opposing temperature effect, it will underestimate the concentration differences. As no simultaneous temperature maps are at our disposal, the temperature dependence can only be treated as an error on the obtained concentration maps. Assuming a worst case temperature difference in the liquid of 1°C, this corresponds to a refractive index difference of 0.0001 (in pure water; the worst case scenario). This, in turn, is equivalent to a concentration change of 0.13% mass concentration. Thus, the obtained concentration map of Fig. 7(a) might be underestimating the concentration difference by up to 0.13%. Dividing this number by the maximum concentration difference in the unstable structure, an error of 7.6% is obtained. While this could be acceptable, it clearly shows the need to have a good estimate of the maximum temperature difference in the fluid.
5. Conclusions

In this paper we only scratched the surface of water-ethanol evaporation. The main conclusions are that Mach-Zehnder interferometry can be a suitable device to study this phenomenon but, unless complemented by temperature maps, it can only reach a limited precision as the conversion from refractive index to ethanol concentration is complicated by the dependency on the temperature. Nevertheless, it was shown that ethanol is preferentially evaporated at the surface, thus creating a denser boundary layer rich in water. This induces a Rayleigh-Taylor instability and falling tears were noticed during the experiments. Doubling the ethanol reference concentration also approximately doubled the concentration differences in the liquid.

References

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