FLOW INSTABILITIES AND REVERSALS IN NON-UNIFORMLY THERMOCAPILLARY DRIVEN MELT POOL

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Abstract With transient LES and DNS simulations, we investigate flow in melt pools driven by thermocapillary forces. The developing pool is at first axisymmetric as are the boundary conditions, but flow instabilities arise that lead to 3D oscillatory flow patterns. At higher laser powers a sign-change in the surface tension temperature coefficient occurs, resulting in a flow reversal in the pool and thus two counter-rotating vortices, which exhibit similar though more complex flow instabilities.

INTRODUCTION

Many technical applications, such as welding, electron beam evaporation or crystal growth, involve low Prandtl number fluids which are non-uniformly heated. If the fluid is not kept in an enclosed container, the applied thermal gradients will result in surface tension gradients at the free surface, driving fluid motion. Such flows have been investigated for various domains and boundary conditions, though low-Prandtl fluids in cylindrical domains with non-uniform heating applied to the center have received little attention [1]. A linear stability analysis of thermocapillary driven flows in cylindrical enclosures [2] revealed a critical Marangoni number above which the axisymmetric base flow would become unstable towards three-dimensional perturbations. For a very large applied heat flux of 50kW ($Ma>10^7$), the resulting thermocapillary flow in a shallow cylindrical pool has experimentally been found to be turbulent [3]. Both studies were conducted for materials with a constant, negative surface tension temperature coefficient $d\gamma/dT$. Zhao et al [4] observed flow instabilities and reversals in a melt of liquid steel contaminated with oxygen, which acts as a surface active agent.

RESULTS

Here, we investigate the melting and subsequent thermocapillary flow of a low Prandtl number material (Pr=0.18). The shape of the pool is thus not predetermined, but depends on the transfer of heat from the free surface to the pool interior due to the thermocapillary flow. Furthermore, we don't assume the surface tension temperature coefficient $d\gamma/dT$ to be constant, but assume the presence of a homogeneously distributed surface active element (surfactant), which leads to a positive surface tension temperature coefficient with a sign-change at a high critical temperature. To the authors' knowledge, the onset of instabilities of thermocapillary flows including melting/solidification phase change or non-constant surface tension temperature coefficients has not been previously studied. A sketch of the axisymmetric problem setup is shown in Figure 1 (H=R=7.5mm).

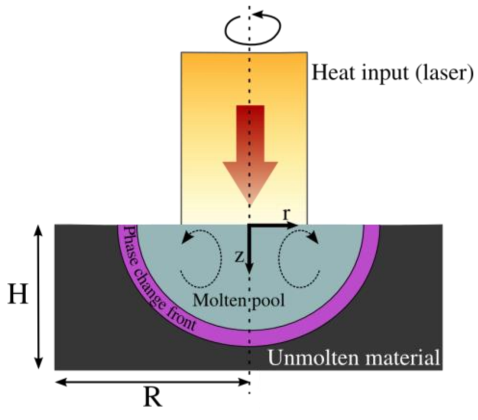

Figure 1. Problem sketch

We investigate the fluid flow and heat transfer in the pool and its surrounding material for a number of applied heat fluxes using three-dimensional Large Eddy Simulations (LES) with a dynamic Smagorinsky subgrid closure. The Large Eddy Simulation is validated using a direct numerical simulation (DNS) for one fixed heat flux. Our results show a rotational instability for low laser powers (Figure 2), where due to the surfactant the surface tension temperature coefficient is positive and thus the resulting flow is directed towards the center of the pool. The rotational motion itself is not stable, but reverses its direction at irregular time intervals (Figure 3). A cross section of the pool shows a finger like cavity due to the axisymmetric base flow forming a downward jet near the center of the pool, with significant perturbations (Figure 4). For higher laser powers the surface tension temperature coefficient changes its sign at a critical temperature, resulting in two instable counter rotating vortices and more complex, perhaps even turbulent, flow patterns (Figure 5).

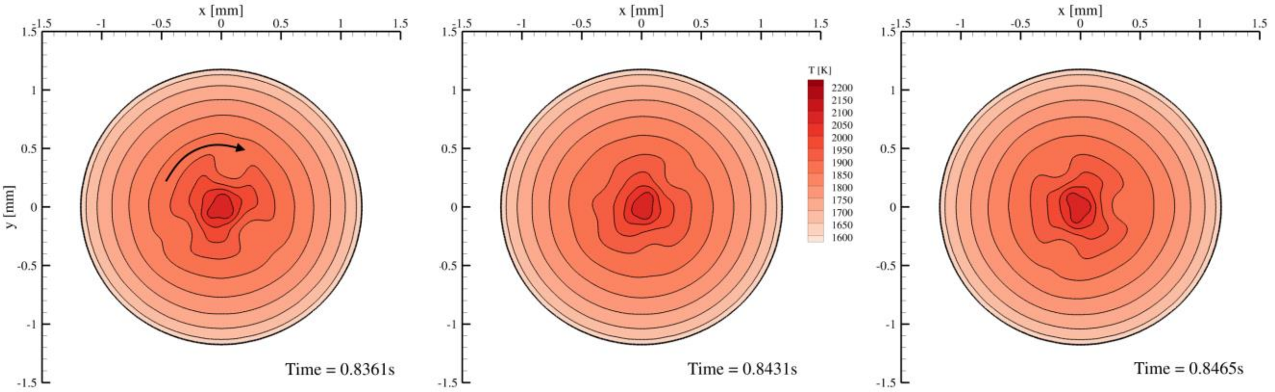

Figure 2. Temperature isolines on pool surface at three time instances, showing the rotational instability

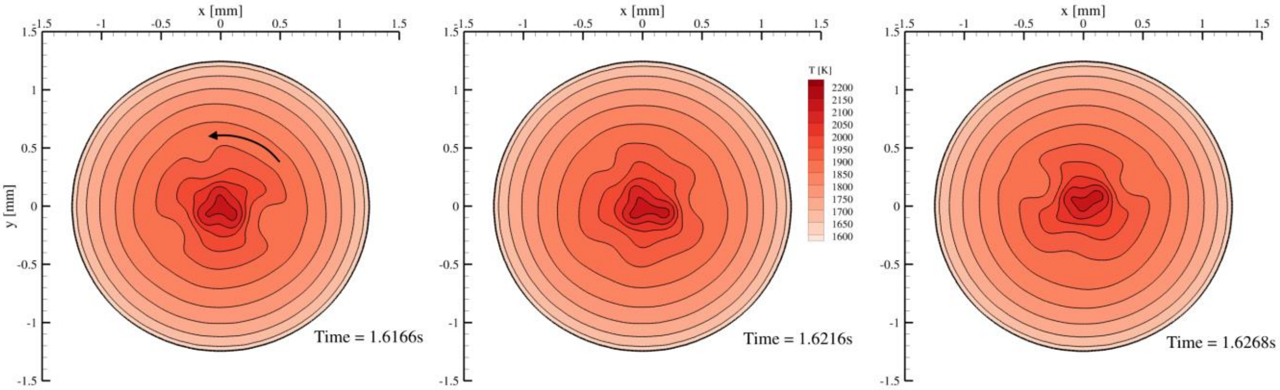

Figure 3. Temperature isolines on pool surface at three time instances, showing the reversal of the rotational motion compared to Figure 2.

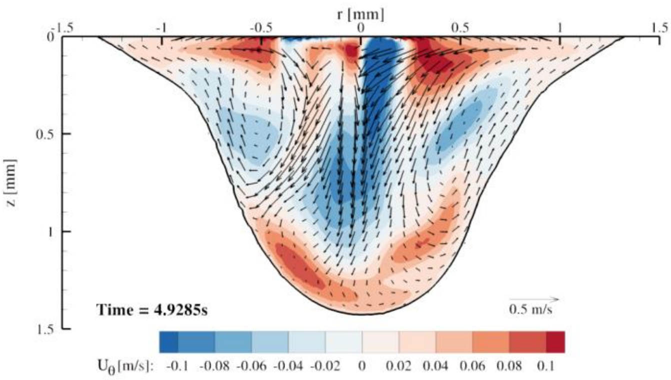

Figure 4. Cross section of pool with in-plane velocity vectors and out-of-plane velocity contours.

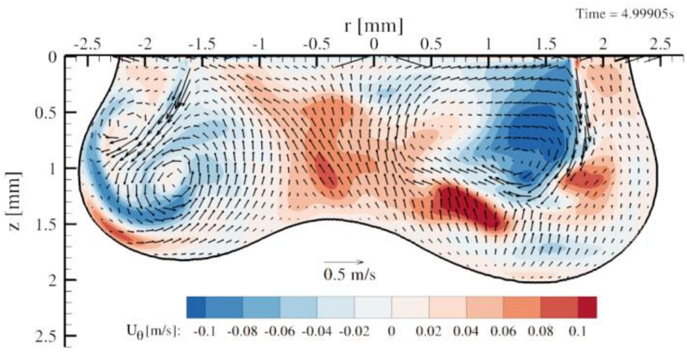

Figure 5. Cross section of pool with in-plane velocity vectors and out-of-plane velocity contours.

References

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