Dynamic Wetting and Solidification

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Abstract : The modelling of the non-isothermal free-surface flows coupled with the solidification process has become the topic of intensive research with the advent of additive manufacturing, where complex 3-dimensional structures are produced by successive deposition and solidification of microscopic droplets of different materials. The issue is that both the spreading of liquids over solids and the propagation of the solidification front into the fluid and along the solid substrate pose fundamental difficulties for their mathematical modelling. The first of these processes, known as ‘dynamic wetting’, leads to the well-known ‘moving contact-line problem’ where, as shown recently both experimentally and theoretically, the contact angle formed by the free surfac with the solid substrate is not a function of the contact-line speed but is rather a functional of the flow field. The modelling of the propagating solidification front requires generalization of the classical Stefan problem, which would be able to describe the onset of the process and the non-equilibrium regime of solidification. Furthermore, given that both dynamic wetting and solification occur concurrently and interactively, they should be described within the same conceptual framework. The present work addresses this formidable problem and presents a mathematical model capable of describing the key element of additive manufacturing in a self-consistent and singularity-free way. The model is illustrated simple examples highlighting its main features. The main idea of the work is that both dynamic wetting and solidification, as well as some other fluid flows, are particular cases in a general class of flows where interfaces form and/or disappear. This conceptual framework allows one to derive a mathematical model from first principles using the methods of irreversible thermodynamics. Crucially, the interfaces are not considered as zero-mass entities introduced using Gibbsian ‘dividing surface’ but the 2-dimensional surface phases produced by the continuum limit in which the thickness of what physically is an interfacial layer vanishes, and its properties are characterized by ‘surface’ parameters (surface tension, surface density, etc). This approach allows for the mass exchange between the surface and bulk phases, which is the essence of the interface formation. As shown numerically, the onset of solidification is preceded by the pure interface formation stage, whilst the Stefan regime is the final stage where the temperature at the solidification front asymptotically approaches the solidification temperature. The developed model can also be applied to the flow with the substrate melting as well as a complex flow where both types of phase transition take place.

Keywords : dynamic wetting, interface formation, phase transition, solidification
Conference Title : ICFMHTT 2024 : International Conference on Fluid Mechanics, Heat Transfer and Thermodynamics
Conference Location : Hanoi, Vietnam
Conference Dates : March 18-19, 2024