PhD opening in Computational Mechanics and Applied Mathematics

CEMEF Research Center, Mines Paris – CNRS UMR 7635, Sophia Antipolis, France

Advanced Simulation of Polymer Quenching for Sustainable Aerospace Manufacturing

We are looking for a highly motivated PhD candidate in computational science, applied mathematics, or mechanical engineering to join a project at the frontier of industrial sustainability and high-performance simulation.

Challenge

Heat treatment is a cornerstone of aerospace manufacturing, where safety, performance, and reliability are non-negotiable. Traditional oil-based quenching methods, while effective, pose serious environmental and safety concerns. Polymer-based quenchants offer a cleaner, safer alternative — but their physics is complex and still poorly understood. This project aims to change that.

Objective

You will develop a next-generation, high-fidelity numerical framework to simulate the full polymer quenching process — capturing heat transfer, turbulent flow, and the dynamic formation of a polymer insulating film. Formed at the vapor-liquid interface during boiling, it governs the cooling behavior and is key to controlling material microstructure and mechanical properties. Indeed, it requires to create physically grounded, predictive simulations based on the true coupled dynamics of the process. Your work will extend advanced boiling models and integrate them into a robust finite-element solver infrastructure developed by the research team.

Validated against in-house experiments, your simulations will directly support the transition to cleaner, polymer-based quenching processes for aerospace-critical parts. This includes turbine blades, structural elements and components where performance and safety are of extreme importance.

Environment

You will work at CEMEF (Mines Paris – CNRS), an internationally recognized center for materials processing, based in Sophia Antipolis — Europe's leading tech park. You will interact with engineers and researchers at Safran Tech. You will collaborate with researchers in computational mechanics, heat transfer, and advanced manufacturing, with access to high-performance computing and experimental facilities.

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Project details

Heat treatment of nickel-based alloy, steel and titanium parts are a crucial factor to ensure the reliability and durability of components in the aeronautics industry. Tank quenching is an industrial process where a metal component, heated to a high temperature, is immersed in a cooling bath. This method has been the most common for hardening alloys due to its economic benefits and its ease of control and maintenance. Water has been widely used as a quenchant because it is inexpensive, readily available, non-hazardous, and provides high cooling rates even in high-temperature ranges where desired material transformations occur, typically above the martensitic temperature for steel. However, excessively high cooling rates and violent boiling regimes can lead to hardenability issues, distortions or cracks, which can degrade the component's performance or cause a failure. This is unacceptable for components used in highly technological systems as designed by Safran, where high-value parts are produced for critical applications such as turbine disks, structural components in aircrafts. Therefore oil-based quenchants have been used in the past decades in order to control the cooling rate.

However, for environmental and safety reasons due to flammability of the oil, polymer-based quenchant have been more and more used in the industry [4]. Although polymer quenchants have been studied since the 1960s, they have not been widely used due to the challenges in formulating solutions that meet the desired cooling rates. The application of polymer quenchants requires a proper understanding of the influence of parameters such as formulation, concentration, temperature, and agitation during the different stages of the coupled heat transfer and flow dynamics system. Despite the degradation of polymers by thermal effects, which requires more maintenance, the lower procedural costs, lower health/safety hazard, and significantly smaller environmental impact of polymers compared to oil make them viable candidates. Control of the cooling rate is achieved as a polymer film is formed at the liquid/vapor interface during boiling to moderate the heat transfer compared to that of a pure water quenching medium. The creation of such membrane is essentially the result of the vaporization of the aqueous phase for most polymer quenchants [5], except for the polyalkylene glycol (PAG) quenchants for which it is the consequence of an inverse solubility property. However, the focus of the project will be on polyvinyl pyrrolidones (PVP) so the formation of the membrane is the result of boiling only. The underlying mechanism driving polymer quenching consists of the combined effect of the ability to form an insulating film composed mainly of a polymer phase, and a viscosity varying with the temperature and the concentration affecting convective heat transfer. The novelty of this project is the development of a high-fidelity numerical framework for heat transfers during polymer quenching, while common approaches rely on averaged correlations and tabulated data [3].

The work will be based on the solvers developed by the research team [1], using stabilized finite element methods on anisotropic meshes for the simulation of the entire process in realistic configurations. One main challenge is to extend the existing water-quenching boiling model [2] to turbulent heat transfer in a polymer solution with creation of a polymer-rich membrane driven by vaporization, then validate the numerical results against membrane formation and drasticity experiments performed at the laboratory.

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[2] C. Brissot, L. Cailly-Brandstäter, E. Hachem, and R. Valette. A Vaporization Model for Continuous Surface Force Approaches and Subcooled Configurations. Fluids, 8(8):233, August 2023.

[3] N. I. Kobasko and D. M. Kostanchuk. Calculation of the cooling capacity of quenching media by using the characteristics of the boiling process. Metal Science and Heat Treatment, 15(10), 1973.

[4] V. E. Loshkarev and É. Yu. Kolpishon. The use of polymer quenchants for hardening of large parts. Metal Science and Heat Treatment, 28(10):746–749, 1986.

[5] H. Manzanarez, J. P. Mericq, P. Guenoun, and D. Bouyer. Modeling the interplay between solvent evaporation and phase separation dynamics during membrane. Journal of Membrane Science, 620:118941, 2021.