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The Percolation Law of the Boiling Crisis

Abstract: Nucleate boiling is an exceptionally effective heat transfer process. However, a boiling crisis suddenly occurs when the heat flux to remove from a heated surface is too high. The maximum heat flux that can be sustained by nucleate boiling depends on surface properties and operating conditions, and it is an important operational limit in many scientific and industrial applications. Many scientists and engineers have attempted to describe this phenomenon and predict this limit mechanistically. However, a universal theory has eluded the thermal science community for almost a century.

Here, we reveal theoretically and experimentally the presence of a unifying law of the boiling crisis. This law emerges from an instability in the near-wall bubble interaction phenomenon, described as a percolation process driven by three fundamental boiling parameters: nucleation site density, average bubble radius and product of bubble growth time and detachment frequency. Our analysis demonstrates that the boiling crisis occurs on a well-defined critical boundary in the multidimensional space of these parameters for a wide variety of boiling surfaces and operating conditions. We anticipate that this fundamental property of the boiling process can inspire the design of engineered surfaces that enhance the nucleate boiling limit, as well as mechanistic modelling criteria for the design of advanced two-phase heat transfer system.

Bio: Dr. Matteo Bucci is Associate Professor of Nuclear Science and Engineering at MIT. He has joined the MIT faculty in 2016, where he teaches undergraduate and graduate courses in nuclear reactor engineering and design, and two-phase heat transfer. His thermal-hydraulics group at MIT focuses on two major research axes related to nuclear reactor safety and design: (1) New understanding of heat transfer mechanisms in nuclear reactors, (2) Engineered surfaces and coatings to enhance two-phase heat transfer. His group also develops and uses advanced diagnostics, such as high-speed infrared thermometry and phase-detection, and post-processing algorithms to perform unique heat transfer experiments. Matteo has published over 40 articles in the areas of two-phase flow and heat transfer, and surface engineering technology. For his research work and his teaching, he won several awards, among which the MIT Ruth and Joel Spira Award for Excellence in Teaching (2020), ANS/PAI Outstanding Faculty Award (2018), the UIT-Fluent Award (2006), the European Nuclear Education Network Award (2010), and the 2012 ANS Thermal-Hydraulics Division Best Paper Award (2012). In 2022, Matteo received the inaugural DOE Early Career Award for Nuclear Energy. Matteo is Editor of Applied Thermal Engineering and a consultant for the nuclear industry.