Detecting and Controlling Flow Boiling Instabilities with Machine Learning

Introduction: Applications that demand large cooling capacities, such as high-power electronics, rely on the elevated thermal energy density that is associated with the latent heat of vaporization. Flow boiling of a liquid in a channel is one of the most effective approaches for ensuring high heat transfer efficiencies. *For example, single-phase convection can remove heat with a rate up to 20 kW/m²K, whereas flow boiling easily reaches 100 kW/m²K.*[1] Flow boiling within microchannels increases the heat transfer potential even further, due to the enhanced surface-to-volume ratio. Many electronics and microelectromechanical systems (MEMS) with high power densities thus rely on microchannel flow boiling as their primary cooling strategy. **Consequently, an efficient and reliable operation and control of this chaotic multi-phase flow process is hence indispensable.** In both macro- and microchannels, the two-phase mixture can be characterized by different flow regimes, which are defined by the relative amounts and configuration of the liquid and vapor phases, and ranges from bubbly flow (few vapor bubbles in the center) to slug flow, annular flow, and eventually mist flow (few liquid droplets in the center).

Despite the great promise that two-phase flow boiling poses, it presents many challenges. For example, dry-out, or the critical heat flux (CHF), occurs at the onset of mist flow and leads to a drastic rise in wall superheat that can induce material thermal fatigue and ultimately failure. Unfortunately, its occurrence and location there-of is difficult to predict, leading to the implementation of large safety margins during the initial design of the thermal management system. A different flow instability arises from the rapid expansion of bubbles, which causes pressure oscillations that can ultimately jeopardize the structural integrity of the channel and even initiate flow reversal.[2] *These instabilities have presented major challenges toward flow boiling applications and serve as a focal point for recent studies.* **To overcome the existing limitations, I propose to use machine learning (ML) to detect and ultimately control the onset and nature of these flow instabilities.** *Autonomous detection and self-stabilization of flow boiling instabilities would significantly enhance the reliability of two-phase cooling systems, while reducing costs and greenhouse emissions.*

Intellectual Merit: The use of ML in thermal management is a novel method for predicting heat transfer properties. A recent publication by Ravichandran *et al*.[3] has shown that neural network models can predict the margin to the boiling crisis in a pool setting. **I propose that in flow boiling, the onset detection and solution to mitigating flow instabilities can similarly be accomplished through the implementation of a deep learning algorithm.**

Aim 1: Collect images and videos of various flow instabilities for different flow conditions. ML requires the collection of large amounts of data to train an algorithm. I will construct an apparatus for recording various instabilities. Korniliou *et al*.[4] describes a method for microchannel fabrication onto a polydimethylsiloxane (PDMS) substrate with an infrared transparent tin indium oxide back wall. I will implement IR imaging to record wall surface temperatures while simultaneously recording high speed optical imagery at identical frame rates. The setup will include a pressure transducer mounted at both ends of the channel to monitor differential oscillations. A micropump will serve to circulate the fluid after it passes through a vacuum degasser. The ratio of heat flux to mass flux has been used to quantify microscale instabilities by defining their oscillation periods.[5] I plan to induce various instabilities within the microchannel by adjusting flow rate and heat generation while recording the resultant effects on temperature and pressure. Each instability will be categorized into an appropriate set of resultant conditions. In addition to recording my own footage, I will also use data available in open literature and contact authors of recent publications to share their data.

<u>**Aim 2:**</u> **Train a machine learning algorithm to predict each type of instability based on pre-defined conditions.** I propose to train an artificial neural network (ANN) model by inputting measurements of pressure oscillations, nucleation site density, surface temperature changes, and bubble movement into each instability category. A feature ranking algorithm will be implemented to define the key measurement parameters. I will incorporate Google's machine learning library TensorFlow to accomplish these tasks. The data will be split appropriately among sets for training, validating, and testing the model. Model evaluation will be conducted through 10-fold cross validation to ensure proper fitting. I will utilize the model's mean absolute percentage error as the primary evaluation metric. The results of the model will be used to determine the corresponding flow, thermal, and differential pressure conditions associated with specific instability types.

<u>**Broader Impacts:**</u> This project serves as a vital proof-of-concept for validating the use of machine learning to detect flow instabilities. Time permitting, I plan to program the model into a closed-loop control algorithm. Upon the detection of a specific instability, the algorithm would contain and implement a pre-programmed solution, such as the adjustment of the flow rate or pulsation of ultrasonic waves. **This solution will serve as a pioneering step toward the implementation of machine learning in thermal management and demonstrates a potential method for revolutionizing the peak performance and safety of electronics cooling applications.** The development of a working control algorithm would allow for system optimization and self-stabilization, which would answer direct needs of the thermal fluids community.

During our STEM club sessions for EduMate NYC, as introduced in my personal statement, we received strong positive feedback from the students during the computer science presentation. **I therefore intend to use this project to initiate an *Introduction to Artificial Intelligence* virtual workshop for high school and middle school students in the St. Louis area.** *The St. Louis metro region is one of the most segregated cities in the United States, and its long history of racial disparity contributes to educational inequity to this day.* I will discuss the fundamentals of artificial intelligence, including machine learning, natural language processing, and computer vision in weekly sessions throughout 5 weeks in the summer months. An additional 5 weeks will be spent discussing the applications of artificial intelligence, such as robotics, transportation, and my proposed project. *The goal behind these events is to create a foundational understanding of artificial intelligence while inspiring students to pursue these topics in their future studies and careers.* **Allowing young innovators to develop skills in one of the most important technologies today is valuable for contributing to their future success.** I will collaborate with the St. Louis Academy of Science to host these events and provide outreach assistance.

References: [1] Bergman, et al. (2011) *Fundamentals of Heat and Mass Transfer* [2] O'Neill, et al. (2020) International Journal of Heat and Mass Transfer [3] Ravichandran, et al. (2021) Appl. Phys. Lett. [4] Korniliou, et al. (2017) Applied Thermal Engineering [5] Prajapati, et al. (2017) Experimental Thermal and Fluid Science