Title

Topical: Investigation of Flow Boiling and Flow Condensation Configurations to Benefit Future Space Missions

Author
Chirag Kharangate
Director, Two-Phase Flow and Thermal Management Laboratory
Assistant Professor, Mechanical & Aerospace Engineering Department

Phone Number
Office: 216-368-2029, Cell: 765-513-7009

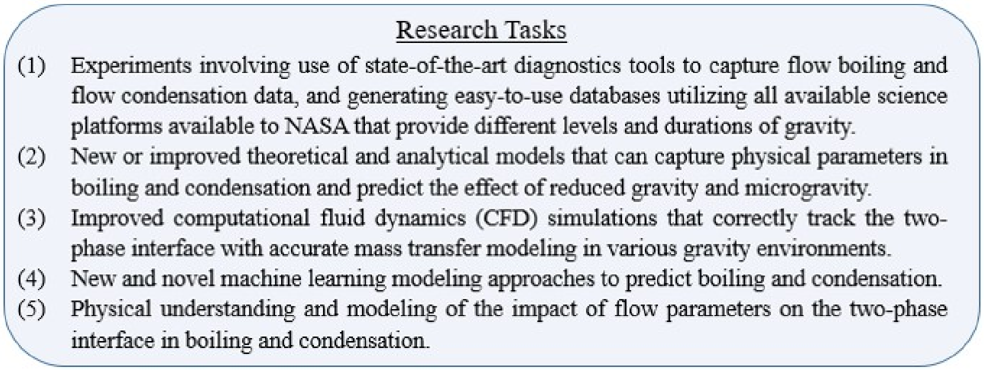
Institution
Case Western Reserve University (CWRU)
10900 Euclid Ave, Cleveland, OH 44106

E-mail: chirag.kharangate@case.edu

1. Motivation: NASA is planning future missions to land humans on Mars. Compared to past missions, these missions are expected to not only increase in scope, but also size and duration. A direct consequence of this is an increase in vehicle power as well as the rate of rejection of waste heat which are expected to have a profound adverse impact on the vehicle's size and weight. To tackle these issues, Fission Power Systems (FPSs), which feature both very high power and very low mass-to-power ratios, have been recommended for long-duration manned missions using a Rankine power cycle [1,2]. In a recent testimony to the U.S. House Space and Aeronautics Committee, NASA recommended that an aggressive research and development effort is necessary to develop Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) technologies for being successful in these future Mars missions, while also staying competitive and a leader in space technology. NASA also noted that USA's strategic competitors, including China, are aggressively pursuing these technologies which can be considered critical to such long-duration mission's success [3]. Current power conversion systems for NTP and NEP can utilize Brayton power cycles that are based on single-phase flows and that has seen significant development efforts [2]. While these cycles show good reliability and less issues for use in reduced gravity environments, they suffer from low efficiency and higher weights, which is critical for long-duration missions. Current Brayton cycles demonstrated power levels for space-qualified systems are orders of magnitude below that required for a 1 to 2 MWe system [2]. Rankine power cycle technology involves many complex two-phase flow boiling and flow condensation processes but is capable of meeting this required power level. Additional reductions in vehicle size and weight are possible by replacing present single-phase Thermal Control Systems (TCSs) with two-phase boiling and condensing counterparts [1]. These systems play a vital role in life support in a space vehicle by controlling the temperature and humidity of the internal environment. They are comprised of three subsystems including heat acquisition, heat transport, and heat rejection. In most space vehicles, including space shuttles, these tasks have been tackled by a single-phase TCS. The two-phase TCS designs now being projected for use on future vehicles greatly decrease the size and weight of the system by capitalizing upon the orders-of-magnitude enhancement in two-phase heat transfer coefficients compared to those possible with a single-phase TCS.

However, for utilizing two-phase flows in FPS and/or TCS, a few critical challenges need to be addressed. While in terrestrial systems, we have a better understanding of how gravity can impact two-phase behaviors, the existence of two phases with large density differences (liquid and vapor) pose challenges to the handling of this mixture in reduced and zero-gravity environments. Improper handling could result in system over-heating, unwanted vapor accumulations, and even catastrophic failures if dryout is observed. Critical and sustained research efforts are needed in this direction over the next decade to make this technology ready for future NASA space missions.

2. State-of-the-art: To gain the benefits provided by two-phase flows, NASA and other space agencies have made significant investments over the last four decades and researchers worldwide are making progress in developing a fundamental understanding of the boiling phenomena in reduced-gravity and microgravity conditions. Early work concentrated on investigating the nucleate boiling phenomena, understanding and predicting the mechanism impacting the heat transfer, performing simulations, and developing gravity scaling parameters in the pool boiling configurations [4–29]. Three sustained research efforts on pool boiling were conducted with NASA's support that included first terrestrial investigations, followed by reduced gravity parabolic flight investigations, and finally experimentation and modeling based on Space Shuttle or International Space Station investigations. Even though the pool boiling studies have helped us to better understand the fundamental physics of the impact of reduced gravity and microgravity on nucleate boiling phenomena, future FPS and TCS systems are in need of much higher heat dissipation capabilities only possible with flow boiling and flow condensation configurations. That has led to investigations of these two configurations performed at Purdue University in collaboration with NASA over the last two decades, where a full-scale two-phase flow loop that could perform flow boiling and flow condensation experiments was successfully tested for terrestrial experiments, parabolic flights, and is now in the final stage of ISS experimentation [30–46]. For flow boiling, the effort includes conducting experiments in a rectangular channel flow boiling configuration to measure heat transfer coefficients, pressure drop, and critical heat flux while simultaneously capturing flow images of the boiling phenomena, database generation, and mechanistic modeling for CHF. For flow condensation, the effort includes conducting experiments in an annular flow condensation configuration to measure heat transfer coefficients and pressure drop with one test module, separately capturing flow images of the flow condensation phenomena with another test module, database generation, and mechanistic modeling of the heat transfer coefficient. Other space agencies have also contributed to understanding flow boiling. For e.g., Japan Aerospace Exploration Agency (JAXA) recently conducted a flow boiling experiment on the ISS [47–49]. Their effort includes conducting flow boiling experiments in a tube configuration to provide a fundamental understanding of the behaviors of bubble formation, liquid-vapor flow, and how heat transfers in cooling systems. Overall, the research efforts have, until now, been limited to database generation and developing a fundamental understanding of a few important parameters that include mostly heat transfer coefficients and pressure drop in mini-channel flow boiling and flow condensation, and critical heat flux for mini-channel flow boiling configurations.



Research Tasks

(1) Experiments involving use of state-of-the-art diagnostics tools to capture flow boiling and flow condensation data, and generating easy-to-use databases utilizing all available science platforms available to NASA that provide different levels and durations of gravity.
(2) New or improved theoretical and analytical models that can capture physical parameters in boiling and condensation and predict the effect of reduced gravity and microgravity.
(3) Improved computational fluid dynamics (CFD) simulations that correctly track the two-phase interface with accurate mass transfer modeling in various gravity environments.
(4) New and novel machine learning modeling approaches to predict boiling and condensation.
(5) Physical understanding and modeling of the impact of flow parameters on the two-phase interface in boiling and condensation.

Figure 1 Research method and individual tasks to achieve project goals.

3. Methods: Further research that can address the fluid management issues in boiling and condensation configurations caused by the change in gravity levels are critical to making this technology mission-ready for NASA. Sustained research on understanding, capturing, and predicting the behavior of the individual liquid and vapor phases, and their interactions across the two-phase interface in terrestrial, reduced gravity, and microgravity environments is critical to future FPS and TCS systems. To achieve those goals, several important research tasks must be undertaken (Figure 1).

3.1 Experimentation and Database Generation

While past experiments are able to provide us with accurate information on boiling and condensation in mini-channels (hydraulic diameters 1-6 mm) with data and models for heat transfer coefficient, pressure drop, and CHF, where a fixed surface roughness and one fluid was used; future experiments need to be able to account for surface engineering concepts that help enhance heat transfer performance as well as other relevant working fluids and channel sizes. Channel sizes impact heat transfer performance, with micro-scales (channel hydraulic diameters < 1 mm) showing reduced effect of gravity and macro-scales (channel hydraulic diameters > 6 mm) showing enhanced effect of gravity in comparison to mini-scales. All the scales are relevant to the designs encompassing the future FPS and TCS systems as micro-scales can help make systems more compact and light-weight, while some devices and systems need large fluid volumes only possible with macro-scale designs. These investigations need to be conducted on all available science platforms including those that provide zero or partial gravity, are in Low Earth Orbit, are terrestrial analogs of spaceflight or space conditions, and those that may soon be in deep space or lunar environments. Also, the use of state-of-the-art diagnostic tools can play a vital role in these experiments and improving the physical understanding of the effect of gravity. Aside from maximizing the use of conventional pressure, temperature, and flow rate measurement instrumentation, experiments can implement sophisticated diagnostic tools like the following:

1. High-speed imaging that can capture multiple overlapping interfaces and reduce distortion due to reflections at the heated or cooled walls [50,51].
2. Better temperature measurements at the wall, including fast response and higher spatial resolution sensors [52,53] and infrared (IR) thermography to capture thermal patterns on a heated wall [54,55].
3. Better fluid temperature measurement with techniques like a thin blade fitted with an array of micro-thermocouples to measure instantaneous fluid temperature profile [56–58].
4. Multi-sensor conductivity and optical probes [59,60] and wire mesh probes [61] that can be used to measure bubble diameter and velocity during boiling.
5. Better velocity measurements in the fluid using laser Doppler velocimetry (LDV) to measure velocity profile [62,63], particle image velocimetry [64], and micro-particle shadow velocimetry (μ-PSV) [65].

These techniques are good examples of the type of experiments and diagnostics tools that can be used individually or simultaneously during boiling and condensation testing. The resulting data obtained from the different gravity environment science platforms can be used to generate databases that cover large geometric, operating, and parametric variations.

3.2 Theoretical and Mechanistic Modeling

While the most common predicting tool available in two-phase literature is empirical and semi-empirical correlations [66–76], it is advisable not to use them outside the tested range they were developed for due to the complex flow behaviors in phase-change systems. A better approach that captures the physical behaviors in two-phase systems is the use of mechanistic or theoretical models [46,77–80]. For example, the Interfacial Lift-off CHF Model is a mechanistic model that can predict CHF due to departure from nucleate boiling (DNB) by using information predicted by a separated flow control volume model in combination with the hydrodynamic instability analysis [81,82]. It has been shown by various studies that such models perform better than traditional predicting techniques as they capture physical behaviors more accurately. However, the models' applicability is only to the type of regime or flow configuration that they represent. Even though boiling and condensation flows can be represented by a large number of flow regimes, analytical and/or mechanistic models are needed for only the dominant regimes and configurations. The following includes a non-exhaustive list of the modeling efforts that are recommended:

1. Theoretical model/s that can accurately predict heat transfer and pressure drop in flow boiling and flow condensation with minimal empiricism.
2. Theoretical or mechanistic model/s that can accurately predict boiling parameters like bubble departure diameters, bubble departure frequency, and nucleation site density including for configurations that include surface engineering concepts.
3. Mechanistic model/s that can accurately predict CHF due to dryout or DNB for all scales.

3.3 CFD Simulations

CFD is a very useful tool available to us for modeling phase-change configurations because it can predict local parametric variations of phase fractions, velocity, and temperature across individual phases during transient and steady state conditions [83–87]. It is the only available modeling tool that can inherently handle complex geometric shapes and is successfully being used as a design tool in predicting thermal performance in single-phase configurations. However, this method does not show adequate accuracy in two-phase flows like boiling and condensation because it is unable to accurately track or capture the two-phase interface [88].

An integral part of the research needs to be devoted to the development and validation of comprehensive state-of-the-art CFD models to simulate the flow boiling and flow condensation configurations relevant to the FPS and TCS. A multi-pronged strategy that addresses all the current shortcomings in CFD needs to be adopted with the following recommended tasks:

1. Develop sub-grid boiling models for thermal coupling with CFD codes that can describe the complex mechanisms of flow boiling and phase change at the heated wall [89].
2. Develop CFD codes to accurately predict the dominant annular flow condensation regime.
3. Develop and improve interface tracking techniques in CFD simulations so they can better represent the two-phase interfacial behavior by finding better treatment methods of interface thickness [90–92], better models to capture surface tension effects at the interface [93–95], improved phase change models to estimate mass and energy transfer across the interface [96–98], and accurate turbulence models that can estimate turbulent eddies behavior around the interface [99].
4. Develop a full-CFD model without any coupling that can capture flow boiling and flow condensing behaviors with minimal empiricism in the formulations [83,100,101].

It is recommended to develop full 3-dimensional (3-D) simulations as and when possible.

3.4 Data Sciences-Driven Machine Learning (ML) Modeling

Conducting two-phase experiments or full CFD simulations can be time-consuming and expensive. Boiling and condensation performance parameters like heat transfer coefficients, CHF, and pressure drop can usually be a function of many independent dimensionless numbers, each valid only over a finite range of values, making some of the current modeling efforts futile [88]. Using new data-driven computing techniques, we can deduce the relationship between these parameters and their relevance to performance parameters. These data models might play a key role in addressing the shortcomings of traditional modeling approaches. In the past three decades, we have seen unprecedented development of soft computing techniques, such as Artificial Neural Networks (ANNs), Genetic Algorithm (GA), Genetic Programming (GP), Fuzzy-logic Control, and Data Mining to many scientific and engineering practices [102–104]. However, their application to thermal-fluids has been limited [105–108]. With the possibility of generating large databases from experimentation, we will have the capability to develop models based on large datasets, correlating soft computing tools for these systems. Some preliminary success has been seen in developing machine learning-based predicting tools for pressure drop and heat transfer in mini/micro-channel boiling and condensation configurations [109,110]. Similar efforts are needed to develop ML models for performance parameters in flow boiling and condensation. In addition, a multitude of two-phase experiments in the past have utilized high-speed flow visualization as an important diagnostic tool to capture two-phase interfacial features during phase-change [31,45,81]. With the advent of ML, autonomous vision has revolutionized and initiated new industrial applications, such as robot vision, autonomous driving, and medical diagnosis, by enabling the creation of new information and statistics. However, past studies in two-phase flows have rarely conceptualized the use of autonomous vision with only some work on pool boiling [111,112]. We need to utilize these novel techniques to study the flow boiling and flow condensation modes, which feature complex liquid-vapor intermixing, turbulence, and instabilities, and in turn, use the insights to link the flow behaviors with physical parameters like heat transfer and pressure drop.

3.5 Developing a Fundamental Understanding of the Two-Phase Interface

While we have a good understanding of the individual phase behaviors from single-phase flow studies, one major obstacle to understanding the physical behaviors and predicting boiling and condensation configurations accurately is that we do not know how to effectively resolve the combined effect of parameters impacting the two-phase interface including the turbulence, surface tension, inertia, gravity, and mass transfer [56–58,62,63,99]. For example, gravity, which is extremely important to interfacial behavior in terrestrial environments is negligible in microgravity, and that can significantly change the corresponding fluid and thermal transport behaviors. We need to develop models that can help us better understand, capture, and predict the physical interactions of various parameters impacting the interface. This requires a sustained effort to use the earlier tasks like experimental data acquisition including diagnostic tools data in combination with theoretical/mechanistic model, CFD simulations, and machine learning models for validation to develop improved interfacial fluid dynamics models and specific conduction and convection models that predict thermal transport around the two-phase interface. The impact of this research effort will be felt across the other research tasks as we can better formulate theoretical models, mechanistic models, CFD simulations, ML models, and correlations.

4. Research Relevance and Relationship to NASA's Priorities: The proposed research (summarized in Figure 2) will impact the following technology areas identified in the 2020 NASA Technology Taxonomy: **(1) TX01.4** Advanced Propulsion » **TX01.4.3** Nuclear Thermal Propulsion; **(2) TX03.1** Power Generation and Energy Conversion » **TX03.1.4** Dynamic Energy Conversion; **(3) TX14** Thermal Management Systems » **TX 14.2.1** Heat Acquisition, **TX14.2.2** Heat Transport, and **TX14.2.2** Heat Rejection and Storage [113]. This work will contribute to three NASA research priorities. First, as discussed in the motivation, this research on understanding two-phase flow and heat transfer in flow boiling and flow condensation has significant benefits to human exploration goals and will play a critical role in future FPSs and TCSs. Second, there is still a lack of clear understanding of the effect of gravitational acceleration on boiling and condensation systems. The reduced gravity environments enable cleaner analysis of the impact of gravity on individual phases and the two-phase interface which can improve our physical understanding of the configurations. Third, although flow boiling and flow condensation are energy efficient in comparison to single-phase flows, they are not widely used across terrestrial systems due to their complexity and a lack of clear understanding of parameters like gravity on thermal performance. This research will improve understanding of these systems even in the presence of gravity. This will have an impact on a wide range of industrial processes including power generation, air-conditioning, aerospace, defense, and thermal management, providing significant value to humans on Earth including benefits to space systems.

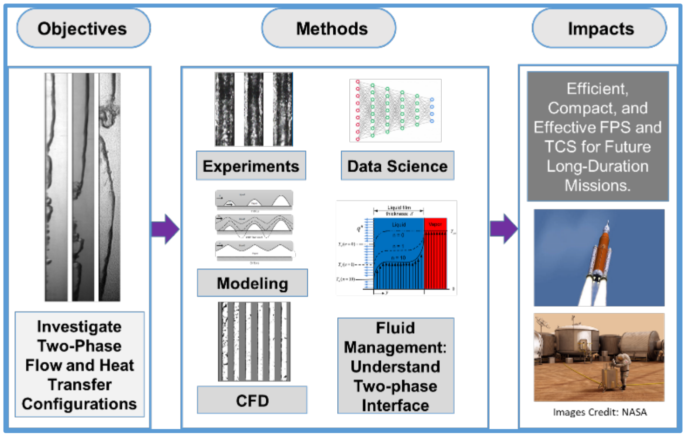


Figure 2 Project objectives, methods and impacts to NASA missions.

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