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Project Title:	Line Chilldown and Transfer Process in Microgravity Onboard the International Space Station (ISS)		
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Task Description:	Effective cryogenic fluid management will be important to the success of future crewed and uncrewed NASA missions. A key technological challenge in this, as recognized by NASA, is the line chilldown and transfer process. The objective of this proposal is to develop a thorough understanding of the fluid flow and thermal transport process during chilldown of transfer lines by utilizing a combination of experimental diagnostic techniques and high-fidelity computational fluid dynamics (CFD) simulations to investigate the boiling process under both terrestrial and microgravity environments. We will achieve this objective by designing a new experimental test module concept to investigate the line chilldown and transfer process that can be integrated with the Flow Boiling and Condensation Experiment (FBCE) facility onboard the International Space Station (ISS). In addition, we plan to develop a computational fluid dynamics framework for simulation of the boiling phenomena and also a reduced-order theoretical framework for the line chilldown and transfer process under terrestrial and microgravity conditions. The proposal directly addresses the critical need in Fluid Physics for NASA's future missions where reduced-gravity multiphase flows, cryogenics, and heat transfer are identified as areas of particular interest. The research will lead to the generation of a large database of chilldown tests under terrestrial and microgravity environments, and closure theoretical and computational models to aid NASA engineers in future mission planning.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	In-Space Cryogenic Line Chilldown and Transfer Process: Success of NASA's future space exploration missions is dependent on cryogenic fluid management systems being able to provide safe, effective, and reliable supply of cryogenic fluid to a variety of systems.1 Two very common systems that need this supply are in-space cryogenic engines and in-space cryogenic fuel depots. A key technological challenge in this, as recognized by NASA, is the line chilldown and transfer process. In-space transfer lines during chilldown are subjected to a combination of near-saturated fluid flow with large temperature gradients as the lines are usually much warmer than the supply tanks. This leads to the occurrence of multiple transient flow boiling regimes and corresponding heat transport phenomena during the chilldown and transfer process. In the case of in-space cryogenic engines, during the initial restart of the engines, ineffective chilldown can lead to strong unwanted combustion instabilities.1 Cryogenic engines lines are usually characterized by a large diameter working in short time scales. While this process is also interesting and has its challenges, it is not the focus of this project. In the project, we are interested in transfer lines specifically relating to cryogenic fuel-depots. Cryogenic fuel-depots have been planned to serve the purpose of low-Earth orbit cryogenic storage and supply to meet in-space fuel needs of customers.1 Cryogenic fuel-depot lines are usually characterized with smaller diameter pipes needing longer time scales in terms of the chilldown and transfer process. There is a need for a clear understanding of the boiling process occurring in such lines in microgravity. In addition, during chilldown of transfer lines, an ineffective boiling process can cause significant energy losses due to the possibility of unwanted evaporation and a need for venting of the cryogenic fluid mass. Therefore, effective and efficient techniques need to be developed for chilldown of the transfer process. Flow Boiling during the Line Chilldown Process: When a warmer transfer line comes in contact with a colder fluid close to its saturation temperature, the process that ensues is the transient quenching or chilldown process until the fluid flow can reach steady state. When the near saturated fluid comes in contact with the warm walls, the first step that occurs is flashing of the fluid to initiate the film boiling regime. In this domain, either a dispersed flow film boiling regime or the inverted annular flow film boiling regime is observed. As the chilldown process continues with no liquid to wall contact in this regime, the process will reach the Leidenfrost Point (LFP) before seeing an increase in heat flux in the transition boiling regime where the liquid starts to rewet the heated surface. This increase in heat flux continues until the critical heat flux point (CHF) is reached, where complete liquid is in contact with the wall followed by transition to the nucleate boiling regime. The heat flux then continues to drop until all the vapor is extinguished and the single-phase forced convection domain is reached, ending the chilldown process. Gaps in Line Chilldown and Transfer Process Research: The accurate capture and prediction of this heat flux vs. wall temperature difference data in microgravity for the complete quenching curve is a big motivation for conducting line chilldown experiments on the ISS. The past 60 years have seen numerous researchers trying to understand this phenomenon experimentally, mostly in terrestrial environments with a few experiments conducted under reduced gravity conditions. In a recent study, Darr et al. summarized a list of all available worldwide databases investigating quenching using cryogenic fluids. These studies could have served the basis for a thorough understanding on this phenomenon in 1-g and to some extent in reduced gravity. However, most of them include data that are deemed unusable due to missing information on rebuilding the full quenching curve, including missing data on either the temperature as a function of time, the pressure as a function of time, the mass flux, the inlet state, and/or the wall and parasitic heat fluxes. The remaining data including the two common fluids with usable data are Liquid Hydrogen (LH2) and Liquid Nitrogen (LN2). There are 12,137 datapoints for LH2 tested in vertical upflow configuration. In addition, there are 62,917 datapoints for LN2 tested in various orientations with respect to Earth gravity and another 4,211 datapoints under reduced gravity conditions of 2*10-2g. In other studies, quenching tests of transfer lines under reduced gravity have been performed with non-cryogenic fluids, including R113 tested by Westbye et al. and Kawaji et al., and Freon-113 by Adham-Khodaparast et al., all onboard the NASA KC-135 flight. Celata et al. also performed quenching experiments with FC-72 as the working fluids onboard a Zero-G flight, which is a modified Airbus-300. While the issue of non-reporting of all the necessary information to recreate the quenching curve makes their data also unusable for further analysis and investigation, but also important to note is none of their data is under pure microgravity conditions. We can see four major gaps in the available literature for accurately understanding and predicting the line chilldown and transfer quench process in microgravity environments, and thus, developing good modeling and/or computational predicting tools: (1) Non-availability of data under pure, sustained microgravity environments. (2) Majority of the usable data is in the high liquid Reynolds number region with Ref > 20,000, which can limit developing a fundamental understanding of flow boiling behaviors that can be better investigated starting at slow or laminar flows. (3) Low availability of overall datapoints covering large geometric variations. (4) Not much published data on varying inlet flows conditions including pulse flows that can be highly effective for cryogenic chilldown and transfer processes for the proposed fuel-depot application. Objectives of the current project: The discussion above clearly demonstrates the gaps in today's research on the line chilldown and transfer process. In this project, we plan to address the major limitations by an integrated experimental and numerical approach, which combines the strengths of both techniques, to develop a thorough understanding of the fluid flow and thermal transport under terrestrial and microgravity environments. The availability of the FBCE facility onboard the ISS with normal perfluorohexane (C6F14 or nPFH) as the working fluid will help us investigate the flow boiling during quenching inside a tube in detail under sustained, long-duration microgravity, and the data will help us develop the computational framework and a theoretical model to predict the boiling behavior accurately.

Task Progress:	The second-year progress of the present research on “Line Chilldown and Transfer Process in Microgravity Onboard the International Space Station (ISS)” can be summarized in three parts as follows: Development and Testing of a Closed Loop Two-Phase Flow Chill-down Test Module for Integration with the Flow Boiling and Condensation Experiment (FBCE) Module at the International Space Station (ISS): Terrestrial chilldown experiments are performed on a 0.375" OD, 0.065" thickness SS-316 tube in a horizontal closed loop flow configuration with PF-5060 as the working fluid. The experiments are performed for a wide range of inlet mass fluxes ranging from 132.83-1303.96 kg/m2s, corresponding to inlet Reynolds numbers of 1,291-12,679 covering the entire regime of laminar to transition to turbulent inlet flows. With the help of a bypass loop and preheating of the test section, the present experiments mimic the cryogenic transfer line chilldown process and capture the entire chilldown curve including the film, transition, and nucleate boiling regimes, along with the single phase liquid convective regimes. The results of the tests yielded useful data for temperature transition points, critical heat flux, regime-specific heat flux, and heat transfer coefficients. Further, the effect of inlet subcooling was investigated by carrying out an elaborate set of 99 experimental tests, and the data is being processed now. Transparent Pyrex test sections for flow visualization during the chilldown process are also ready and will be tested next year. CFD Studies on Flow Boiling during the Cryogenic Transfer Line Chill-down Process under Terrestrial and Microgravity Conditions: 2-D axisymmetric computational fluid dynamics (CFD) simulations were validated for the 1-ge LN2 vertical upflow chilldown experiments in the film boiling regime at 4 different inlet mass fluxes. The chilldown curves deviated from the experimental data in the transition and nucleate boiling regimes. 3-D CFD simulations were performed for 3 low inlet mass flux test cases for 1-ge LN2 vertical upflow chilldown experiments and the predictions seem to improve in the transition and nucleate boiling regimes, though a user-defined function (UDF) for sub-grid nucleate boiling is being developed to validate these regimes. 2-D axisymmetric CFD simulations are being performed to validate the microgravity chilldown results with LN2 as the working fluid. The preliminary results are promising, and the simulation methodology is being extended to predict chilldown curves at different axial locations along the tube. Finally, 2-D axisymmetric CFD simulations are performed to predict the LH2 chilldown process in a vertical upflow configuration. The initial results are encouraging and are being extended to different test cases. Development of a 1-D Nodal Model for Line Chill-down Process: No progress this year. The experimental results obtained from the terrestrial chilldown tests will be used to develop correlations for use in the 1-D nodal model next year. In addition, the Science Requirements Document (SRD) and Integrated Science Requirements Document (ISRD) for the project have been submitted in collaboration with the University of Illinois, Urbana-Champaign (UIUC), along with the Experiment Data and Management Plan (EDMP) and Mission (Level -1) Requirements Documents, for the Science Requirement Review (SRR) planned for January 2024.
Bibliography Type:	Description: (Last Updated: 11/26/2024)
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