Experiments to complete scientific understanding of how reduced gravity affects boiling and condensation

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An experiment designed by Purdue University researchers to study the effects of reduced gravity on boiling is loaded onto a Cygnus spacecraft in preparation for launch onboard an Antares rocket to the International Space Station. Credit: Northrop Grumman/NASA

With temperatures on the moon ranging from minus 410 to a scorching 250 degrees Fahrenheit, it's an understatement to say that humans will need habitats with heat and air conditioning to survive there long term.

But heating and cooling systems won't be effective enough to support habitats for lunar exploration or even longer trips to Mars without an understanding of what reduced gravity does to boiling and condensation. Engineers haven't been able to crack this science—until now.

"Every refrigerator, every air conditioning system we have on Earth involves boiling and condensation. Those same mechanisms are also prevalent in numerous other applications, including steam power plants, nuclear reactors and both chemical and pharmaceutical industries," said Issam Mudawar, Purdue University's Betty Ruth and Milton B. Hollander Family Professor of Mechanical Engineering. "We have developed over a hundred years' worth of understanding of how these systems work in Earth's gravity, but we haven't known how they work in weightlessness."

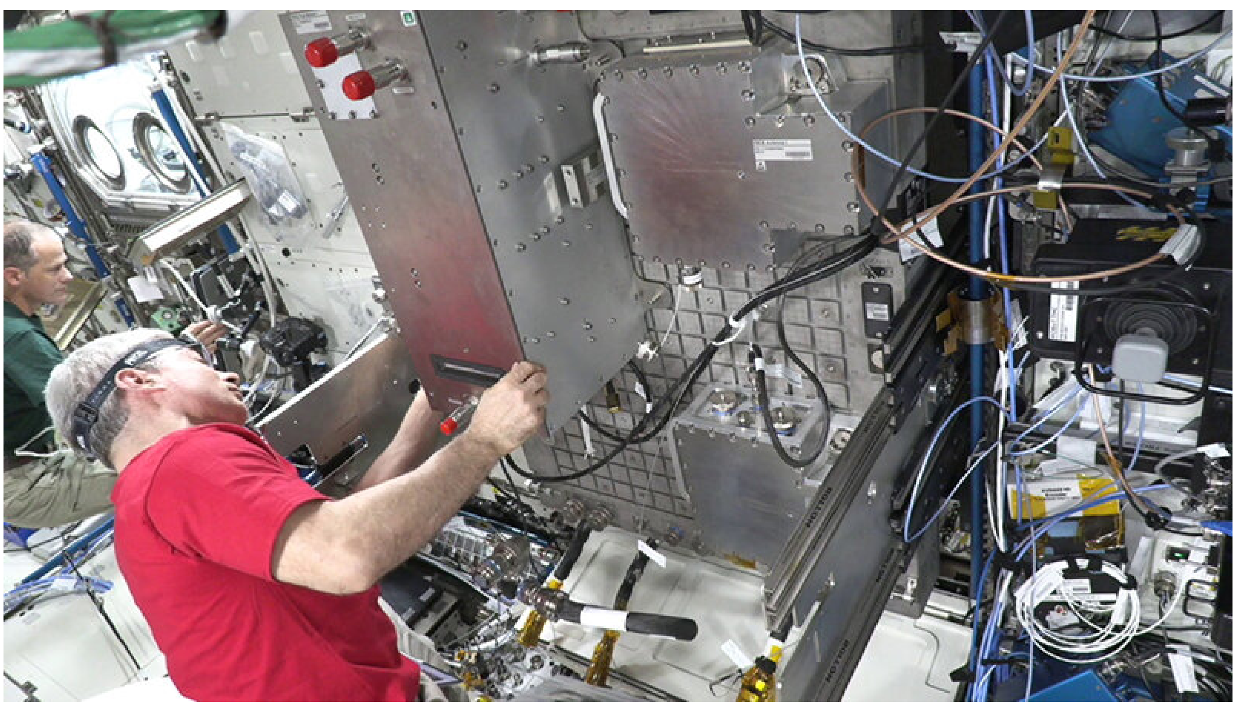
A team of engineers at Purdue led by Mudawar, who is collaborating with NASA's Glenn Research Center in Cleveland, has spent 11 years developing a facility to investigate these phenomena.

The facility is called the Flow Boiling and Condensation Experiment (FBCE). Initial designs were tested on Zero Gravity Corporation's (Zero-G) weightless research lab, a specially modified Boeing 727 that flies parabolic maneuvers to create the reduced gravities on the moon and Mars as well as the weightless conditions in space.

Following in-flight testing, NASA Glenn and the agency's Biological and Physical Sciences Division assisted Mudawar's team in creating a smaller version of the experiment to fit into the Fluids Integrated Rack on the International Space Station. After passing NASA safety and readiness reviews, FBCE launched to the space station in August 2021 and has since helped researchers to begin to unlock the mystery of how boiling and condensation work in the extreme environments of space.

These answers are in data the team is collecting from two sets of FBCE experiments taking place on the station. Last July, the facility's first experiment finished gathering all the data that Mudawar says scientists need to understand how reduced gravity affects boiling. In the coming months, the equipment for the second experiment will launch to the orbiting laboratory as part of a Northrop Grumman commercial resupply services mission for NASA (NG-19) to gather data on how condensation happens in a reduced gravity environment.

Both experiments making up the facility will remain in orbit through 2025, allowing the fluid physics community at large to take advantage of this data.



Astronaut Mark Vande Hei assembles components of the Flow Boiling and Condensation Experiment on the International Space Station. Credit: NASA

"We are ready to literally close the book on the whole science of flow and boiling in reduced gravity," Mudawar said. "Astronauts on the moon will need air conditioning systems, refrigeration systems and many other systems that all require boiling and condensation. Because of the new understanding we've received from data showing how these phenomena are influenced by reduced gravity, we are able to provide guidance into how to size the equipment, how to design it effectively and how to predict its performance."

The researchers are preparing a series of research papers unpacking data the FBCE has collected on the International Space Station, adding to more than 60 papers they have published on weightlessness and fluid flow since testing their facility on Zero-G flights at the beginning of the project.

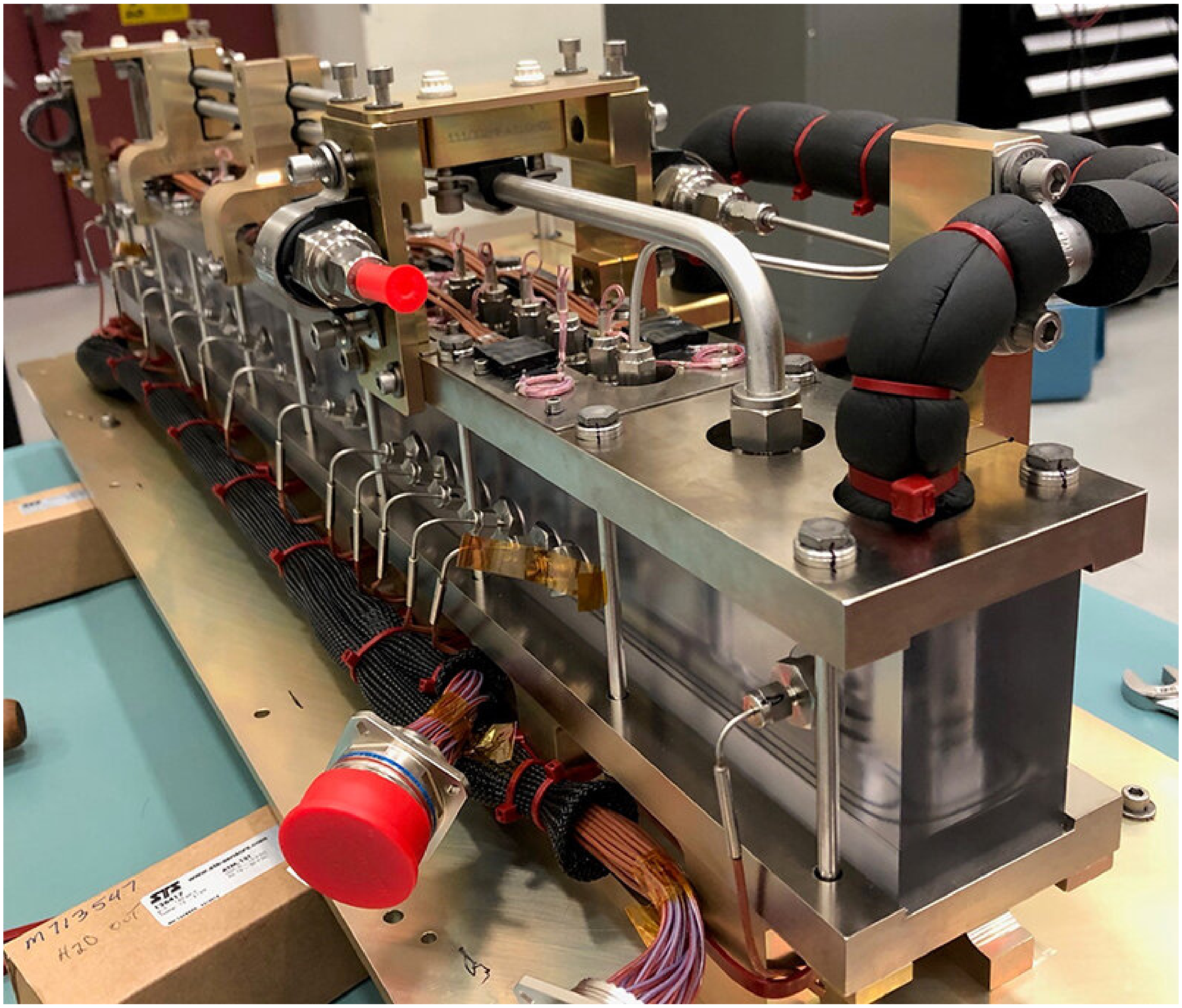
Answering decades-old questions

"The papers we have published over the duration of this project are really almost like a textbook for how to use boiling and condensation in space," Mudawar said. "For more than 60 years, since the beginning of spaceflight, the field has known that boiling and condensation would be ideal for space, but previous attempts to study these concepts in microgravity hadn't been successful."

Each decade the National Academies publishes a report that guides NASA, the White House and Congress on areas of research to prioritize for funding over the next 10 years. In the 2011 report, numerous scientists recommended that the role of gravity in controlling vapor-fluid behavior be considered as one of those priorities for space exploration. The FBCE project was created in response to the decadal report.

The farther missions are from Earth, the more likely that the spacecraft for those missions will need nuclear power. Compared to other types of processes that enable heating and cooling in space, boiling and condensation are much more effective at transferring heat for these nuclear-powered vehicles and habitats. Boiling and condensation would also allow heat, ventilation and air conditioning systems to be more compact and lightweight.

Since the 1970s, Mudawar has been working to make it possible to use boiling and condensation to tackle energy transfer and temperature control challenges for a wide range of systems. Examples include high-temperature turbine systems, supercomputers, data centers, avionics, hybrid vehicle power electronics, hydrogen fuel cells, metal alloy heat treating, particle accelerators and fusion reactors.



Purdue University engineers conducted the first phase of the Flow Boiling and Condensation Experiment using the Flow Boiling Module, which gathered data on how boiling happens in reduced gravity. Pictured here is this module prior to being launched for installation on the International Space Station. Credit: NASA Glenn Research Center

The largest experiments of their kind

According to Mudawar, FBCE is the first set of experiments to provide data that is extensive and systematic enough for developing the models engineers need to design all sorts of space systems using boiling and condensation in reduced gravity.

"We now have a basis for comparing and contrasting data for both Earth gravity and reduced gravity in pursuit of modeling tools that can be applicable to a broad range of gravities," Mudawar said.

Mudawar and his students have been developing three sets of predictive tools over the past 11 years based on FBCE data. One set of tools puts the data into the form of equations that engineers can use to design space systems. Another set identifies fundamental information about fluid physics from the data, and the third set is computational models of the fluid dynamics.

All together, these models would make it possible to predict which equipment designs could operate in lunar and Martian gravity.

FBCE is NASA's largest and most complex experiment for fluid physics research. Between February and July last year, the facility successfully conducted 234 tests, yielding nearly 3,800 data points and an equal number of high-speed video records.

More than 35 engineers and technicians from different teams across NASA Glenn have worked on this project, helping turn design concepts from Mudawar and his students into a facility that could be installed into the space station. These teams included Glenn's FBCE Engineering, Safety and Mission Assurance, Science, Software, and Technician teams, and Fluids and Combustion Facility Operations teams.

Fifteen past and current Purdue Ph.D. students have assisted Mudawar on all aspects of collaborative work with NASA. Two Purdue doctoral candidates, V.S. Devahdhanush and Steven Darges, assisted in monitoring the experiments on the space station via a dedicated workstation set up at Purdue. The Purdue team also provided recommendations for refinement of operating conditions for subsequent tests to continuously improve science yield per test.

Data from the FBCE would benefit not only space systems, but also technology on Earth. Using lessons they learned about boiling from this data, Mudawar and his team invented a new charging cable design for electric vehicles that would allow them to charge in less than five minutes. Today's most advanced charging cables take more than 20 minutes to charge an electric vehicle. A patent application for this fast-charging cable invention has been filed through the Purdue Research Foundation Office of Technology Commercialization.

"The amount of data coming out of the FBCE is just absolutely enormous, and that's exactly what we want," Mudawar said.

Provided by Purdue University

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