Simulation-Based Engineering Fosters Innovation and Invention

Simulation-based engineering design helped generate a first physical prototype of a micro-channel heat exchanger that worked largely as expected.

BY CATHLEEN LAMBERTSON, CONTRIBUTING EDITOR, TECH BRIEFS MEDIA GROUP

Founded in 2000, Intellectual Ventures (IV, Bellevue, WA) is a global leader in the business of invention, boasting one of the largest intellectual property portfolios in the world. IV has accomplished this by building, buying, and collaborating to create inventions and then supplying those inventions to companies through various licensing and partnering programs. They invest both expertise and capital in the process of invention in diverse technology areas including healthcare, medical devices, semiconductors, information technology, software, financial services, and manufacturing. In 2008, IV launched an invention/prototype laboratory to support the company's mission of energizing and streamlining an invention economy that will drive innovation around the world.

Intellectual Ventures Laboratory (IVL) employs broad interdisciplinary teams of physicists, engineers, chemists, biologists, and physicians tasked with discovering, inventing, and developing advanced technology solutions in a variety of fields. According to Ozgur E. Yildirim, Ph.D., Engineering Program Manager at IVL, simulation and analysis have been one of the cornerstones of research and development (R&D) at the lab from the beginning. "The lab and the extended R&D we support under IV is highly multidisciplinary. The types of simulations range from very large epidemiological models, neutronics models for nuclear reactors, and sophisticated continuum models for electromagnetics, structural, thermal, and fluidics analysis, and transport phenomena in general," said Dr. Yildirim.

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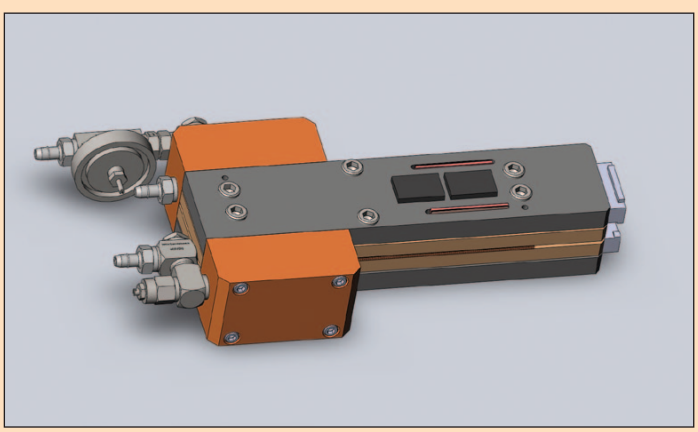
Simulation at IVL

Much of the progress at IVL relies on modeling and simulation simply because experiments can take a long time to accomplish. This is especially true in areas such as epidemiological modeling or neutronics. Further, modeling and simulation can provide different and unique insights that would not be easily possible by experimentation. Additionally, in more traditional hardware R&D, researchers at IVL use modeling and analysis very closely and iteratively with prototyping and direct experimentation to guide the design directions, interpret experimental observations, reduce cycle times, and in general to maximize understanding.

Almost all of the projects at IVL use some type of modeling and analysis and, according to Dr. Yildirim, a significant portion of them lend themselves to finite element analysis (FEA). This is why COMSOL Multiphysics software is used extensively at IVL. For example, COMSOL was used on such projects as the TerraPower nuclear reactor conceptual design, IV's passive cold storage device for vaccine distribution, the "Photonic Fence" that uses lasers for malaria vector control, and a new beam-steering metamaterials satellite antenna. COMSOL is even used in IVL's state-of-the-art culinary sciences lab. A fairly new area of study, culinary physics is the convergence of physics and



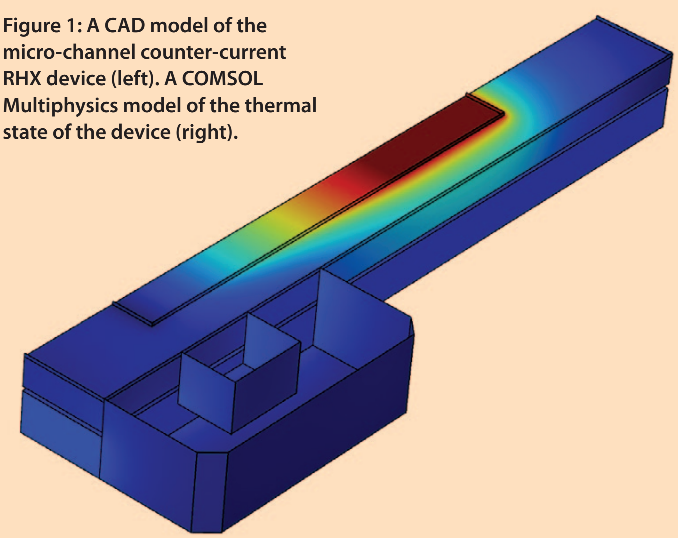


Figure 1: A CAD model of the micro-channel counter-current RHX device (left). A COMSOL Multiphysics model of the thermal state of the device (right).

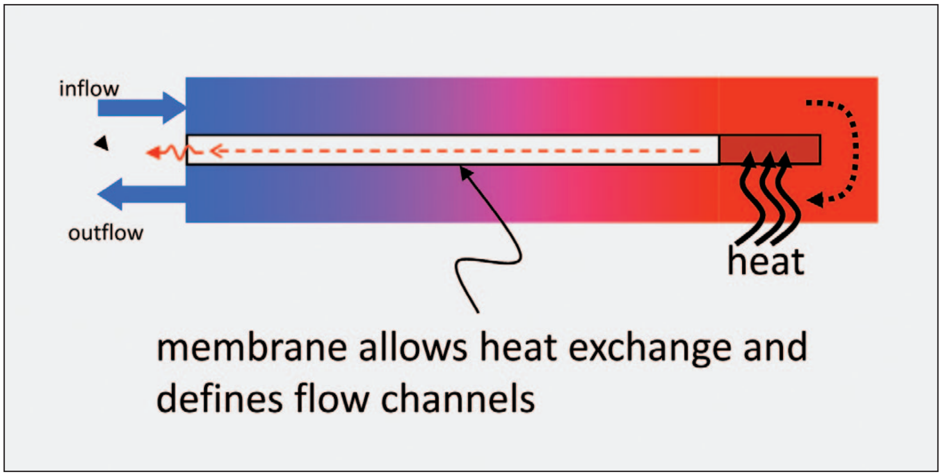


Figure 2: A schematic representation of a unit flow loop in the micro-channel counter-current RHX device. A small amount of added heat is enough to maintain the temperature profile in the device once steady state is reached, thanks to very high regenerative efficiency.

mathematical analysis with food science. This large project recently culminated in a very untraditional "cookbook" called the *Modernist Cuisine*.

Recently, Dr. Yildirim and his team used COMSOL Multiphysics to model the design and development of a novel micro-channel counter-current regenerative heat exchanger (RHX) to thermally process a liquid stream with exceptionally high heat-recapture efficiency (Figure 1). "COMSOL is a state-of-the-art computational tool that gives a lot of visibility and control into the kind of physics being simulated. It is unique in that it allows the user to be a scientist, mathematician, and engineer, all at the same time, going way beyond a black-box modeling tool," stated Dr. Yildirim.

The RHX Explained

An RHX is a type of heat exchanger in which the same fluid is both the cooling fluid and the cooled fluid, meaning the hot fluid leaving the system gives up its heat to "regenerate" (heat up) the fluid returning to the system (Figure 2). RHXs are usually found in high-temperature systems where a portion of the system's fluid is removed from the main process and then returned in the opposite direction for further processing. Because the fluid removed from the main process contains energy (heat), the heat from the fluid leaving the main system is used to regenerate (reheat) the returning fluid instead of being rejected to an external cooling medium. And since most of the heat energy is reclaimed, the process gives a considerable net savings in energy. For example, a typical RHX can have a thermal efficiency in the vicinity of 80-90%, transferring almost all the relative heat energy from one flow direction to the other.

A wide variety of fluid-handling applications involve RHX operations. According to Dr. Yildirim, RHXs may be useful in liquid food or pharmaceutical processing in order to thermally inactivate microorganisms or enzymes, or in achieving controlled temperature cycling for bio-chemical reactions as with flow-based polymerase chain reaction systems.

"Micro" Modeling

Whereas "large" RHX systems have been in use for a long time, their smaller micro-channel counterparts are a more recent area of interest. "Large RHX systems are almost always found integrated as part of industrial plants and are capital intensive. Micro-channel RHX accomplish the same function at a much smaller

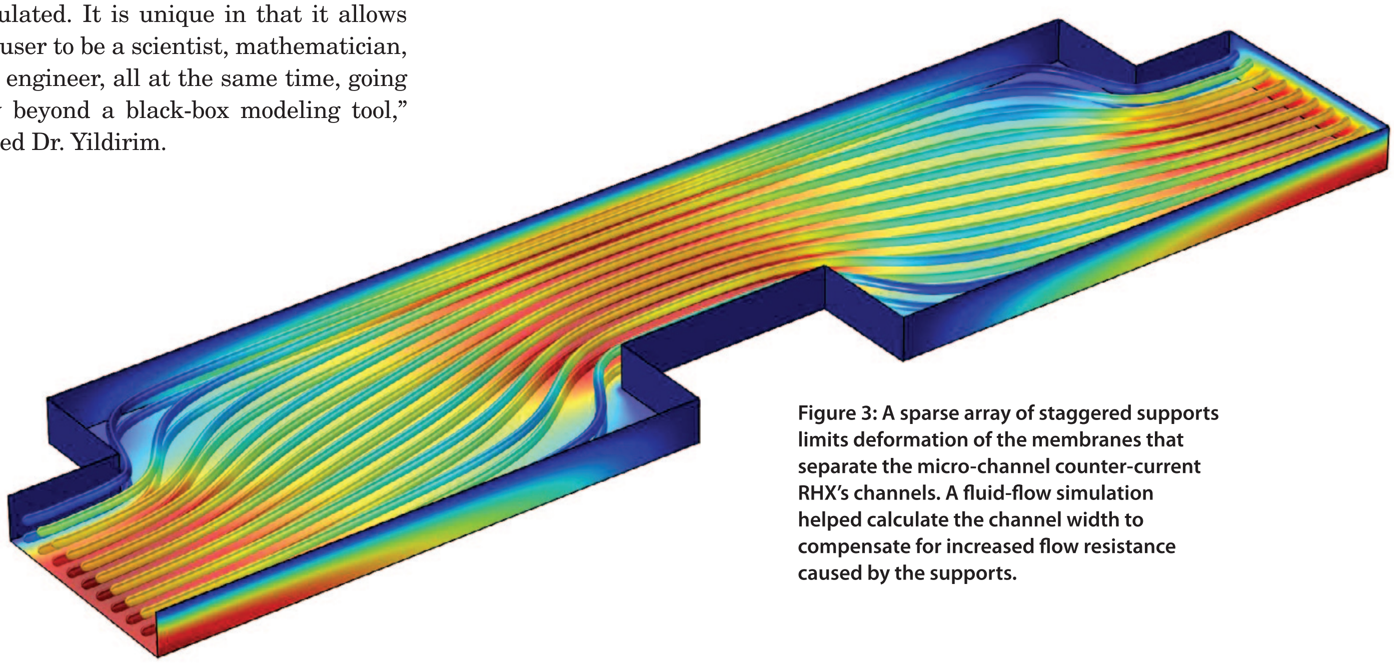


Figure 3: A sparse array of staggered supports limits deformation of the membranes that separate the micro-channel counter-current RHX's channels. A fluid-flow simulation helped calculate the channel width to compensate for increased flow resistance caused by the supports.

scale, thereby opening up areas for potential new applications where the device footprint and/or process stream quantities are small," explained Dr. Yildirim. For example, the micro-channel RHX devices would be useful in modular applications where small quantities of liquid need to be treated without having access to a large infrastructure and/or energy supply. In addition, micro-channel RHX is easily scalable in a way that large systems may not be. "You can think of it as a small miniaturized factory that requires much less infrastructure — the task can be performed on a benchtop or out in the field," he added.

The novel micro-channel counter-current flow RHX system developed by the IVL team is designed to thermally process a liquid stream with exceptionally high heat-recapture efficiency. "Since micro-channel RHXs are a less well-studied area of application, one cannot necessarily rely on the large amount of engineering knowledge base that has been painstakingly developed over time and is available when it comes to traditional heat exchangers; rather more groundwork needs to be re-done from first principles. Fortunately, COMSOL makes this easy and fun," said Dr. Yildirim.

After laying out the basic device architecture, COMSOL was used as the main analysis tool to investigate the effect of primary design variables on the device performance. Dr. Yildirim explained that the most important performance attributes of interest were the heat exchange (regenerative) efficiency, i.e., the fraction of heat energy re-captured from the hot stream after it is first transferred into it, which plays into the device power requirement; and the pressure drop/flow rate relationship, which plays into the pumping requirements. COMSOL was also used to explore the structural stability of the device in detail (Figure 3) and to help interpret the experimental results after the first physical prototype was built and tested. "This is one of COMSOL's biggest strengths — the multiphysics, and unlimited and unrestricted physics couplings that are possible," stated Dr. Yildirim.

In addition, when it comes to making a physical prototype, challenges such as selecting the correct material set to withstand the inherent temperatures and pressures, or choosing prototyping processes to assemble a functional device can arise. "Thus not only have we had to study the basic physics using COMSOL, we have also had to do significant amount of hardware and assembly process work to come up with a viable way to make functioning prototypes. This involved exploration of adhesives, thermal vias, as well as photolithography techniques. We used COMSOL in a very integrated manner with prototyping activities," said Dr. Yildirim.

Dr. Ozgur Yildirim (left) and Dr. Zihong Guo — core members of the novel micro-channel counter-current RHX team — with a prototype of the device.

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The Advantage

Utilizing a simulation-based engineering design approach resulted in the first physical prototype working largely as expected: The prototype design of the micro-channel RHX system was shown to be capable of thermally treating a water stream by ramping its temperature from room temperature to about ~130 °C under pressure to prevent boiling, and back to ambient again with close to 98% regenerative energy recapture in a compact, very low-energy thermal treatment device. The concept was proved quickly and the number of subsequent design iterations was minimized. "During this project, I took full advantage of [COMSOL's] ability to represent parts of the physics analytically rather than trying to solve everything blindly starting from the partial differential equations and focus only on the part of the physics I wanted to isolate and investigate computationally. This resulted in significant speedups and allowed for very nimble use of modeling and analysis," explained Dr. Yildirim. "Furthermore, the ability to couple different kinds of physics [with COMSOL] came in handy as well." ■

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