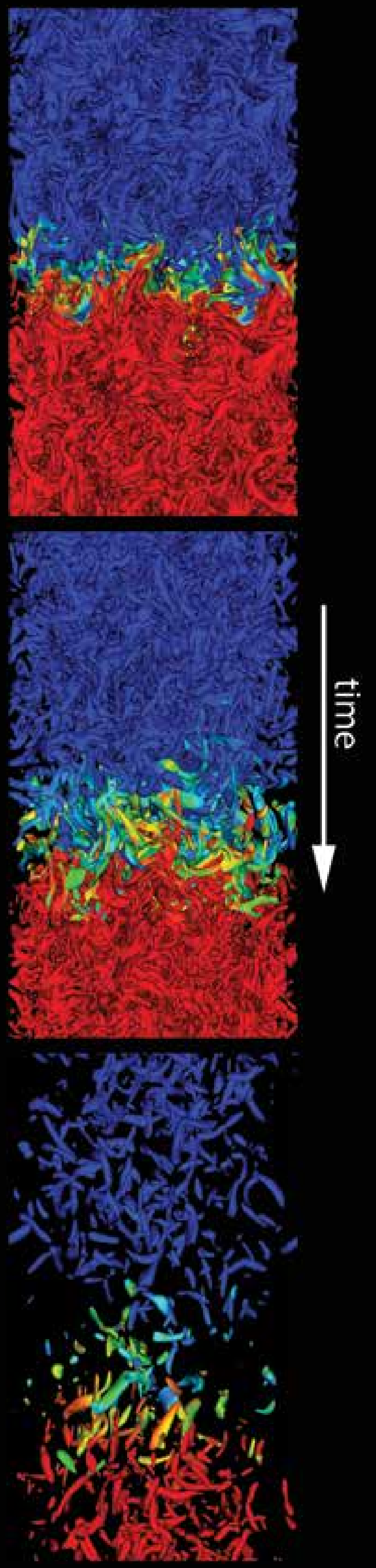
Extreme Computations of Fluid Flows



The work of Assistant Professor **Eric Johnsen** blends the traditional and the modern—core mechanical engineering disciplines of fluid dynamics and continuum mechanics with high-fidelity numerical simulations enabled by "extreme" computing technology. The combination allows him to investigate high-speed and high-energy-density phenomena in the U-M Computational Flow Physics Laboratory, which he directs. The fluid mechanics problems he looks at impact applications that span aeronautics to medicine, astrophysics to naval engineering.

A NEW PARADIGM IN EXTREME-SCALE COMPUTING

"A lot of problems we're interested in require us to develop our own algorithms and codes," said Johnsen. "Although we tend to focus on fundamental problems, no existing software produces results that we think are accurate enough to predict these complex multiscale, multi-physics flows."

To investigate such problems, Johnsen's research team uses high-performance computing, including performing parallel computations with tens of thousands of the "traditional workhorse," central processing units (CPUs). However, "the current paradigm of adding more and more CPUs to speed processing time is just not sustainable. At some point soon, we'll need a mini nuclear plant to power the computing cluster," Johnsen joked. "It's time for a new paradigm for extreme-scale computing, but the new technology means we must rethink how we integrate our algorithms to the hardware."

More recently, Johnsen has begun using graphics processing units (GPUs), processors akin to video cards, with each running about as fast as 100 CPUs. Now he and his group are working with many GPUs, which accelerates processing time tremendously but also poses new challenges—such as communicating information efficiently between GPUs—that his group is working to overcome.

SIMULATING TURBULENT FLOWS

Accurate numerical methods are critical to better understanding high-speed turbulent flows, yet simulating these phenomena is difficult because of the huge span in length and time scales.

"Let's say you're looking at turbulent flow over an aircraft," said Johnsen. "The scale spans tens of meters down to the sub-millimeter, maybe lower. It could be a five or six order-of-magnitude change, and the higher the speed, the larger that difference in scale becomes."

Addressing the challenges involves developing high-order accurate methods for compressible turbulence. His approaches include a variety of solution-adaptive discontinuity-capturing schemes and low-dissipation methods based on finite difference, finite volume and discontinuous finite element frameworks.

"Methods that scale well to extreme computing are especially interesting to us," Johnsen said. "By reducing discretization errors sufficiently, we can resolve all dynamical scales and conduct DNS, Direct Numerical Simulation. Under these circumstances, our simulations produce an 'exact' solution to the equations of motions—albeit numerical." For this reason DNS is an ideal tool to interrogate fundamental flow physics.

One particular application area of this work is mixing during combustion. Instabilities develop at interfaces between different fluids subjected to the accelerations that occur in combustion, ultimately leading to mixing.

LEFT: Isosurfaces of Q-criterion colored with mass fraction.

"We want to know how different fluids mix in these high-speed turbulent flows, since this directly impacts the combustion process and fuel efficiency," Johnsen said.

Direct numerical simulation is generally too computationally expensive for design purposes. More commonly, multiscale methods are used, such as large-eddy simulation (LES), in which large-scale features are resolved on the computational mesh, and the subgrid-scale dynamics are modeled.

Johnsen works with Ford Motor Company and colleagues in U-M's departments of Naval Architecture and Marine Engineering and Aerospace Engineering to improve fuel economy by reducing vehicle drag using LES. Vortex generators, placed in strategic locations, energize airflows over vehicles so the flow more closely follows the contours of the car. This reduces the low-pressure regions that cause drag. But what size and shape are optimal? How should they be arranged on the vehicle? Those are the questions Johnsen and his students are answering.

HARNESSING THE EFFECTS OF CAVITATION

Flows around underwater objects create regions of varying pressures. When pressure drops by a sufficient amount, cavitation bubbles form. Their rapid growth, to many times their original size, and collapse produce shock waves that interact with neighboring solid surfaces and cause erosion. Johnsen's group is looking at cavitation erosion of modern materials such as composites and polymeric coatings as part of his Young Investigator Award from the Office of Naval Research. He also has been trying to understand, and potentially make use of, its destructive aspects in therapeutic applications.

Ultrasound-induced cavitation is used in lithotripsy, to destroy kidney stones, and in histotripsy, a technique pioneered at U-M to destroy pathogenic tissue in conditions such as prostate cancer. Johnsen and colleagues in U-M's Radiology department are also looking at the potential for stabilized microbubbles to enhance contrast during cardiac imaging. And the dynamics of cavitation bubbles may play a role in traumatic brain injuries that result from blasts.

"The big hurdle in these applications is that we don't know how tissue behaves at the very fast rates of cavitation and shock waves. The knowledge we've acquired about cavitation in water does not directly translate to tissue," said Johnsen, who received a National Science Foundation CAREER Award in 2013 for his work in this area (see related story on page 10).

"At the end of the day, we're developing general theoretical and computational frameworks to study fundamental problems that have widespread applications in science and engineering," Johnsen said. Gaining insights and having an impact on society are important to him, and he finds working with such a talented group of student-researchers one of the most rewarding parts of his job.

"Students at U-M are outstanding: In many cases, all they need from me is a slight nudge to take the research to places I wouldn't have imagined. In addition to great graduate students, I work with fantastic undergraduate researchers, who regularly present and publish at conferences and in scientific journals. Getting to interact with such smart people on a day-to-day basis is a real privilege."

ABOVE: Shock-induced collapse of a bubble near a rigid surface. The incoming shock wave (moving right to left) in water interacts with a preexisting gas bubble and causes its collapse. High pressures and temperatures are achieved during this process, leading to potential structural damage to the neighboring solid (on the left side). This mechanism is thought to play a critical role in cavitation erosion to propellers, in high-intensity focused ultrasound and in certain traumatic brain injuries.

> "The current paradigm of adding more and more CPUs to speed processing time is just not sustainable. It's time for a new paradigm for extreme-scale computing, but the new technology means we must rethink how we integrate our algorithms to the hardware." —ERIC JOHNSEN