Multiscale fluid flows: two motivating experiments

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The focus of my research is the development of efficient and accurate numerical algorithms for capturing multiscale flows in gas dynamics.

An example of the type of problem we are interested in is shown in Figure 1. This image is from an experiment conducted in 1959 by D. W. Boyer [2]. The experimental setup is as follows: a 3 ft diameter spherical "shock chamber" contains a 2 in diameter sphere made of soda-lime glass and filled with pressurized air. The sphere is hand-blown and fitted with a small hollow stem that is then cemented to a pipe (shown at the top of the figure), suspending the sphere in the center of the shock chamber. Air is pumped into the glass sphere through the pipe until the pressure inside reaches 400 psi, roughly the same as the pressure at a depth of 275 m underwater. The experiment is initiated when a spring-loaded mallet, visible at the bottom of the figure, strikes the glass sphere, shattering it. The resulting gas flow, driven by the escaping pressurized air, is visualized along a two-dimensional slice using shadowgraph photography.

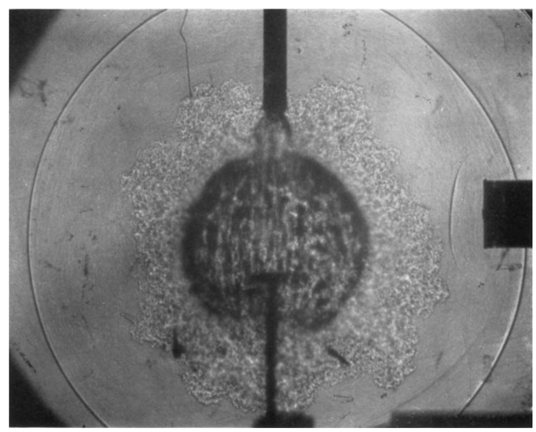

Figure 1: Shadowgraph taken 300 μsec after initiation in the exploding glass sphere experiment. Figure taken from [2].

The *multiscale* nature of the flow is clearly demonstrated in Figure 1. The shattering of the glass sphere generates a spherical *shock wave*: a thin[1] adjustment layer across which certain fluid properties (such as pressure, density, temperature, flow velocity, etc.) vary rapidly. This shock wave then propagates radially outwards into the surrounding air. Meanwhile, the compressed air in the sphere is expanded through a spherical *rarefaction wave* that propagates radially inwards. Lying between the two waves, separating the air compressed by the shock from the expanded sphere gas, is another wave: a *contact discontinuity*. The contact discontinuity is inherently *unstable*; the initial spherically symmetric flow quickly develops asymmetries, visualized in Figure 1 as the small whorls and eddies of the contact surface. The instability is enhanced by the asymmetries introduced by the experimental apparatus: the pipe, the cemented hollow stem, and the fragments of shattered glass flowing through the air. Eventually, we observe the emergence of a *turbulent mixing region* containing flow structures across a wide range of spatial scales.

[1]Shock waves in air have been measured to have a width of approximately 200 nm, which is roughly 4 times the mean free path of air molecules and 100 times smaller than the width of a human hair.

In 1960, less than a year after Boyer's experiments, the laser was invented. It was quickly realized that this new technology appeared to be the perfect mechanism for driving *inertial fusion* devices, a concept proposed in 1957 by J. Nuckolls. In a 1972 paper, Nuckolls introduced laser-based *inertial confinement fusion* (ICF) [13]. The numerical simulation in Figure 2 is taken from [3] and is one of several described therein, with each simulation representing an experiment that might be conducted at the National Ignition Facility (NIF), the world's largest and most powerful ICF device [5].

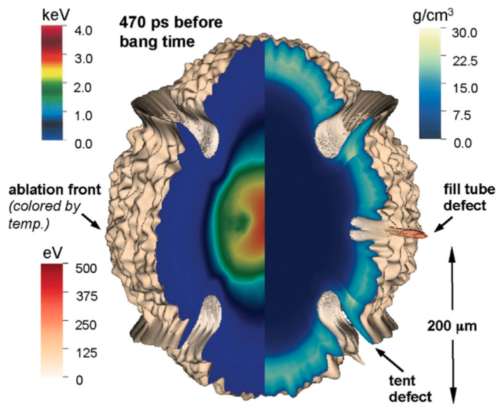

Figure 2: Numerical simulation of an ICF experiment at the NIF. Figure taken from [3].

The NIF is the size of 3 football fields; the bulk of the facility is occupied by an array of 192 beamlines forming a laser delivery system. The beamlines are connected to a 10 m diameter spherical target chamber which contains, at its center, a 1 cm cylindrical cavity made of gold and depleted uranium known as a *hohlraum*. Inside the hohlraum is a 2 mm diameter spherical *fuel capsule* composed of a thin layer of frozen Deuterium-Tritium (DT) ice surrounded by a diamond *ablator*. The fuel capsule is fitted with a *fill tube* through which DT gas is pumped, then suspended at the center of the hohlraum via a capsule support *tent*.

An experiment at NIF begins with the passage of the 192 laser beams through the beamlines, where they are energized to 30 quadrillion watts. The lasers are then focused into the center of the target chamber, where they enter the hohlraum and reflect off the internal walls, creating an x-ray bath that turns the surface of the fuel capsule into a superheated plasma. The surface explodes outwards, which, in turn, causes the DT gas to *implode* inwards: the gas is compressed down to a core half the width of a human hair. At peak compression, the pressure/temperature of the DT gas is more than two times (respectively, five times) the pressure/temperature at the center of the sun. Large enough compression of the gas at high enough temperatures for a sufficiently long amount of time then results in *ignition*: a series of self-sustaining fusion reactions and a thermonuclear burn wave that replicate, in a laboratory on Earth, the energy production method that powers the stars.

The key to achieving ignition is maintaining a highly uniform compression of the DT gas; controlling the instability at the ablation front is the main difficulty in doing so. As shown in Figure 2, asymmetries introduced by the fill tube and the capsule support tent cause the ablation front to penetrate into the interior "hot spot", which is then cooled down and cannot ignite. Enormous resources are invested into removing the asymmetries seeding the instability: the capsule support tent is manufactured to be just 12 nm thick, the diameter of the fill tube is just 2 μm, and the surface of the ablator is meticulously smoothed to remove tiny non-uniformities in the capsule. In addition, the lasers are focused into the hohlraum in a carefully designed sequence of pulses, which, in turn, generates a set of converging shock waves that help suppress the instability [3, 15]. The purpose of numerical simulations like the one shown in Figure 2 is to help inform the specific design choices for an ignition experiment; these simulations are incredibly computationally expensive, requiring roughly one month to complete while running on six thousand processors [3].

In December 2022, NIF conducted experiment N221204, in which ignition was achieved for the first time. Separating N221204 and Boyer's experiments are six decades of advances in theoretical, computational, and experimental physics; mathematics; computer science and hardware; mechanical engineering; materials science; laser science, and numerous other scientific fields. And yet, remarkably, the two experiments share many of the same qualitative features.

Multiscale fluid flows are ubiquitous. They are observed in: atmospheric flows, such as cyclones, jet streams, and wildfires [16, 10]; astrophysical phenomena, such as relativistic jets, star/galaxy formation, and black hole accretion disks [6, 7, 8, 17, 4]; and industrial applications, such as fusion reactors, combustion engines, and wind flow around turbines [11, 1, 9, 14]. Already, this short and entirely non-exhaustive list of applications indicates the necessity of having robust numerical algorithms for simulating such flows. However, capturing their wide range of dynamically evolving and interacting spatial and temporal scales efficiently and accurately is a formidable problem that usually requires massive supercomputing resources. Even with such resources, it is the case that many, if not most, problems of interest remain out of reach of traditional numerical algorithms [12].

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