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Comparison between Kelvin–Helmholtz instability experiments on OMEGA and simulation results using the CRASH code

E.M. Rutter [a,*], M.J. Grosskopf [a], G. Malamud [a,c], C.C. Kuranz [a], E.C. Harding [b], P.A. Keiter [a], R.P. Drake [a]

[a] *The University of Michigan, Ann Arbor, MI 48109, USA*
[b] *Sandia National Laboratory, Albuquerque, NM, USA*
[c] *Department of Physics, Nuclear Research Center, Negev, Beer-Sheva 84190, Israel*

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ABSTRACT

The Center for Radiative Shock Hydrodynamics (CRASH) at the University of Michigan has developed a Eulerian radiation-hydrodynamics code with dynamic adaptive mesh refinement, CRASH, which can model high-energy-density laser-driven experiments. One of these experiments, performed previously on the OMEGA laser facility, was designed to produce and observe the Kelvin–Helmholtz instability. The target design included low-density carbonized-resorcinol-formaldehyde (CRF) foam layered on top of polyamide–imide plastic, with a sinusoidal perturbation on the interface and with the assembled materials encased in beryllium. The results of a series of CRASH simulations of these Kelvin–Helmholtz instability experiments are presented. These simulation results show good agreement both quantitatively and qualitatively with the experimental data.

1. Introduction

The Kelvin–Helmholtz instability arises from a tangential velocity gradient across the interface of two fluids and is integral to many astrophysically relevant phenomena such as mixing layers in supernovae [1,2]. It is also relevant to inertial confinement fusion [3]. Although this instability has been studied extensively in classical systems [4,5], it was only recently that experiments, carried out at the OMEGA laser facility in the Laboratory for Laser Energetics [6], specifically investigated this instability in the high-energy-density physics regime [7–9].

The Center for Radiative Shock Hydrodynamics (CRASH) at the University of Michigan has developed an adaptive mesh refinement (AMR) radiation hydrodynamics code, in order to model radiative shocks, and other high-energy-density systems [10,11]. The CRASH code was specifically developed to model and predict laser-driven, radiative shock-tube experiments [12], which required implementing a number of physical models needed to simulate high-energy-density systems, discussed further below. In order to validate CRASH for this application and others, it is imperative to exercise the code to simulate a variety of experiments that differ from the nominal case, and for which there are existing data [13,14]. The Kelvin–Helmholtz experiments are ideal for this purpose because there exists analytical, experimental, and simulation data to which to compare our results. Although other codes have simulated this exact experiment [8,15], CRASH is one of the few such codes with a high-fidelity laser package. The higher-fidelity laser package in CRASH deposits laser energy along the ray, traced in three dimensions even for two-dimensional simulations [11]. CRASH is a publicly available code, so the present work also helps determine its potential utility to a range of academic research groups.

2. Experimental and simulation set-up

A basic schematic of the Kelvin–Helmholtz target is displayed in Fig. 1. The target has a polyamide–imide plastic layer and a low-density carbonized-resorcinol-formaldehyde (CRF) foam (0.1 g/cc) layer separated by sinusoidal perturbations with a 400 μm wavelength and 60 μm amplitude, with the materials encased in a beryllium box. This is capped by a thin polystyrene plastic ablator. The layered plastic has a density of 1.42 g/cc, and the plastic ablator has a density of 1.05 g/cc. The 30-μm thick plastic ablator is then irradiated with 4.3 ± 0.1 kJ of laser energy in a 1 ns square pulse composed of 10 OMEGA laser beams, for an irradiance of 8×10^{14} W/cm^2, driving a blast wave into the carbon foam. The plasma flow behind the blast wave forms a sheer layer along the rippled, plastic–foam interface. X-ray radiography was used to observe the Kelvin–Helmholtz growth on this interface at 25 ns, 45 ns, and 75 ns after the beginning of the laser pulse [7].

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* Corresponding author.
E-mail address: ruttere@gmail.com (E.M. Rutter).

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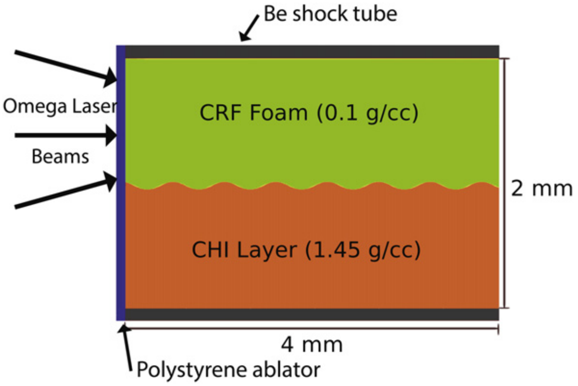

Fig. 1. Schematic of the Kelvin–Helmholtz target from Harding (2009). This cross-section displays the sinusoidal perturbation, ablator foil, and the encasing beryllium tube.

The CRASH simulations presented here use a 2D Cartesian geometry, a flux-limited, multigroup, radiation–diffusion model with 30 groups, flux-limited, single-group, diffusive, electron-heat-conduction and related physics necessary to model the electron internal energy, tabular equations of state and opacities, and the CRASH 3D ray-tracing laser package. The equation-of-state and opacity tables used were a mix of tables developed for the CRASH predictive science project and tables constructed with the PROPACEOS model developed by PrismSpect, Inc. Specifically, carbon foam tables were generated by PROPACEOS and the plastic and beryllium tables were generated from the CRASH EOS model. Both these models are based on the determination of material properties from standard statistical physics based on tables of atomic data, assuming local thermodynamic equilibrium. Outflow boundary conditions were used in order to mimic the plasma flow into the OMEGA vacuum chamber. In order to reconstruct the shock wave shape in the foam, an accurate description of the experimental system including the beryllium walls is needed. The laser was deposited in a super-Gaussian profile with a power of 4.2 and a full-width half-maximum of 430 μm. It is common in radiation-hydrodynamics codes to use a laser energy scale factor in order to account for energy loss from laser-plasma interaction processes that the code does not model and due to dimensions not accounted for in this simulation – in this case, 3D effects [16,17]. As will be discussed later, a laser energy scale factor of 60% leads to the optimal match in shock location between the CRASH simulations and the experimental system. Even with the use of the laser-energy scale factor, using 3D rays is important in order to properly evaluate the spatial profile of the laser ablation.

During the course of these simulations, spatial resolution studies were conducted to optimize run time, and it became apparent that a spatial resolution of 10 μm over the perturbed zone was sufficient. Due to the small length scales needed for a reliable description of the laser-ablation interaction, a much smaller effective resolution of 0.62 μm in the plastic ablator was optimal. We decided this by performing a study to determine what resolution was required in order to converge the time it takes for the shock wave to break out of the plastic ablator.

Using simulated radiographs in conjunction with a high-fidelity laser package to simulate this experiment is unique. The simulated radiographs are created first by specifying the optical depths of the materials at the specific X-ray photon energy, in this case, 5.18 keV. This is the He-α-like energy of the backlighter material, vanadium. The user then specifies the location of the 'film', in coordinate space. From this 'film' area, ray-tracing probes the target along lines of sight in the x, y, z coordinate system. The signal from these lines of sight is then accumulated to produce the images. In addition, Poisson noise and radiographic smearing can be introduced to mimic the effects in the actual experiment. In this case, the radiograph is smeared over 30 μm because there is a source-limited resolution on the order of the pinhole size, in this case, a 20 μm–35 μm tapered pinhole, in addition to motion smearing via the time of exposure.

The comparisons between the simulation and experiments will be both qualitative and quantitative. Density plots and simulated radiographs are compared to the experimental radiographs at relevant times as a qualitative comparison. The quantitative comparison consists of measuring the growth of the Kelvin–Helmholtz roll-ups and comparing those to experimental, analytical, and other computational results.

3. Results

Fig. 2 displays the comparison of simulated radiographs with the experimental radiographs at three times during the evolution of the vortices in the instability. The color scale on the simulated radiographs is adjusted in order to obtain a similar range in signal to the experimental image. At the 25 ns radiograph, the blast wave is still visible within the field of view, stripping material from the dense plastic. As the blast wave passes the crest of each perturbation, a reflected shock is visible in both the simulations and experiments. As time progresses, the perturbations begin to grow and roll up. In later times, three large vortices are clearly visible, displaying the evolution of Kelvin–Helmholtz growth. The lighter regions above the roll-ups, appearing as bubbles, have been explained as 3D effects, involving the blow-out of the beryllium walls [15].

As previously mentioned, a laser-energy scale factor must be applied to the simulation to account for energy losses not present in the model. Table 1 displays a comparison of the shock location at 25 ns in the experimental system to simulation results varying the laser energy scale factor. At a laser energy scale factor of 60%, the CRASH simulation shows the blast wave near 1550 μm from the drive surface for an average velocity of 62 μm/ns. This agrees with the experimentally measured velocity of 60 ± 8 μm/ns as previously reported [7].

We measured the total height $h(t)$ (e.g. peak to valley amplitude, PTV) of the roll-ups to quantitatively compare the CRASH simulations to experimental data [7], linearized KH analytical solution, and the simulation data extracted from [8]. These are recorded in time after the blast wave has passed, and the height is measured from the top to the bottom of the roll-up. The analytical curve was obtained by implementing the linear solution of the incompressible flow equations, yielding $h(t)_{\text{lin}} = h_0 \exp(\gamma t)$, where $\gamma = \Delta u k/2 \cdot \sqrt{1 - A^2}$, Δu is the shear velocity, $k = 2\pi/\lambda$ is the wave number and A is the Atwood number [18]. We note that as there were very few radiographs from the experiments, only one of which shows the blast wave, it became imperative to create an estimate for the velocity of the blast wave, in order to determine the time since the blast wave passed. The paper reporting the experimental results showed that one can describe the position as a 1D blast wave with a position equal to $(220 \pm 30)\, t^{3/5}$, where t is the total time elapsed since the experiment began [7] (The power-law dependence of 3/5 is appropriate to a planar blast wave [19]).

In the initially reported simulations of these experiments the amplitude of the Kelvin–Helmholtz roll-ups appeared to grow in height much faster than they did in the actual experiment at later times [8]. This does not hold true for the CRASH simulations. Fig. 3 displays a graphical comparison of the roll ups peak to valley amplitude versus the time elapsed since the blast wave passed. While the 2D CALE simulation does not reproduce the experimental results at late times, the CRASH model agrees well with the

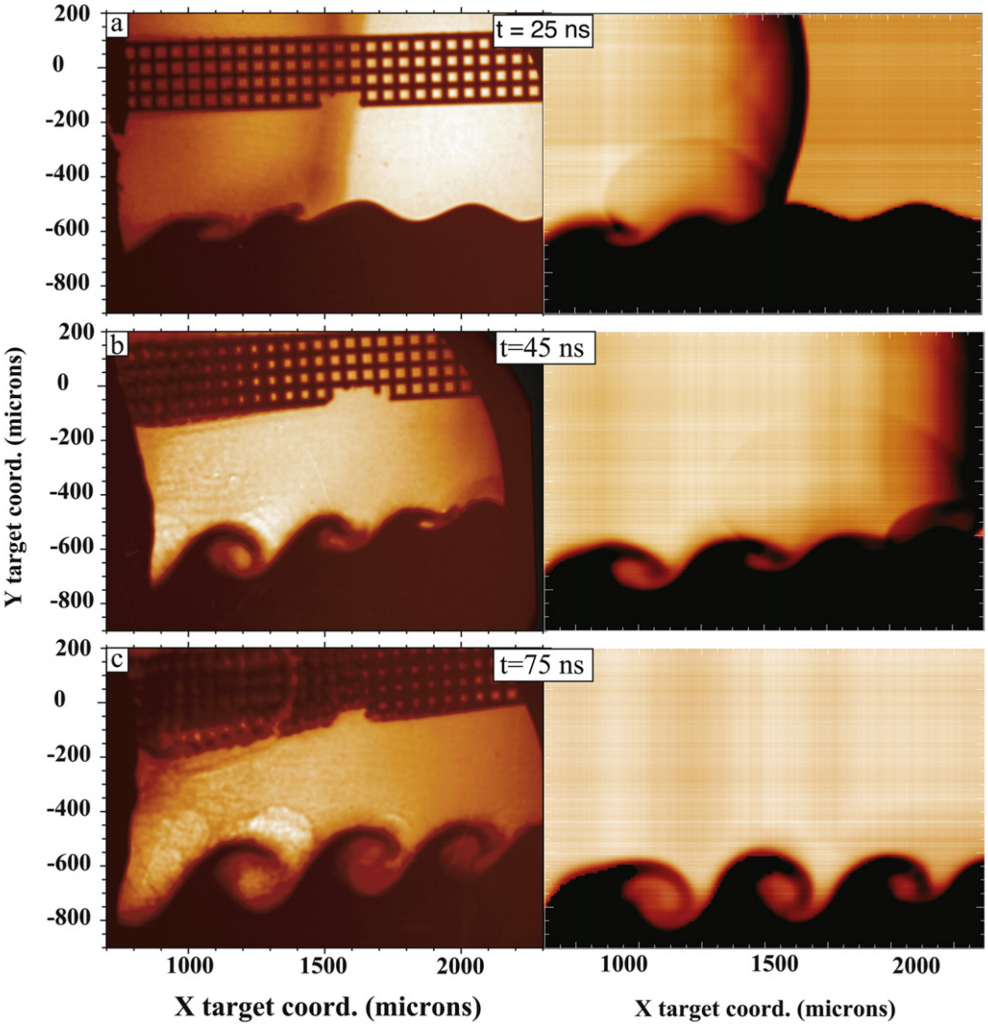

Fig. 2. Experimental radiographs reported by Harding (2009) of a Kelvin–Helmholtz experiment on the OMEGA laser (left) and simulated radiographs (right) using the CRASH code. The blast wave is visible at 25 ns, and nearly in identical positions in (a). The roll-ups evolve in (b) at 45 ns and curl over in (c) at 75 ns.

measured growth, and the initial compression of the perturbation soon after the blast wave passes is evident.

Also presented is the analytical linear growth, obtained using a constant shear velocity of $\Delta u = 12$ μm/ns, $A = 0.8$, and $h_0 = 40$ μm. None of the simulations match very well with analytical solution except for the first ∼15 ns. This is expected because nonlinear alterations of the growth rate sets in once the modulation amplitude (half of the PTV amplitude) exceeds 10% of the modulation wavelength. In this case the initial post-shock modulation amplitude of ∼44 μm [7] is close to that limit. One could attempt more sophisticated models of the time-dependent shear velocity, but there is little point since one does not expect the analytical model to ever accurately describe the observed growth.

Table 1
Results of a series of simulations to determine optimal laser energy scale factor to match simulation with experimental results. A laser scale factor of 60% appears to be optimal.

Laser scale factor	Position at 25 ns (μm)
100%	1850
75%	1650
60%	1550
50%	1450
25%	1100
Experimental	1500

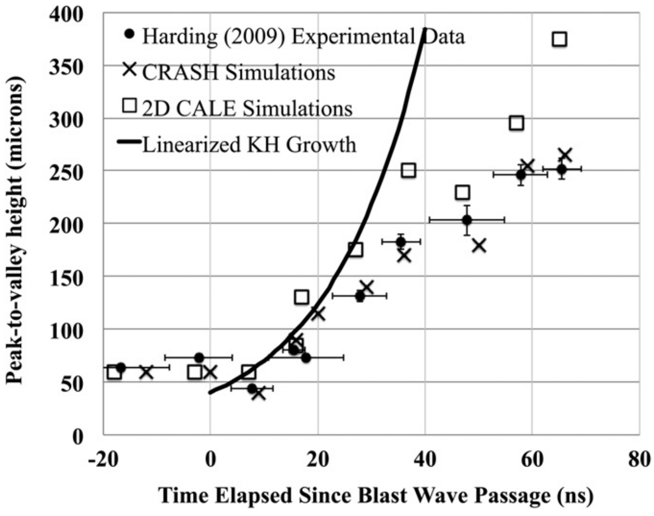

Fig. 3. Measurements of the height from peak-to-valley of the Kelvin–Helmholtz perturbations versus time elapsed since the blast wave passed. The measurements from experimental radiographs [7], analytical solutions, as well as two simulations, CALE [8] and CRASH are compared.

Recently performed 3D simulations find that the Kelvin–Helmholtz growth is reduced, an effect attributed to beryllium wall expansions, which send a rarefaction wave toward the center tracer strip, which in turn depresses the growth [15]. This result suggests that the CRASH model may underpredict the actual growth. However, one must beware of drawing firm conclusions from simulations using different models that all have their own limitations. In the case of the 3D simulations, the energy deposition was not accurately handled, and in particular it's spatial profile was not realistically addressed. In the case of the CRASH simulations, the calculations were not 3D. In addition, the equation of state data was different in the two cases, and equation of state is a significant uncertainty [20]. Moreover, no simulation is able to accurately assess the losses due to laser-plasma instabilities. Further work will be needed to assess the uncertainties in fact associated with these differences between, and limitations of, these models. Accounting for possible limitations of the simulations, the simulated radiographs and experimental radiographs appear to be in agreement.

4. Conclusions

Experiments documenting the Kelvin–Helmholtz instability in the high-energy-density physics system were first demonstrated in 2009 [7], and further experimental development is ongoing [9]. These experiments provide a valuable test for assessing the abilities of the CRASH code against other simulations and experimental data in order to test code capabilities in new regimes of high-energy-density physics. The synthetic radiographs compared well with the experimental data, and the quantitative comparison measuring Kelvin–Helmholtz growth was consistent with the radiographs and comparable to other simulations.

Future directions include expanding the simulation to 3D in order to account for additional effects. Recent publication indicates that the bubble-like structures visible in experimental radiographs, but not in 2D simulations may be a 3D effect of the beryllium walls being blown out [15]. It is important to attempt to reproduce these results with CRASH and to observe the effects on the Kelvin–Helmholtz growth.

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