Modeling & Analysis of AGS Thermal Shock Experiments

by

Rusi P. Taleyarkhan, Seokho H. Kim, John R. Haines
Oak Ridge National Laboratory
Oak Ridge, Tennessee, 37831, USA

ABSTRACT

An overview is provided on modeling and analysis of thermal shock experiments conducted with high-energy, short-pulse energy deposition in a mercury filled container in the Alternating Gradient Synchrotron (AGS) facility at Brookhaven National Laboratory (BNL). The simulation framework utilized along with results of simulations for pressure and strain profiles are presented. While the magnitude of peak strain predictions versus data are in reasonable agreement, the temporal variations were found to differ significantly in selected cases, indicating lack of modeling of certain physical phenomena or due to uncertainties in the experimental data gathering techniques. Key thermal-shock related issues and uncertainties are highlighted.

INTRODUCTION

In accelerator-driven neutron sources such as the Spallation Neutron Source (SNS)1 with powers in the 1 MW range (time-averaged), the interaction of the energetic proton beam with the mercury target can lead to very high heating rates in the target. Although the resulting temperature rise is relatively small (a few °C), the rate of temperature rise is enormous (~10° C/s) during the very brief beam pulse (~0.5 μs). The resulting compression of the mercury leads to the production of large amplitude pressure waves in the mercury that interact with the walls of the mercury target and the bulk flow field. Understanding and predicting propagation of pressure pulses in the target (either liquid or solid) are considered critical for establishing the feasibility of constructing and safely operating such devices. Along with other objectives, in order to develop a code validation and benchmarking database, a collaborative arrangement was set up2 to conduct experiments with close to full-scale target chambers filled with mercury subjected to (as close-to prototypic) short-pulse energy pulses. The AGS facility at Brookhaven National Laboratory (BNL) was chosen to conduct these experiments.

Specific experiments conducted at BNL’s AGS facility (the subject of this paper) involved high energy (24 GeV) proton energy deposition in the mercury target over a time frame of ~0.1 μs. The target consisted of an ~1 m long cylindrical stainless steel shell with a hemispherical dome at the leading edge. It was filled with mercury at room temperature and pressure. Several optical strain gages were attached to the surface of the steel target. Figure 1 shows a schematic representation of the test vessel along with main dimensions and positions of three optical strain gages at which meaningful data were obtained. The proton pulse shape was roughly parabolic and was estimated to be of ~0.05 m in radius. Details of the estimated pulse shape and spatial variation are provided elsewhere2. This paper provides a perspective overview of ongoing modeling and analysis work related to the above-mentioned experiment in which about 7-9 kJ of thermal energy was deposited into the mercury-filled target over 0.1 μs.

MODELING AND ANALYSIS FRAMEWORK

The CTH code system3 was used as a basis for developing the appropriate simulation framework. CTH is a three-dimensional (3-D), shock-physics code, sometimes loosely referred to as a hydrocode. This code and associated technology base have been used extensively to simulate explosive processes (such as molten metal-water vapor explosions, and hydrogen detonation) in enclosed fluid-structure systems.4-6

It is now being adopted5 for characterizing the current thermal-shock process in a coupled manner, simultaneously accounting for localized compression pulses from rapid heat deposition, the transport of the compression wave through the
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
mercury, interaction of this wave with the surrounding structure, feedback to the mercury from these structures, and multi-dimensional reflection patterns including rarefaction-induced material fracture (i.e., cavitation in fluids).

Modeling and analysis work are being performed in several areas. Modeling is conducted in a staged manner starting with a simple two-dimensional (2-D) geometry, followed by full-scope 3-D model development (using CTH by itself, or combining it’s core capabilities with a finite-element structural mechanics code).

Although the geometry of the AGS experiment target has some three-dimensional features (e.g., flanges, supports, fill tube), it was deliberately designed to remain as two-dimensional as possible. As a first cut, a 2-D model was built using CTH with cylindrical symmetry. This model is shown in Figure 1 in which key dimensions are depicted along with locations of key tracer points (in the fluid and shell).

The following key assumptions were made:

1) Mercury and steel interfaces will be characterized by perfect contact. This assumption was necessary to permit modeling to proceed, although it is recognized that imperfect contact (with a mercury-gas layer) between mercury and steel is a distinct possibility. This is one of the key attributes necessary for successful depiction of complex fluid-structural behavior. The interface between steel and fluid is characterized by absence of strength in mixed (fluid-steel) cells.

2) The Mie-Gruniesen (MG) equation-of-state (EOS) adequately represents the mercury liquid at 100 °C in compression and tensile states. The MG-EOS is well-known to be useful for use for materials in the compression state. It is recognized, however, that extension to tensile states may not be adequate, especially when gaseous or vaporous cavitation may occur below a certain pressure threshold.

3) Cavitation effects are negligible. This is a key presumption, since evidence exists to indicate cavitation in mercury (without degassing) can take place at relatively modest tensile pressures (see companion paper by R. P. Taleyarkhan et al.)

4) Thermal energy transfer from mercury to the steel is negligible. This assumption is valid for the relatively short durations (~ 300 micro seconds) of time for thermal shock studies reported herein. It is recognized, however, that for longer durations approaching the time constant of the shell structures, thermal energy transfer will need to be accounted for.

The energy deposition profile used for simulation was taken from Ref. 2. Since CTH requires energy deposition to be introduced in discrete material regions, the profile of Ref. 2, was divided into 5 radial and 10 axial zones. About 7 kJ of thermal energy is deposited in the mercury and steel over 100 ns. A total of ~68,000 cells were used to represent the AGS target and surroundings. Tracer points were attached to the steel shell at selected locations (where strain gages were positioned). Additional tracer points were introduced in the steel and mercury to assess wave propagation phenomena along with assessment of variations in shear stresses at key locations.

RESULTS OF SIMULATIONS

Selected results of simulations are shown in Figures 2 through 6. The locations for these transient variations of pressure and strain values are indicated in Figure 1. As indicated in Figure 1, the locations of strain gages #4, #11, and #12 coincide with Lagrangian tracer points L20, L16 and L12, respectively.

In the absence of cavitation, it is seen from Figs. 2 that negative pressures in mercury imply that mercury can support a rarefaction process. This result is an artifact of assuming a solid-like equation-of-state (EOS) for mercury and the presumption that liquid mercury will not cavitate. It is realized that developing a more realistic EOS model for mercury in the regime expected in the SNS target, along with simulation of more realistic physics of cavitation and geometry are required to improve our understanding and predictive capabilities. It is also seen from Figs. 2 that, for the geometry under investigation, tensile fluid pressures will vary from ~ -20 MPa in the central regions (see trace for L2) to between ~ - 6 MPa (for L4 next to the front window) and ~ -1 MPa at the side wall regions (see pressure trace for L6). Comparing these values with data taken in the past it is apparent that cavitation of mercury can not be ruled out, neither in the bulk region, nor at the
mercury-steel interfaces. However, the intensity of cavitation near steel walls is clearly greater for the fluid in the front window region than at the side walls (where most of the strain gages were located).

Figures 3 through 5 present predicted versus measured strain values at L16, L12 and L20 tracer points corresponding to locations for gages #11, #12 and #4, respectively. As can be clearly seen, in all cases the magnitude of strain predicted is reasonably close to that recorded in the experiments. For example, at L12 (Figure 4) the magnitude of circumferential strain monitored varied between +40 microstrain to ~ -30 microstrain. The predictions are between +50 microstrain to ~ -10 microstrain. As seen from Figure 3, the overall transient profile is predicted with good accuracy for L16 (Gage #11). However, at the other two locations the time span of oscillations disagreements exist between predictions and experimental data. At L12 (Figure 4) the predicted period of oscillation is ~ 140 µs, whereas, the strain gage data indicate the period at a relatively large ~1,200 µs. Again, at L20 the peak magnitude is predicted well. However, the predictions indicate a ringing nature after the initial pulsation, whereas, the measured value indicates a pulse width lasting a relatively long ~ 1000 µs.

Figure 6 presents results for circumferential strain at L12, L16 and L20, respectively. As noted therein, the trends appear well behaved and follow the energy deposition spectrum in the axial direction. Also noted is the degree of relative reduction in strain magnitudes with subsequent oscillations (approximately 20% reduction in amplitude with successive oscillation) indicating energy loss to the surroundings and system as a whole. The period of oscillation (~ 140 µs) corresponds very closely (as expected) with the transit time (~ 133 µs) of pressure waves in the radial direction over a diameter of 0.2 m. Unfortunately, the data from strain gages does not reflect this feature.

It should be noted that, the above-mentioned comparisons were made without accounting for onset of cavitation in the mercury fluid. Recent data⁸ (see companion paper by R. P. Taleyarkhan et al.) indicate the onset threshold for cavitation at tensile pressures of less than -1 MPa. Scoping simulations conducted (but not reported herein) indicate a significant change in predicted strain spectra (especially with time) when cavitation onset is allowed - especially at locations close to the front window where the proton beam strikes the mercury filled chamber. As may be expected, the degree of cavitation and resulting spectrum of pressure pulsation in the mercury and the steel shell structure will vary with position. This may explain some of the wide variations in measured strain values between strain gages #12, #11, and #4.

Another point of caution concerns the science of making appropriate comparisons. The predictions of strain from a computer code against strain gage data should be made with due caution, especially when comparing against longitudinal strain values in a body with cylindrical symmetry. A strain gage monitors variations in separation between two "glued" points, whereas, computer code predictions arise out of the strain tensor for a given cell or node. Minor differences in epoxy performance (or lack of it) may present unusual differences in monitored strain, which may account for the highly different transient variations seen between strain gages #11 and #12 (which were very close together). For a body with cylindrical symmetry, it is far more appropriate and straightforward to compare circumferential strain (due to absence of variations in the azimuthal direction). However, this point must be tempered somewhat, since practical problems and uncertainties emanate when positioning optical strain gages around curvilinear surfaces.

SUMMARY AND CONCLUSION

To summarize, preliminary assessments for thermal shock in the cylindrical mercury target used in the AGS experiment have indicated reasonably good agreement between predictions and data. Peak strain magnitudes agree reasonably well with those observed experimentally. However, the transient variations in pulse shape did not agree in all cases. It is not clear what degree of uncertainty exists in the data gathering technique itself, or if three-dimensional effects played a significant role (since the target assembly does incorporate a series of instrumentation taps and flanges). Based on recent experimental evidence, it appears that cavitation in the mercury should have played a
significant role in terms of modifying the time-varying shape of strain measurements.

REFERENCES


Disclaimer
This work was performed as part of the AGS Spallation Target Collaboration (ASTE). The ASTE collaboration has been performed between several US, European, and Japanese laboratories, to carry out a test program at BNL’s AGS facility.

Figure 1. Schematic Representation of Mercury-Filled Test Vessel Used in AGS Experiments & Location of Selected Tracer Points

Note: Optical Strain Gages #4,#11 and #12 were located at tracer locations L20, L16 & L12, respectively
Figure 2a. Predicted Bulk Mercury Pressures vs Time at Locations L1 and L2

Figure 2b. Predicted Pressures Vs Time at Mercury Steel Interface Locations L4 & L6
Figure 3. Predicted Vs Measured Longitudinal Strains at L16 (Gage#11)

Figure 4. Predicted Vs Measured Circumferential Strain (L12 /Gage#12)
Figure 5 Predicted Vs Measured Longitudinal Strain at L20 (Gage#4)

Figure 6. Predicted Circumferential Strain Vs Time at Locations L12, L16 and L20