Abstract—Compressible liquid/gas jets offer the opportunity to limit and mitigate the mechanical consequences of rapid heating/evaporation of the protective jets in a high-yield, low repetition rate Inertial Fusion Energy (IFE) system such as the Z-Pinch IFE reactor. In this investigation, experiments have been conducted to quantify the extent by which a two-phase jet can attenuate a shock wave. The experiments have been conducted using annular two-phase (water/air) jets with different velocities, void fractions, and initial shock strength. The shock is produced using an exploding wire located along the jet axis. Three different confinement geometries (i.e. boundary conditions) have been used in the experiments, namely, "unconfined" shocks, "radially-confined" shocks, and "radially-and-axially-confined" shocks. A total of 738 experiments corresponding to 39 different test conditions have been conducted. Quantitative data for the transient pressure history at the confinement wall with and without an intervening jet have been obtained; both single-phase (liquid) and two-phase (liquid-gas) jets at different velocities and void fractions have been tested. The data shows that the experiments are highly repeatable, and that two-phase jets at moderate void fractions (∼1%) can attenuate a shock wave significantly more than a single-phase (liquid) jet.

Index Terms—Z-Pinch, Shock Mitigation, Two-Phase Jets.

I. INTRODUCTION

FUTURE Z-Pinch IFE reactor designs will likely utilize high-yield targets (>1 GJ) at low repetition rates (<1 Hz) [1]. Appropriately-arranged “thick” liquid jets (circular, planar, or annular) can adequately protect the cavity walls from the target X-rays, ions, and neutrons. Attenuation of the fusion neutrons within the liquid jets will significantly reduce or eliminate radiation damage to the first wall, so that it may be possible to design cavity structures to last the entire reactor life. However, the shock waves and mechanical loadings produced by rapid heating and evaporation of the nearly-incompressible liquid jets may be challenging to accommodate within a small reactor cavity. To this end, "compressible," two-phase, liquid/gas jets have been proposed as a means of protecting the cavity walls from the target photons, ions, and neutrons, while attenuating the shock waves, thereby limiting and mitigating the mechanical consequences of rapid energy deposition within the liquid. Such attenuation would allow the Z-Pinch IFE reactor to use a much smaller, i.e. more economical, reactor cavity to contain the high yield, low repetition rate explosions. The concept is made possible by the Z-Pinch reactor cavity’s high allowable pressure (∼10-20 torr) [1], which makes it possible to introduce a gas within the wall-protection jets, without excessively increasing the vacuum pumping requirements. Previous work on compressible two-phase jets focused on forming and examining the behavior of “free” planar and circular two-phase (gas-liquid) jets [2]. Experiments were conducted to examine the effect of gas void fraction and nozzle/flow conditioning system design on the behavior and stability of the two-phase jets as they are discharged into an open cavity. Experiments were conducted over wide ranges of jet velocities and void fractions for both planar and circular jets [2]. The results showed that stable, coherent jets with relatively high void fractions (up to 25%) can be established and steadily maintained. Typical photographs showing the near-field behavior of two-phase planar and circular jets with different void fractions are shown in Figures 1 and 2, respectively. The success of these experiments has provided the motivation for the work presented here, which is aimed at quantifying the extent by which two-phase (gas/liquid) jets can attenuate shock waves. Experiments have been conducted using annular two-phase (water/air) jets with different velocities, void fractions, and initial shock strength.
II. EXPERIMENTAL APPARATUS AND PROCEDURES

An experimental test facility has been constructed with the general goal of producing steady, annular two-phase, liquid/gas, jets with controllable velocities and gas void fractions. A schematic diagram of the test loop is shown in Figure 3. Filtered water from the reservoir (1000-liter open tank) is allowed to enter a centrifugal pump through the 2-inch diameter suction line. The pump discharge line includes a water flow meter, a control/shutoff valve, a mixing “Y” where gas (air) is introduced into the water stream, a flow conditioner, and finally, a nozzle. The jet issuing from the nozzle is discharged into the ambient air, thereby returning the liquid to the reservoir. A schematic diagram of the nozzle and flow conditioner for the annular jets used in this investigation is shown in Figure 4. The flow conditioner includes a perforated plate, a honeycomb section, and a fine-mesh screen; a boundary-layer cutter is placed at the nozzle exit. Annular jets with an outside diameter of 5.2 cm and an inside diameter of 4.0 cm are produced. The size of the honeycomb cells within the flow conditioner has been selected to produce the desired bubbly flow regime within the nozzle at the anticipated jet velocities and void fractions. Filtered air is supplied to the test loop by an air compressor connected to a regulated house line. The gas supply line includes two flow meters connected in series to allow accurate measurement over a wide range of gas flow rates. The gas supply line terminates in a stainless steel porous tube placed within the mixing “Y” in the 2” pump discharge line (See Figure 3).

The porous tube end is plugged so that all of the supply air can be uniformly dispersed into the water stream along the entire 20-cm length of the porous section. An air shut-off valve is placed immediately upstream of the porous tube. Needle valves placed at the inlet to each of the two flow meters are used to control the gas flow rate. The air compressor is also used to provide low-pressure air (2 psig) to the center of the annular jet in order to prevent it from collapsing.

A shock wave is produced by an exploding 11.5 cm long, 0.4 mm diameter, Ni-chrome wire placed along the center of the jet immediately after the nozzle exit (see Figure 5). The wire is clamped between two electrodes connected to a discharge pulser. The pulser can store up to 6 kJ at a maximum charge of 2400 volts. This provides the means to control the initial shock strength produced by the exploding wire. The enclosure surrounding the annular jet has been designed to allow experiments to be conducted with three different boundary conditions (see Figure 6). The first boundary condition (radially-and-axially confined shocks) pertains to the case where a cylindrical polycarbonate shield (10.0 cm ID) is placed along the entire length of the annular jet (5.2 cm OD) extending from the top of the flow conditioner to a point approximately 5.0 cm below the free surface of the water reservoir. This geometry allows the shock waves produced by the exploding wire to be confined within the polycarbonate shield while allowing the two-phase jet to enter and leave the enclosed volume unimpeded; the transient pressure histories at two different axial locations along the shield wall are measured (see below). The second boundary condition (radially-confined shocks) pertains to the case where the polycarbonate shield surrounding the jet axially extends only to the level corresponding to bottom of the exploding wire. This geometry allows the shock waves produced by the exploding wire to be radially confined, while allowing ambient air to axially enter/exit the shielded region as pressure changes due to the reflection/expansion of the shock waves from/toward the 10.0 cm ID polycarbonate shield; the transient pressure history at the shield wall at an axial elevation corresponding to the mid elevation of the exploding wire has been measured. The third boundary condition (unconfined shocks) pertains to the case where no shield is placed around the jet, thereby allowing the shock wave produced by the exploding wire to freely expand; a rigidly-mounted transducer is used to measure the transient pressure history at a point 5.0 cm from the center of the jet at the mid elevation of the exploding wire.

For experiments with either radially-confined or radially-and-axially-confined shocks, a pressure transducer with a
calibrated pressure range of 0-50 psi is mounted within a reinforced (30 mm thick) segment of the 3.2 mm thick polycarbonate shield wall so that its surface is flush with the shield’s inner surface (10.0 cm ID) at an elevation corresponding to the mid elevation of the exploding wire (7.5 cm below the jet entrance point). For experiments with radially-and-axially confined shocks, a second pressure transducer with a calibrated range of 0-500 psi is mounted within the shield wall at an elevation immediately above the free surface in the water reservoir (100 cm below the jet entrance point). The same transducer is used for experiments with unconfined shocks by rigidly mounting it at a point 5.0 cm away from the jet axis at the mid elevation of the exploding wire. Each transducer is connected by a low-noise coaxial cable to its dedicated amplifier. Transient pressure signals from the amplifier outputs are digitized and stored using a digital oscilloscope with two identical input channels. The top pressure transducer signal has been used to trigger the scope. The oscilloscope is interfaced with a host computer.

III. RESULTS

Experiments have been conducted at three different liquid flow rates (13.5, 27, and 54 GPM) corresponding to superficial liquid velocities of 1.0, 2.0, and 4.0 m/s, with different void fractions (zero to 10%), using three different boundary conditions. The maximum void fraction (10%) has been limited by the ability to maintain a stable, thin (6.0 mm thick), annular jet at higher void fractions. A total of 738 experiments at 39 different test conditions have been performed. For each combination of test conditions, the experiment has been repeated between 10 and 24 times. Photographs of the annular jets with different void fractions and superficial liquid velocities of 1.0, 2.0, and 3.0 m/s, are shown in Figures 7, 8, and 9, respectively. At low velocities, the jet is highly stable and the surface remains relatively smooth even at high void fractions (∼10%). At higher velocities, the jet remains stable despite the increased surface ripple resulting from higher turbulence, particularly at elevated void fractions, where the gas randomly crosses the jet surface as it proceeds downstream.

Figure 10 shows the transient pressure histories for 6 “air-only” experiments (i.e., experiments conducted without a jet present in the enclosure); the experiments are conducted using the radial-and-axial confinement boundary configuration with pulser input energy of 2.4 kJ. The pressure signal captured by the transducer at the bottom of the confinement tube is shown. The data show a high degree of repeatability between experiments. The shock wave produced by the exploding wire propagates radially and axially, and reflects from the enclosure boundaries (i.e., tube walls and liquid free surface at the bottom of the enclosure). The shock wave is dissipated into thermal energy within the medium (air).

The initial shock speed for air-only experiments can be estimated using the system geometry (distance, L, between the exploding wire mid point and the transducer location), along with the initial shock travel time (time, t, between pulser trigger and arrival of first peak at the transducer location). The air within the enclosure can be treated as an ideal gas; hence, the corresponding Mach number, M, can be calculated using the relation:

$$M = \frac{L}{T \cdot \sqrt{\gamma \cdot R_{air} \cdot T}}$$

Where $\gamma$ is the specific heat ratio ($\gamma = 1.4$), $R_{air}$ is the gas constant for air, and $T$ is the gas temperature (assumed to be equal to the ambient temperature, 291 K). The uncertainty in the computed value of the Mach number is estimated using a Taylor expansion.

Figure 11 shows the calculated Mach number values for twelve air-only experiments (including the six shown in Figure 10); the experiments correspond to the radial-and-axial confinement geometry with pulser input energy of 2.4 kJ. The data shows that the shock wave produced by the exploding wire propagates at an initial Mach number of nearly 4.0. Figure 11 shows that the experiments are highly repeatable; differences in the estimated Mach number values are within the computed uncertainties. The air-only experiments serve two purposes; first, they provide a simple set of test conditions (ideal gas within a well-defined geometry and sensor locations) against which predictions of shock attenuation models can be compared (without concern about the model’s ability to correctly account for two-phase effects). These results provide the basis for estimating the initial conditions (i.e., the initial shock speed for a given pulser energy input) necessary for
Fig. 9. Photographs Showing Near-Field Behavior of Two-Phase Annular Jets with different Void Fractions (liquid superficial velocity $v = 3$ m/s)

Fig. 10. Transient pressure history at the bottom transducer location for air-only experiments with radially-and-axially-confined shocks modeling shock propagation when a jet (single or two-phase) is present within the enclosure.

Fig. 11. Estimated Mach number values for air-only experiments with radially-and-axially-confined shocks

Figure 12 shows typical data for the transient pressure histories obtained for experiments on shock attenuation through either a single-phase (liquid) jet or a two-phase jet with a void fraction of 1% or 10%. For all three cases, the superficial liquid velocity of the jets is 2 m/s. The experiments are conducted using the unconfined boundary condition with pulser input energy of 2.4 kJ. These data show that two-phase jets attenuate the pressure pulse by a greater extent than a single-phase jet with the same geometry and superficial velocity, as evidenced by the lower magnitude of the pressure pulse. The data also suggest that beyond a relatively moderate value of the void fraction ($\sim 1\%$), further increase in the jet void fraction does not result in a commensurate attenuation of the pressure pulse. The shift in the arrival time of the pressure peak to the transducer location indicates significant slowing down of the shock within the two-phase medium versus the corresponding case of a single-phase (liquid) jet.

Figure 13 shows the effect of pulser input energy on the resulting pressure history. The data pertain to a two-phase (water-air) annular jet with a superficial liquid velocity of 2.0 m/s and a void fraction of 10%. The experiments are conducted using the unconfined boundary condition with pulser input energy of 2.4, 2.7, and 3.0 kJ. As expected, an increase in the pulser input energy produces a stronger initial shock, which increases the pressure pulse amplitude before and after its attenuation by the jet. The shift in arrival time of the peak to the transducer location reflects the increase in initial shock speed as the pulser input energy is increased.

IV. CONCLUSIONS

Experiments have been conducted to quantify the extent by which a two-phase jet can attenuate a shock wave. The experiments have been conducted using annular two-phase (air/water) jets with different velocities, void fractions, and initial shock strength. The shock is produced using an exploding wire located along the jet axis. Three different confinement geometries have been used in the experiments. Quantitative data (738 experiments) for the transient pressure history with and without intervening jet have been obtained. The data show that two-phase jets at moderate void fractions ($\sim 1\%$) can attenuate a shock wave significantly more than a single-phase liquid jet. The data obtained in this study can be used to validate computer models used to assess the mechanical loadings on the walls of high yield, low repetition rate reactors such as the Z-pinch IFE system.

REFERENCES
