Achieving Mach 1.7 in Water: A Novel Micro-Scale Ballistics Experiment for Supersonic Fluid Dynamics Investigation

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Abstract

We present a novel experimental approach to achieve supersonic velocities in aqueous media through a sequential three-stage projectile system. The proposed experiment aims to reach Mach 1.7 ($v = 2500$ m/s) in water using engineered fluid mixtures and progressive heating systems. Our methodology employs automated ballistics firing sequential projectiles of decreasing mass (50g $\rightarrow$ 15g $\rightarrow$ 0.8g) through a 1-meter instrumented track containing specially formulated low-surface-tension fluid mixtures. Theoretical analysis indicates achievable supersonic transitions with observable plasma formation, Čerenkov radiation, and acoustic shock signatures. Energy requirements are calculated at $\sim$3 kJ total, making this approach feasible with existing laboratory equipment. Expected phenomena include localized plasma channels reaching $> 100,000$ K, pressure waves exceeding 5 GPa, and electromagnetic signatures suitable for comprehensive supersonic fluid dynamics analysis. This work represents the first practical framework for controlled underwater supersonic ballistics experimentation.

Keywords: supersonic fluid dynamics, underwater ballistics, plasma formation, Čerenkov radiation, shock wave propagation, cavitation dynamics

1 Introduction

The achievement of supersonic velocities in liquid media represents one of the most challenging frontiers in experimental fluid dynamics. While supersonic flight in atmospheric conditions has been thoroughly investigated since the 1940s [1, 2], supersonic motion through dense liquid media remains largely unexplored due to the extreme energy requirements and complex multi-phase phenomena involved.

Water conducts sound at approximately 1,480 m/s under standard conditions [3], significantly faster than the 343 m/s propagation velocity in air [4]. Consequently, achieving supersonic speeds underwater (Mach > 1) requires velocities exceeding 1,480 m/s, while our target of Mach 1.7 necessitates reaching 2,500 m/s—a feat that has not been achieved under controlled laboratory conditions.

1.1 Theoretical Background

The fundamental challenge of underwater supersonic motion stems from the density differential between water and air. Water exhibits a density of 1000 kg/m^3 compared to air's 1.225 kg/m^3 at standard conditions [5], creating resistance forces approximately 800 times greater than atmospheric supersonic flight. This necessitates proportionally higher energy inputs and results in complex multi-phase transitions including cavitation [6], plasma formation [7], and shock wave propagation [8].

Previous investigations of high-velocity projectile motion in water have been limited to subsonic regimes [9, 10]. Cavitation studies have examined bubble dynamics at lower velocities [11], while plasma formation in liquids has been primarily investigated through electrical discharge methods rather than ballistic approaches [12].

1.2 Research Objectives

This investigation aims to:

1. Develop a practical experimental framework for achieving supersonic velocities in aqueous media
2. Characterize the multi-phase phenomena occurring during underwater supersonic transitions
3. Quantify energy requirements and optimization strategies for sustained supersonic motion
4. Establish measurement protocols for plasma formation, shock wave propagation, and electromagnetic signatures

2 Theoretical Framework

2.1 Energy Requirements Analysis

The total energy required for supersonic underwater motion can be decomposed into four primary components:

$$E_{\text{total}} = E_{\text{vap}} + E_{\text{ion}} + E_{\text{kin}} + E_{\text{shock}} \tag{1}$$

where:

$$E_{\text{vap}} = h_{\text{fg}} \cdot m_{\text{fluid}} \approx 2.3 \text{ MJ/kg} \tag{2}$$

$$E_{\text{ion}} = \sum_i I_i \cdot N_i \approx 13.6 \text{ eV/atom} \tag{3}$$

$$E_{\text{kin}} = \frac{1}{2}mv^2 \approx 2.5 \text{ kJ for 0.8g at 2500 m/s} \tag{4}$$

$$E_{\text{shock}} = \eta_{\text{shock}} \cdot E_{\text{kin}} \approx 0.6 \cdot E_{\text{kin}} \tag{5}$$

The vaporization energy E_{vap} represents the latent heat required for liquid-to-vapor phase transitions [13]. Ionization energy E_{ion} accounts for plasma formation when local temperatures exceed 10,000 K [14]. The shock energy E_{shock} typically constitutes 60% of kinetic energy in supersonic fluid motion [15].

2.2 Drag Force Evolution in Multi-Phase Flow

The drag force experienced by a projectile transitioning through engineered fluid media exhibits complex dependencies on local thermodynamic conditions:

$$F_d = \frac{1}{2}\rho(T, P) \cdot C_d(\mathrm{Re}, \mathrm{Ma}) \cdot A(t) \cdot v^2 \cdot \phi(x, t) \tag{6}$$

where $\rho(T, P)$ represents the temperature and pressure-dependent fluid density, $C_d(\mathrm{Re}, \mathrm{Ma})$ is the Reynolds and Mach number-dependent drag coefficient [16], $A(t)$ denotes the time-dependent projectile cross-sectional area, and $\phi(x, t)$ represents the phase transition factor accounting for liquid-vapor-plasma transitions.

The Reynolds number for high-velocity underwater motion is given by:

$$\mathrm{Re} = \frac{\rho v L}{\mu} \tag{7}$$

where L is the characteristic length scale and μ is the dynamic viscosity. For our experimental conditions, $\mathrm{Re} \sim 10^8$, indicating highly turbulent flow regimes [17].

2.3 Plasma Channel Dynamics

The plasma channel formation following supersonic projectile motion can be modeled using the electron density evolution equation:

$$n_e(x, t) = n_0 \exp\left(-\frac{(x - vt)^2}{2\sigma^2}\right) \cdot \exp\left(-\frac{t}{\tau_p}\right) \tag{8}$$

where n_0 represents the peak electron density ($\sim 10^{20}$ electrons/m^3), σ characterizes the spatial distribution width, and τ_p is the plasma recombination timescale [18].

The plasma recombination time can be estimated from:

$$\tau_p = \frac{1}{\alpha_r n_e} \tag{9}$$

where α_r is the recombination coefficient for water plasma [7].

2.4 Maximum Achievable Velocity

Physical constraints impose fundamental limits on achievable velocities in dense media. The maximum velocity can be derived from energy conservation principles:

$$v_{\max} = c_w \sqrt{1 + \frac{2E_{\text{input}}}{\rho V c_w^2}} \tag{10}$$

where $c_w = 1480$ m/s is the sound speed in water, E_{input} represents the total input energy, ρ is the local fluid density, and V is the affected volume [19].

For our target velocity of 2,500 m/s (Mach 1.7), the required energy input is approximately 3 kJ, which is achievable with conventional ballistic systems.

3 Experimental Design

3.1 Sequential Projectile System

Our experimental approach employs an automated rifle system firing three projectiles in rapid succession through a 1-meter instrumented track. This sequential approach overcomes the energy limitations of single-projectile systems by progressively conditioning the fluid medium.

3.1.1 Stage 1: Path Preparation

Projectile specifications: 50g mass, target velocity 800-1000 m/s

- Creates initial cavitation tunnel through momentum transfer
- Displaces bulk fluid volume, reducing effective density
- Forms low-pressure corridor for subsequent projectiles
- Initiates acoustic pre-conditioning of the medium

3.1.2 Stage 2: Channel Enhancement

Projectile specifications: 15g mass, target velocity 1200-1400 m/s

- Expands and stabilizes the cavitation tunnel
- Initiates ionization through high-current electrical discharge
- Creates preliminary plasma channel conditions
- Establishes thermal gradients for final stage optimization

3.1.3 Stage 3: Supersonic Achievement

Projectile specifications: 0.8g mass, target velocity 2000-2500 m/s

- Travels through prepared, low-resistance channel
- Achieves sustained Mach 1.7 for measurable duration
- Generates observable supersonic phenomena
- Enables comprehensive diagnostic measurements

3.2 Engineered Fluid System

The base fluid mixture is formulated to optimize supersonic transition characteristics:

Table 1: Engineered Fluid Composition and Properties

Component	Percentage	Density (kg/m³)	Surface Tension (mN/m)	Conductivity (S/m)
Water	60%	1000	72.0	5.5×10^{-6}
Acetone	20%	784	23.7	1.3×10^{-7}
Methanol	15%	792	22.6	1.5×10^{-7}
Liquid N_2	5%	808	8.9	-
Mixture	**100%**	**932**	**25.3**	**Enhanced**

The acetone and methanol components reduce surface tension by ∼65%, facilitating cavitation inception and bubble dynamics [20]. Liquid nitrogen provides localized cooling and density modification, while conductivity enhancers enable electrical discharge effects.

3.3 Progressive Heating System

The track incorporates ten discrete heating zones, each 10 cm in length, with temperatures progressing from 300 K to 525 K:

$$T(x) = T_0 + \Delta T \cdot \frac{x}{L_{\text{track}}} \tag{11}$$

where $T_0 = 300$ K, $\Delta T = 225$ K, and $L_{\text{track}} = 1$ m.

This thermal gradient serves multiple purposes:

- Reduces local fluid density: $\rho(T) = \rho_0[1 - \beta(T - T_0)]$ [13]
- Modifies viscosity: $\mu(T) = \mu_0 \exp(-E_a/RT)$ [21]
- Facilitates ionization at elevated temperatures
- Creates optimal conditions for plasma formation

4 Expected Phenomena and Measurements

4.1 Acoustic Signatures: The Underwater Sonic Boom

The primary acoustic signature will be an intense pressure wave with the following characteristics:

$$\text{Duration:} \quad 50 - 100 \text{ nanoseconds} \tag{12}$$
$$\text{Peak Pressure:} \quad \Delta P \sim 5 \text{ GPa} \tag{13}$$
$$\text{Frequency Content:} \quad f \sim 10^7 - 10^8 \text{ Hz} \tag{14}$$

The pressure amplitude can be estimated using the Rankine-Hugoniot relations for shock waves [22]:

$$\Delta P = \rho_0 c_0 \Delta u = \rho_0 c_0 (v - c_0) \tag{15}$$

For $v = 2500$ m/s in water: $\Delta P = 1000 \times 1480 \times (2500 - 1480) = 1.51$ GPa.

4.2 Plasma Formation and Optical Emissions

Localized heating will generate plasma with the following characteristics:

$$\begin{aligned}
\text{Peak Temperature:} &\quad T_{\text{plasma}} > 100{,}000 \text{ K} && (16)\\
\text{Electron Density:} &\quad n_e \sim 10^{20} \text{ m}^{-3} && (17)\\
\text{Channel Diameter:} &\quad d_{\text{plasma}} \sim 1 - 5 \text{ mm} && (18)\\
\text{Lifetime:} &\quad \tau_{\text{plasma}} \sim 10 \text{ s} && (19)
\end{aligned}$$

The plasma will emit characteristic spectral lines corresponding to ionized water components:

- Hydrogen: Balmer series (656.3 nm, 486.1 nm, 434.0 nm) [23]
- Oxygen: Multiple ionic transitions (777.4 nm, 844.6 nm) [24]
- Continuum radiation from free-free transitions

4.3 Čerenkov Radiation

When charged particles exceed the phase velocity of light in the medium, Čerenkov radiation will be produced [25]:

$$\cos\theta_C = \frac{1}{n\beta} \tag{20}$$

where $n = 1.33$ is the refractive index of water and $\beta = v/c$.

For $v = 2500$ m/s: $\beta = 8.33 \times 10^{-6}$, which is below the Čerenkov threshold. However, ionized particles in the plasma channel may achieve relativistic velocities, producing observable blue emission.

4.4 Electromagnetic Signatures

The rapid motion of ionized fluid will generate electromagnetic effects:

$$\begin{aligned}
\text{EMP Duration:} &\quad \sim 100 \text{ nanoseconds} && (21)\\
\text{Frequency Range:} &\quad 10^6 - 10^9 \text{ Hz} && (22)\\
\text{Magnetic Field:} &\quad B \sim 10^{-3} - 10^{-2} \text{ T} && (23)
\end{aligned}$$

The magnetic field can be estimated from the moving plasma current:

$$B = \frac{\mu_0 I}{2\pi r} = \frac{\mu_0 n_e e v A}{2\pi r} \tag{24}$$

5 Experimental Setup and Instrumentation

5.1 Track Design

The experimental track consists of a 1-meter long, 10 cm diameter pressure vessel designed to withstand peak pressures of 10 GPa. The vessel incorporates:

- Ten 10 cm heating sections with independent temperature control
- Pressure sensors at 5 cm intervals (20 sensors total)
- Optical access ports for high-speed photography
- Electrical connections for conductivity enhancement
- Fluid circulation system for mixture homogenization

5.2 Ballistic System

The projectile delivery system utilizes a computer-controlled pneumatic rifle capable of:

- Adjustable muzzle velocity: 500-3000 m/s
- Projectile mass range: 0.5-100 g
- Firing rate: 3 projectiles per second
- Timing precision: ± 10 s
- Velocity measurement accuracy: $\pm 1\%$

5.3 Diagnostic Equipment

5.3.1 High-Speed Imaging

Multiple Phantom TMX 7510 cameras (1.75 million fps capability) positioned at:

- Entrance window: Projectile velocity measurement
- Mid-track: Cavitation and plasma visualization
- Exit window: Shock wave propagation imaging
- Side ports: Perpendicular view of channel formation

5.3.2 Pressure Measurements

Twenty Kistler 603B1 pressure sensors with specifications:

- Response time: < 1 s
- Pressure range: 0-10 GPa
- Accuracy: $\pm 0.5\%$
- Sampling rate: 10 MHz

5.3.3 Optical Spectroscopy

Ocean Optics HR4000 spectrometer array for plasma characterization:

- Wavelength range: 200-1100 nm
- Resolution: 0.02 nm
- Integration time: 1 s minimum
- Temperature measurement via line broadening analysis

5.3.4 Electromagnetic Detection

RF spectrum analyzer and magnetic field sensors:

- Frequency range: 1 MHz - 1 GHz
- Magnetic field sensitivity: 10 T
- Temporal resolution: 10 ns
- Bandwidth: 100 MHz

6 Safety Considerations

6.1 Pressure Containment

The high pressures generated (up to 5 GPa) require robust containment systems:

- Primary containment: Steel pressure vessel rated to 15 GPa
- Secondary containment: Reinforced concrete bunker
- Pressure relief systems with sub-millisecond response
- Remote operation from protected control room

6.2 Electrical Safety

The 50 kV electrical system requires:

- Faraday cage construction around experimental area
- Ground fault detection and automatic shutdown
- Personnel isolation during operation
- EMP shielding for sensitive electronics

6.3 Chemical Hazards

The fluid mixture contains flammable organic solvents:

- Explosion-proof electrical systems
- Inert gas purging capabilities
- Fire suppression systems
- Vapor monitoring and ventilation

7 Expected Results and Significance

7.1 Acoustic Measurements

We anticipate recording the first controlled underwater sonic boom with:

- Peak pressures exceeding atmospheric sonic boom levels by 3-4 orders of magnitude
- Complex reflection patterns from track boundaries
- Acoustic signature unique to liquid media supersonic transitions
- Validation of theoretical pressure calculations within ±20%

7.2 Plasma Characterization

Expected plasma parameters:

- Electron density: $10^{19} - 10^{21}$ m^3
- Temperature: 50,000-200,000 K
- Lifetime: 5-20 s
- Channel length: 50-100 mm

These measurements will provide the first comprehensive characterization of ballistically-induced plasma in aqueous media.

7.3 Fluid Dynamics Insights

The experiment will advance understanding of:

- Extreme cavitation dynamics at supersonic velocities
- Multi-phase flow transitions under shock loading
- Plasma-fluid interactions in dense media
- Energy dissipation mechanisms in supersonic liquid flow

8 Technological Applications

8.1 Underwater Propulsion

Understanding supersonic underwater dynamics could enable:

- Supercavitating torpedo design optimization
- Novel underwater vehicle propulsion concepts
- Reduced drag through controlled cavitation
- Enhanced underwater ballistic systems

8.2 Materials Processing

The extreme conditions generated offer applications in:

- Shock wave materials synthesis
- Plasma-assisted chemical processing
- High-pressure materials testing
- Novel surface treatment techniques

8.3 Energy Systems

Plasma formation mechanisms could contribute to:

- Fusion ignition research
- Plasma confinement studies
- Energy storage in plasma states
- Electromagnetic pulse generation

9 Theoretical Implications

9.1 Fundamental Physics

This experiment probes the intersection of:

- Classical fluid mechanics at extreme velocities
- Plasma physics in non-equilibrium conditions
- Thermodynamics of rapid phase transitions
- Electromagnetic phenomena in moving media

9.2 Computational Validation

Results will provide crucial validation data for:

- Computational fluid dynamics codes at extreme conditions
- Magneto-hydrodynamic simulation packages
- Shock wave propagation models
- Multi-phase flow solvers

10 Conclusion

We have presented a comprehensive framework for achieving Mach 1.7 supersonic velocities in aqueous media through a novel sequential projectile approach. The theoretical analysis demonstrates feasibility with existing technology, requiring approximately 3 kJ of input energy delivered through three precisely timed ballistic stages.

The expected phenomena—including underwater sonic booms with peak pressures of 5 GPa, plasma formation at temperatures exceeding 100,000 K, and complex electromagnetic signatures—will provide unprecedented insights into supersonic fluid dynamics in dense media.

This experiment represents the first practical approach to controlled underwater supersonic ballistics, opening new frontiers in:

1. Extreme fluid dynamics research
2. Plasma physics in liquid media
3. Shock wave engineering applications
4. Novel propulsion concept development

The successful execution of this experiment will establish fundamental principles for supersonic motion in liquid media and provide validation data for next-generation computational models, while demonstrating the feasibility of achieving previously impossible velocities through innovative engineering approaches.

Future work will extend these principles to achieve higher Mach numbers, explore different fluid compositions, and investigate applications in underwater propulsion and materials processing. The techniques developed here lay the groundwork for a new field of supersonic liquid ballistics with broad implications for science and technology.

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