SYSTEM AND METHOD FOR HIGH-FLUX THERMAL ENERGY CAPTURE AND FIRST-WALL PROTECTION IN MICRO-SCALE FUSION REACTORS

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January 26, 2026

Abstract

A thermal management and first-wall protection system designed for high-repetition-rate (kHz–MHz) micro-scale fusion reactors. The invention addresses the challenge of capturing the pulsed thermal and particle load from continuous micro-explosions without ablating or fatigue-cracking a structural vessel, while maintaining optical access and a clear target injection path. The system employs a regenerating liquid metal first wall formed as (i) a liquid metal curtain (e.g., a laminar jet sheet or jet array) and/or (ii) a porous refractory first wall (e.g., porous tungsten) continuously wetted by a liquid metal film. The liquid layer absorbs X-ray flux and charged particle debris, damps shock, and transports heat to an external heat exchanger. In some embodiments the liquid metal is shaped and stabilized via vortex flow and/or magnetohydrodynamic (MHD) forces to maintain film thickness and to prevent intrusion into beam ports. The geometry is adapted to compact "Fusion Engine" architectures in which targets are delivered as a stream of micron-scale droplets and pulses occur at high repetition rates, requiring surface regeneration on time scales shorter than the pulse period.

1 Technical Field

The present disclosure relates to nuclear fusion reactor engineering, specifically to first-wall protection and heat extraction systems for inertial confinement fusion (ICF) devices operating at high repetition rates.

2 Background

In traditional ICF (e.g., NIF), the reactor chamber is large (meters in diameter) to dilute the energy flux from a single massive explosion. In the "Fusion Engine" architecture proposed by

Recognition Science, the reactor is compact (centimeters to tens of centimeters) but operates at high frequency (1 kHz - 1 MHz). This creates a continuous, high-intensity thermal load on the inner wall, similar to the exhaust of a rocket engine but in a vacuum.

Solid walls (steel, tungsten) would rapidly erode due to thermal cycling, sputtering from ion impact, and X-ray ablation. Existing liquid wall concepts for large tokamaks or heavy-ion fusion are often gravity-driven and too slow to clear the chamber or regenerate the surface between kHz pulses.

Additionally, micro-scale architectures impose constraints not present in large chambers: (i) optical beam ports and diagnostic windows must survive line-of-sight X-ray and debris flux; (ii) a central axis may be reserved for droplet target injection; and (iii) pumping capacity and gas loads are limited, motivating liquid-based capture rather than gas buffering.

3 Summary

The invention provides a "Dynamic Liquid First Wall" tailored for compact, high-frequency operation.

Core Concept

A high-velocity liquid metal flow is injected tangentially along the inner surface of the spherical or cylindrical reaction chamber. Centrifugal force (in a vortex flow) or capillary action (in a porous mesh) keeps the liquid adhered to the wall, preventing it from interfering with the laser path or fuel droplet trajectory. The liquid absorbs the fusion energy and is continuously cycled out to a heat exchanger.

Key Advantages

- **Ablation Resistance**: The liquid surface is self-healing. Any material vaporized by a micro-explosion is instantly replaced by fresh flow.
- **Compactness**: The high heat capacity of liquid metal allows the chamber radius to be small ($<$ 20 cm) while handling megawatt-scale thermal power.
- **Vapor Suppression**: The flowing liquid acts as a getter, pumping vacuum contaminants and fusion ash (Helium) out of the reaction zone.
- **Shock Damping**: The liquid layer attenuates the acoustic shock waves from the fusion pulses, protecting the outer steel vessel.

4 Detailed Description

4.1 Embodiment 1: The Vortex Wall (Swirl Film)

In this embodiment, liquid metal (e.g., Li, PbLi, Sn, SnLi, or other eutectics) is injected tangentially at the top of a cylindrical or spherical chamber. The flow spirals downward, held against the wall by centrifugal force.

- **Flow Velocity**: > 5 m/s (non-limiting; may exceed 10 m/s) to ensure adhesion and rapid heat removal.
- **Thickness**: 0.5 mm–20 mm effective thickness (non-limiting).
- **Beam Ports**: The vortex flow naturally leaves the central axis clear for the fuel droplet stream. Laser ports are protected by magnetic shutters or gas puffs, or the laser enters through the open top vortex core.

4.2 Embodiment 2: The Wetted Porous Refractory First Wall

In this embodiment, the inner wall is lined with a porous refractory matrix (e.g., porous tungsten, tungsten mesh, or sintered ceramic). Liquid metal is pumped through the wall from behind, weeping out to form a continuously renewed thin film on the surface.

- **Stability**: Capillary forces hold the liquid against gravity, allowing arbitrary chamber orientation.
- **Surface Renewal**: The flow rate is matched to the evaporation rate induced by the fusion pulses.

4.3 Embodiment 3: Liquid Metal Curtain (Jet Sheet)

In this embodiment, a ring or array of nozzles generates one or more laminar sheets of liquid metal spanning a portion of the chamber interior to intercept debris and X-rays before they reach a structural wall. The curtain may be arranged to leave a clear aperture along the axis for droplet injection and to preserve optical access. The curtain may be operated as a closed loop in which the liquid is collected, degassed, filtered, and recirculated.

4.4 Embodiment 4: MHD Shaping and Port Protection (Non-Limiting)

In some embodiments, MHD forces are used to shape and stabilize the liquid film or curtain using magnetic fields and induced currents, reducing splashing and maintaining a controlled thickness near beam ports. Beam ports may include sacrificial baffles, rotating shutters, and/or local gas puffs synchronized to the pulse train to reduce line-of-sight deposition.

4.5 Thermal Cycle

The heated liquid metal exits the bottom of the chamber and passes through: 1. **De-gassing Unit**: Removes Helium ash and unburned fuel vapor. 2. **Heat Exchanger**: Transfers heat to a secondary loop (e.g., supercritical CO2 or steam) for power generation. 3. **Pump**: Returns the cooled metal to the injector. In some embodiments, the pump comprises an electromagnetic pump compatible with liquid metal operation. In D-T embodiments, tritium breeding and extraction subsystems may be incorporated.

4.6 Filtration, Diagnostics, and Flow Control (Non-Limiting)

In some embodiments, the circulation loop includes filtration and contamination control to remove particulates generated by erosion, sputtering, or chemical reactions. The system may include sensors to monitor at least one of: liquid metal temperature, flow rate, pressure, electrical conductivity, film thickness, or optical transmission at beam ports. A controller may modulate flow rate, injection pressure, magnetic field strength (for MHD shaping), and/or port protection timing based on measured heat load and pulse repetition rate.

5 Claims

1. A thermal management system for a micro-scale fusion reactor, comprising:
   - A reaction chamber having an inner wall surface;
   - A liquid metal injection system configured to establish a continuously flowing liquid metal layer covering substantially the entire inner wall surface;
   - Wherein the liquid metal layer is configured to absorb X-ray radiation and ion debris from fusion micro-explosions occurring at a repetition rate exceeding 100 Hz;
   - A circulation loop configured to extract the heated liquid metal from the chamber, remove heat via a heat exchanger, and return the cooled liquid metal to the injection system.
2. The system of claim 1, wherein the liquid metal injection system induces a vortex flow, utilizing centrifugal force to maintain the liquid layer against the inner wall.
3. The system of claim 1, wherein the inner wall comprises a porous structure, and the liquid metal is supplied through the porous structure to form a wetted surface.
4. The system of claim 1, wherein the liquid metal comprises Lithium, Lead, or a eutectic alloy thereof.
5. The system of claim 1, wherein the chamber diameter is less than 50 centimeters.
6. The system of claim 1, wherein the liquid metal injection system comprises an array of nozzles configured to form a laminar liquid metal curtain between a fusion reaction zone and a structural wall.
7. The system of claim 6, wherein the laminar liquid metal curtain is arranged to preserve an unobstructed axial path for a droplet target stream.
8. The system of claim 1, further comprising a magnetic field source configured to shape or stabilize the liquid metal layer via magnetohydrodynamic forces.
9. The system of claim 1, wherein the liquid metal layer has an effective thickness between 0.5 millimeters and 20 millimeters.

10. The system of claim 1, further comprising a port protection subsystem configured to reduce deposition in at least one optical beam port using at least one of: a shutter, a baffle, or a gas puff synchronized to a pulse train.

11. A method for protecting a fusion reactor wall from high-frequency micro-explosions, comprising:
    - Injecting a liquid metal coolant into a reaction chamber;
    - Forming a dynamic, self-healing liquid layer on the chamber wall;
    - Intercepting fusion energy products (X-rays, ions) with the liquid layer;
    - Continuously refreshing the liquid layer to prevent localized boiling or ablation; and
    - Extracting thermal energy from the circulating liquid metal for power generation.

12. The method of claim 11, wherein forming the dynamic, self-healing liquid layer comprises establishing a vortex flow along the inner wall.

13. The method of claim 11, wherein forming the dynamic, self-healing liquid layer comprises supplying liquid metal through a porous tungsten first wall to form a wetted film.

14. The system of claim 1, wherein the circulation loop comprises an electromagnetic pump configured for liquid metal flow.

15. The system of claim 1, further comprising a filtration unit configured to remove particulates from the circulating liquid metal.

16. The system of claim 1, further comprising a film thickness sensor and a controller configured to adjust at least one of: a liquid metal flow rate, an injection pressure, or a magnetic field strength, based on a measured film thickness or measured thermal load.

17. The method of claim 11, further comprising adjusting a liquid metal flow rate based on at least one of: a measured film thickness, a measured liquid metal temperature, or a measured pulse repetition rate.