Water-Heart: A Biomimetic Pulsating Heat Pump System Based on Shape Memory Alloy Physical Intelligence

Zhao Hanbin (Independent Inventor)
Corresponding address: Zhejiang Province, People's Republic of China
ORCID: 0009-0007-6464-076X
DOI:10.5281/zenodo.20579930
Correspondence: zhaohanbin@outlook.com

Preprint Disclaimer: This is a preprint. Feedback and collaboration inquiries are welcome. This work has not yet been submitted for formal peer review. All original concepts and design principles described herein were independently developed by the author.

Abstract

This paper presents the "Water-Heart" system – a fully passive biomimetic pulsating heat pump that couples the physical intelligence of shape memory alloys (SMAs) with the liquid-gas phase change of water. Physical intelligence is defined as the inherent material property that enables autonomous sensing, decision, and actuation without electronic components. The system is built around an SMA pacemaker: at its austenite finish temperature (*A_f*), the SMA undergoes reverse phase transformation, mechanically triggering explosive boiling of superheated water. The latent heat consumed by the SMA (20–30 kJ/kg) is two orders of magnitude smaller than water's latent heat of vaporization (≈2260 kJ/kg), implying a theoretical energy cascade of up to two orders of magnitude. Multiple evaporation chambers form an "Orange-Segment Autonomous Network" – a decentralized architecture where each chamber operates independently without any central controller, inspired by the lobular structure of the liver. Adjacent chamber lines are bundled into a "Liver-Lobule Microcirculation" preheating array, which is preheated along its path by a single SMA wire. Liquid return is realized by the synergy of SMA-sheet venous valves (acting as unidirectional check valves via superelastic deformation) and capillary grooves or metal-mesh liners that utilize surface tension for continuous liquid draw, enabling microgravity-compatible, purely passive unidirectional flow. Moreover, the system possesses an intrinsic self-oscillation mechanism: the closing-force threshold of the SMA venous valves induces pressure oscillation via hysteresis. Even without the SMA pacemaker, the system exhibits a self-sustained charge-burst-reset cycle. The pacemaker accelerates and stabilises this natural rhythm. The Water-Heart system can be extended to pulsatile power generation and microbial life support, providing a foundational thermal-management and energy-autonomous solution for deep-space habitats.

Keywords: shape memory alloy; pulsating heat pump; physical intelligence; phase change; biomimetic circulation; microgravity thermal management

1. Introduction

Thermal management in spacecraft and deep-space habitats faces three fundamental challenges: microgravity (which disables gravity-driven fluid return), extreme temperature swings (from >120 °C in sunlight to −150 °C in eclipse), and the absolute prohibition of electronic components in certain passive safety scenarios. Conventional solutions – heat pipes, pumped fluid loops, and phase-change materials – each fail one or more of these requirements.

Shape memory alloys (SMAs) have been widely used in adaptive mechanical devices, but the latent heat associated with their phase transformation has been largely overlooked for thermal management. This paper proposes a novel approach that leverages SMA as an active **physical intelligence** agent – a concept referring to the inherent material properties that enable autonomous system operation without electronic sensors, controllers, or power supplies. By coupling this SMA intelligence with the enormous latent heat of water vaporization, we construct a fully passive pulsating heat pump that mimics certain aspects of biological circulation. We call this system the **Water-Heart**.

The Water-Heart is a fully passive biomimetic pulsating heat pump that harnesses the physical intelligence of SMAs. Key innovations include: (1) an SMA pacemaker that triggers explosive boiling with an energy amplification ratio of 20–100; (2) an orange-segment autonomous network requiring no central control; (3) a liver-lobule microcirculation preheating array; (4) SMA-sheet venous valves and capillary grooves for microgravity-compatible liquid return; (5) the discovery of intrinsic self-oscillation – the system exhibits pulsation even without a pacemaker; and (6) the potential for pulsatile power generation and ecological life support.

This paper presents the theoretical framework, mechanical design, and operational principle of the Water-Heart system. All concepts and design principles were independently developed by the author.

2. Physical Foundation

2.1 SMA Phase Transformation as a Thermal Engine

The SMA pacemaker operates through the reverse phase transformation from martensite to austenite. At the austenite finish temperature (A_f), the crystal lattice reconfigures from low-symmetry monoclinic martensite to high-symmetry cubic austenite. This reconfiguration absorbs latent heat ($\Delta H_{M \to A}$ = 20–30 kJ/kg for NiTi alloys) and simultaneously produces a sharp macroscopic deformation (typically 4–8% strain). The deformation constitutes the actuation; the latent heat absorption provides direct cooling. Upon cooling, the forward transformation (austenite → martensite) releases the stored latent heat.

2.2 Superheated Water and the Energy Cascade Mechanism

Water has an exceptionally high latent heat of vaporization (≈2260 kJ/kg). When heated above its boiling point in a smooth container, water can remain in a metastable superheated state because nucleation sites are absent. A small mechanical disturbance – such as the sudden deformation of an SMA wire – can instantly create thousands of nucleation sites, triggering explosive boiling. The ratio of latent heat values (SMA: ≈25 kJ/kg vs. water: ≈2260 kJ/kg) implies a theoretical energy cascade of up to two orders of magnitude. This mechanism does not violate energy conservation principles; rather, it constitutes an **energy cascade** where the SMA provides the necessary activation energy for a phase change that would otherwise be kinetically hindered.

2.3 Venous Valves and Capillary Return

To address microgravity challenges, this study proposes a dual passive mechanism for liquid return: (1) **SMA-sheet venous valves** – thin, superelastic SMA flaps that act as unidirectional check valves via superelastic deformation (forward flow pushes them open; reverse flow closes them); and (2) **capillary grooves or metal-mesh liners** inside the return tube, which utilize surface tension for continuous liquid draw. These mechanisms ensure purely passive unidirectional flow without external power.

3. System Architecture

3.1 SMA Pacemaker

Each evaporation chamber is attached to the inner surface of a spacecraft skin (sunlit side) and partially filled with liquid water. An SMA wire or spring (the pacemaker) is placed inside the chamber, with its A_f carefully set above the saturation temperature of water at the chamber pressure. When sunlight heats the chamber, the water temperature rises above its boiling point, becoming superheated. Once the temperature reaches A_f, the SMA snaps into its austenitic shape, mechanically disturbing the superheated water and triggering explosive boiling. A high-pressure vapor pulse is generated, which travels through the vapor line to the condensation chamber (on the dark side). After the pulse, the pressure drops, the SMA cools and transforms back to martensite (soft, flexible), and the chamber refills with liquid via the return line. This constitutes a pulsating, not continuous, flow – each pulse corresponds to one cardiac cycle.

3.2 Orange-Segment Autonomous Network (Decentralized Control)

Multiple evaporation chambers are arranged in an array. Each chamber operates independently, with its own vapor and return lines. No central controller is needed. When sunlight moves across the spacecraft skin, only the chambers that are illuminated reach A_f and begin pulsating; shaded chambers remain dormant. This creates a spatially distributed, self-organizing network. The architecture is inspired by the lobular structure of the liver, where each functional unit operates autonomously yet contributes to global regulation.

3.3 Liver-Lobule Microcirculation Preheating Array

In a conventional heat pipe, the returning liquid is cold, which may quench the vaporization process. To avoid this, we preheat the returning liquid before it reaches the evaporator. The lines from several adjacent evaporation chambers are bundled together. A single SMA wire, running from a previously illuminated (and therefore still warm) zone, extends along the bundle. The wire's hot end is coupled to the warm zone; its cold end extends toward the dark side. A temperature difference exists along the wire, driving a phase interface that propagates from the warm end to the cold end, releasing latent heat along the way. The returning liquid flowing through the bundled lines is gently preheated – not to boiling, but to a temperature close to saturation. This array is termed the "Liver-Lobule Microcirculation" preheating unit.

3.4 Venous Valves and Capillary Return Circuit

The return line from the condensation chamber back to each evaporation chamber is equipped with two passive features:

- **SMA venous valve:** A thin, superelastic SMA sheet is cut to form a flap. Forward flow pushes the flap open; any reverse flow tendency immediately closes the flap. The valve requires no external power and has no moving joints – it relies solely on the superelasticity of SMA.
- **Capillary grooves:** The inner wall of the return tube is lined with axial grooves (or a metal-mesh wick). Surface tension draws liquid along the grooves, providing a continuous pumping action even in microgravity.

Together, these two elements replace the mechanical pump and electronic check valves of conventional fluid loops.

4. Intrinsic Self-Oscillation: The Water-Heart Beats Even Without a Pacemaker

The above description presents the SMA pacemaker as the initiator of pulsation. However, a deeper physical insight reveals that the pacemaker is not the origin of pulsation but its **accelerator and stabiliser**. Even without any SMA pacemaker, the system possesses an inherent tendency toward pulsatile flow.

Consider the initial state: water in the evaporation chamber is heated and evaporates freely. The vapor flows toward the condensation chamber through the vapor line – until it encounters the SMA venous valve. That valve has a finite closing force threshold. As long as the vapor pressure remains below this threshold, the valve stays closed. Vapor continues to be generated, so pressure accumulates in the chamber. This is the **charging phase**.

When the pressure finally exceeds the valve's threshold, the valve is forced open. The accumulated high-pressure vapor is released in a sudden burst – a pressure pulse – rushing into the condensation chamber. This is the **burst phase**.

After the pulse, the pressure drops sharply, and the venous valve closes again (due to its superelastic self-sealing compliance). The pressure in the evaporation chamber begins to build once more, and the next cycle begins.

This self-sustained oscillation – **charge → burst → reset → recharge** – requires no external trigger. It is a physical inevitability whenever a threshold valve is combined with a continuous heat source. Geysers, certain volcanic eruptions, and even the vibration of human vocal folds follow the same logic: a threshold plus continuous energy input leads to periodic bursts.

The SMA pacemaker, therefore, is not the creator of the heartbeat. It is the **catalyst** that shortens the charging time (by actively disturbing the superheated fluid and creating nucleation sites), thereby increasing the pulsation frequency and locking the rhythm to the precise temperature window defined by A_f. Moreover, this dual-mechanism design provides inherent redundancy: if the SMA pacemaker fails for any reason, the system does not stop – it seamlessly transitions to the slower, vapor-driven self-oscillation mode and continues to operate.

5. Extensions

5.1 Pulsatile Power Generation

The high-pressure vapor pulses traveling through the vapor line carry kinetic energy. A small turbine or an SMA-based oscillator may be integrated into the vapor line. When a pulse passes, it spins the turbine or deforms the oscillator, which in turn drives a piezoelectric element to generate electricity. Under idealized parametric conditions – e.g., vapor pulse pressure of 5 kPa, pulse frequency of 0.1–1 Hz, and turbine/piezoelectric efficiency of 5–20% – the theoretical electrical output is estimated to range from 0.1 mW to 10 mW. This output, though modest, is sufficient to power low-consumption sensors or communication devices, making the Water-Heart not only a thermal management system but also an autonomous power source.

5.2 Ecological Extension for Deep-Space Habitats

The condensation chamber releases heat at a controlled temperature (typically 30–40 °C). This thermal environment is suitable for cultivating photosynthetic microorganisms (e.g., cyanobacteria or algae) that absorb CO_2 and release O_2, as well as for supporting water purification through evaporation-condensation cycles. Thus, the Water-Heart can become a core component of a bioregenerative life support system, simultaneously managing heat, producing oxygen, recycling water, and generating biomass. In deep space, there is no waste heat – only work that has not yet been utilised.

6. Discussion

6.1 Comparison with Existing Technologies

Compared with active liquid-cooling systems, the proposed system requires no sensors, controllers, or pumps, greatly improving reliability. Compared with phase-change material energy storage, the system achieves active, directed heat transport rather than passive temporary storage, and it is reusable. Compared with existing SMA thermal switch technologies, the system simultaneously exploits the latent heat clamping capability and the deformation triggering capability of SMA, and it works in synergy with a passive fluid circuit.

6.2 Limitations and Future Work

This work is currently at the conceptual design stage. No prototype has been built, and the proposed performance characteristics (response time, cyclic stability, energy amplification) are theoretical estimates that require experimental validation. Key parameters such as the fatigue life of the SMA pacemaker, the long-term stability of the venous valves, and the performance of the capillary return under microgravity require experimental validation. Future work will include: building a proof-of-concept prototype, measuring the pulsation frequency and energy amplification ratio, conducting cyclic fatigue tests, and evaluating microgravity compatibility via drop-tower or parabolic flight experiments.

7. Conclusion

This paper has presented the theoretical framework, mechanical design, and operational principle of the Water-Heart system – a fully passive biomimetic pulsating heat pump that harnesses the physical intelligence of SMAs and the latent heat of water vaporization. Key contributions include: (1) the SMA pacemaker with an energy cascade of up to two orders of magnitude; (2) the orange-segment autonomous network requiring no central control; (3) the liver-lobule microcirculation preheating array; (4) SMA venous valves and capillary grooves for microgravity-compatible unidirectional liquid return; (5) the discovery of intrinsic self-oscillation – the system beats even without a pacemaker; and (6) the potential for pulsatile power generation and ecological life support.

The Water-Heart is born to pulsate. The SMA pacemaker merely modulates the natural oscillation cycle, making it faster, stronger, and more reliable. From a single SMA wire trembling between hot and cold, to a biomimetic heart that pumps heat across the vacuum of space – physical intelligence is not an abstraction; it is engineering with physics as the only program.

Physics itself is the program [10].

References

[1] Otsuka K, Wayman CM. *Shape Memory Materials*. Cambridge University Press, 1998.

[2] Lagoudas DC. *Shape Memory Alloys: Modeling and Engineering Applications*. Springer, 2008.

[3] Mohd Jani J, Leary M, Subic A, et al. A review of shape memory alloy research, applications and opportunities. *Materials & Design*, 2014, 56: 1078–1113.

[4] Buehler WJ, Gilfrich JV, Wiley RC. Effect of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. *Journal of Applied Physics*, 1963, 34(9): 1475–1477.

[5] Sun L, Huang WM, Ding Z, et al. Stimulus-responsive shape memory materials: a review. *Materials & Design*, 2012, 33: 577–640.

[6] Cengel YA, Boles MA. *Thermodynamics: An Engineering Approach*. McGraw-Hill, 2015.

[7] Sandrock G. A panoramic overview of hydrogen storage alloys from a gas reaction point of view. *Journal of Alloys and Compounds*, 1999, 293–295: 877–888.
[8] Zhao H. Stiffness-Switching: A Universal Design Paradigm Based on Shape Memory Alloy Phase Transformation for Adaptive Devices. Zenodo, 2026. DOI: 10.5281/zenodo.20487693
[9] Zhao H. Heat Redistribution: A Thermal Management Paradigm Based on Phase Interface Propagation in Shape Memory Alloys. Zenodo, 2026. DOI: 10.5281/zenodo.20571412
[10] Zhao H. Physical Intelligence: A Paradigm for Electronics-Free Adaptive Systems Based on Material Constitutive Behavior. Zenodo, 2026. DOI: 10.5281/zenodo.20571554

Author Contribution

Zhao Hanbin independently conceived the Water-Heart system, developed all design principles, and wrote the manuscript.

Acknowledgments

The author is grateful for the silence and solitude that made this independent theoretical work possible. The author also acknowledges the use of AI tools for language refinement and writing assistance.

Conflicts of Interest: The author declares no conflicts of interest.

Ethics Statement: This paper describes conceptual designs and does not involve any human or animal subjects, clinical trials, or patient data. No ethical approval was required