Autonomous Waste Heat Recovery Interface: Converting Vertical Heat Supply into Horizontal Motion for Self-Powered Fluid-Transport in Microenvironments

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Microelectronic power densities surge due to the rise of high-performance-computing utilizing AI and its extended applications due to its rapid scaling down and increasing packing density. With this an increasing amount of waste heat is produced and thermal management has become a critical bottleneck. [1-3] Traditional micropumps for active cooling solutions are often energy-intensive and difficult to integrate at the microscale. In this work, we introduce a fundamentally new class of self-powered and sustainable micro pumping classified as \`passive pump´ that transform unavoidable waste heat autonomously into productive fluid motion and is well integrate able on the microscale. [4] The core innovation lies in the conversion of vertical heat supply on only one channel wall into horizontal fluid motion. In addition, it takes place under autonomous waste heat recovery as a self-powering phenomenon due to the microstructural interfacial design. While existing experimental thermocapillary (Marangoni) pumping requires a heat supply applied along the flow in the channel's length direction [5-7] , a condition rarely met in real-world electronics and other applications, our design enables horizontal pumping with a uniform and vertical heat flux applied across only one channel wall. By combining geometric symmetry breaking with a heterostructure of varying thermal conductivities on a superhydrophobic surface, we demonstrate that this combination supports the autonomously conversion of vertical heat supply into horizontal fluid motion. **Key highlights Proof-of-Principle:** We validated the mechanism through both rigorous numerical simulations and experimental implementation, showing excellent agreement between the respective flow fields. **Operational Effectivity:** Due to the interfacial microstructural design the pumping operates under significantly lower temperature differences along the channel height than that was required by previous designs that applied the temperature difference along the channel's length (flow direction). **Modular Scalability:** The modular design of the pump allows for complex, non-linear microfluidic routing and "lab-on-a-chip" architectures. **Sustainability:** The concept enables fully autonomous waste heat recovery and offers potential for solar-driven applications via light-absorbing self-heating coating. Our findings offer a versatile platform for heat-driven microfluidics, providing a starting point for sustainable and thermal management utilizing autonomous fluid transport on the microscale for high energy density applications in electronics, manufacturing, energy harvesting, research laboratories and other future applications.

Keywords:
waste heat recovery, autonomous, self-powering, complex interface, Marangoni flow, sustainability, microfluidics, micropumping, functional interfaces.

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