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"Experimental Analysis On Filling Ratio And Inclination Angle For Pulsating Hat Pipe Performance"

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Abstract: Pulsating Heat Pipes (PHPs) are compact, wickless, and highly efficient two-phase passive thermal management devices that operate through the self-sustained oscillatory motion of liquid slugs and vapor plugs. Owing to their simple construction, rapid thermal response, and exceptionally low thermal resistance, PHPs have become indispensable in modern high-power electronics cooling, renewable energy systems, aerospace thermal control, and advanced waste heat recovery. This review presents a consolidated and deeply detailed synthesis of theoretical foundations, historical progression, working mechanisms, geometrical and operational factors, and key experimental insights from two comprehensive source documents. Critical factors—including filling ratio, working fluid properties, inclination angle, number of turns, heat input, and emerging nanofluid enhancements—are analyzed comparatively. The review also identifies research gaps and outlines future directions for next-generation PHP development, including additive manufacturing, hybrid working fluids, microgravity operation, and predictive AI-enabled modeling.

I. Introduction

The rise of compact, high-flux electronic devices and the increasing utilization of renewable and aerospace technologies have intensified global demand for efficient, passive, and reliable heat spreaders. As electronic components continue to shrink while power densities increase, traditional cooling methods—such as forced convection systems, liquid-cooled loops, and conventional heat pipes—often struggle to meet stringent performance and size constraints. In this context, Pulsating Heat Pipes, invented by Akachi in the early 1990s, represent one of the most promising next-generation thermal management solutions. PHPs leverage capillary-scale thermohydraulic phenomena to transport heat without mechanical pumps or complex wicks. Their operation depends on the spontaneous formation and cyclic expansion and contraction of vapor plugs, which generate pressure waves that move liquid slugs along a serpentine tube. These oscillations promote simultaneous latent heat transfer, sensible heat exchange, and thin-film evaporation, enabling high thermal efficiency even under variable heat loads.

Over the last two decades, rigorous research has expanded understanding of PHP transient behaviour, thermal performance, and geometric optimization. Key studies have emphasized how thermophysical fluid properties, filling ratio (FR), inclination angle, tube diameter, turn count, and heat load fundamentally shape oscillation stability and thermal resistance. In addition, researchers have explored the influence of tube material, surface roughness, and manufacturing precision, all of which critically impact startup behaviour and long-term performance. The complex interplay between vapor pressure pulsations, internal flow regimes, and heat input has also been shown to determine whether the device operates in intermittent, chaotic, or fully developed oscillation modes.

Recent investigations further highlight the role of nanofluid suspensions, hybrid fluids, and binary mixtures in enhancing heat transfer capability through improved thermal conductivity and modified interfacial behaviour. Novel PHP architectures—such as flat-plate PHPs for compact electronics cooling, dual-diameter configurations for directional oscillations, and check-valve-assisted PHPs for enhanced flow uniformity—are expanding the design space. The introduction of advanced manufacturing techniques, including precision micromachining and 3D metal printing, enables more intricate geometries with better dimensional consistency. These advancements, combined with real-time monitoring techniques, artificial intelligence–based predictive modelling, and space-oriented research, continue to push the boundaries of PHP performance across both terrestrial and microgravity environments.

2. Historical Development of PHP Technology

1990–1994: Conceptualization and Patenting

- Akachi introduces the basic closed-loop PHP structure.
- First theoretical hypotheses on slug/plug formation and capillary-driven oscillation behaviour appear.

1995–2005: Foundational Experiments

- Demonstrations confirming the influence of filling ratio, tube inner diameter, inclination, and working fluid.
- Introduction of early mathematical correlations for thermal resistance and oscillation frequency.

2005–2015: Expanded Applications

- Widespread integration into electronics cooling and LED modules.
- Development of flat-plate PHPs for compact systems.
- Improved visualization methods for slug/plug dynamics.

2015–Present: Advanced Architectures & Materials

- Research on nanofluids, hybrid working fluids, and ionic liquids.
- Emergence of 3D-printed PHPs and check-valve PHPs enabling directional oscillations.
- Significant focus on microgravity and aerospace viability.

3. Classification of PHPs

3.1 Loop Configuration

Closed-Loop PHP (CLPHP)

- Ends are sealed; oscillations form naturally and continuously.
- Suitable for high-heat-flux applications and stable long-duration operation.

Open-Loop PHP (OLPHP)

- Tube ends are open; used mainly for visualization and flow-pattern analysis.
- Less thermally efficient than closed-loop variants but valuable for research diagnostics.

3.2 Geometry and Channel Design

- **Single- and multi-turn serpentine PHPs**: More turns generally yield stronger pressure waves.
- **Circular, square, and rectangular channels**: Shape affects capillary pressure and slug stability.
- **Flat-plate PHPs**: Preferred for CPUs, GPUs, and LEDs; excellent spreader capability.
- **Dual-diameter PHPs**: Promote directional flow and improved restart behaviour.
- **Check-valve PHPs**: Introduce flow rectification, reducing chaotic oscillation modes.

4. Working Principle

The core operating mechanism consists of four interdependent processes:

1. **Evaporation (Heat Input Region)**
   Heat causes liquid in the evaporator to vaporize, forming expanding vapor plugs that push adjacent slugs.
2. **Adiabatic Transport (Centre Section)**
   Vapor expansion and collapse generate pressure-driven oscillations, transporting fluid without external power.
3. **Condensation (Heat Rejection Region)**
   Vapor releases latent heat and contracts, pulling liquid back toward the evaporator region.
4. **Self-Sustained Oscillations**
   Oscillation amplitude and frequency depend on fluid properties, FR, and geometry. Heat transfer occurs through:
   - Latent heat exchange
   - Sensible heat transport in liquid slugs
   - Thin-film evaporation/condensation around the meniscus

5. Review of Experimental Studies

5.1 Effect of Filling Ratio (FR)

Experimental studies consistently show:

- **Too low FR (<30–40%)**:
  Leads to dry-out in evaporator and insufficient liquid slug volume.
- **Too high FR (>60–70%)**:
  Reduces vapor space, weakens oscillations, and increases thermal resistance.
- **Optimal FR ≈ 40–60%**:
  Achieves stable oscillation and highest thermal conductivity.

5.2 Effect of Number of Turns

- Increasing the number of turns increases the internal volume available for slug/plug formation.
- More turns promote stronger and more frequent pressure fluctuations.
- Typical stable operation occurs for **5–23 turns**, depending on tube diameter and working fluid.
- Higher turn count generally reduces thermal resistance due to enhanced circulation.

5.3 Working Fluid Properties

Performance depends strongly on the fluid's thermophysical attributes:

Property	Influence on Performance
Thermal conductivity	Determines sensible heat transport efficiency
I Latent heat	Lower latent heat facilitates rapid bubble generation
Surface tension	Affects meniscus stability and slug formation
Viscosity	Lower viscosity reduces frictional resistance

Fluids such as nitrogen, acetone, ethanol, methanol, and water exhibit distinct advantages depending on operating temperature. Nanofluids (e.g., Al_2O_3, CuO, graphene) can enhance thermal conductivity but may introduce sedimentation challenges.

5.4 Inclination Angle

Inclination significantly influences gravitational return flow:

- **45° inclination**:
  Most experiments report this orientation as optimal, balancing gravity and capillary forces.
- **Vertical orientation**:
  Eases liquid return and lowers thermal resistance.
- **Horizontal orientation**:
  Requires higher heat input to initiate oscillation; prone to stop-start behaviour.

5.5 Heat Input Effects

- Increasing heat input strengthens oscillation amplitude and frequency.
- Lower heat loads often produce intermittent or localized oscillations.
- Effective thermal conductivity increases with heat input until **critical heat flux** or **dry-out** occurs.
- Derived equations for thermal resistance and effective thermal conductivity indicate sharply decreasing thermal resistance with rising power.

6. Comparative Analysis of Key Factors

Integrated analysis from the two documents shows:

- **Filling Ratio:** Most influential parameter for startup and oscillation stability.
- **Working Fluid:** Must align with operating temperature range and material compatibility.
- **Number of Turns:** Directly impacts flow path and pressure wave formation.
- **Inclination:** Strongly governs gravity-assisted circulation.
- **Heat Input:** Defines operational regimes (inactive, intermittent, fully oscillatory).

The synergy of these factors determines whether the PHP operates in a chaotic, intermittent, or fully developed oscillatory mode.

7. Applications of PHPs

- High-power CPU/GPU/LED thermal management
- Solar thermal collectors and heat recovery systems
- Electric vehicle battery cooling
- Aerospace and microgravity thermal regulation
- Portable refrigeration units
- HVAC systems and compact heat exchangers
- Thermal management in satellites and small spacecraft

8. Research Gaps

Despite extensive progress in the development and understanding of Pulsating Heat Pipes, several important research gaps remain. One major challenge is the lack of universal predictive mathematical models capable of accurately describing the highly nonlinear multiphase oscillations that govern PHP behavior. Additionally, the startup process and the transitions between different oscillation modes are still not fully understood, making it difficult to predict or control PHP performance under varying conditions. Technology also remains highly sensitive to manufacturing imperfections, such as internal tube roughness and slight variations in diameter, which can significantly affect flow stability and heat transfer efficiency. Long-term reliability issues under repeated thermal cycling continue to raise concerns, particularly for high-demand applications like aerospace or electric vehicle cooling. Moreover, while nanofluids offer enhanced thermal properties, problems related to particle sedimentation, fluid instability, and long-term compatibility with PHP materials limit their practical application. Finally, binary working fluids, hybrid mixtures, and phase-change-enhanced fluids—which may offer improved performance and tunable operating characteristics are still insufficiently explored, leaving considerable room for further investigation.

9. Future Scope

The future scope of Pulsating Heat Pipe research is extensive, with several promising directions emerging to enhance performance, reliability, and application versatility. The development of advanced AI and machine-learning predictive models offers significant potential for accurately forecasting slug–plug dynamics, optimizing design variables, and improving operational stability under varying thermal conditions. Innovations in additive manufacturing, particularly 3D printing, may enable the fabrication of complex, multilayered, and customized PHP geometries that were previously impossible to construct using traditional techniques. Further exploration of novel working fluids—such as ionic liquids, binary mixtures, and hybrid nanofluids—could provide superior thermal stability, improved heat transfer characteristics, and better long-term compatibility with PHP materials. Integrating PHP systems with smart sensing networks and real-time thermal diagnostics may also pave the way for intelligent thermal management solutions capable of adaptive control. Additionally, the development of advanced PHP architectures tailored for microgravity environments could significantly expand their use in aerospace and space technologies. Finally, future research must prioritize long-term reliability assessments, standardized testing methodologies, and robust validation protocols to ensure consistent and dependable PHP performance across diverse industrial applications.

10. Conclusion

Pulsating Heat Pipes represent a transformative solution in passive thermal management, offering unparalleled performance with minimal structural complexity. Their operation is governed by complex interactions among geometric design, thermophysical fluid properties, filling ratio, inclination, and heat input. Experimental findings across multiple studies confirm that optimizing these parameters considerably improves thermal performance by promoting stable oscillations and lowering thermal resistance. Although substantial progress has been made, foundational mechanisms such as startup behavior, oscillation stability, nanofluid interaction, and predictive modeling require deeper exploration. Continued interdisciplinary research promises to advance PHP technology toward next-generation high-performance thermal systems in electronics, renewable energy, transportation, and aerospace applications.

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