RIGA TECHNICAL
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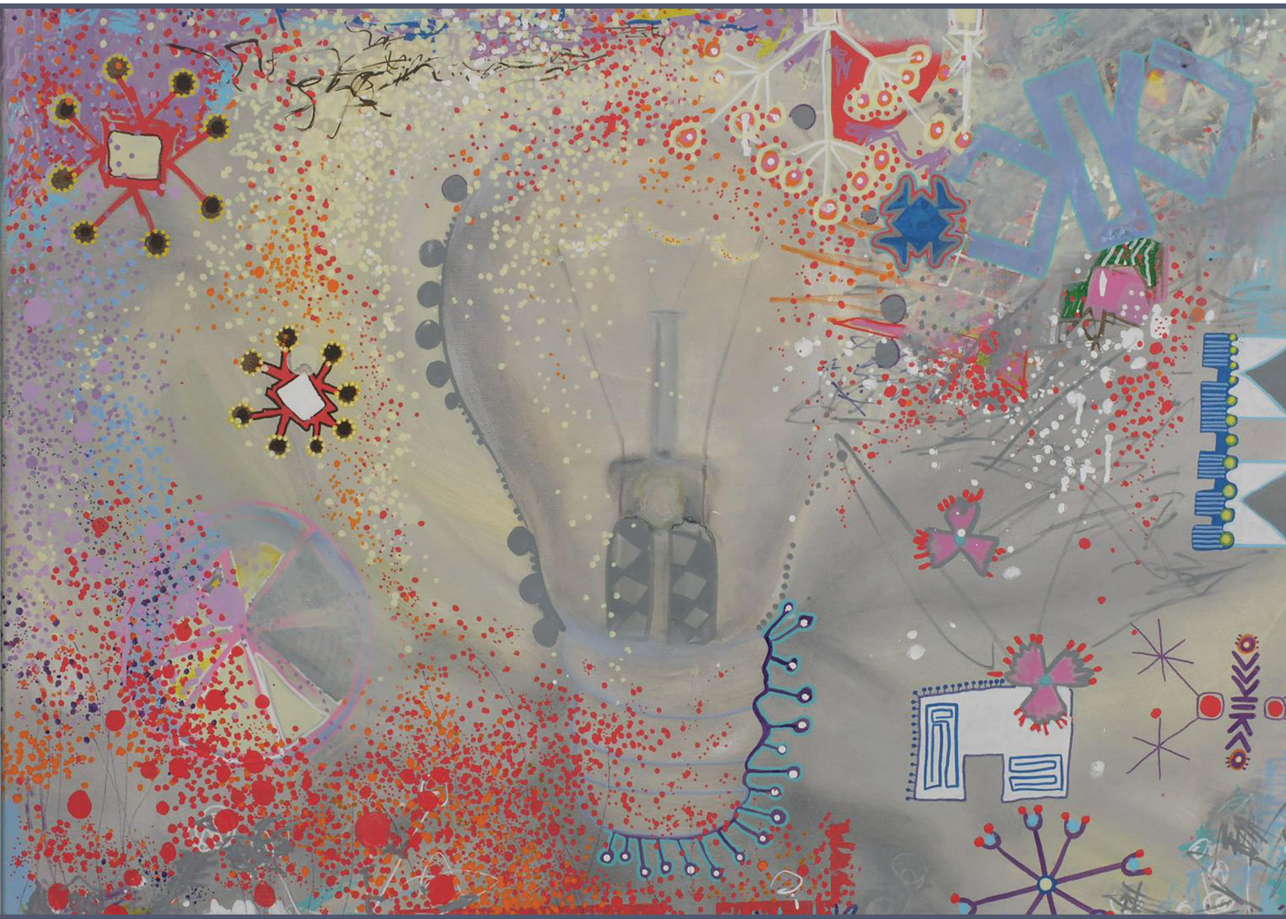
Igors Ušakovs

SMART THERMAL MANAGEMENT OF ELECTRICAL EQUIPMENT

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of Industrial Electronics, Electrical Engineering and Energy

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Doctoral Student of the Study Programme “Computerised Control of Electrical Technologies”

SMART THERMAL MANAGEMENT OF ELECTRICAL EQUIPMENT

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 29 May 2026, at 14.00 in the Conference Hall of RTU Conference and Sports Centre “Ronīši”, Klapkalnciems, Engure County.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own.

I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Igors Ušakovs ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, five chapters, Conclusions, 84 Figures, and eight Tables; the total number of pages is 176. The Bibliography contains 82 titles.

ABSTRACT

This Doctoral Thesis is devoted to the development of a scientifically grounded approach to the application of passive two-phase heat loops as a universal platform for smart thermal management of electrical and electronic equipment.

The relevance of the research is determined by the continuous growth of heat-flux densities and compactness of modern electrical devices, which increasingly exceed the capabilities of conventional cooling systems. While active cooling solutions require external energy input and control systems, passive two-phase devices rely on internal physical mechanisms – phase transitions, capillary forces, and gravity – providing energy-independent heat redistribution with high reliability.

The objective of the research is to formulate physical principles, mathematical models, and engineering methodologies enabling the transition from specialised heat-loop applications toward universal modular two-phase cooling platforms adaptable to different classes of electrical equipment.

The research hypothesis states that replacing conventional cooling systems with properly designed passive two-phase heat loops modifies the thermal regime of electrical devices in a way that leads to improved performance characteristics, including increased heat-flux density, enhanced efficiency, reduced mass, and extended operational lifetime.

The scientific novelty of the Thesis includes the introduction of the concept of smart thermal management as a class of self-regulating two-phase thermal systems; the proposal of a modular multi-evaporator architecture based on the Altom technology; the development of steady-state and transient mathematical models of loop heat pipes (LHPs); the formulation of a thermodynamically consistent interpretation of heat leak and subcooling; the introduction of working-fluid quality parameters for loop thermosyphons (LTSs); and the development of the original software tool Altom-LHP for loop design and analysis.

The proposed approaches are experimentally validated on four different classes of electrical devices: an in-wheel electric motor, an LED luminaire, a fuel-cell stack and a traction motor. For the in-wheel motor, an LHP-based cooling system and a novel stator-integrated evaporator architecture are developed and tested. For the LED luminaire, a new Heat Loop Pipe (HLP) concept combining features of heat pipes and LHPs is implemented and experimentally verified. For fuel-cell applications, a conceptual loop-thermosyphon-based cooling architecture is developed, and prototype evaporators are fabricated and tested. For the traction motor, a cooling system based on six loop thermosyphons was developed, manufactured, and tested.

The results confirm that passive two-phase heat loops can serve as a universal physical and engineering platform for scalable, energy-independent thermal management.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Relevance of Research

Thermal management is a determining factor for the reliability, efficiency and service life of modern electrical and electronic systems. In the general sense, it encompasses methods for maintaining a prescribed temperature regime; however, in high-power electrical equipment, the dominant challenge is heat removal. Increasing power density, compactness and functional integration intensify thermal constraints and make cooling a primary design limitation rather than an auxiliary function. According to [1], temperature-related factors account for more than half of electronic equipment failures, emphasizing the critical role of effective heat removal.

Fundamentally different classes of electrical equipment operate according to different energy-conversion principles. In electric motors, electrical energy is converted into mechanical work; in LED luminaires, into radiation; in fuel-cell stacks, chemical energy is converted into electrical energy. Despite these differences, in all cases a substantial fraction of the processed energy is inevitably transformed into heat. This heat must be efficiently collected, transported, and dissipated without excessive increase in mass, volume or parasitic energy consumption. Thus, despite different physical conversion principles, these systems share a common bottleneck: the limited capability of conventional cooling technologies under high heat-flux conditions [2], [3].

The general trend in thermal management development is the increasing use of phase-change heat transfer, particularly in two-phase systems operating in a closed thermodynamic cycle, where the working fluid evaporates in the heat-input zone and condenses in the heat-rejection zone. Passive two-phase heat loops (HLs), including loop heat pipes (LHP), capillary pumped loops (CPL), and loop thermosyphons (LTS), driven by capillary forces or gravity, offer high reliability, energy-independent operation and the capability to transport heat over significant distances with small temperature differences. However, their application remains largely confined to specialized domains due to structural complexity and integration challenges.

This creates a scientific and technical problem: the development of universal design and integration principles for passive two-phase HLs that enable overcoming thermal limitations while ensuring technological feasibility and scalability of implementation.

1.2 Objective of Research

The objective of this Doctoral Thesis is to develop a scientifically grounded framework for applying passive two-phase heat loops as a universal platform for smart thermal management of electrical equipment. The Thesis includes: 1) development of physical and mathematical models of heat loops; 2) formulation of design and integration principles; and 3) experimental validation on representative classes of electrical devices.

The study aims to extend the application of HLs beyond specialized domains while addressing the associated structural and technological challenges of their integration.

1.3 Research Hypothesis

The working hypothesis states that the replacement of conventional cooling systems with properly designed passive two-phase heat loops modifies the thermal regime of electrical equipment in a manner that expands its operational limits and improves key performance characteristics, including useful power, efficiency, mass–volume parameters, operational reliability and service life.

It is assumed that this effect is of a general nature and is governed by fundamental mechanisms of two-phase heat transfer and, therefore, can be realized for different classes of electrical devices, provided that the heat loop architecture is properly adapted to their geometry and thermal operating conditions.

1.4 Research Novelty

The scientific novelty of the Thesis consists of the following conceptual, theoretical, methodological and engineering contributions.

Conceptual Contributions

- Introduction of the concept of smart thermal management as a class of systems based on passive two-phase heat loops utilizing internal physical mechanisms for self-regulated heat redistribution without external energy input or active control.
- Formulation of the principle of transition from specialized heat loops to universal modular cold-plate platforms enabling scalable integration into electrical devices of different geometries and power levels.

Theoretical Contributions

- Development of a mathematical model for steady-state and transient operating regimes of loop heat pipes (LHPs), adapted to complex multi-evaporator configurations.
- Formulation of a thermodynamically consistent interpretation of heat leak and subcooling in LHPs, demonstrating the fundamental role of heat leak in closing the steady-state energy balance of the cycle.
- Introduction of working-fluid quality parameters for loop thermosyphons (LTS), analogous to figures of merit for LHPs but accounting for gravity-driven circulation.
- Proposal of a hypothesis and physical explanation of a low-efficiency heat-transfer regime in LHPs.

Methodological Contributions

- Development of a method for estimating LHP parameters that are not directly measurable from experimental data.
- Development of an algorithm for tuning the mathematical model based on experimental results.
- Creation of the original software tool Altom-LHP for the design and analysis of modular LHP systems.

Engineering Implementation and Experimental Validation

- Proposal of a new heat-transfer device design, HLP (heat loop pipe), combining structural features of conventional heat pipes and LHPs.
- Design and experimental validation of two-phase cooling systems for:
  - an in-wheel electric motor;
  - a high-power LED luminaire;
  - a fuel-cell stack;
  - traction motor (not included in Thesis).
- Proposal of an in-wheel electric motor architecture with structurally integrated evaporators enabling direct heat removal from stator teeth and reduced thermal resistance.
- Development of a conceptual design of a two-phase cooling system for a fuel-cell stack based on a loop thermosyphon.

1.5 Publications and Patents Related to the Thesis

The main results of the Thesis have been published in the following peer-reviewed journal articles and conference proceedings.

Journal Articles

1. **I. Ušakovs**, D. Mishkinis, I. A. Galkin, “Concept and experimental study of two-phase cooling loops for PEM fuel cells with a flat aluminum evaporator”, *Results in Engineering*, 2026 (Under review)
2. P. S. Ghahfarokhi, P. Rasilo, A. J. M. Cardoso, **I. Ušakovs,** D. Mishkinis, A. Podgornovs, “Proof of Concept of a Two-Phase Thermal Management System for Railway Traction Motors,” *IEEE Trans. Energy Convers.*, 1–10, 2025. https://doi.org/10.1109/TEC.2025.3583076
3. **I. Ušakovs**, L. Ivanovskis, “Advanced Loop Heat Pipe Application for Cooling High Power LED Lights”, *Case Studies in Thermal Engineering*, vol. 57, p. 104320, 2024. https://doi.org/10.1016/j.csite.2024.104320
4. **I. Ušakovs**, D. Mishkinis, I. A. Galkin, A. Bubovich, and A. Podgornovs, “Experimental thermal characterization of the in-wheel electric motor with loop heat pipe thermal

management system,” *Case Stud. Therm. Eng.*, vol. 47, p. 103069, Jul. 2023. https://doi.org/10.1016/j.csite.2023.103069

Conference Proceedings

1. Donatas Mishkinis, **Igors Ušakovs**, Luka Ivanovskis, Marco Gottero, Albino Quaranta, Federica Negri, Antonio Rotondi, Stéphane Lapensée, Paula Prado, “MECOP – A Novel Two-Phase Capillary Technology for the Thermal Control of Space Systems”, 54th International Conference on Environmental Systems, ICES-2025-300, 13–17 July 2025, Prague, Czech Republic.
2. Luka Ivanovskis, **Igors Ušakovs**, Donatas Mishkinis, Marco Gottero, Albino Quaranta, Stéphane Lapensée, “Multievaporator Cold Plate (MECOP) Heat Loop characterization with butane and R134a”, Joint 22nd IHPC and 16th IHPS, Thailand, November 2024.
3. Donatas Mishkinis, **Igors Ušakovs**, Luka Ivanovskis and Ilya A. Galkin, “Heat Loop Pipe for Thermal Management of Powerful LED-based Applications”, Joint 21st IHPC and 15th IHPS, Melbourne, Australia, 5–8 February 2023.
4. P. Gakal, D. Mishkinis, A. Leilands, **I. Usakovs**, R. Orlov, and Y. Rogoviy, “Analysis of working fluids applicable for high-temperature loop heat pipe applications”, IOP Conf. Series: Materials Science and Engineering, 1226 (2022) 012036 doi:10.1088/1757-899X/1226/1/012036. https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012036
5. D. Mishkinis, **I. Ušakovs,** D. Nasibulin, “Novel Modular Evaporator Architecture for Electronics Cooling Applications”, Joint 19th International Heat Pipe Conference and 13th International Heat Pipe Seminar, Pisa, Italy, 2018.

Patents

1. Mishkinis, D., **Ušakovs, I**. SILTUMA CILPAS CAURULE (HEAT LOOP PIPE). LV 15883 A — patent application publication. Application No. LVP2023000021; filing date 2023-03-07; publication date 2024-09-20. Applicant: ALLATHERM, SIA, LV.

2 SMART THERMAL MANAGEMENT CONCEPT

2.1 Passive Two-Phase Heat Loops and Heat Loop Pipe Architecture

Passive two-phase heat loops utilizing capillary forces for working-fluid circulation (LHP, CPL) represent a technological evolution of the conventional heat pipe (HP). Their development was driven by the need to overcome the hydraulic and performance limitations inherent to classical HP technology.

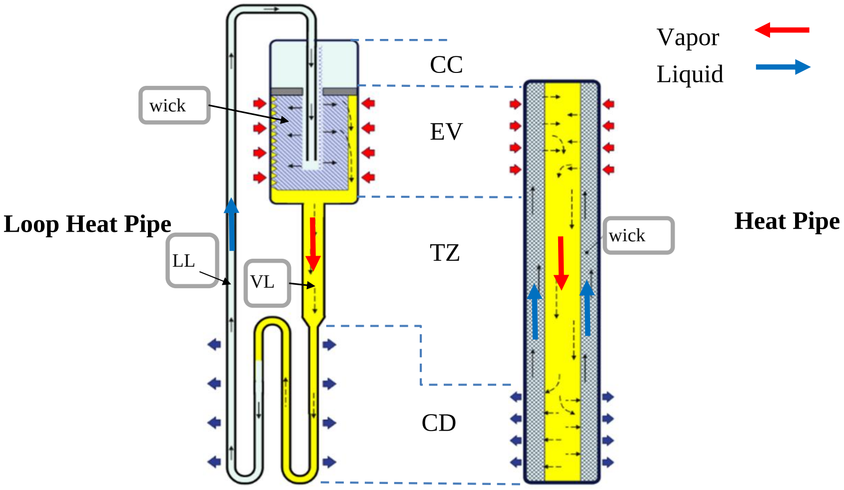


Fig. 2.1. Comparison of HP and LHP.

Fig. 2.1 schematically compares HP and LHP configurations. Both devices comprise the same fundamental functional zones: evaporator (EV), condenser (CD), and transport zone (TZ). In LHPs, an additional compensation chamber (CC) is located near the EV and serves as a fluid reservoir during transients while compensating for thermal expansion.

The principal architectural distinction between HP and LHP lies in the organization of fluid circulation. In conventional HPs, the porous structure extends along the transport zone, increasing hydraulic resistance and limiting heat-transfer distance. In LHPs, the wick is confined to the evaporator region, while vapor and liquid flow through separate transport lines. As a result, the liquid passes through a porous structure only over a short distance, allowing the use of micro-porous wicks with pore sizes on the order of micrometres. This significantly increases capillary pressure and enables heat transport over distances of several meters or even tens of meters, whereas typical HPs are limited to shorter distances (~0.5 m) and perform poorly against gravity.

A simplified comparison of hydraulic resistances for geometrically comparable devices shows that

$$\frac{\Delta P_{\mathrm{HP}}}{\Delta P_{\mathrm{LHP}}} \sim 10^5 - 10^7, \tag{2.1}$$

where ΔP_{HP} and ΔP_{LHP} denote the pressure drop in the liquid channel of HP and LHP, respectively. This order-of-magnitude difference explains the superior heat-transfer capability of LHPs under high heat-load and long-distance transport conditions.

At the same time, the geometric simplicity of a conventional HP – typically a cylindrical tube – remains advantageous for integration into many technical systems. In contrast, LHPs require separated transport lines and additional components, which increases structural complexity and complicates integration.

To combine the geometric simplicity of HPs with the hydraulic advantages of LHPs, a new thermal architecture termed “the heat loop pipe” (HLP) was proposed [4]. Its layout is shown in Fig. 2.2.

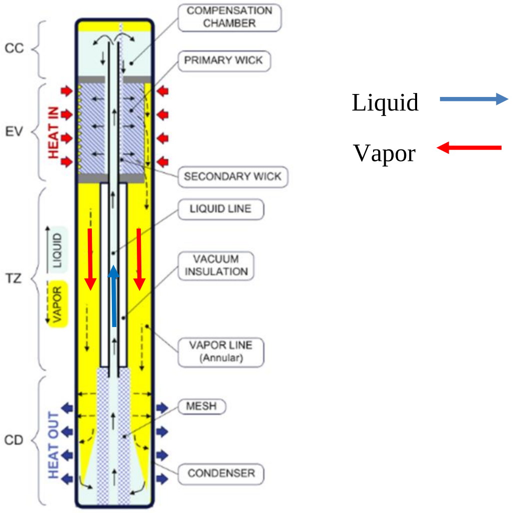


Fig. 2.2. HLP layout: EV – evaporator; CD – condenser; CC – compensation chamber; TZ – transport zone.

In this configuration, EV, CC, and transport lines are arranged within a single cylindrical housing. Vapor and liquid channels are separated, while the overall external geometry remains similar to that of a conventional HP. This allows a significant reduction of hydraulic resistance without sacrificing integration flexibility. The TZ is no longer limited by porous-structure resistance and may be extended or made flexible, enabling application in systems with complex spatial configurations. Several HLP prototypes have been manufactured and experimentally validated, including their application in LED luminaire cooling.

2.2 Altom Modular Technology – Universal Platform for the Two-Phase Heat Loops

While the HLP architecture addresses geometric integration constraints, the broader problem of scalability and technological reproducibility requires a modular design approach.

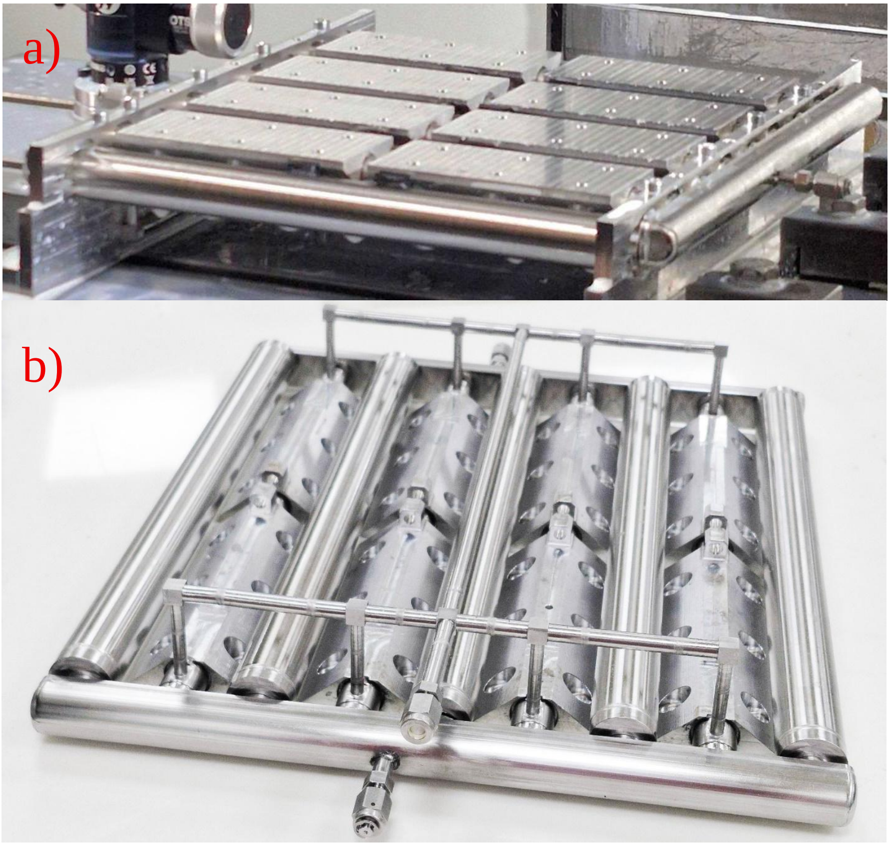


Fig. 2.3. MECOP evaporator: a) rear side view; b) top view.

Since the evaporator is the most complex and technologically demanding component of an LHP, a modular evaporator concept referred to as Altom technology was developed. In this approach, evaporators are assembled from standardized capillary pump (CP) modules with well-characterized and reproducible parameters. By connecting these modules in series and/or parallel configurations, the required heat-transfer capacity can be achieved while maintaining predictable performance.

This modular architecture enables the realization of multi-evaporator cold-plate systems, in which multiple electronic components with different thermal loads can be mounted on a single two-phase cooling platform. An example is the MECOP (Multi-Evaporator Cold Plate) configuration, which has demonstrated the capability to transfer up to 3200 W of thermal power over a distance of 6 m using ammonia as the working fluid. Such performance approaches that of pumped two-phase systems while preserving passive operation [5].

2.3 Single-Phase versus Passive Two-Phase Cooling

Fig. 2.4 schematically compares a single-phase cooling loop and a passive two-phase loop designed to accomplish identical thermal tasks.

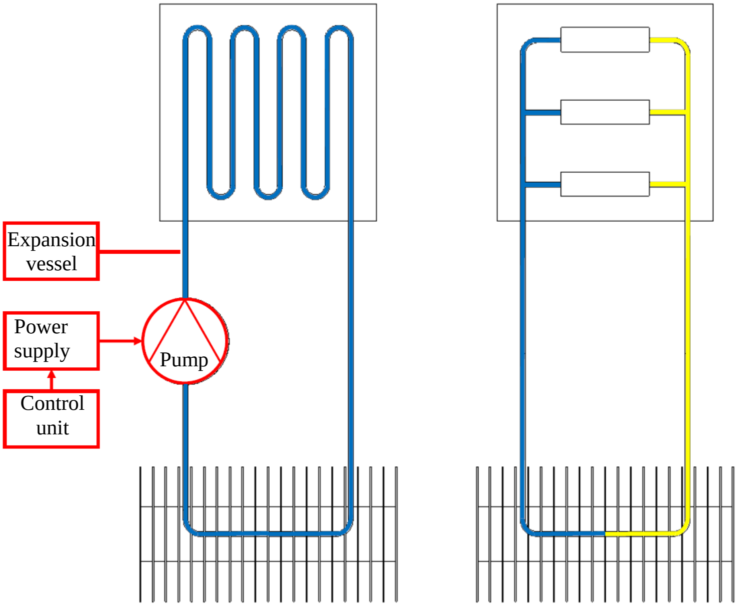


Fig. 2.4. Comparison of single-phase and two-phase cooling loops.

A single-phase loop operates exclusively in active mode and requires forced circulation of the working fluid by a pump. This necessitates additional subsystems for power supply and control, increasing both energy consumption and failure probability. In contrast, a passive two-phase loop relies on internal thermodynamic mechanisms and initiates circulation automatically when a temperature difference arises between the heat source and heat sink. Their self-initiated circulation and intrinsic thermodynamic feedback eliminate the need for external control logic, which forms the physical basis of the smart thermal management concept introduced in this work.

Beyond energetic and reliability advantages, significant differences arise in mass-flow requirements. For comparable heat-transfer power, the required mass flow rate in a single-phase system is typically an order of magnitude higher than in a two-phase loop, where latent heat transport dominates. This difference directly affects structural parameters: single-phase systems require larger transport-line diameters, greater coolant volume, and additional expansion tanks to compensate for thermal expansion. Consequently, single-phase systems are generally bulkier and less compact than equivalent passive two-phase loops.

Despite these advantages, passive two-phase loops face important challenges. Their manufacturing complexity results in higher cost, and they are typically non-serviceable devices. Moreover, phase-change processes introduce additional modelling complexity compared to single-phase systems. The further development of two-phase thermal technologies is therefore directed not only toward improving thermal performance but also toward reducing technological complexity and enhancing integration feasibility.

3 MODELLING OF PASSIVE TWO-PHASE HEAT LOOPS

3.1 General Principles of Modelling Passive Two-Phase Loops

A passive two-phase heat loop performs three functions: heat collection at the evaporator, heat transport within the loop, and heat rejection at the condenser. Modelling consists of representing each functional element by a mathematical model and coupling the elements by the conservation laws of mass and energy, complemented by continuity conditions for pressure and temperature at their interfaces.

In most engineering applications, the primary objective is to determine the steady-state temperature of the cooled device as a function of applied heat load. Therefore, steady-state modelling is often sufficient. However, in systems with large, distributed evaporators such as MECOP, the transition between equilibrium states may require several hours due to the high thermal inertia of the evaporator and the working-fluid inventory. In such cases, transient modelling becomes necessary.

3.2 Steady-State Mathematical Model of Loop Heat Pipe

The developed mathematical model belongs to the class of quasi-one-dimensional steady-state models. It determines the steady operating points of an LHP based on:

the energy-balance equation

$$\sum \dot{Q}_i = 0, \tag{3.1}$$

the pressure-balance equation

$$P_{cc}(T_{cc}) = P_{ev}(T_{ev}) - \sum \Delta P_i, \tag{3.2}$$

the mass-conservation law

$$\dot{m} = \frac{\dot{Q}_{ev}}{h_{ev}(T_{ev})} = const \tag{3.3}$$

and an iterative numerical procedure, the concept of which is described in [6]. The model accounts for heat exchange with the environment and for gravitational effects. The one-dimensional assumption is relaxed when calculating heat transfer between the evaporator and condenser and the surrounding environment.

Equation (3.1) is written sequentially for the heat-flow rates $\dot{Q}_i$ of each LHP element (EV, VL, CD, LL, CC) along the direction of working-fluid circulation.

Equation (3.2) relates the saturated vapor pressure P_{cc} in the compensation chamber to the saturated vapor pressure P_{ev} in the evaporator and allows determination of the steady-state compensation-chamber temperature T_{cc}. The summation term on the right-hand side of (3.2) represents the total hydraulic pressure drop in the loop from the evaporator to the compensation chamber. This pressure drop is calculated sequentially for each LHP element along the flow path.

In Equation (3.3), $\dot{m}$ denotes the mass flow rate generated in the evaporator, which is identical throughout the entire loop. The term $\dot{Q}_{ev}$ represents the portion of the heat load supplied by the cooled device that is used for evaporation of the working fluid, while h_{ev} is the specific enthalpy of vaporization. The external inputs are the heat load $\dot{Q}_{in}$ and ambient temperature T_{amb}. The primary output is the source temperature T_{src}.

$$\dot{Q}_{in} = \dot{Q}_{hl} + \dot{Q}_{ev}. \tag{3.4}$$

The total input heat $\dot{Q}_{in}$ is divided into evaporation $\dot{Q}_{ev}$ and heat leak $\dot{Q}_{hl}$. Although commonly treated as parasitic, the heat leak plays a fundamental thermodynamic role. Since condensation occurs at a lower temperature than evaporation, the enthalpy released during condensation exceeds that required for evaporation of the same mass flow. The steady-state regime therefore requires an additional heat-transfer path compensating for this difference. This compensation is provided by the heat leak, which balances the subcooling heat $\dot{Q}_{sc}$:

$$\dot{Q}_{hl} = \dot{Q}_{sc}, \tag{3.5}$$

where

$$\dot{Q}_{sc} = c_{p,l} \times \dot{m} \times \left(T_{ev} - T_{ll,out}\right). \tag{3.6}$$

Here, $c_{p,l}$ is the specific heat capacity of the liquid working fluid, and the liquid temperature $T_{ll,out}$ appearing in Equation (3.6) is determined from the solution of the sequence of energy-balance Equation (3.1). This equality closes the energy balance of the loop and defines the steady operating point. The heat leak may include radial conduction through the wick and additional conductive paths, which can be approximated in linear form using an effective thermal resistance parameter R_{HL}. This parameter is determined either numerically or through experimental calibration.

3.3 Transient LHP Model Based on the Thermal Dynamics of Compensation Chambers

For large multi-evaporator systems, transient behavior is governed by the thermal inertia of the compensation chambers (CCs). The model assumes that hydraulic and phase-equilibrium processes occur on time scales much shorter than thermal equilibration in the CCs. Consequently, the CC temperature T_{cc} serves as a governing state variable whose evolution determines the loop dynamics.

Under this assumption:

- mass flow adjusts instantaneously to load variations;
- pressure equalizes rapidly throughout the loop;
- evaporation and condensation temperatures follow quasi-instantaneously;
- working-fluid redistribution is fast compared to CC thermal inertia.

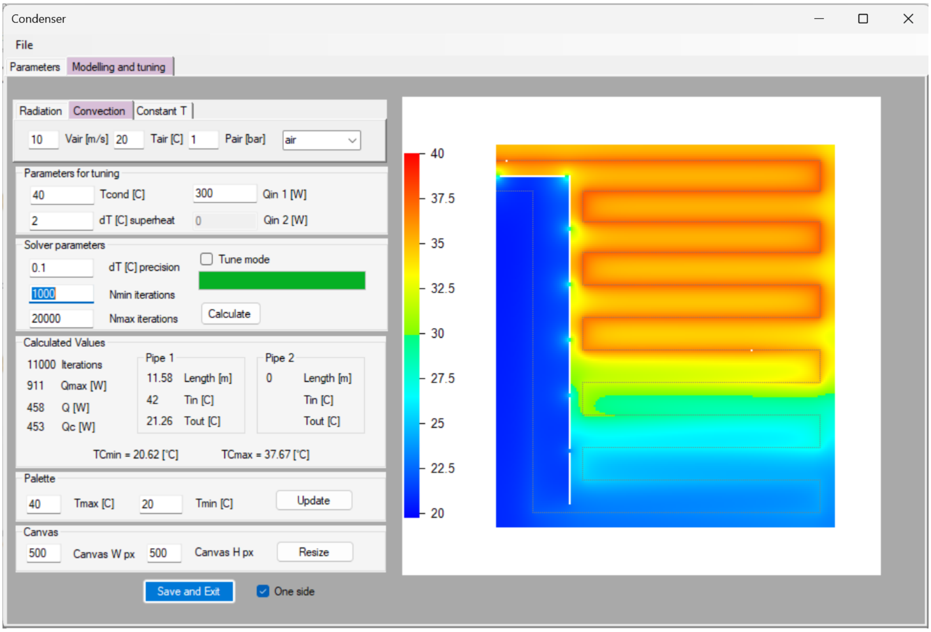
The transient model therefore reduces to the thermal dynamics of the CCs coupled with the steady-state relations. Three tuning parameters are introduced:

- bayonet conductance per unit length g_b;
- effective heat-leak resistance R_{HL};
- effective evaporator heat capacity $C_s M_s$.

These parameters are identified from experimental data and structural characteristics of EV.

3.4 The Altom-LHP Software for LHP Design and Analysis

The described steady-state and transient models were implemented in a computational tool written in C#. The software enables configuration and analysis of complex LHP systems, including multi-evaporator architectures, composite transport lines, environmental heat exchange, gravitational effects, and various condenser boundary conditions. An example of the condenser-modelling interface is shown in Fig. 3.1. The tool allows parametric studies, tuning against experimental data, and evaluation of steady and transient operating regimes for practical LHP designs.



10 Vair [m/s] 20 Tair [C] 1 Pair [bar] air

Parameters for tuning

40 Tcond [C] 300 Qin 1 [W]

2 dT [C] superheat 0 Qin 2 [W]

Solver parameters

0.1 dT [C] precision ☐ Tune mode

1000 Nmin iterations

20000 Nmax iterations

Calculated Values

11000 Iterations

911 Qmax [W]

458 Q [W]

453 Qc [W]

Pipe 1

11.58 Length [m]

42 Tin [C]

21.26 Tout [C]

Pipe 2

0 Length [m]

Tin [C]

Tout [C]

TCmin = 20.62 [°C] TCmax = 37.67 [°C]

Palette

40 Tmax [C] 20 Tmin [C]

Canvas

500 Canvas W px 500 Canvas H px

☑ One side

Fig. 3.1. Condenser modelling window.

4 EXPERIMENTAL VALIDATION OF PASSIVE TWO-PHASE HEAT LOOPS IN ELECTRICAL SYSTEMS

The hypothesis is verified using four types of devices that differ in heat-load level, geometry, spatial distribution of heat generation, operating modes, and requirements for temperature stability:

- in-wheel electric motor;
- LED luminaire;
- fuel cell;
- traction motor.

The results obtained for the first three devices are presented in this Thesis and have been published in the form of scientific articles [7]–[9].

For the traction motor application, a cooling system based on six loop thermosiphons was developed and experimentally tested. The complete results of this study are not included in the present Thesis; however, selected findings have been partially published in [10].

4.1 In-Wheel Electric Motor

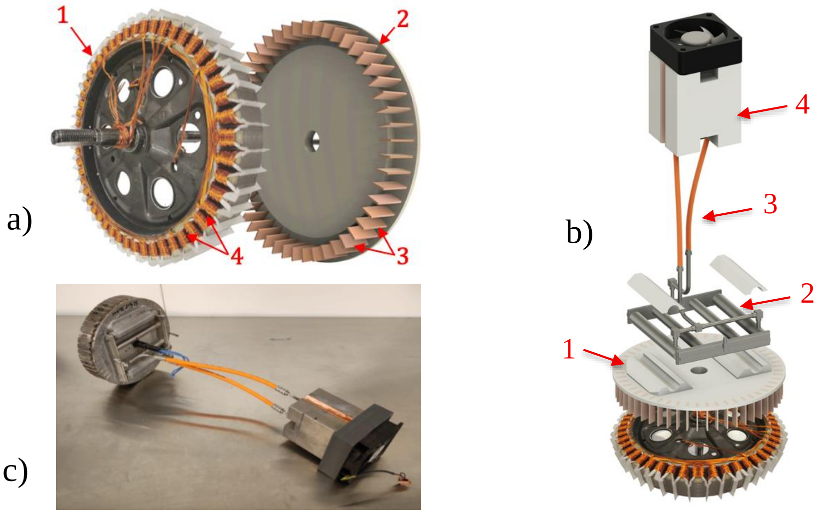


Fig. 4.1. a) LHP – stator interface: 1 – stator; 2 – interface; 3 – copper fins; 4 – gaps in winding. b) LHP structure: 1 – interface; 2 – capillary pumps; 3 – transport lines; 4 – condenser. c) Photograph of the motor with integrated LHP.

An in-wheel electric motor with an integrated three-phase induction machine (rated power 500 W) was selected as a test object. Based on the manufacturer's declared efficiency, the expected thermal losses were approximately 70 W, primarily generated in the stator windings.

In the baseline configuration, heat from the winding propagates through the stator core and across the air gap to the motor housing, where it is dissipated by natural convection. To enhance direct heat extraction from the winding region, a dedicated thermal interface incorporating two Altom capillary pumps was developed (Fig. 4.1 a)). The relatively large stator diameter (~200 mm) required distributed heat collection over a wide surface, which determined the use of a multi-evaporator configuration.

Flexible polymer transport lines were employed to demonstrate the integration potential of the LHP architecture. Heat rejection was achieved by a compact finned condenser operating under forced convection. The complete system layout and integrated motor assembly are shown in Fig. 4.1 b) and Fig. 4.1 c).

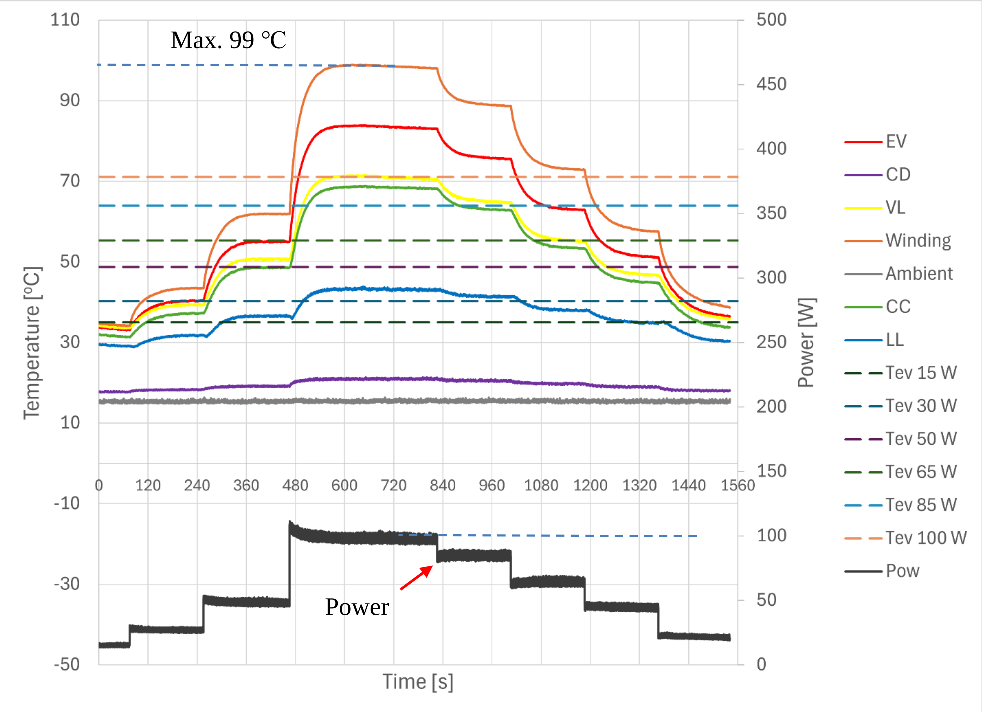


Fig. 4.2. Temperature distribution over LHP for different powers. The stator is thermally isolated. EV – evaporator and saddle; VL – vapor line; LL – liquid line; CC – compensation chambers; CO – condenser's fins. The dashed lines correspond to the vapor temperatures calculated based on the model.

Experimental testing revealed that heat removal through the LHP operated in parallel with the conventional heat path through the motor hub, resulting in a substantial increase in admissible thermal load. The allowable heat dissipation increased by approximately 2.5 times compared to the baseline configuration. Considering that the motor had been modified under laboratory conditions to accommodate the evaporator interface (which reduced the effective winding cross-section), the net performance gain can be conservatively estimated at approximately 1.8 times.

These results demonstrate that the maximum benefit of two-phase cooling is achieved when the evaporator architecture is integrated at the motor design stage rather than retrofitted. A conceptual stator design with structurally integrated evaporators is proposed in this work.

Comparison of experimental data with predictions obtained using the Altom-LHP model confirmed the adequacy of the developed mathematical framework. As shown in Fig. 4.2, the calculated vapor temperature closely follows the measured values (yellow curve), indicating correct representation of mass flow and pressure balance within the loop.

4.2 LED Luminaire

The HLP architecture was successfully implemented for thermal management of a high-intensity LED luminaire. The combination of geometric configuration and enhanced heat-transport capability enabled the development of a compact lighting device with a localized high-power light source.

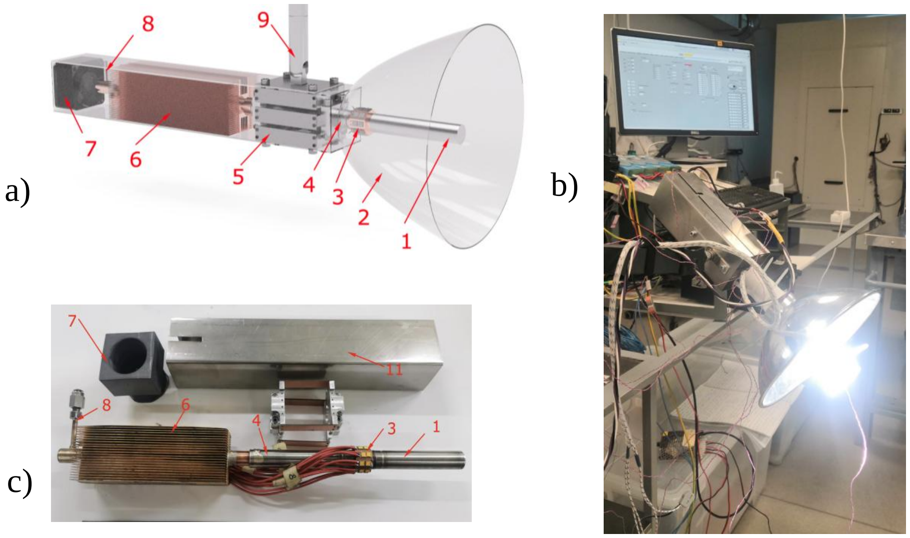


Fig. 4.3. a) HLP-based luminaire architecture: 1 – compensation chamber; 2 – parabolic reflector; 3 – evaporator with 18 LEDs; 4 – transport zone; 5 – LED drivers; 6 – CD with air heat exchanger; 7 – fan; 8 – charging port. b) Luminaire in test setup. c) Cooling system components.

As shown in Fig. 4.3 a), the cylindrical HLP serves not only as a heat-transfer element but also as the structural backbone of the luminaire. This dual functionality simplifies mechanical integration and reduces overall system mass. Eighteen LEDs were mounted directly on the evaporator housing, forming a compact light source located at the focal point of a parabolic reflector. This configuration ensures a quasi-parallel luminous flux while maintaining unobstructed optical geometry.

The luminaire prototype, including LEDs and reflector but excluding driver electronics, has a total mass below 1.2 kg. The HLP was charged with 20 g of n-butane as the working fluid.

Experimental testing was conducted for different spatial orientations relative to gravity and at input powers ranging from 10 W to 80 W.

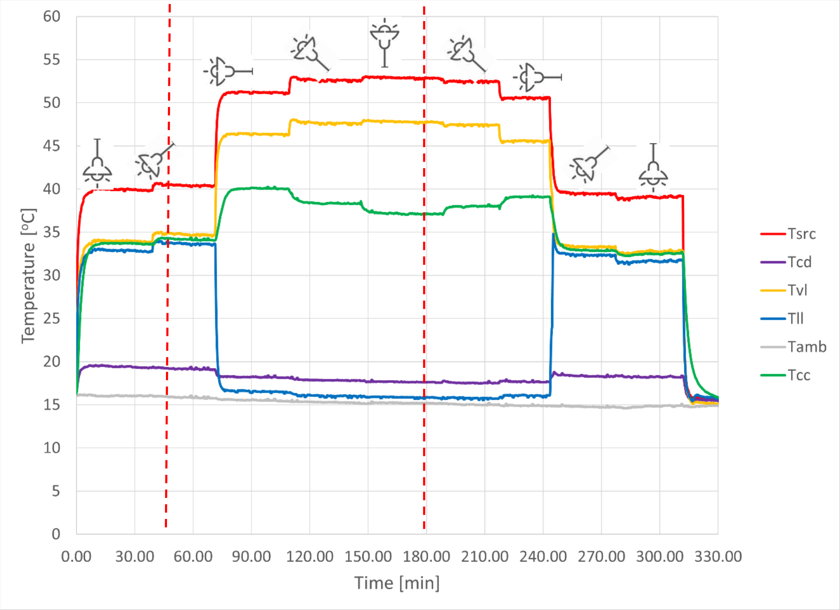


Fig. 4.4. Temperature measurement locations and temperature profiles at various luminaire orientations (LED power 60 W).

The experiments demonstrated that the HLP maintained LED temperatures within the allowable range across the investigated power levels. However, orientation tests revealed a significant increase in HLP thermal resistance when the condenser was positioned at the same level as, or below, the evaporator.

The observed effect was analysed theoretically. It was shown that the gravitational head alone cannot explain the measured resistance increase. A physically consistent interpretation is obtained by assuming that, under gravity-unfavorable orientations, the evaporation front recedes deeper into the wick structure, leading to partial vapor superheating before entering the vapor line.

This regime does not represent a fundamental limitation of the HLP concept but rather a design-sensitive operating condition. It may be mitigated through further optimisation of wick geometry, capillary structure, and hydraulic configuration of the transport channels.

4.3 Fuel Cell Stack

Despite the well-recognized advantages of passive two-phase devices, reliable integration of heat-loop architectures at the proton exchange membrane fuel cell (PEMFC) cell level remains an unresolved challenge. The evaporator, in particular, represents the key limiting element, as it must simultaneously satisfy strict geometric, electrical, and thermodynamic constraints.

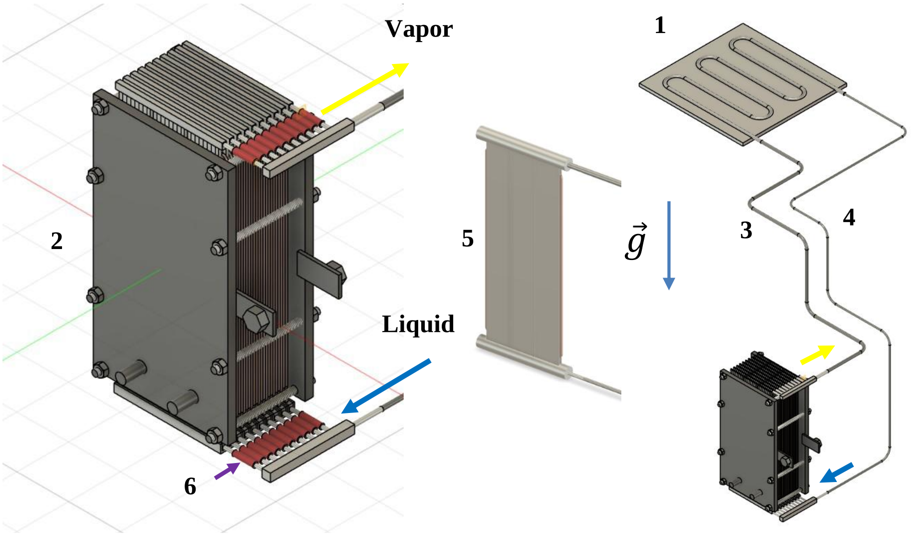


Fig. 4.5. PEMFC two-phase heat loop layout: 1 – condenser; PEMFC stack; 3 – riser (vapor line); 4 – downcomer (liquid line); 5 – flat evaporator; 6 – insulating inserts.

The layered architecture of PEMFC stacks effectively restricts evaporator geometry to flat configurations compatible with bipolar plates (BPs). At the same time, the stack forms an electrically series-connected system. Therefore, evaporators integrated into a common heat loop must be electrically conductive to maintain compatibility with the BP environment, yet electrically isolated from each other to prevent parasitic current paths.

To address these constraints, a conceptual multi-evaporator loop thermosyphon (LTS) architecture was proposed (Fig. 4.5).

Aluminium was selected as the primary structural material due to its low density and acceptable electrical compatibility. The working fluid was chosen based on dielectric properties, compatibility with aluminium, operating temperature range (both LT-PEMFC: 60–80 °C and HT-PEMFC: 120–200 °C), moderate vapor pressure, and favorable thermophysical characteristics. Toluene was selected, as it is electrically insulating, compatible with aluminium, and thermodynamically suitable for both low- and high-temperature PEMFC operation. LT-PEMFC operation corresponds to sub-atmospheric pressures, while HT-PEMFC operation occurs at moderate overpressure.

The experimental study focused on identifying an optimal evaporator configuration suitable as a building block for a full-scale system. Four evaporator variants (wickless and wick-assisted) were investigated in thermosyphon configurations with different condenser positions.

Microchannel aluminium flat tubes (MAFTs) with thicknesses of 2.15 mm and 3.72 mm were used for evaporator fabrication. For practical integration into bipolar plates, a target thickness on the order of 2 mm was established.

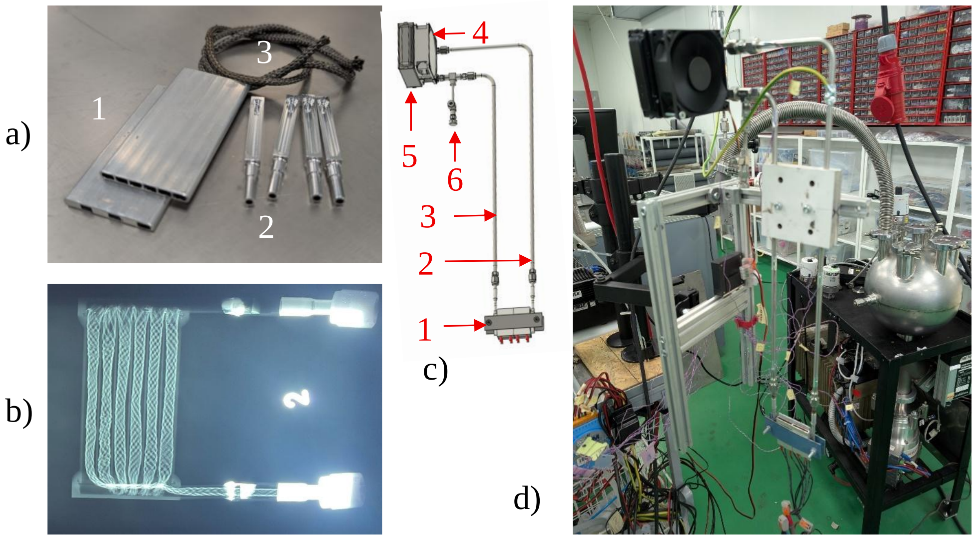


Fig. 4.6. a) Evaporator components: 1 – evaporator body; 2 – side manifolds; 3 – wick. b) Internal wick-assisted structure. c) LTS configuration: 1 – evaporator; 2 – riser; 3 – downcomer; 4 – condenser with air heat exchanger; 5 – fan; 6 – charging port. d) Test setup.

The experiments demonstrated that wick-assisted evaporators provide superior operational stability. As shown in Fig. 4.7, start-up was achieved at a superheat of approximately 7 °C, with an initial required input power of about 8 W (reducing to ~5 W after accounting for environmental heat losses). The presence of a wick also enabled stable operation during abrupt power increases of 40 W, which was not achievable in wickless configurations.

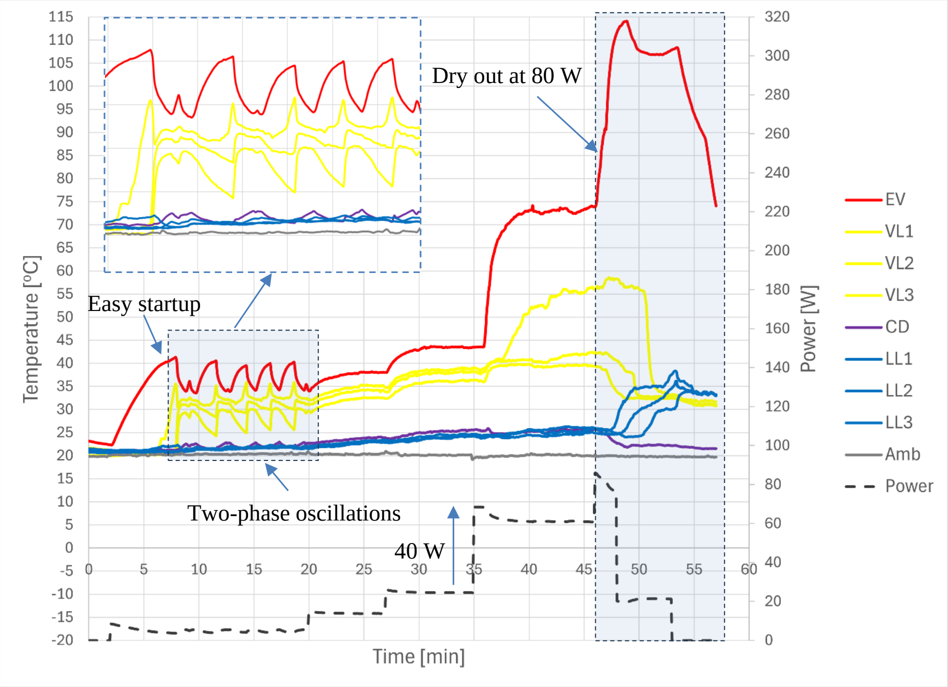


Fig. 4.7. LTS testing with a wick-assisted evaporator.

Dry-out occurred at approximately 80 W, corresponding to a heat-flux density roughly twice that typical for PEMFC applications. This indicates a sufficient operational margin for practical implementation. Importantly, the tested evaporator thickness remained compatible with bipolar-plate integration requirements.

High-temperature experiments confirmed the expected improvement in thermosyphon performance due to the thermophysical properties of toluene. This result supports the universality of the proposed architecture for both LT-PEMFC and HT-PEMFC systems.

CONCLUSIONS

The working hypothesis stated that replacing conventional cooling systems with passive two-phase heat loops, designed in accordance with the structural and thermal characteristics of a specific device, leads to modification of its thermal regime and improvement of its technical characteristics.

The conducted theoretical and experimental investigations confirm this hypothesis.

For the in-wheel electric motor, integration of a loop heat pipe-based cooling system increased the allowable thermal load and reduced operating temperature. The proposed stator architecture with structurally integrated evaporators demonstrated the feasibility of direct heat extraction from stator teeth and reduction of internal temperature gradients, indicating the importance of early-stage integration of two-phase cooling in motor design.

For the LED luminaire, implementation of the Heat Loop Pipe architecture enabled efficient heat removal from a concentrated source while preserving compact cylindrical geometry and optical functionality. The analysis of orientation-dependent behavior clarified the governing physical mechanisms and identified design-sensitive operating regimes.

For the fuel-cell stack, experimental investigation of thin aluminium loop thermosyphons demonstrated stable operation within PEMFC-relevant heat-flux ranges. The feasibility of cell-level integration was established, and the key parameters governing startup stability and operational margins were identified. The results confirm the applicability of passive two-phase loops to both low- and high-temperature PEMFC systems.

The scientific contribution of the Thesis consists of the development of a unified conceptual, theoretical, and experimental framework for the application of passive two-phase heat loops as smart thermal-management systems.

The concept of smart thermal management was introduced as a class of systems based on intrinsic thermodynamic feedback mechanisms enabling autonomous heat-flow redistribution without external energy input. In contrast to active cooling systems, such loops inherently adjust their operating state to boundary conditions.

A thermodynamically consistent interpretation of heat leak and subcooling in loop heat pipes was developed, establishing their fundamental role in closing the steady-state energy balance of the loop and resolving common misconceptions regarding so-called parasitic heat flows.

A steady-state and transient mathematical model of loop heat pipes was formulated, incorporating environmental heat exchange, gravitational effects, and internal energy redistribution. An algorithm for model tuning based on experimental data was proposed, along with a method for estimating parameters not directly measurable.

Working-fluid quality parameters for loop thermosyphons were introduced, extending the classical figures-of-merit approach to gravity-driven systems.

A new heat-transfer architecture – the heat loop pipe – was proposed, combining the compact cylindrical geometry of conventional heat pipes with the hydraulic advantages of loop heat pipes.

A modular evaporator technology (Altom) was developed, enabling scalable construction of multi-evaporator cold plates and facilitating the transition from specialized loop heat pipe systems toward universal two-phase platforms.

Collectively, these results establish a methodological foundation for extending passive two-phase heat-loop technology beyond highly specialized applications toward broader classes of electrical equipment.

Further advancement of this technology – particularly in the areas of manufacturing simplification, integration with electrical architectures, and enhancement of operational robustness – may significantly expand its industrial applicability and contribute to the development of energy-efficient thermal-management systems.

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His research interests include two-phase heat transfer, loop heat pipes (LHP), thermosyphons, and smart thermal management of electrical equipment.