

Article

Design of Real-Time Browser-Based Platform for Thermohydraulic Characterization of a Laboratory Heat Exchanger Using PolyVR

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Abstract

This paper presents a real-time browser-based platform for thermohydraulic characterization of a compact laboratory heating system, developed using the PolyVR research-grade virtual reality engine. Experimental measurements are retrieved at 1 Hz from a cloud-based database and processed via browser-native computational framework that continuously performs thermophysical modeling, hydraulic analysis and energy balance evaluation. The system calculates the rate of heat transfer ($\dot{h}$), overall heat transfer coefficient (U), dimensionless numbers (Re , Pr , Gr , Nu), pump performance, heater efficiency and cumulative thermal energy. PolyVR provides the immersive environment in which the partial digital twin functionality is integrated alongside the browser-based thermohydraulic calculations. The whole system includes support for animations regarding flow diagrams, valve state indicators, thermal field visualization and manipulation of system elements. The system architecture is designed to work on desktops, head-mounted devices, as well as in CAVE (cave automatic virtual environment) systems with remote connection made possible via using ngrok tunnels. The experiments were separated into three categories (steady-state, dynamic and validation). Steady-state and dynamic datasets show that the browser computation with PolyVR achieves high-fidelity thermohydraulic analysis similar to that done in laboratory settings. The steady-state and transient datasets illustrate that browser-based computation provides highly accurate thermohydraulic simulation close to that of the laboratory reference computations. For all experiments performed on the platform, the deviation of measurements does not exceed ± 0.5 K in temperature, $\pm 5\%$ in flow rate and $\pm 1\%$ in pressure. The energy balance is closed with a deviation of $\pm 2\text{--}3\%$.

Keywords: cyber-physical system; digital twins; heating systems; thermal sensors; thermodynamics



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1. Introduction

In real-time thermohydraulic characterization, which is an essential part of designing, optimizing and operating modern energy systems, thermal process equipment and engineering laboratories, the experimental study of heat exchanger and heating systems involves collecting and analyzing data related to temperature, flow rate, pressure and electrical properties to analyze heat transfer characteristics and hydraulics and overall energy efficiency. Standard laboratory DAQ (data acquisition) systems usually employ proprietary

software, local computing and hardware interfaces, which affect the accessibility, scalability and interoperability of DAQ systems [1,2].

Rapid advancements in the fields of cloud computing, IoT (Internet of Things) and browser-based scientific computing have greatly increased the capabilities of contemporary engineering tools [3–6]. Sensor nets that are cloud-enabled provide a reliable method for real-time delivery of data, which was obtained during experiments, whereas improvements in web-based technologies, including WebAssembly, make it possible to implement computational heavy numerical algorithms inside browsers at near-native application speeds [5–7]. This type of innovation is facilitated by the use of distributed engineering processes where one can experiment and collaborate remotely in the analysis of data without the installation of any special software. Moreover, recently conducted studies prove the growing importance of laboratory IoT infrastructure in thermal devices. Cloud computing monitoring technologies were successfully used for the constant acquisition of data on temperature, pressure, flow and electrical characteristics, which facilitates the diagnostics of the equipment, performance evaluation and preventive maintenance [3]. At the same time, the technology of digital twins proved to be a good way to combine the data of experiments and numerical modeling, allowing for monitoring, forecasting system performance and optimizing the process of operation [8,9]. Recently, the use of this technology for the purposes of heat exchangers was tested in the conditions of experimental operations [10,11]. However, despite these successes, platforms for web engineering are currently focused mainly on simulation and designing, but not on the experimental characterization of processes [4–7,12,13]. Also, there are many laboratory systems using IoT, where the process of data collection and visualization takes place, but the calculation of thermohydraulic processes is carried out offline using desktop engineering software [3]. As a consequence, not many approaches integrate cloud computing with interactive visualization on a single platform for use in engineering research and laboratory training [3–6,12,13]. Modern thermal and energy digital twin systems generally include features like real-time monitoring, predictive modeling, analysis and supervisory control, whereas browser-based engineering systems typically include simulation, design and numerical computation. Likewise, IoT laboratory systems have shown capability in terms of real-time data acquisition and visualization, with further engineering analysis usually done by special software. Laboratory environments created with the help of VR and AR (augmented reality) technologies allow one to visualize interaction and even incorporate real-time experimental data, depending on the case. Nevertheless, these reviewed systems differ in the way these features are combined with browser-based thermohydraulic computation and physical system measurements. In order to highlight the unique characteristics of HeatLab regarding these types of solutions, Table 1 provides a comparative overview of recent digital twin, web-based and VR/AR laboratory systems considering key capabilities pertinent to this research, such as physical experimentation, real-time sensing, cloud connection, computations in the browser, thermohydraulic analysis, immersion, interaction with physical objects and experimental validation. In summary, the comparative study shows that HeatLab enables a combination of continuous measurements of physical systems, calculation of thermal and hydraulics properties via browser computing, and visualization of both browser and VR simultaneously in one experimental setup. In addition, the whole process of measurement to computation is assessed numerically through validation experiments. The significance of HeatLab is not in the use of one technology but in the combination of all these technologies in one experimental setup.

Table 1. Comparative analysis of representative laboratory and digital twin systems.

REF	APP	PE	RTS	DT	BNC	THC	VR/AR	PSI	EV
[10]	Heat-exchange station	+	+	+	—	+	—	+	+
[14]	Jet-pump laboratory	+	+	+	—	+	+	+	+
[15]	Wind-tunnel laboratory	+	+	—	—	+	+	+	+
[16]	Engineering laboratory	—	—	—	—	—	+	+	+
[17]	Biomedical laboratory	—	—	—	—	—	+	—	+
[3,5,6,11]	Scientific computation	—	—	—	+	—	—	—	+
HeatLab	Water heating system	+	+	partial	+	+	+	+	+

REF—reference; APP—application; PE—physical experiment; RTS—real-time sensing; DT—digital twin; BNC—browser-native computation; THC—thermohydraulic computation; VR/AR—virtual/augmented reality; PSI—physical system interaction; EV—experimental validation. “+” indicates that the capability is explicitly reported in the cited work; “—” indicates that it is not reported; “partial” indicates that the capability is available only to a limited extent.

Deficiency in this regard is solved in this paper by developing a real-time browser-based tool for thermohydraulic characterization of a compact water-to-water laboratory heat exchanger. Real-time data is gathered from the cloud database at a sampling rate of 1 Hz and all the thermophysical computation is done in the browser itself. The computational scheme computes the instantaneous heat transfer coefficient h , Reynolds number (Re), Prandtl number (Pr), Nusselt number (Nu), Grashof number (Gr), pump hydraulic efficiency (η_{hyd}) and performance, heater performance and total thermal energy transferred. Additionally, the tool has real-time process flow animation, valve status monitoring and thermal imaging capability. The innovations of this research include:

- Cloud-enabled DAQ architecture for conducting real-time thermohydraulic experiments;
- Browser-native computational engine for thermophysical and hydraulic analyses;
- Interactive visualization environment for laboratory monitoring;
- Experimental evaluation of the proposed platform through its application to steady-state and transient conditions.

The proposed architecture serves as a scalable basis for browser-based remote laboratories, partial digital twin applications and engineering education in thermofluidic systems. The scientific innovation of the present research resides in the real-time combination of cloud-based measurement acquisition, browser-native thermohydraulic computation and visualization within one framework. The existing IoT laboratory solutions only enable measurement streaming or offline analysis but not complete thermophysical modeling, hydraulic analysis and compliance with the EN 442 [18,19] energy balance calculation in the browser. Immersive virtual reality (VR) is another powerful technology for visualization and interaction with thermohydraulic systems. Several thermal phenomena—such as flow field, temperature profile and transient energy transfer—cannot be observed in physical labs and are difficult to visualize. With the integration of the browser-native physics engine in PolyVR, the proposed platform enables real-time visualization of partial digital twin representations, supporting immersive manipulation and observation of system behavior. The integration allows experiments to move from a simple measurement exercise to an interactive VR lab experience.

2. Materials and Methods

The physical experimental setup is shown in Figure 1a and the principal scheme is shown in Figure 1b. The laboratory bench [2,20] represents a thermohydraulic closed loop water system that consists of a laboratory heat exchanger, HE-001 (double steel panel

type 22 K radiator; Korado a.s., Česká Třebová, Czech Republic); a heater block, B-001 (ELTHERM MM6 electric boiler; Erato, Haskovo, Bulgaria); a three-speed circulation pump, P-001 (RS 25/6-180; Norwik, Casella d’Asolo, Treviso, Italy) [21]; and an expansion vessel, EV-001 (BG Therm, Sofia, Bulgaria). The system is filled with water from the main water supply network through a control valve (CV-009) at a certain pressure, allowing rapid conduct of the experiment (150 kPa). After filling the system, adjustable valves are regulated (CV-001–CV-008) in order to reach the required connection scheme, which is represented in Table 2. After choosing the required connection scheme, the circulating pump is turned on. By means of automatic deaerator AD-001, air from the system is removed. Once there is no air in the system, heater block B-001 is turned on. If the pressure in the system rises, safety valve SV-001 with a pressure limitation of 250 kPa opens and discharge of the system is carried out. The power of the circulation pump and heater block is controlled via a control panel, CP-002, and an autotransformer, AT-001 (VEMARK, Plovdiv, Bulgaria). There are seven DS18B20 (Maxim Integrated, San Jose, CA, USA) temperature sensors (T1–T7) for measuring inlet/outlet, surface and ambient (room) temperature. The Hall-effect flow meter, FM-001 (YF Technology Co., Shenzhen, China), provides the volumetric flow rate measurement; for measurement of the pump head, there are two pressure sensors, M-001 and M-002 (BOLA spol. s.r.o., Charkovská, Czech Republic), which are, respectively, mounted before and after the circulation pump. Electrical variables such as voltage, current, power and energy consumption are acquired from the heater and pump modules.

Table 2. Control valve positions depending on the connection scheme.

Valve	Connection Scheme					
	TBD	TBU	BTD	BTU	TT	BB
001	C	C	O	C	O	C
002	O	C	C	C	C	O
003	O	O	C	O	O	C
005	C	O	O	O	C	O
006	C	O	C	C	C	C
007	C	C	O	O	C	O
008	O	O	C	C	O	C

TBD—top–bottom (diagonal); TBU—top–bottom (unilateral); BTD—bottom–top (diagonal); BTU—bottom–top (unilateral); TT—top–top; BB—bottom–bottom; O—opened; C—closed.

The entire workflow is shown in Figure 2. Real-time data acquisition is done by means of the Firebase Realtime Database (Google LLC, Mountain View, CA, USA) [22]. Sensor modules send temperature, flow rate, pressure and electrical measurements at 1 Hz, providing the possibility of remote experiments and IoT measurement acquisition synchronization. The system receives each measurement frame asynchronously, including:

- T1–T7 temperatures;
- Raw flow meter pulses, filtered in L/min, volumetric flow (m^3/s);
- Pressure measurements in kPa;
- Electrical measurements from heater block and pump;
- Measurement calibration information;
- Valve statuses.

The tolerance of the flow meters is checked against nominal values (0.03, 0.08 and $0.12 \text{ m}^3/\text{h}$) with an acceptance band $\pm 5\%$. The specifications of all sensors used in the experimental platform are provided in Table 3. The table shows the range of measurement, resolution, sampling frequency and position of each sensor.

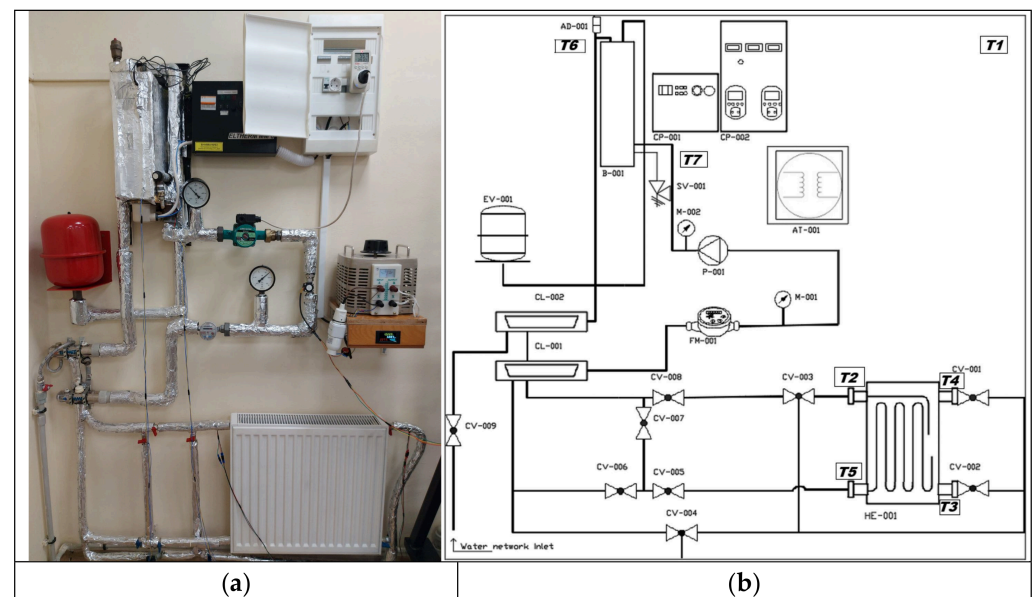


Figure 1. (a) Thermohydraulic laboratory bench physical representation. (b) Principal scheme of the laboratory bench.

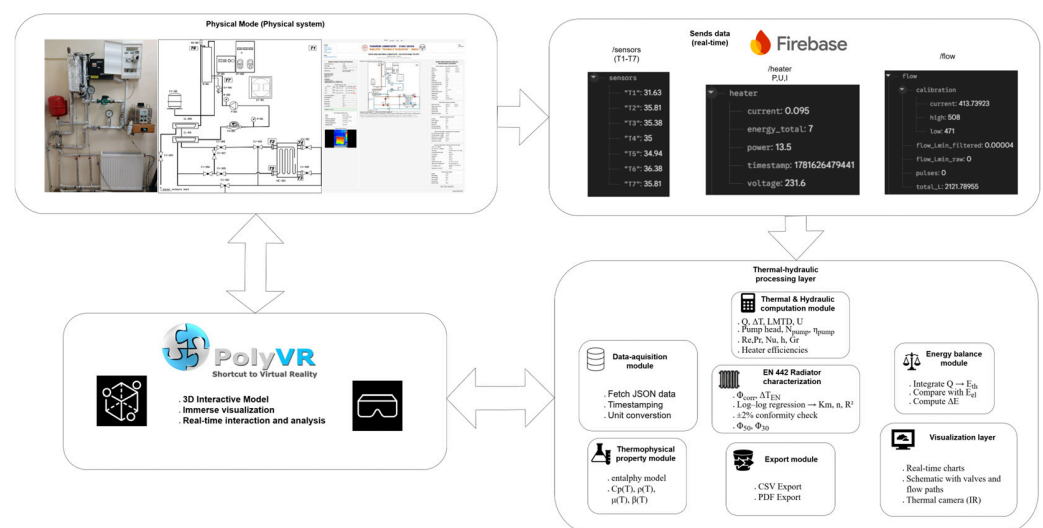


Figure 2. Workflow of the designed platform.

The entire platform (HeatLab) is implemented in PolyVR (PolyVR—Victor Haefner, GitHub Repository; Version 26.07) [23,24], a research-grade virtual reality 3D engine developed at the Institute for Information Management in Engineering (IMI), Karlsruhe Institute of Technology (KIT), in 2009. PolyVR has several capabilities essential for this work, such as:

- Modular architecture—enables rapid extension with new computational modules and visualization components;
- Open-source foundation—built on OpenSG and OpenGL, providing a high-performance scene-graph backbone with clustering and threading;
- Scalable deployment—supports cave automatic virtual environments (CAVEs) [25], visualization clusters, desktops, head-mounted devices (HMD) and 3D displays;
- Flexible device integration—through VRPN, ARTTMDTrack and HTTP sockets, PolyVR interfaces with tracking systems, mobile devices and external simulations;
- Rich data import—supports glTF, COLLADA, VRML, STL, OBJ, IFC, STEP, E57, SVG, DWG, DXF and more.

Table 3. Sensor specification and sampling rates.

Sensor Type	Measured Quantity	Range/Resolution	Sampling Rate	Location in System	Interface Protocol
DS18B20 digital sensor	Temperature	−55 to 125 °C, ±0.5 °C	1 Hz	T1–T7 (inlet, outlet, radiator surface, ambient)	1-Wire digital
Hall-effect flow meter YF-S201	Volumetric flow rate	0–30 L/min, ±5%	1 Hz	Main loop return line	Pulse counting -> cloud-filtered
Pressure sensor M-001	Gauge pressure	0–400 kPa, ±1%	1 Hz	Pump inlet	Analog-ADC-cloud
Pressure sensor M-002	Gauge pressure	0–400 kPa, ±1%	1 Hz	Pump outlet	Analog-ADC-cloud
Heater electrical module	Voltage, current, power, energy	V: ±1%; I: ±1%, P: ±2%	1 Hz	Heater block (B-001)	Digital (cloud JSON)
Pump electrical module	Electrical power	±2%	1 Hz	Pump (P-001)	Digital (cloud JSON)
Testo 860i thermal camera	Radiator surface temperature field	256 × 192 px thermal map	9 Hz	Radiator frontal surface	Virtual camera stream

Here, PolyVR is the runtime host for a browser-native computational engine, the visualization engine for animated hydraulic diagrams, valve sensors, flow markers, streaming thermal cameras and local servers for offline execution on laboratory computers. In addition, when PolyVR is tunneled via ngrok (ngrok Inc., San Francisco, CA, USA; Version 3.X) [26], it becomes the public host for the visualization system, thus allowing remote participation in live experiments. The cross-platform functionality of the system has been verified using both the PICO 4 headset (PICO Interactive Inc., Beijing, China) and a custom-built CAVE system named MAGURA. Thus, the research background of PolyVR and its extensible architecture make it a reliable starting point for building browser-native partial digital twin functionality.

The complete pipeline of visualization is demonstrated in Figure 3, starting from the physical laboratory system in Figure 3a, followed by a PolyVR virtual replica in Figure 3b, implementation in the MAGURA CAVE immersive environment in Figure 3c, and user interaction in Figure 3d. All the computations of thermohydraulic properties are done directly in the browser by means of JavaScript and WebAssembly compatible functions, without usage of external numerical libraries and server-side computing. When a new frame from the sensors (1 Hz) is received, a complete update of thermophysical properties, hydraulics, thermal performance indicators and dimensionless numbers takes place in order to ensure synchronized visualization and analysis in the PolyVR environment. All internal calculations are done exclusively in SI units (K, Pa, m³/s, kg/s, W, J), providing physical consistency and EN 442 standard compliance [18,19]. For user clarity, the platform simultaneously displays both SI and “user-friendly” units, such as temperature in K and °C, flow rate in m³/s, L/s, L/min and mass flow in kg/s, as shown in Figure 4.

Representative performance measures of the browser-native computing and communication chain were measured during a 100-iteration real-time experiment (Figure 5). Browser computation time remained consistently low, with an average 6.12 ms (min 2.10 ms, max 35.6 ms). The communication delays exhibited higher variability where heater delay averaged 1603 ms, flow delay averaged 1521 ms and sensor delay averaged 1670 ms, with occasional peaks caused by cloud-side congestion. End-to-end latency, defined as the total time from sensor acquisition to browser-side visualization and thermohydraulic update,

averaged 10.14 s, ranging between 0.67 s and 20.98 s. Since all measurements are retrieved through cloud endpoints, the communication delays and the resulting end-to-end latency depend strongly on the stability and bandwidth of the internet connection. Local browser computation remains fast and stable, while network conditions dominate the overall responsiveness of the system. The thermophysical characteristics of water are determined using empirically based correlations which are chosen on account of their accuracy at the operating range of the radiators and heating systems (293.15–353.15 K). Water density is calculated using linearized correlation, presented in Equation (1).

$$\rho(T) = 1000 - 0.3(T - 293.15), \left[\text{kg/m}^3 \right] \quad (1)$$

In order to verify the correctness of the linearized density correlation, the computed values were verified against the reference data on water properties taken from the IAPWS formulation for the thermodynamic properties of normal water substance [27]. Absolute and relative errors were calculated using Equation (2) and Equation (3), respectively.

$$e_{abs} = \left| \rho_{model} - \rho_{ref} \right|, \left[\text{kg/m}^3 \right] \quad (2)$$

$$e_{rel} = \frac{\left| \rho_{model} - \rho_{ref} \right|}{\rho_{ref}} \cdot 100, [\%] \quad (3)$$

Comparison of the calculated density value with that of the reference is given in Table 4.

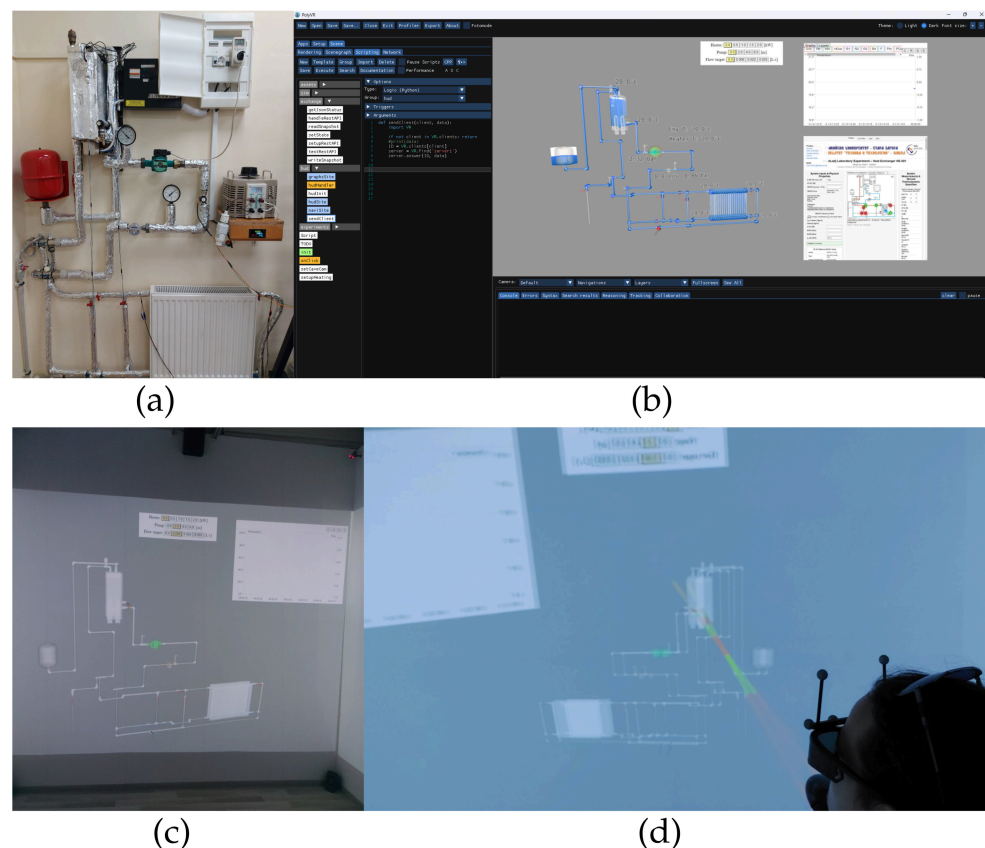


Figure 3. Overview of the PolyVR-based visualization pipeline for the HE-001 partial digital twin (a) physical laboratory system. (b) VR model of the system (PolyVR rendering). (c) MAGURA CAVE deployment (triple-wall projection). (d) User interaction with VR.

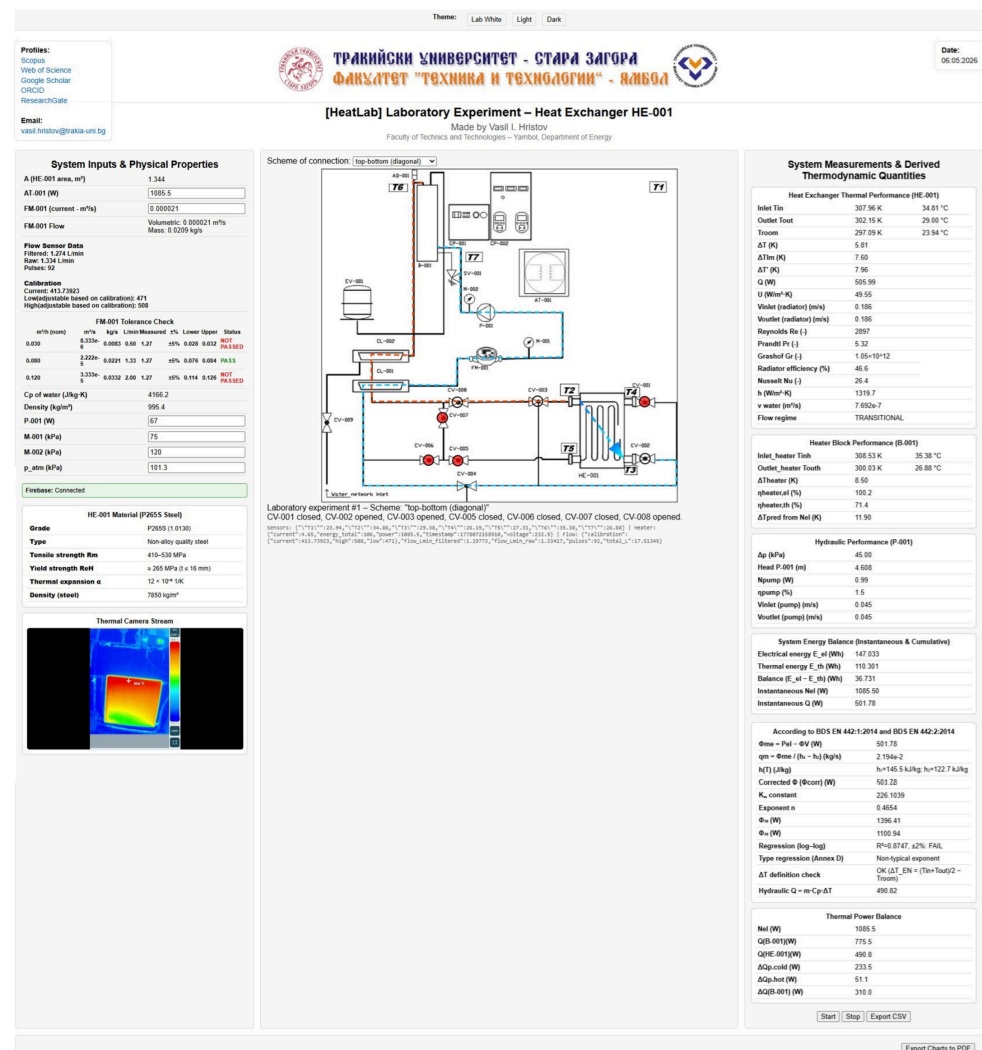


Figure 4. HeatLab UI during a laboratory experiment showing values in both SI and “user-friendly” units.

Table 4. Comparison of linearly correlated water density with reference values.

Temperature	Temperature	Calculated Density	Reference Density	Relative Error
[°C]	[K]	[kg/m ³]	[kg/m ³]	[%]
20	293.15	1000.0	998.2	0.18
40	313.15	994.0	992.2	0.18
60	333.15	988.0	983.2	0.49
80	353.15	982.0	971.8	1.05

Based on the analysis of the comparison, it can be said that there exists relative deviation from the linearized correlation within approximately 1.1%. Thus, the correlation can be regarded as adequate enough for the current thermohydraulic analyses since it will be mainly used to determine the mass flow rate through water density. Density is determined by a linear correlation that is applicable between 293.15–353.15 K to ensure proper calculation of mass flow and hydraulic power. The correlation accounts for the decline in density with increase in temperature in the process of calculating mass flow,

Re number and hydraulic power. The specific heat capacity is determined as shown in Equation (4)

$$c_p(T) = 4184.4 - 0.9(T - 293.15), \text{ [J/kg}\cdot\text{K]} \quad (4)$$

Equation (4) can be regarded as a simple linear equation that illustrates the temperature dependence of the specific heat capacity of water. Value 4184.4 shows the reference value at 293.15 K, whereas -0.9 stands for its temperature dependence. The physical characteristic directly defines thermal power and enthalpy flux. This parameter is applied in all calculations related to heat, including determination of heat output, heater efficiency and enthalpy mass flow rate.

$$\mu(T) = A_{exp} \left(\frac{B}{T - C} \right), \text{ [Pa}\cdot\text{s]} \quad (5)$$

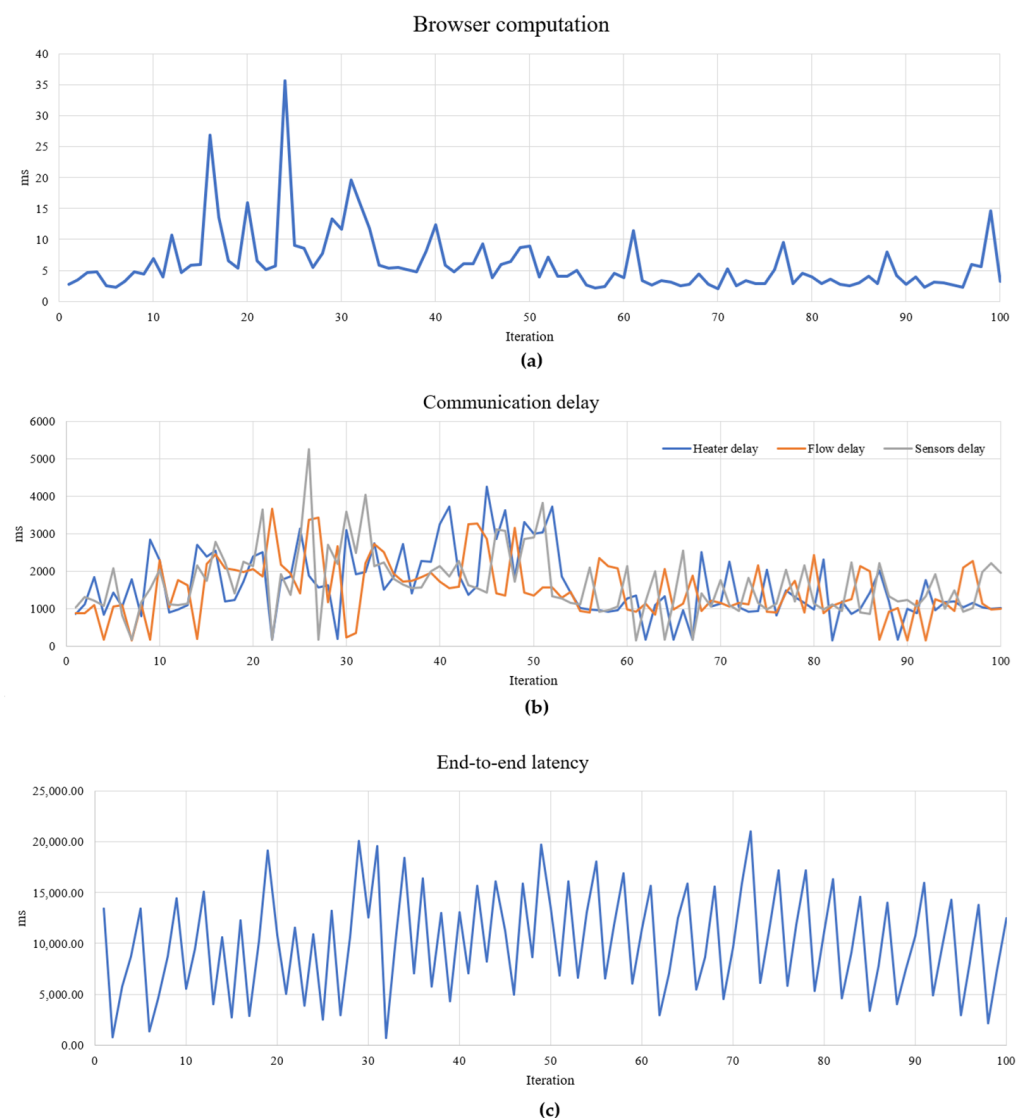


Figure 5. Representative performance metrics of the browser-native computation and communication pipeline. (a) Browser computation. (b) Communication delay. (c) End-to-end latency.

Dynamic viscosity is evaluated through the use of the Vogel equation [28], shown in Equation (5). This method takes into account the nonlinear dependence of the viscosity on temperature from 293.15 K to 353.15 K. The coefficients of the empirical formula, A , B and C , are chosen to correspond to the operating regime of the HeatLab loop in order to

correctly calculate the Reynolds number. The thermal expansion coefficient is shown in Equation (6).

$$\beta = \frac{1}{T_{ref}}, [\text{K}^{-1}] \quad (6)$$

In Equation (6), β is the volume expansion per unit change in temperature. T_{ref} is the reference absolute temperature. The following is a simplification that is applied only in calculating buoyancy for the Grashof number and not in the real tabular water data for buoyance-induced natural convection. The kinematic viscosity is determined as per Equation (7).

$$\nu = \frac{\mu}{\rho}, [\text{m}^2/\text{s}] \quad (7)$$

where ν denotes momentum diffusivity, μ is dynamic viscosity and ρ is density. This value determines the ratio between viscous and inertial forces. It is considered while determining Re and the Gr number. The values regarding the thermophysical properties shown in Equations (1)–(7) are constantly updated in order to get consistent prediction of flow regime, convective heat transfer and energy balance. Hydraulic parameters are calculated from instantaneous values of volumetric flow rate and pressure. Then the mass flow rate is determined as:

$$\dot{m} = \rho \dot{V}, [\text{kg/s}] \quad (8)$$

Equation (8) provides conversion from volume flow rate to mass flow rate, which is necessary for calculation of heat output, efficiency of the heater and advective heat transfer. The pump head equation is provided in Equation (9), which is an expression of mechanical energy imparted to the fluid per unit weight.

$$H = \frac{p_{out} - p_{in}}{\rho g}, [\text{m}] \quad (9)$$

Hydraulic power is then calculated as per Equation (10), which represents the actual hydraulic work done by the pump; the efficiency of the pump is calculated as per Equation (11), where hydraulic power is compared with the electrical input power.

$$P_{hyd} = \dot{m} g H, [\text{W}] \quad (10)$$

$$\eta_{pump} = \frac{P_{hyd}}{P_{el.pump}}, [-] \quad (11)$$

Thermal performance is calculated based on the inlet and outlet temperatures, which depend on the hydraulic circuit configuration (Table 2) and the mass flow rate. The heat transfer rate is calculated by:

$$Q = \dot{m} c_p (T_{in} - T_{ou}), [\text{W}] \quad (12)$$

Equation (12) is an expression of the advective thermal energy removed from the radiator by the circulating water. It is the main parameter in the EN 442 compliance test. LMTD [20] (log-mean temperature difference) is calculated using the formula:

$$\Delta T_{lm} = \frac{(T_{in} - T_{room}) - (T_{out} - T_{room})}{\ln\left(\frac{T_{in} - T_{room}}{T_{out} - T_{room}}\right)}, [\text{K}] \quad (13)$$

The temperature difference which is not constant between the radiator and the air that surrounds it is considered by Equation (13). After that, the overall heat transfer coefficient is determined using Equation (14).

$$U = \frac{Q}{A\Delta T_{lm}}, [\text{W}/\text{m}^2\cdot\text{K}] \quad (14)$$

Flow regimes and convective processes are expressed using dimensionless numbers. The Reynolds number is calculated according to Equation (15) and indicates whether the flow inside the enclosure is laminar, transitional or turbulent. The Prandtl number is calculated using Equation (17). It is the ratio of momentum diffusivity to thermal diffusivity. The Grashof number is calculated according to Equation (18).

$$Re = \frac{\rho v D_h}{\mu}, [-] \quad (15)$$

where $D_h = \frac{4A_c}{P_c}$ is the hydraulic diameter, with wetted perimeter $P_c = 2(w + d)$ of the radiator channels; ρ is the density; μ is the dynamic viscosity; and v is the channel velocity determined from the volumetric flow rate using Equation (16):

$$v = \frac{\dot{V}}{N_c A_c} \quad (16)$$

with $N_c = 30$ channels and $A_c = wd$ the cross-sectional area of a single channel.

$$Pr = \frac{c_p \mu}{k}, [-] \quad (17)$$

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu_{air}^2}, [-] \quad (18)$$

The Nusselt number is determined by using the traditional correlation for internal forced convective heat transfer, as shown in Equation (19), where, for laminar and transitional regimes ($Re < 2300$), the Shah–London [20] entrance correlation is used and for fully turbulent flow, the Dittus–Boelter [29] ($Re \geq 2300$) correlation is applied.

$$Nu = \begin{cases} 1.86 \left(\frac{Re Pr D}{L} \right)^{1/3}, & Re < 2300 \\ 0.023 Re^{0.8} Pr^{0.4}, & Re \geq 2300 \end{cases}, [-] \quad (19)$$

$$Nu = 0.027 Re^{0.8} Pr^{0.33} \left(\frac{\mu}{\mu_w} \right)^{0.14}, [-] \quad (20)$$

Laminar and turbulent convective flows in the radiator channels are calculated through the Sieder–Tate [30] and Dittus–Boelter [29] equations (Equation 20), following the EN 442 methodology. Due to the small size, high aspect ratio and temperature difference between the wall and the bulk fluid being less than 5 K, viscosity correction equations do not give any benefit. Therefore, the browser engine calculates the convective heat transfer coefficient via Equation (21) according to the EN 442 methodology.

$$h = \frac{Nu k}{D_h}, [\text{W}/\text{m}^2\cdot\text{K}] \quad (21)$$

$$Bi = \frac{h L_c}{k_{steel}} \approx 10^{-4} \div 10^{-3}, [-] \quad (22)$$

The radiator is assumed to be a single thermal mass having constant temperature. The application of lumped capacity is valid if there is fast internal conduction compared to external convection in radiator metal. This criterion is expressed by Biot number, shown in Equation (22). The radiator is treated as a lumped thermal mass, since its Biot number is negligibly small ($Bi \ll 0.1$). Indeed, the steel conductivity of $\approx 45 \text{ W/m}\cdot\text{K}$, experimentally determined heat transfer coefficient of $5\text{--}12 \text{ W/m}^2\cdot\text{K}$ and thickness of $0.5\text{--}1.5 \text{ mm}$ ensure that the internal temperature gradients are negligibly small. The present assumption is fully justified by the standards and allows for the development of the transient model of the first order which is applicable to real-time browser simulation. Thermal power balance represents the way energy transfers through the heater–radiator–water system. It serves as a physically meaningful basis of interpretation of steady and transient data. In HeatLab, thermal power balance is calculated in real time, taking into account SI-unit calculations. As far as the requirements met, one can compare the measurements and theoretical values. The electrical power source in our case is the power input to the heater block. HeatLab calculates electrical energy E_{el} and instantaneous electrical power according to Equation (23).

$$N_{el} = \frac{dE_{el}}{dt}, [\text{W}] \quad (23)$$

Equation (23) describes the overall power rate of electrical energy supplied to the heater. It is the main source of energy that initiates the thermal process in the system. Part of the electrical input energy transforms into the heat energy supplied to the flowing water. The temperature of the water increases from $T_{in,h}$ to $T_{out,h}$. The heater power is calculated according to Equation (24).

$$Q_{heater} = \dot{m}c_p(T_{out,h} - T_{in,h}), [\text{W}] \quad (24)$$

Here, $\dot{m}$ is the mass flow rate and c_p is the instantaneous specific heat of the water. The thermal energy supplied by the heat exchanger to the water system is calculated using this expression. The ratio of the thermal energy output to the electrical energy input is the thermal efficiency of the heater, as shown in Equation (25).

$$\eta_{th} = \frac{Q_{heater}}{N_{el}}, [-] \quad (25)$$

Heater water transfers its energy to the radiator, releasing energy to the surrounding air. The amount of heat released by the radiator depends on the advective energy of the water.

$$Q_{rad} = \dot{m}c_p(T_{in} - T_{out}), [\text{W}] \quad (26)$$

Equation (26) is the real heat emission that takes place under present operating conditions and is the primary parameter utilized in determining EN 442 compliance. It is a reliable and physical indicator of performance because it is directly based on temperature measurement and flow rate. Heat exchange between the radiator and the room takes place both through convection and through thermal radiation. Convection heat losses are calculated as follows:

$$Q_{conv} = hA(T_{mean} - T_{room}), [\text{W}] \quad (27)$$

Equation (27) shows that h is the convective heat transfer coefficient that is calculated using dimensionless expression. A represents the radiator surface area and T_{mean} refers to the mean radiator temperature. Equation (28) provides an equation for radiative heat loss where ε is surface emissivity while σ is the Stefan–Boltzmann constant.

$$Q_{rad,emit} = \varepsilon\sigma A(T_{mean}^4 - T_{room}^4), [\text{W}] \quad (28)$$

In steady-state operation, the above two mechanisms work together to give the overall heat transfer coefficient of U .

$$Q_{loss} = UA(T_{mean} - T_{room}), [W] \quad (29)$$

Equation (29) simplifies the calculations without compromising physical validity. Though small in comparison to the thermal power, the hydraulic system also supplies mechanical power to the water. The hydraulic power supplied by the circulation pump can be found in Equation (30).

$$P_{hyd} = \dot{m}gH, [W] \quad (30)$$

The symbol H in Equation (30) represents the pump head. The term is considered in order for completion, in particular during dynamic testing, where the pump speed variant will affect heat transfer behavior. The energy equation of the system at any time is shown in Equation (31). The equation shows whether the heat exchanger is storing or losing more energy than it gets.

$$\Delta E = N_{el} - Q_{rad}, [W] \quad (31)$$

The heat capacity of the radiator results in $N_{el} > Q_{rad}$ during the warming periods and vice versa during the cooling periods. The cumulative electrical and thermal energy can be determined through the integration of the instantaneous powers given by Equations (32)–(34).

$$E_{el} = \int N_{el} dt \quad (32)$$

$$E_{th} = \int Q_{rad} dt \quad (33)$$

$$\Delta E_{cum} = E_{el} - E_{th} \quad (34)$$

The accumulation sum is widely applied in the validation experiment to discover sensor drifts, miscalibration and inconsistencies between the actual and modeled responses. To meet the requirement of the standard, heat generation should be normalized to the standardized temperature differences. The arithmetic average of temperature differences can be found in Equation (35) and that of corrected heat generation can be found in Equation (36).

$$\Delta T' = \frac{T_{in} + T_{out}}{2} - T_{room}, [K] \quad (35)$$

$$\Phi_{corr} = \Phi_{me} \left(\frac{\Delta T'}{50} \right)^n, [W] \quad (36)$$

In Equation (36), Φ_{me} is the measured heat production while K_m and n are the regression coefficients as defined in Annex D of EN 442. Standardized heat production at 30 K and 50 K is shown in Equation (37) and Equation (38) respectively.

$$\Phi_{30} = K_m(30)^n, [W] \quad (37)$$

$$\Phi_{50} = K_m(50)^n, [W] \quad (38)$$

The heat powers stated in Equations (37) and (38) will then permit a straightforward comparison against manufacturer information and specifications. Thermal power balance serves as the basis of all experimentation work done within the HeatLab laboratory. The entire experimental program is designed based on three series—S, D and V—with each series making use of the power balance equation in its own unique way in order to study radiator characteristics, measurement validation and mathematical modeling. The S-series (Tables 5 and 6) experiments make use of the thermal power balance during steady-state

operation. In this case, the system is permitted to attain thermal equilibrium, hence providing the opportunity to assess the performance of the radiator with respect to heat transfer by using various parameters like U , h , Re , Pr , Gr and Nu . As the system is in a steady state, the instantaneous energy balance closes precisely, enabling confirmation of EN 442 compliance, including the calculation of standard heat outputs Φ_{30} and Φ_{50} . Through these tests, reference operating conditions and effects of the hydraulic arrangement and flow condition on the radiator behavior are established. For the D-series (Table 7) tests, the complete transient equation for the thermal power balance is employed to study the dynamics of the radiator in reaction to deliberate disturbances. Step changes in heater power and speed of the circulation pump and restrictions in the control valve are introduced to generate quick changes in flow condition, temperature differences and convection regime. This set of experiments is crucial for verifying the mathematical model and supporting the development of partial digital twin capabilities. The V-series (Table 8) tests are aimed at verifying the accuracy and consistency of all measurement channels, from the temperature sensors to the flow meter, pressure transducers, pump hydraulic performance and heater electrical output. Validation of each subsystem and the whole system individually serves to establish that the difference between the measured and modeled values of thermal power—both instantaneous and integrated—is a reliable indication of the drift in calibration, sensor offset or hydraulic problems. The HeatLab Protocol is a methodological framework for conducting all three experimental series, and which has been developed specifically for this laboratory heating system. It is completely consistent with the principles of EN 442 but takes into account peculiarities of the HeatLab radiator, heater block, hydraulic circuit and sensor system. EN 442 provides the standardized procedure for radiator testing with definitions of temperature differences, correction factors, regression parameters and steady-state conditions. The HeatLab Protocol applies these principles by:

- Creating experimental matrices for the hydraulic systems, pump speeds and heating power settings;
- Detailing the measurement process, calibration procedure and commissioning process;
- Incorporating the updating of thermophysical properties in real time and computation within the browser;
- Adapting the EN 442 steady-state protocol to D- and V-series;
- Incorporating the mathematical model in the experimental process.

The HeatLab Protocol does not just validate the standard but develops it further and makes it possible to develop a consistent and physically rigorous methodology for the particular laboratory system. This is achieved by making sure that all quantities measured, parameters delivered and responses modeled in the experiment are based on the radiator testing standard and yet have the flexibility needed for research, transient analysis and partial digital twin functionality. Figure 6 demonstrates the PolyVR 3D digital twin model of the HeatLab radiator testing apparatus and shows the fully virtualized version of the thermohydraulic circuit utilized in the experimental protocol.

The model reflects in real time the physical laboratory system, with all the thermohydraulic data obtained from the sensors, such as water temperature, pressure and flow rate values. All parts of the HeatLab system are virtually represented in the model—heater module, circulation pump, radiator, piping and sensors. Temperature data at the inlet/outlet of the heater, the inlet/outlet of the radiator and the return line are displayed on the 3D model, allowing straightforward analysis of heat distribution and flow behavior. Pressure gauges and flow meter data are included in the model in order to provide comprehensive hydraulic performance analysis. At the upper right corner of the 3D model, there is an additional telemetry graph showing time-dependent data on temperatures of several nodes, flow rate, pressure and losses. With the help of this visualization tool, users can analyze transient

effects, the thermal stabilization process and dynamics of the system during the series experiments. This graph is synchronized with the physical test bench; therefore, the partial digital twin representation reflects the real-time state of the system based on synchronized measurements. The PolyVR model follows the HeatLab Protocol that provides an updated version of EN 442 methodology in terms of simulation. This digital tool is a tool for analysis and demonstration of advanced features of the thermohydraulic system. It is the basis for future work on full control strategy development and digital twin-based system optimization. It should be pointed out that the developed solution cannot be considered a fully bidirectional digital twin of the physical thermohydraulic system. The developed architectures feature ongoing synchronization between the physical system and its digital counterpart through temperature, flow rate, pressure and electrical parameters. However, the bidirectional interaction can only be observed in the remote control of the circulation pump and the electric heater. At the same time, the control valves still operate manually and not digitally. Thus, the suggested solution can be regarded as a partial or functional digital twin and not a fully closed loop digital twin. Nonetheless, the developed architecture creates the necessary digital–physical connection for the representation, monitoring, analysis and control of the physical system in real time. Extended thermal power balance represents the heat flow through the heater–radiator–water cycle, providing a complete description of the physical picture of the subsystem work. In the HeatLab framework, the balance equation is calculated in real time. The first term of this equation is the thermal power output of the radiator, as shown in Equation (39).

$$Q_{he} = (T_{in,rad} - T_{out,rad})\dot{m}c_p, [W] \quad (39)$$

The heat actually delivered by the radiator to the ambient air is shown in Equation 39), which directly takes into consideration the effects of convective and radiant energy transfer from the radiator surface; hence, Q_{he} becomes the main metric used in EN 442 performance assessment. The second term, cold line losses, is as shown in Equation (40).

$$Q_{cold} = (T_{out,rad} - T_7)\dot{m}c_p, [W] \quad (40)$$

Equation (40) above gives the amount of heat released in the line running from the radiator exit to the heater inlet. It depends on pipe insulation, environmental temperature and hydraulic arrangement, and thus it can be used to evaluate the efficiency of the distribution line. Equation (41) gives the third term in the form of hot line losses. It accounts for heat loss in the hot line between the heater exit and the radiator inlet.

$$Q_{hot} = (T_6 - T_{in,rad})\dot{m}c_p, [W] \quad (41)$$

The fourth element of the balance is the heater block supplying the thermal power, given in Equation (42).

$$Q_b = (T_6 - T_7)\dot{m}c_p, [W] \quad (42)$$

Equation (42) presents the enthalpy increment of the water while passing through the heater block (B-001). It presents the real values of thermal power from the heater and is needed to check the efficiency of heater operation and electrical-to-thermal power conversion. The fifth element of the balance, internal losses of the heater block, is calculated by Equation (43) and equals the difference between electrical input and useful thermal output.

$$Q_{loss} = N_{el} - Q_b, [W] \quad (43)$$

Table 5. Steady-state experimental matrix (S-series).

ID	Heater [B-001]	Pump [P-001]		Flow Target	Goal
	P W	P W	H m	$\dot{V}$ m ³ /s	-
Scheme of connection: top–bottom (diagonal)					
S1	1000	67	5	8.33×10^{-6}	Low <i>Re</i> , lower convection, laminar-like
S2	1000	67	5	2.22×10^{-5}	Medium <i>Re</i> , reference operating point
S3	1000	67	5	3.33×10^{-5}	
S4	500	67	5	2.22×10^{-5}	Medium <i>Re</i> , low ΔT , low heat output
S5	1500	67	5	2.22×10^{-5}	Medium <i>Re</i> , high ΔT (within safety)
Scheme of connection: bottom–bottom					
S6	1000	67	5	2.22×10^{-5}	Medium <i>Re</i> , compare vs. S2
S7	1000	93	6	2.22×10^{-5}	Medium-high <i>Re</i> , effect of higher pump speed
S8	1000	45	3	8.33×10^{-6}	Low <i>Re</i> , poor distribution
Scheme of connection: top–top					
S9	1000	67	5	2.22×10^{-5}	Medium <i>Re</i> , compare vs. S2, S6
S10	500	67	5	2.22×10^{-5}	Medium <i>Re</i> , low-power alternative
S11	1500	67	5	2.22×10^{-5}	Medium <i>Re</i> , high-power alternative

Table 6. Extended hydraulic configuration (S-series).

ID	Scheme of Connection	Heater [B-001]	Pump [P-001]		Flow Target	Goal
#	-	P W	P W	H m	$\dot{V}$ m ³ /s	-
S12	top–bottom (unilateral)	1000	67	5	2.22×10^{-5}	asymmetry effect
S13	bottom–top (diagonal)	1000	67	5	2.22×10^{-5}	alternative diagonal
S14	bottom–top (unilateral)	1000	67	5	2.22×10^{-5}	worst-case distribution

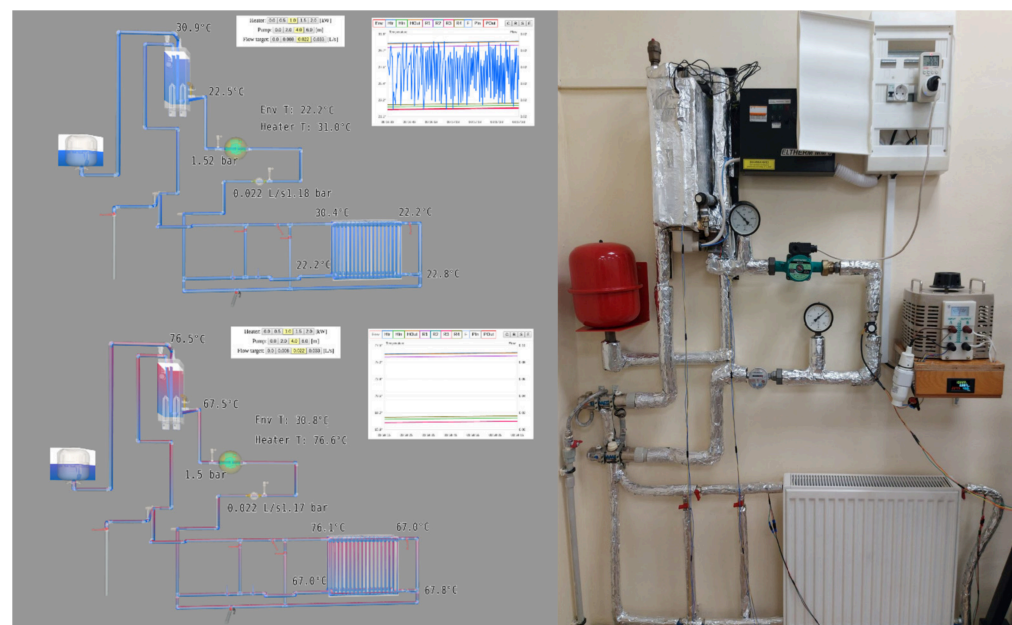
Table 7. Dynamic experimental matrix (D-series).

ID	Heater Change	Pump Change	Valve Action	Goal
#	W	W	-	-
D1	500 → 1500	constant (67)	None	thermal inertia, ΔT response
D2	Constant (1000)	speed (45 → 67 → 93)	None	<i>Re</i> / <i>Pr</i> / <i>Gr</i> / <i>Nu</i> / <i>h</i> jump, regime transition
D3	Constant (1000)	constant (67)	Partially closed	flow reduction, <i>Re</i> drop, ΔT rise
D4	500 → 1500	speed (45 → 67 → 93)	None	coupled thermal + hydraulic transient

Internal losses include conduction loss through the heater housing, convection loss to ambient air, and thermal losses due to insufficient insulation, measurement errors and transient losses. An internal loss term is needed for heater efficiency diagnostics and verification of electrical-to-thermal power conversion. The extended thermal power balance realized in the HeatLab system is demonstrated in Figure 7 by the real-time stacked power balance chart. Real-time stacked power balance shows the dynamics of five thermal power elements simultaneously in one chart during the experiment in the hydraulic circuit.

Table 8. Validation matrix (V-series).

ID	Description	Objective	Acceptance Criteria	Recorded Data
#	-	-	-	-
V1	Temperature sensor calibration	Verify accuracy of temperature sensors T1–T7	ΔT within ± 0.2 – 0.5 K	raw temperature logs, calibration offsets, stability notes
V2	Flow meter validation	Validate FM-001 at low/medium/high flow	relative error $\varepsilon < 5\%$ (recommended)	flow meter readings, manual flow measurements, error calculation
V3	Pump curve validation	Confirm pump performance at speeds 1–3	curve deviation within acceptable envelope; no cavitation or instability	differential pressure, flow rate, pump electrical power
V4	Heater power validation	Verify heater electrical output at 500, 1000, 1500 W	electrical power within ± 3 – 5% of nominal	electrical power logs, voltage/current, thermal output (optional)

**Figure 6.** PolyVR 3D partial digital twin model of the HeatLab radiator test bench, integrating real-time thermal–hydraulic measurements, EN 442-aligned procedures and simulation capabilities for advanced system analysis.

The graph presented in Figure 7 shows radiator useful thermal output Q_{he} , cold line losses Q_{cold} , hot line losses Q_{hot} , heater-block-delivered thermal power Q_b and heater block losses Q_{loss} as well in terms of both absolute power [W] and percentage of electrical input N_{el} . The overlapping blocks show how the contribution of each subsystem changes over time, whereas the overlapping curves demonstrate how the ratio of the supply line losses, return line losses, radiator emission and heater performance change over time. Such real-time analysis allows for observation of transient effects such as changes in fluid flow, heater power, and heating stabilization as well as providing an opportunity to diagnose the quality of the insulation, hydraulic arrangement and efficiency of the heater in real time. In contrast to traditional DAQ laboratories, where only radiator heat is calculated, the HeatLab system breaks down the whole hydraulic circuit into physical–thermal sections and thus allows for the checking of EN 442 regression inputs and detecting of anomalies in the energy balances. The resulting chart therefore serves as a digital twin-aligned diagnostic

tool, demonstrating the capability of the browser-native computation engine to track and interpret complex thermohydraulic interaction with high temporal fidelity.

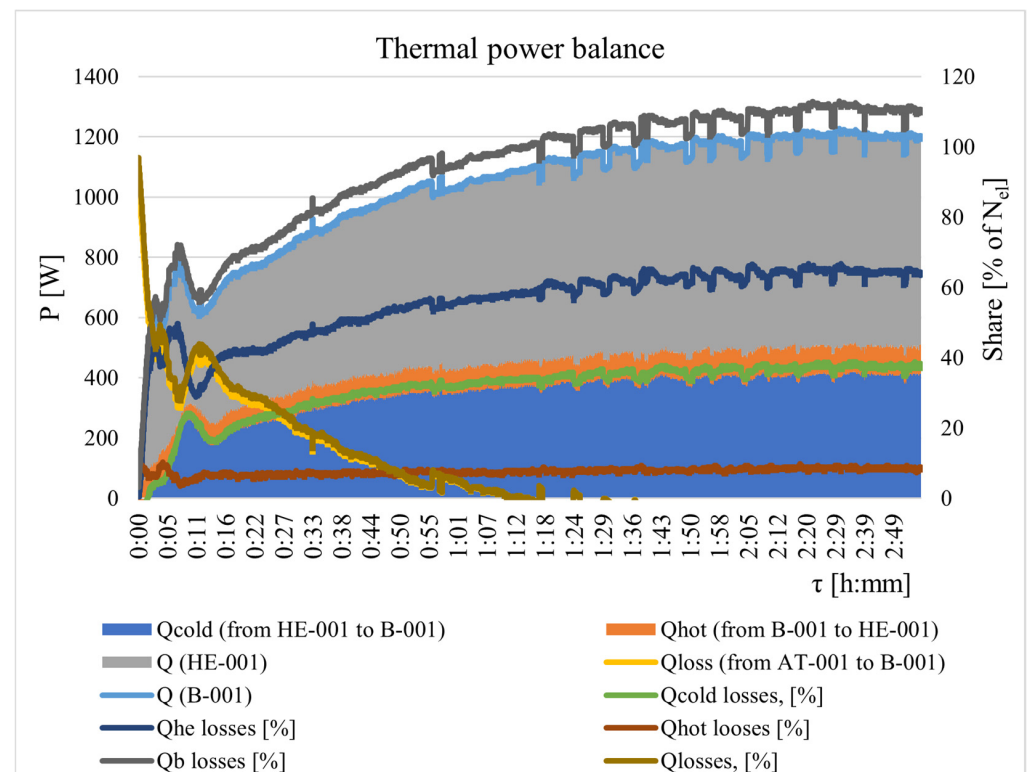


Figure 7. Real-time extended thermal-power balance of the HeatLab system, showing radiator output, line losses, heater thermal output and internal losses.

3. Results

The series of experimental trials performed at the HeatLab test facility covered all possible operational modes outlined in the protocol, such as characterization (S-series), transient tests (D-series) and measurement chain verification (V-series). The experiments were performed in accordance with a series of matrices, providing systematic coverage of hydraulic configurations, heater power, pump speeds and flow regimes. The S-series experiments outlined in Table 5 assessed the thermohydraulic performance of the radiator under stationary conditions. The more complex hydraulic layouts shown in Table 6 helped to gain further understanding of the impact of asymmetric, alternative and deliberately unfavorable flow distribution with respect to temperature stratification and operation of the radiator. The D-series tests, presented in Table 7, studied transient behavior under the conditions of heater power step changes, speed change and flow restriction, thus providing useful data in terms of analyzing system inertia and regime transitions relevant to partial digital twin functionality. Lastly, the V-series validation tests, shown in Table 8, proved the reliability of all measuring elements, including temperature sensors, flow meter, pressure transducers, pump curve and heater power, thus ensuring the traceability and reliability of the following analysis.

3.1. Overview of Conducted Experiments

All the experimental conditions used are tabulated in matrices. Such matrices outline the hydraulics, the level of heater power, pump speed and desired flow regime for each of the experiments conducted, forming the basis for interpreting the results shown in subsequent subsections.

Temperature readings have been taken from seven locations for taking temperature readings. Here, T1 is ambient temperature, T6 is the heater outlet temperature and T7 is the heater inlet temperature. The radiator temperature measurement locations (Figure 1b) are represented by T2 ÷ T5, which may be inlet or outlet depending on the chosen hydraulic connection configuration, as shown in Table 9.

Table 9. Temperature measurement points according to the hydraulic connection scheme.

Hydraulic Connection Scheme	HE-001 Inlet	HE-001 Outlet
top–bottom (diagonal)	T2	T3
top–bottom (unilateral)	T2	T5
bottom–top (diagonal)	T5	T4
bottom–top (unilateral)	T5	T2
top–top	T2	T4
bottom–bottom	T5	T3

3.2. Steady-State Results (S-Series)

There were significant differences in hydraulic circuitry and heater power in the steady-state tests (Table 5). Reference point (S2), which corresponds to the “top-bottom (diagonal)” connection scheme with 1 kW heater power and medium Re number, was characterized by a steady flow regime of $0.08 \text{ m}^3/\text{h}$ ($2.22 \times 10^{-5} \text{ m}^3/\text{s}$) (Figures 8 and 9) and a heat transfer rate of about 600–700 W.

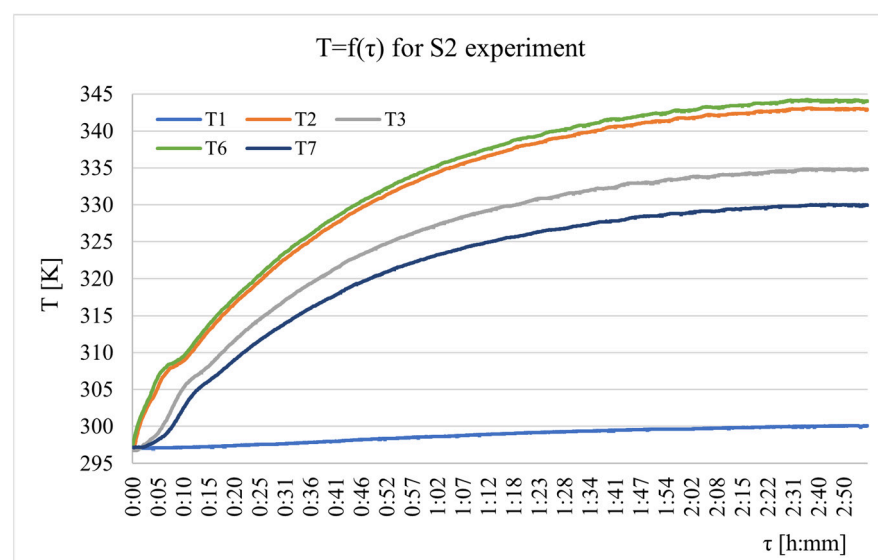


Figure 8. Temperature evolution during the S2 steady-state experiment.

The Reynolds number (Figure 10) was in the transitional range (2500–5000). Together with other parameters that characterize forced convection, the Prandtl number (Figure 11) gradually decreased from about 6.4 to 3.0 depending on the water temperature increase, demonstrating the expected dynamic viscosity decrease and the correctness of the calculation of the thermophysical properties in the browser environment. The Grashof number (Figure 12) tended to reach values on the order of 10^{13} , suggesting the occurrence of natural convection due to buoyancy on the air side of the radiator surface; however, these values were still secondary compared to the forced convection flow in the water channels. The Nusselt number (Figure 13) fluctuated between 15 and 30, denoting a behavior of mixed convection, which is characteristic for compact radiator channels. The thermal reliability of the radiator under steady-state operation is shown in Figure 14. The total heat transfer coefficient U (Figure 15) showed little variation ($12.2\text{--}13.95 \text{ W}/\text{m}^2\cdot\text{K}$).

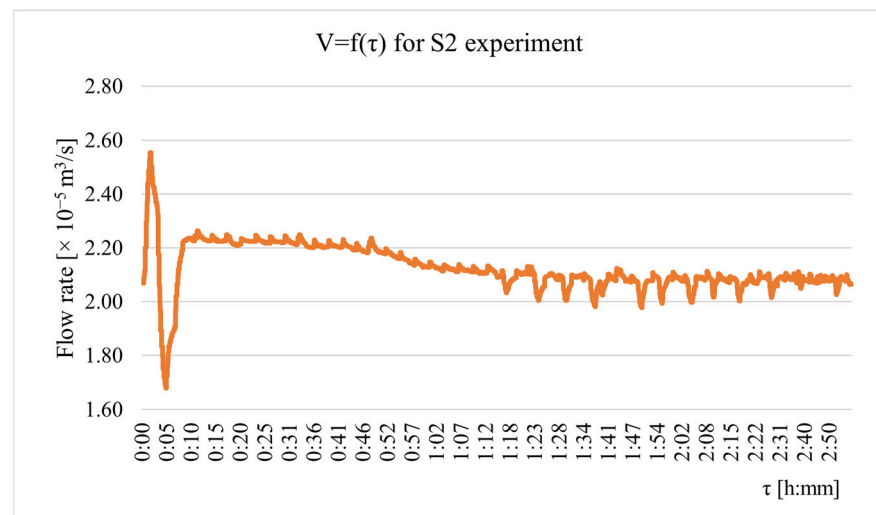


Figure 9. Flow rate stabilization over time during the S2 steady-state experiment.

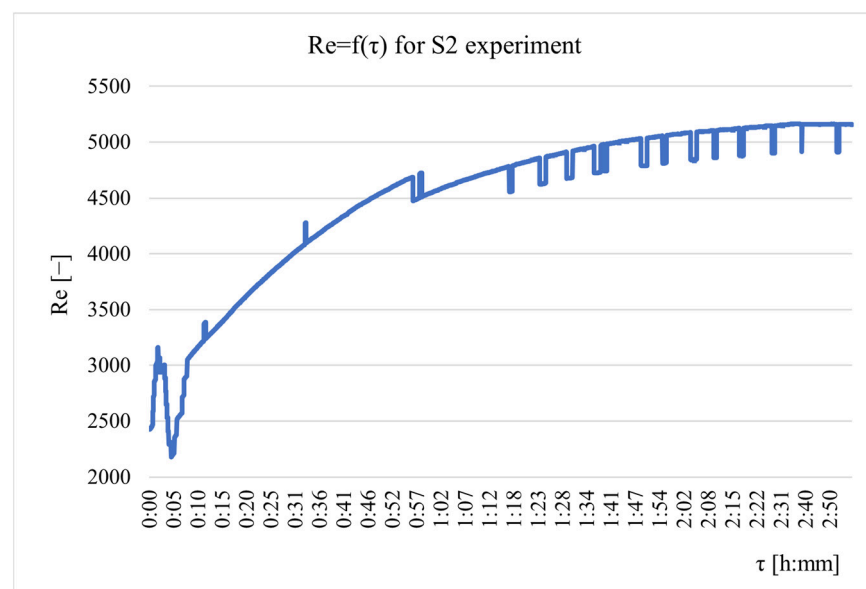


Figure 10. Reynolds number evolution over time during the S2 steady-state experiment.

Analysis of the S2 data using the EN 442 regression equation (Figure 16) yielded a correction line with an accuracy of $\pm 2\%$, proving that computing using a browser delivers laboratory precision. Energy accounting was tight, with total electrical and thermal energies varying only due to the thermal inertia of the radiator.

The left plot in Figure 16 depicts the entire $\Phi - \Delta T'$ function recorded from the beginning to the end of the whole experiment, taking into account the influence of startup, thermal inertia, overshooting and the approach of quasi steady-state operation. Such data provide information about the dynamics of the heat exchange processes in the radiator but cannot be applied to EN 442 characterization. On the right side of Figure 16 is the steady-state $\Phi - \Delta T'$ plot for EN 442 according to the filtered quasi steady-state data retrieved from the HeatLab platform. Reduced temperature difference $\Delta T'$ and corrected heat flux Φ are presented using logarithmic scales according to the EN 442 Annex A approach. This plot follows the regression power law in terms of the form which is presented in Equation (44).

$$\Phi = K_m \cdot (\Delta T')^n \quad (44)$$

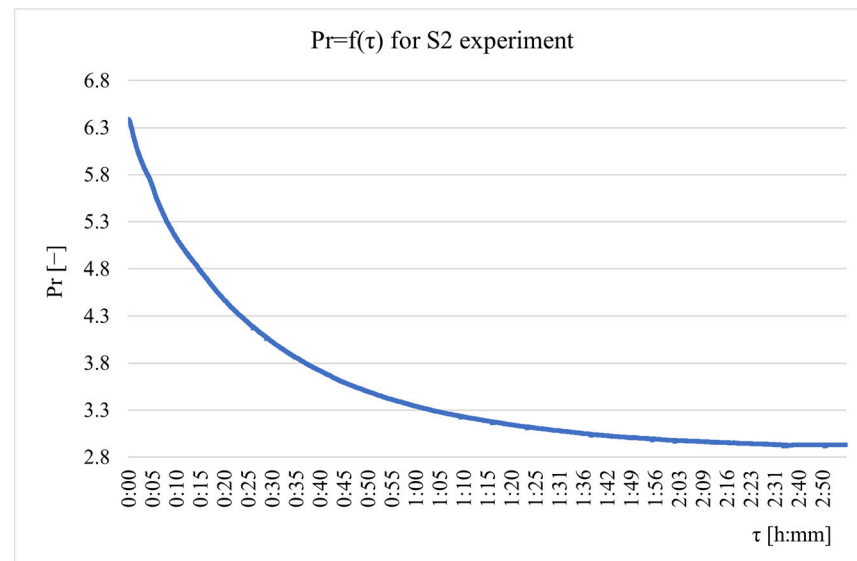


Figure 11. Prandtl number evolution over time during the S2 steady-state experiment.

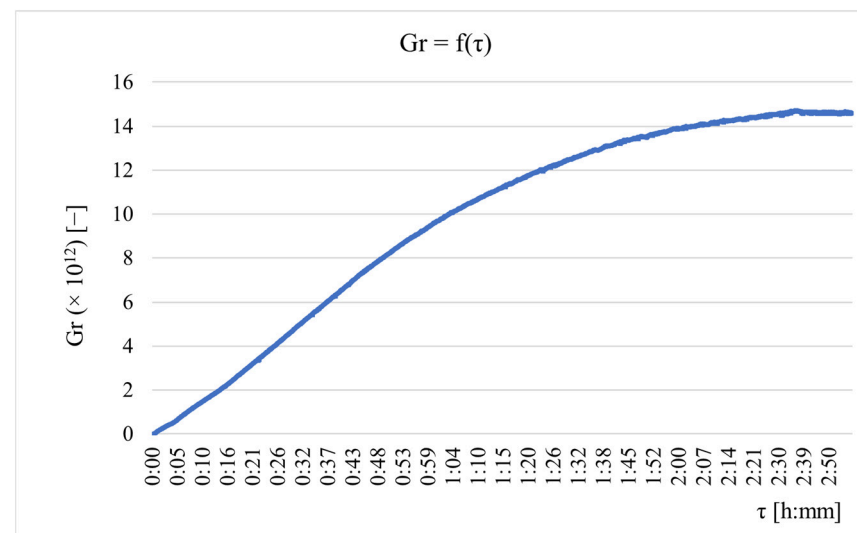


Figure 12. Grashof number evolution over time during the S2 steady-state experiment.

The regression was fitted for the chosen data and resulted in $K_m = 228.77$ and $n = 0.7749$, with the coefficient of determination being $R^2 = 0.9906$. These regression coefficients are related to the EN 442 correction equation provided in Equation (36) and facilitate the calculation of the standardized heat release rates at $\Delta T = 30$ K and $\Delta T = 50$ K by using Equations (37) and (38). The extended hydraulic designs (Table 6) indicated the sensitivity of the radiator efficiency to the asymmetric inlet/outlet design. The unidirectional design of the connection scheme “top-bottom (unilateral)” (Table 6, S12) created temperature stratification and less uniform distribution on the surface of the radiator. The “bottom-top (diagonal)” (Table 6, S13) design was better than the “bottom-top (unilateral)” design (Table 6, S14). This indicates that a diagonal path of the fluid improves convective uniformity. The most unpleasant distribution (S14) creates the lowest Re number, the lowest Nu number and higher line losses, which was expected according to the theory of asymmetric flow. These results illustrate the significance of the hydraulic design for radiator efficiency and confirm the ability of the HeatLab system to detect these differences in distribution.

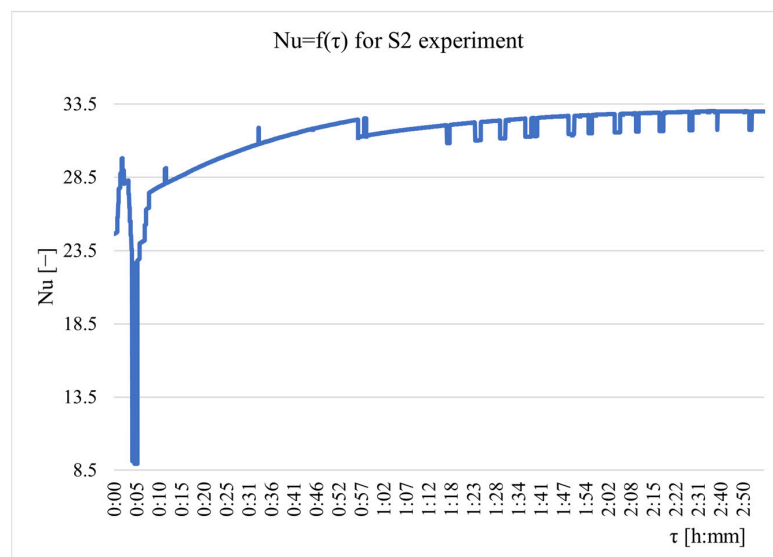


Figure 13. Nusselt number evolution over time during the S2 steady-state experiment.

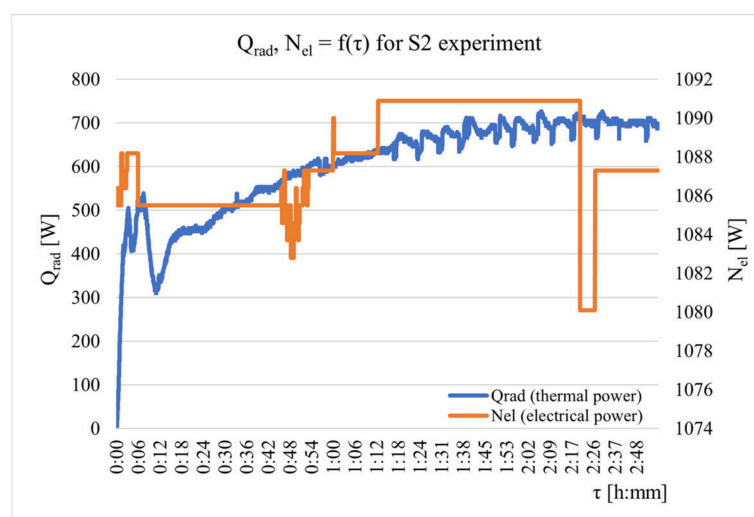


Figure 14. Thermal and electrical power evolution over time during the S2 steady-state experiment.

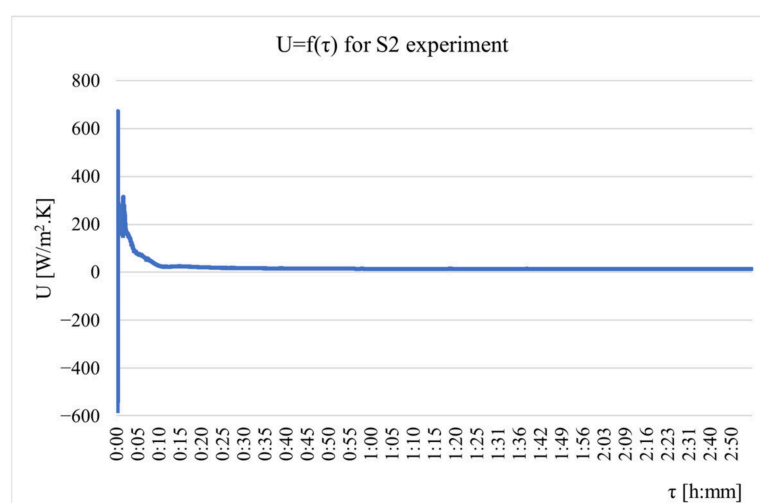


Figure 15. Overall heat-transfer coefficient U over time during the S2 steady-state experiment.

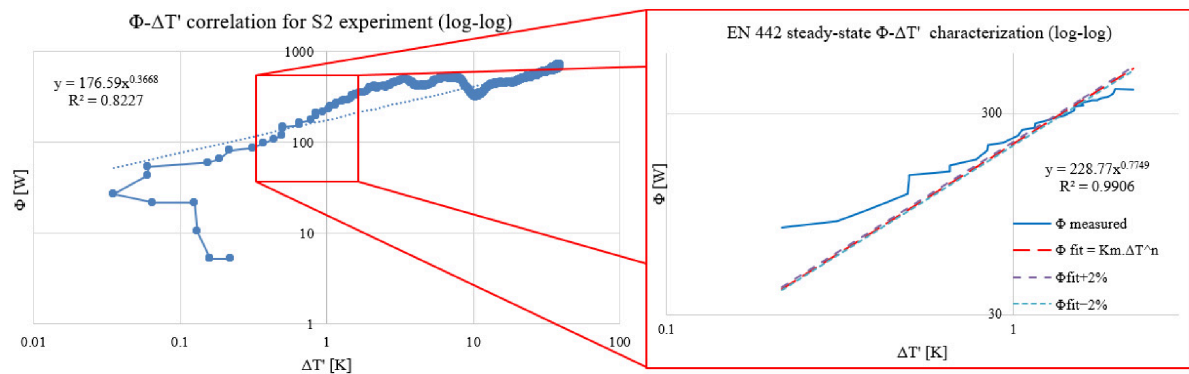


Figure 16. EN 442 steady-state $\Phi - \Delta T'$ regression with $\pm 2\%$ conformity bands for the S2 experiment.

However, in the “top-bottom (unilateral)” setup, the temperature lines demonstrate clear stratification. Indeed, as may be seen in Figure 17, the inlet is characterized by substantially higher temperatures than the outlet. Such a feature is inherent in unilateral flows, in which hot water enters and leaves the radiator from one side. In other words, it causes non-uniform distribution of the thermal medium inside the radiator. Since the flow mainly fills up the upper channels of the radiator, the lower part of the latter receives the medium worse in terms of distribution. Therefore, not all areas of the radiator surface are heated evenly. This stratification proves that the hydraulic performance of the unilateral setup is inferior to the diagonal reference one.

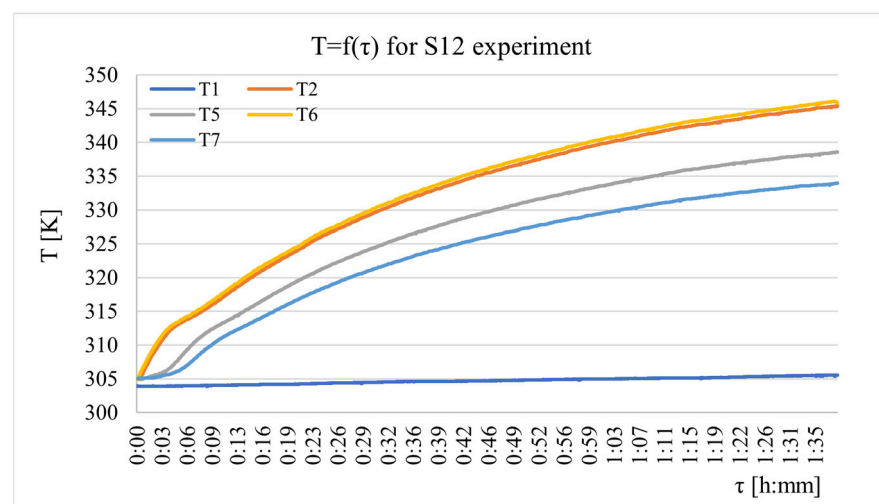


Figure 17. Temperature evolution during the S12 experiment.

The “bottom-top (diagonal)” configuration presents significantly improved temperature uniformity. As shown in Figure 18, temperature curves have increased consistency, with a smaller difference between inlet and outlet temperatures. This means that diagonal flow ensures more homogeneous convective heating of the radiator surface. Thus, it could be considered as a standard case of uniform hydraulic behavior and in compliance with EN 442 requirements for the radiator test. The connection “bottom-top (unilateral)” configuration is the case with the worst temperature distribution. As seen in Figure 19, there is a significant difference in temperature. It means that there is an imbalance in flow and, consequently, a low Re number and low convective effect, resulting in greater temperature gradients than in S12 and S13.

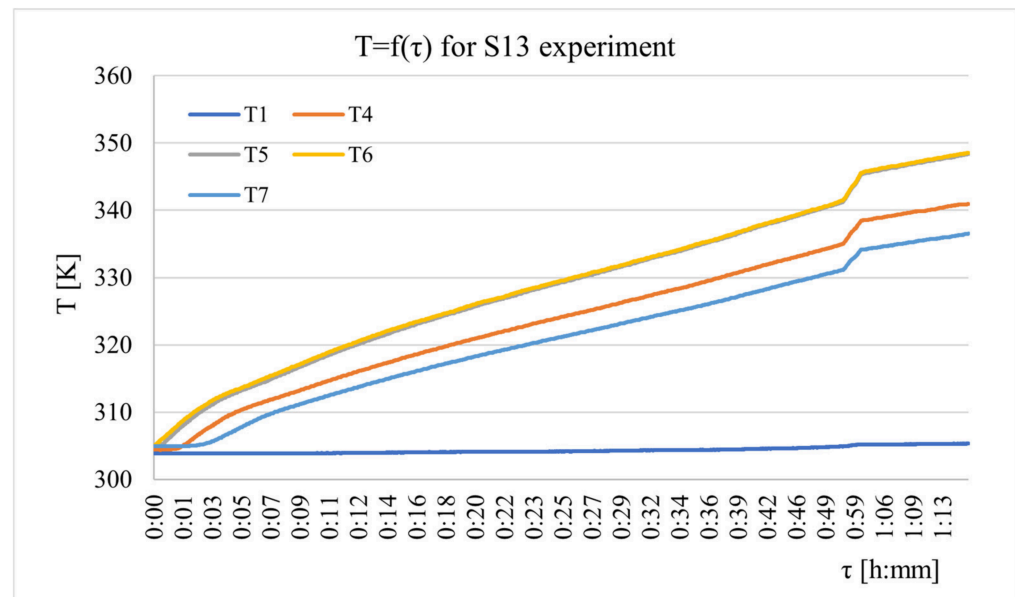


Figure 18. Temperature evolution during the S13 experiment.

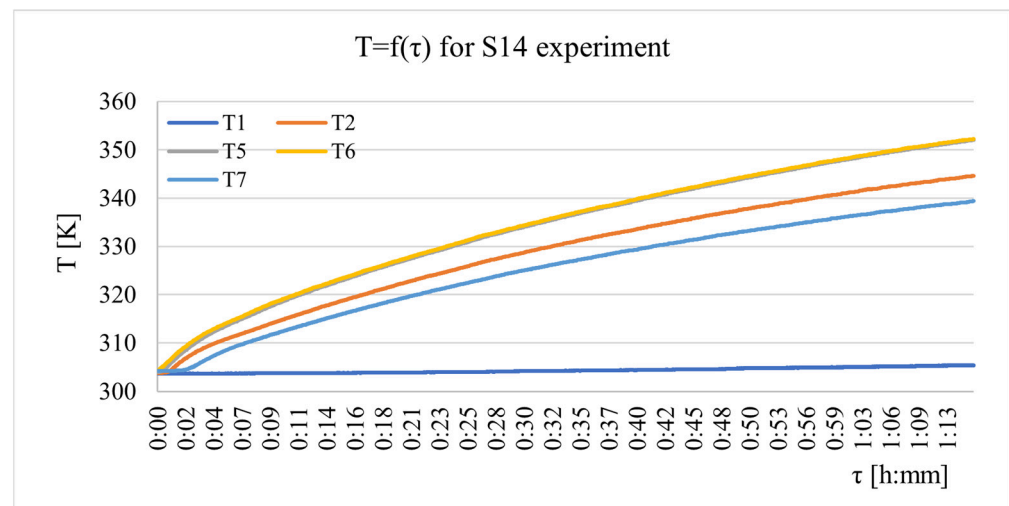


Figure 19. Temperature evolution during the S14 experiment.

3.3. Dynamic Response (D-Series)

Dynamic tests were carried out in order to examine the transient behavior of HeatLab in response to perturbations. These dynamic tests include abrupt changes in heater power, pump speed and flow rate. They assess the transient behavior of heat transfer, convection regime transition and interaction between hydraulic and thermal subsystems. These tests show that the computation engine developed in JavaScript is able to capture transients in a very accurate manner without any numerical instability or oscillations. All dynamic tests are conducted with the “top-bottom (diagonal)” connection scheme with a nominal flow rate of $2.22 \times 10^{-5} \text{ m}^3/\text{s}$, which is a reference case for transient analysis. For the D-series experiments, as shown in Table 7, where there are changes in heater power (D1, D4), electrical power is increased from 500 W to 1500 W (and vice versa) in a single step, where the switch time is less than 5 s; that is, the change is instantaneous compared to the thermal time constant of the system. D4 is the combined thermal and hydraulic transient, where the electrical power of the heater is increased from 500 W to 1500 W within an interval of less than 5 s and where the speeds of the circulation pump are switched based on the scenario specified. Throughout the entire process, the flow rate remains constant at

$2.22 \times 10^{-5} \text{ m}^3/\text{s}$, without the introduction of any further resistance in the system through the valve. Once the transient is over, the system is monitored for 3–5 min to measure the thermohydraulic response. The transient is performed in two steps, as follows:

- Step #1 (thermohydraulic jump)—electric power is increased from 500 W to 1500 W during a time period of less than 5 s and at 1000 W the circulation pump is switched from first stage to second stage (from 45 W to 67 W);
- Step #2 (hydraulic jump only)—the electric power of the electric heater is kept constant at 1500 W but the speed is switched from second stage to third stage (from 67 W to 93 W). After switching of the circulation pump, the system is monitored for 3–5 min.

The D1 experiment investigates the effect of the heat capacity of the radiator through an abrupt increase in power input to 1500 W from 500 W. The temperature response illustrated in Figure 20 reveals the typical first-order behavior of the system. The inlet side of the radiator responds almost instantly to the change in the input power, showing a quick temperature rise, while the outlet side shows a lag due to a delay in transport and heat capacity of the radiator; it can also be observed that the ambient temperature is steady, which confirms the stable environmental condition.

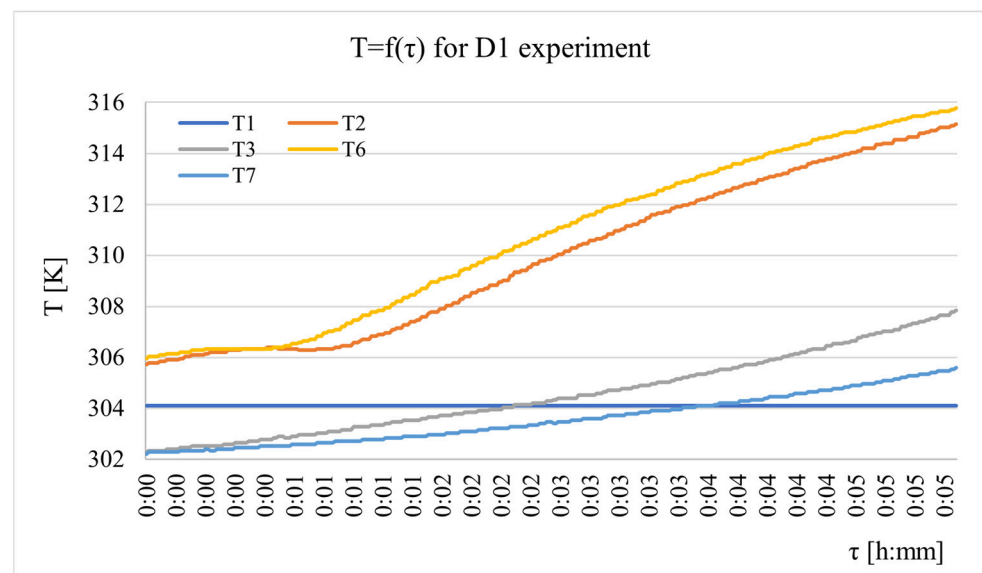


Figure 20. Temperature response to the heater power step during the D1 experiment.

Figure 21 shows the dynamics of electrical and thermal power. Electrical power undergoes an instant jump from 500 W to 1500 W, while thermal power rises steadily from around 350 W to 700 W due to the finite thermal inertia of the radiator and the delay needed for the water to achieve its new steady state. The absence of overshoot in the rise of thermal power confirms the stability of the transient characteristics of the radiator and validity of the assumption of the lumped capacity applied in the mathematical model. The second experiment (D2) studies regime changes in the hydraulic system by changing the speed of the pumps in discrete steps (Table 7). The evolution of flow rate shown in Figure 22 features two clearly discernible stepwise rises that correspond to the pump steps from 45 W to 67 W and, respectively, to 93 W.

The changes in the Re and Nu numbers are illustrated by Figures 23 and 24, respectively. The Re number increases from about 3000 to almost 6000, entering the regime of transitional to initial turbulence. The Nu number exhibits the same trend, increasing from ~ 28 to ~ 42 , thus proving the expected growth in the convective heat transfer coefficient due to increased velocity of the fluid. Thus, it can be said that the calculations performed

by the HeatLab system provide an accurate depiction of the hydraulic disturbances and proper calculation of the dimensionless numbers. The third experiment of the D-series utilizes a partial closing of the inlet valve in order to decrease the amount of fluid and, thus, to decrease the Re number. The temperature change depicted in Figure 25 shows a fast temperature increase in radiator outlet temperatures in response to the partial closing of the valve, whereas inlet temperatures stay practically unchanged.

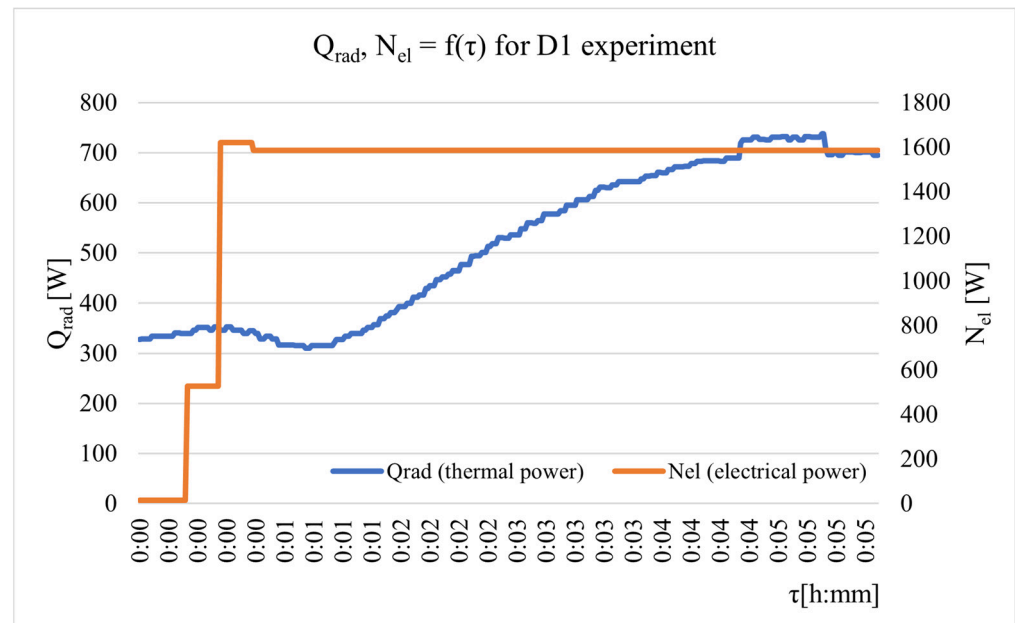


Figure 21. Thermal and electrical power evolution over time with respect to the D1 experiment.

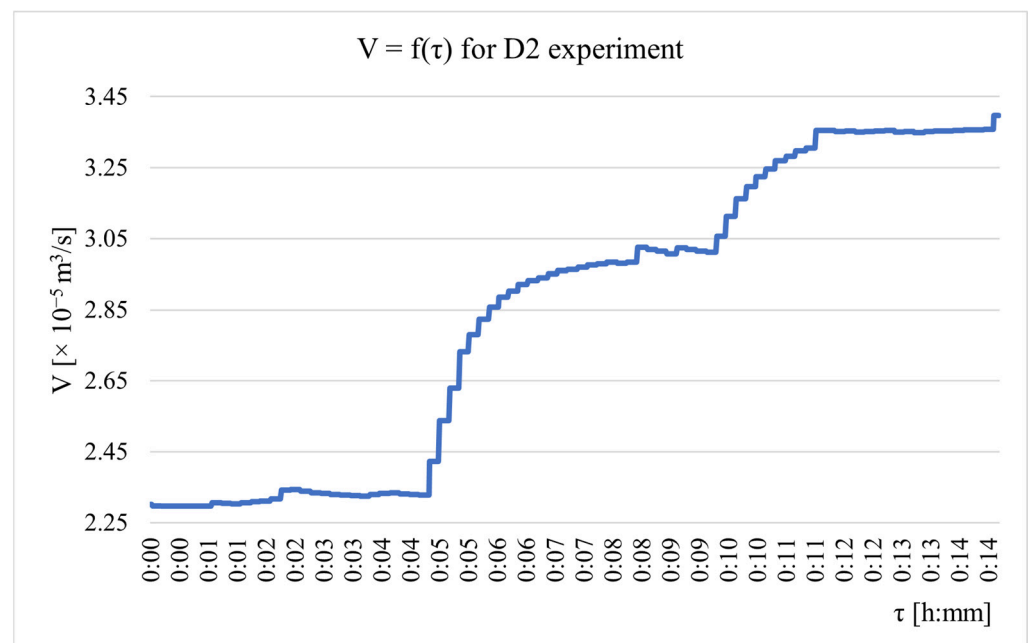


Figure 22. Flow rate evolution over time during the D2 experiment.

The flow rate response seen in Figure 26 indicates a sharp fall from $2.2 \times 10^{-5} \text{ m}^3/\text{s}$ to $1.4 \times 10^{-5} \text{ m}^3/\text{s}$, after which the system settles to a lower flow rate. It is obvious that an inverse relationship exists between the flow rate and temperature difference ΔT since, with a decreasing flow rate, the value of ΔT increases owing to decreased advective flux. This proves the capability of the platform with respect to detection of the thermal transition

caused by the flow rate and calculation of the Re number decrease caused by hydraulic restriction (Figure 27).

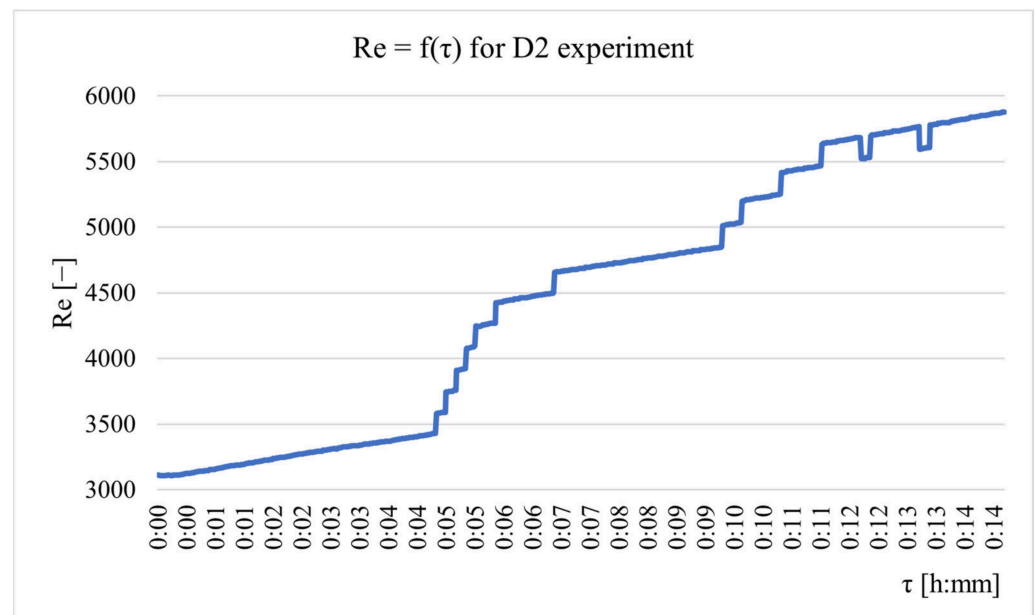


Figure 23. Reynolds number evolution over time during the D2 experiment.

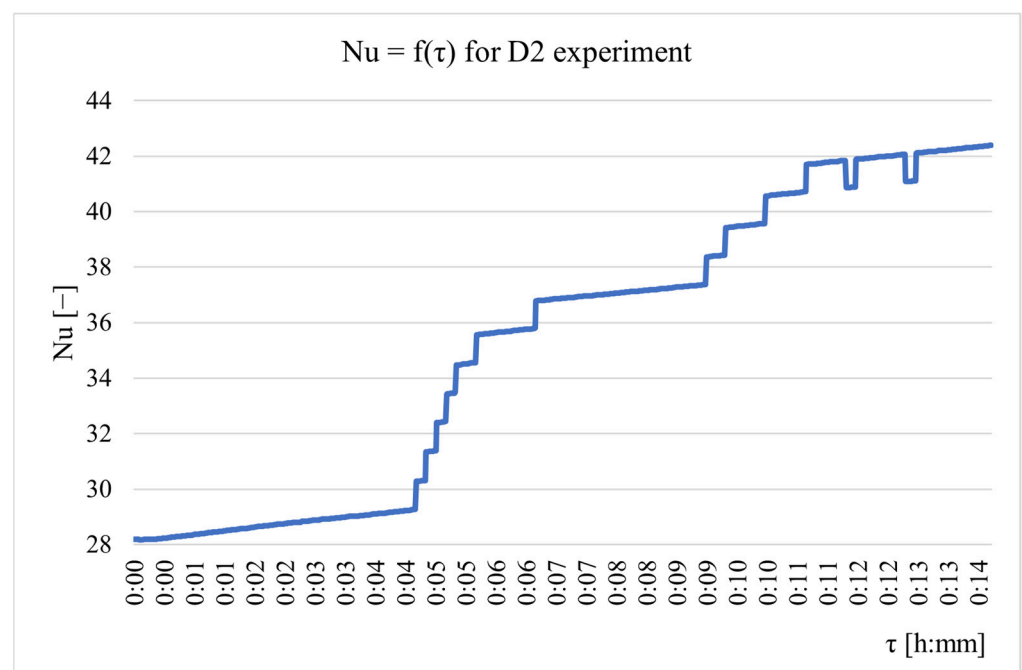


Figure 24. Nusselt number evolution over time during the D2 experiment.

The D4 experiment represents the most complicated dynamic scenario in terms of both heater power and pump speed changes. The evolution of electrical and thermal parameters illustrated in Figure 28 demonstrates the interconnectedness of the disturbance. Electrical power sharply increases from ~500 W to ~1600 W in several seconds, causing an immediate growth in thermal power from ~200 W to ~700 W. In the aftermath of the heater setup, thermal power slowly reaches stable values of 600 W due to the approach of the radiator in terms of the new steady-state point. Flow rate dynamics shown in Figure 29 demonstrate two different hydraulic transitions connected to the three pump power steps, from 45 W to 67 W and 93 W. Each pump step causes an evident increase

in flow rate from $\sim 2.3 \times 10^{-5} \text{ m}^3/\text{s}$ to $\sim 3.0 \times 10^{-5} \text{ m}^3/\text{s}$. The combination of thermal and hydraulic jumps causes a specific pattern of transient behavior— ΔT rapidly grows during heater setup and subsequently decreases with increasing flow rate and convective dissipation. Stabilization of both thermal and hydraulic quantities in a smooth way proves the ability of the HeatLab platform to simulate multi-variable transients as well as handle coupled disturbance by its browser-native computational engine.

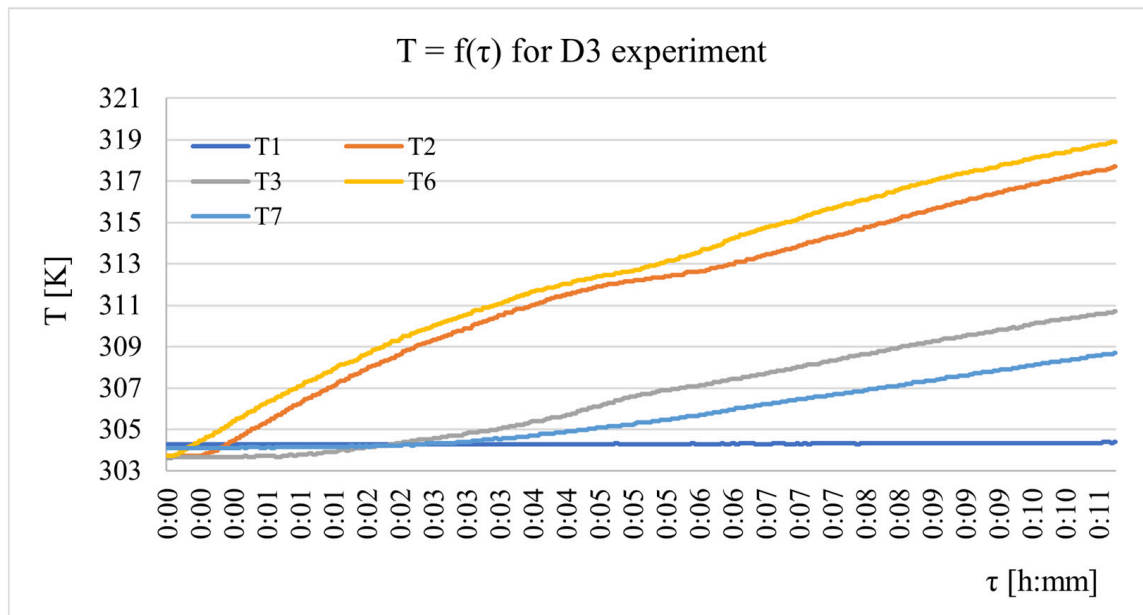


Figure 25. Temperature evolution over time during the D3 experiment.

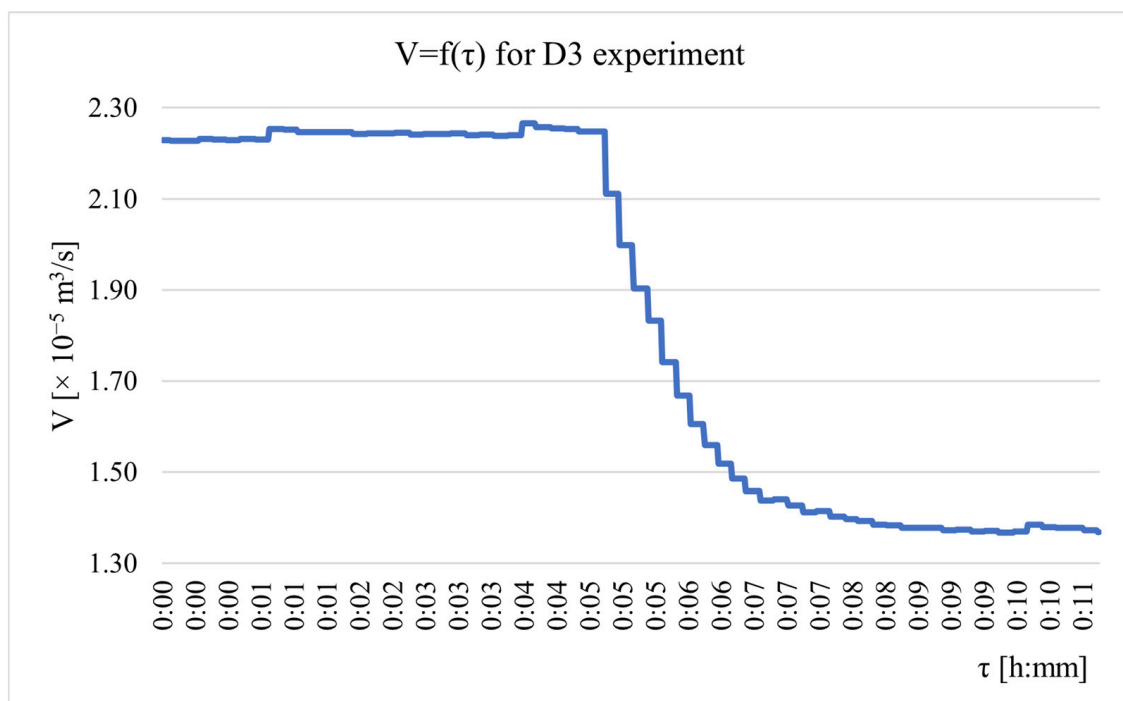


Figure 26. Flow rate evolution over time during the D3 experiment.

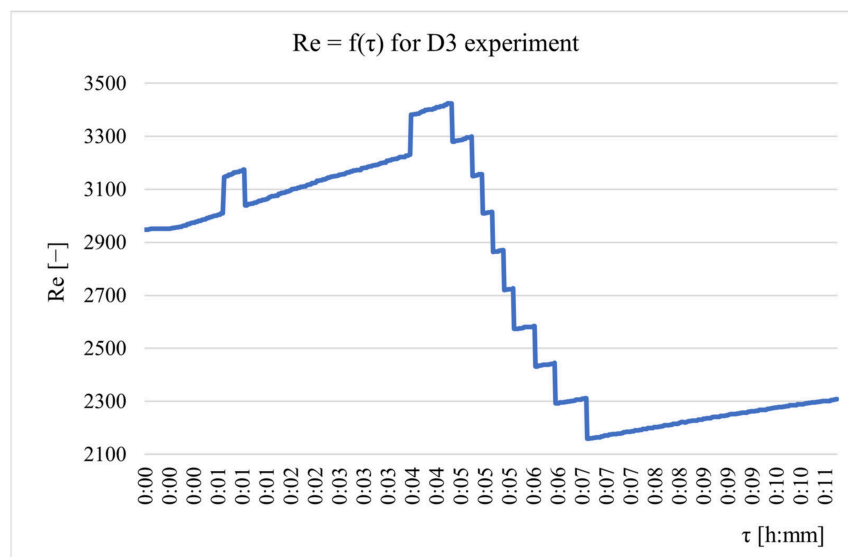


Figure 27. Reynolds number evolution over time during the D3 experiment.

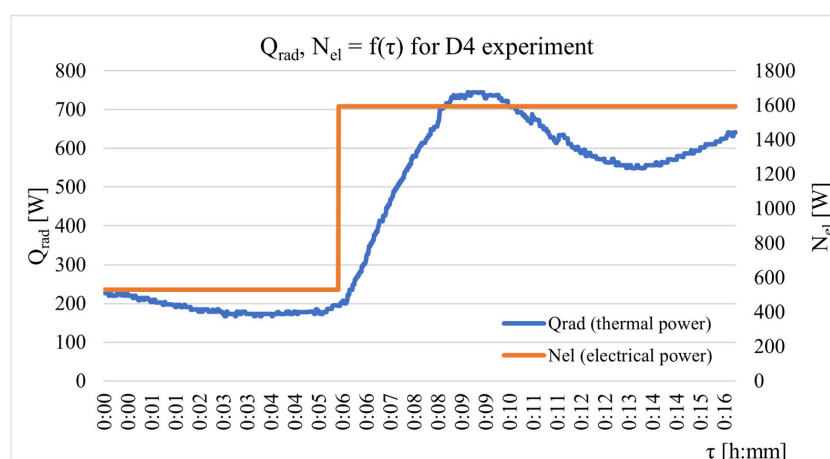


Figure 28. Thermal and electrical power evolution over time during the D4 experiment.

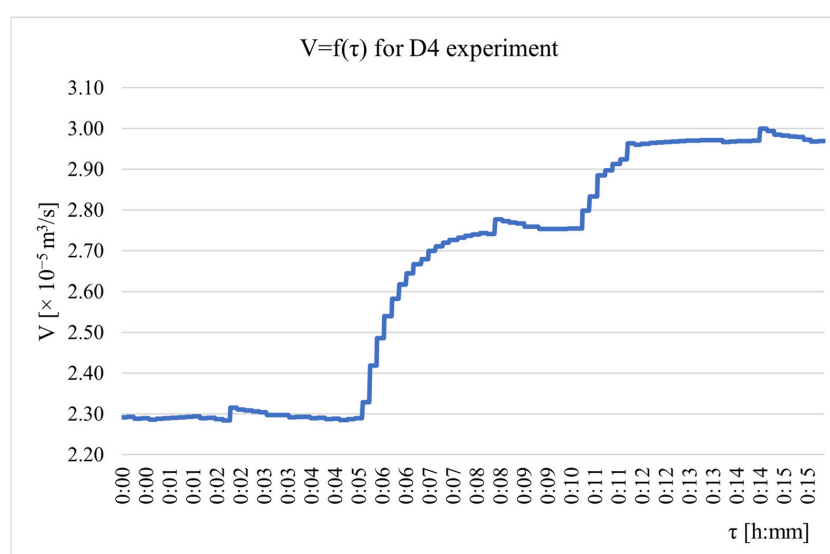


Figure 29. Flow rate evolution over time during the D4 experiment.

3.4. Validation Results (V-Series)

The V1 verification experiment verifies the consistency, stability and repeatability of all seven DS18B20 sensors employed in the HeatLab framework. The test is crucial since inlet, outlet, surface and ambient temperatures provide the foundation for EN 442 heat transfer assessment, Re , Pr , Gr , and Nu number estimation and the balance of thermal energy. Verification of all sensors against the specified tolerance range is an obligatory requirement before conducting any further tests for steady-state and transient analysis. The hydraulic loop was arranged using the endorsed “top-bottom (diagonal)” arrangement, just like in the reference arrangement for the S-series experiments. The circulation pump supplied a constant reference flow rate of $2.22 \times 10^{-5} \text{ m}^3/\text{s}$. For the establishment of an isothermal condition, the heating system was kept off, allowing the sensor measurements to be compared with the infrared measurements obtained from the thermal camera. The temperature distribution was independently monitored using a Testo860i infrared camera (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) (Table 3), with the thermal images processed via Testo IIRSoft (Testo SE & Co. KGaA, Titisee-Neustadt, Germany; Version 5.2) [31]. The data recording process started once the steady state of thermal equilibrium was attained. The deviation of each temperature sensor was calculated from Equation (45) based on the average temperature measured by the DS18B20 sensor and the corresponding infrared measurement during the steady-state data acquisition period. This deviation was then evaluated against the tolerance value $\pm 0.2\text{--}0.5 \text{ K}$, as per Table 7.

$$\Delta T_i = \bar{T}_{i,sensor} - T_{i,IR}, [\text{K}] \quad (45)$$

with

$$\bar{T}_{i,sensor} = \frac{1}{N} \sum_{j=1}^N T_{i,sensor}(t_j), [\text{K}] \quad (46)$$

and

$$T_{i,IR} = \frac{1}{N} \sum_{j=1}^N T_{i,IR}(t_j), [\text{K}] \quad (47)$$

Figure 30 illustrates the deviation of all seven sensors throughout the whole accuracy verification period. All sensors are operating consistently in the acceptable $\pm 0.5 \text{ K}$ tolerance zone (dashed red lines). Typical values of deviations are $0.3\text{--}0.4 \text{ K}$. Slight oscillation around zero corresponds to normal measurement fluctuations, infrared camera noise and minor temperature variations in the water within acceptable limits. In spite of the fact that all DS18B20 sensors have deviations within the acceptable zone (Figure 31), the HeatLab Protocol has a special calibration procedure that performs this procedure if there is an offset in the sensor operation. The DS18B20 sensors are factory calibrated, and no recalibration from hardware level is possible; therefore, the offset is corrected with the help of a software offset. First, the deviation ΔT is calculated according to Equation (45). Then, a software calibration offset is calculated according to Equation (48).

$$\bar{T}_{i,offset} = \frac{1}{N} \sum_{j=1}^N [T_{i,sensor}(t_j) - T_{i,IR}(t_j)], [\text{K}] \quad (48)$$

where $\bar{T}_{i,offset}$ refers to the average deviation of sensor i during the 300 s of calibration time window. N refers to the number of samples collected, $T_{i,sensor}$ refers to the measured temperature by the DS18B20 sensor and $T_{i,ref}$ refers to the corresponding infrared temperature

measurement obtained from the thermal camera. The corrected temperature of the sensor is then calculated as shown in Equation (49).

$$T_{i,corrected}(t) = T_{i,sensor}(t) - \Delta T_{i,offset}, [K] \quad (49)$$

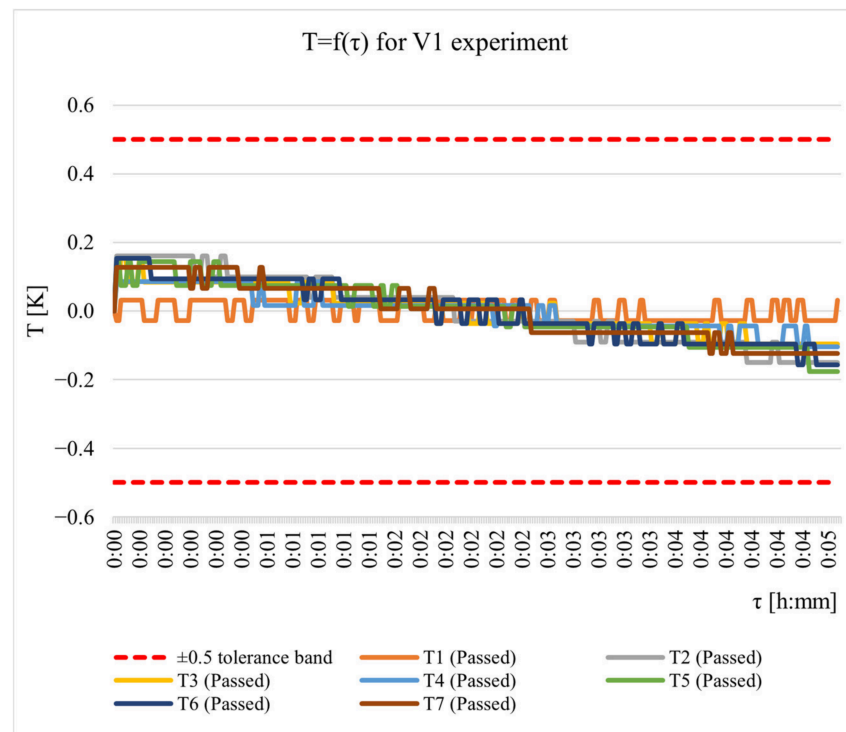


Figure 30. Temperature sensor deviation during the V1 experiment.

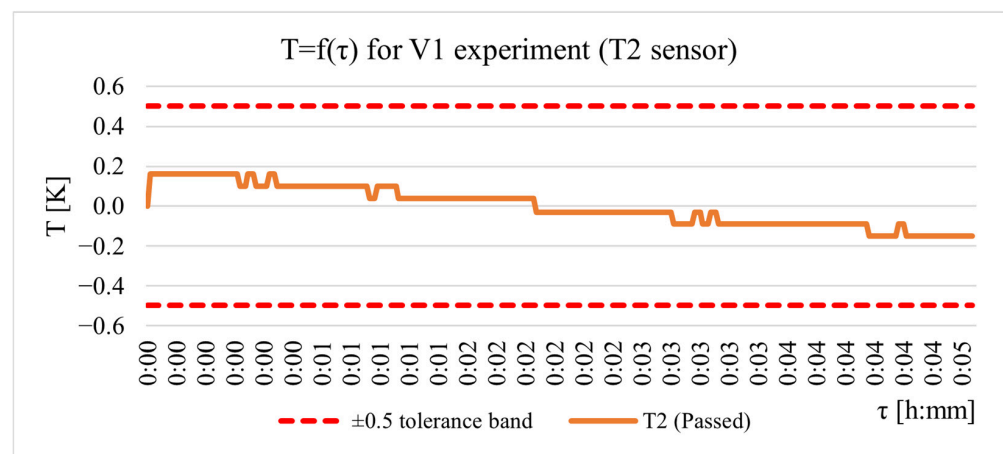


Figure 31. Temperature calibration using an offset for the DS18B20 sensor (T2).

This offset is saved in the HeatLab configuration file and is used automatically when acquiring data in real time. This compensates for the systematic measurement offset for each sensor while maintaining the original sensor response. If a deviation is observed in a particular sensor, this procedure is repeated under isothermal conditions. If a sensor exhibits a deviation greater than ± 0.5 K or shows instability, it is replaced since DS18B20 is cheap and easily replaceable. In combination with the offset correction process, the validation results lead to a standard process that ensures stable and consistent temperature readings in future tests. This process provides temperature measurement consistency and stability, rather than traceably established absolute accuracy.

Figure 31 illustrates the deviation curve for sensor T2, which had the highest initial deviation during the period. As the hydraulic circuit achieves full thermal equilibrium, the deviation steadily drops from about +0.2 K towards zero, verifying the stability of the sensor and the acceptance of the sensor within the ± 0.5 K band. The same result was achieved for all other sensors, with no drift, spikes or instabilities noticed. Figure 32 provides an illustration of the infrared thermal image of the radiator system taken during the offset calibration process. The observed surface temperature distribution over the radiator and the exposed piping was relatively stable, with temperatures ranging from 304.15 K to 311.15 K depending on the measurement region. This indicates that the observed surface temperature distribution remained stable during the calibration period and provides an independent consistency check for the DS18B20 measurements.

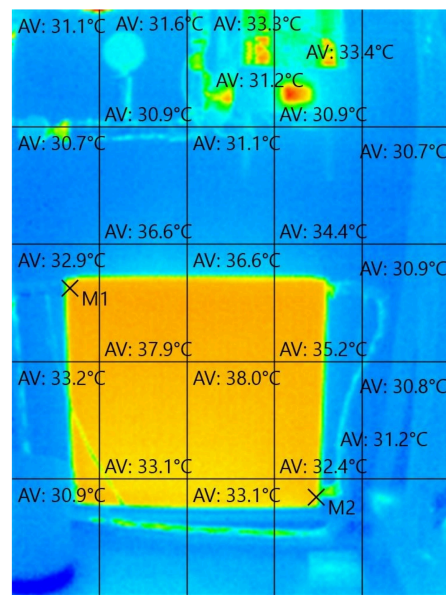


Figure 32. Infrared thermal camera image of the radiator obtained using Testo860i and processed via IIRSoft; M1 and M2 indicate the inlet and outlet measurement points, respectively [31].

The V2 calibration tests confirm the precision and repeatability of the FM-001 flowmeter, which calculates the volumetric flow rate, mass flow rate, Re , Gr , Pr and Nu numbers and, finally, heat output based on the EN 442 formula. As the flow rate affects the thermal power balance and convection type estimation, it needs to be correctly measured during steady-state and transient measurements. The circulation pump has been adjusted to create three reference flow regimes:

- low flow: $\sim 8.33 \times 10^{-6} \text{ m}^3/\text{s}$;
- nominal flow: $\sim 2.22 \times 10^{-5} \text{ m}^3/\text{s}$;
- high flow: $\sim 3.33 \times 10^{-5} \text{ m}^3/\text{s}$.

The operating points meet the calibration need for the chronometric (timed volume) technique (Table 8). The latter is the common procedure for testing the performance of a turbine flow meter like FM-001. During the validation process, the electrical heater was turned off in order to eliminate the thermal expansion effect. The system was allowed to settle at each operating point for some time before collecting the water for a specified time period. Then the volume and time were used to estimate the manual reference flow rate, as given in Equation (50).

$$Q_{\text{manual}} = \frac{\dot{V}}{t}, [\text{m}^3/\text{s}] \quad (50)$$

Relative errors between the readings obtained from FM-001 and the manual values were obtained using Equation (51).

$$\varepsilon = \frac{Q_{FM-001} - Q_{manual}}{Q_{manual}} \cdot 100, [\%] \quad (51)$$

All the measurements were taken under constant hydraulic conditions, without any disturbance such as cavitation, air entrainment or transient phenomena, and the results are presented in Table 10.

Table 10. Individual flow meter validation results (chronometric method).

Test ID	Q_{manual} m^3/s	Q_{FM-001} m^3/s	ε %	Pass/Fail
Individual measurements				
V2-low 1	8.461×10^{-6}	8.500×10^{-6}	+0.47	Pass
V2-low 2	8.469×10^{-6}	8.500×10^{-6}	+0.35	Pass
V2-nom 1	2.103×10^{-5}	2.175×10^{-5}	+3.41	Pass
V2-nom 2	2.089×10^{-5}	2.175×10^{-5}	+4.07	Pass
V2-high 1	3.193×10^{-5}	3.300×10^{-5}	+3.36	Pass
V2-high 2	3.282×10^{-5}	3.300×10^{-5}	+0.56	Pass
Mean values				
Low	8.467×10^{-6}	8.500×10^{-6}	+0.39	Pass
Nominal	2.097×10^{-5}	2.175×10^{-5}	+3.74	Pass
High	3.237×10^{-5}	3.300×10^{-5}	+1.93	Pass

Satisfactory agreement was achieved by the FM-001 flow meter with the manually performed chronometric measurement for all three operational regimes. Errors were kept in the range of 0.35–4.07%, which is well below the usual acceptance limit of $\pm 5\%$ for turbine type flow meters in laboratory-size hydraulic systems. In the low flow regime, errors less than 0.5% indicate very stable pulse detection and low noise level, whereas in the nominal regime, errors in the range of ~ 3 –4% are anticipated due to higher turbulence levels and more sensitivity to pulse rate; in the high flow regime, errors less than 2% ensure proper scaling of pulse frequency at high flow rates. These findings confirm that the FM-001 sensor can be utilized for EN 442 heat output calculation, dimensionless number estimation and flow transition investigation. Chronometric measurements were used to adjust the effective calibration constant $ppl_{current}$ (pulses per liter). Even though the flow meter sensor offers nominal values (usually in the range of 450–500 pulses/L), the HeatLab system uses a software calibration constant that is based on V2 measurements (Equation (52)).

$$ppl_{current} = 413.74, [\text{pulses/L}] \quad (52)$$

The value is stored in the HeatLab configuration and used during real-time acquisition. It allows for consistency between FM-001 measurements and manual measurements throughout the whole operating range. The V2 validation confirms that the FM-001 flow meter is suitable for EN 442 radiator testing in terms of accuracy; it provides stable measurement with respect to the regimes of low, nominal and high flow, gives correct measurement of pulse frequency without any noise or drift, and is completely adequate for thermohydraulic analysis both in steady-state and dynamic cases. It confirms the reliability of all flow-dependent parameters used during the S- and D-series tests. The V3 validation test is used to ensure the hydraulic characteristics of the P-001 circulation pump by means of comparing manufacturer-specified pump curve and experimental data on pump performance

under laboratory conditions. This validation is necessary, since the head, differential pressure and hydraulic efficiency of the pump have direct influence on flow rate, dimensionless numbers and convection regime in both steady-state and dynamic experiments.

The curve of the manufacturer shown in Figure 33 shows the theoretical dependence of pump head H on volumetric flow rate Q for the three possible stages of speeds (*I*, *II*, *III*). Such curves characterize ideal pump operation in standard conditions (clean water at 293.15 K, full opening of valves, no air entrapment). These are the criteria of comparison used to prove the effectiveness of the real pump operation in the HeatLab setup. The experimental pump curve was acquired with the use of chronometric measurements and determination of differential pressure at the pump inlet (M-001) and outlet (M-002). In each speed stage, several points of flow were measured by measuring the volume of water in a certain period of time. Differential pressure was calculated according to Equation (9) and converted to the pump head. The results of the experimental measurements of pump parameters shown in Figures 34–36 allow for a conclusion to be made about the hydraulic behavior of the circulation pump in each of the three possible speed stages. While the manufacturer curve shows the flow rate in m^3/h , the results of the experiment are given in strictly SI units (m^3/s).

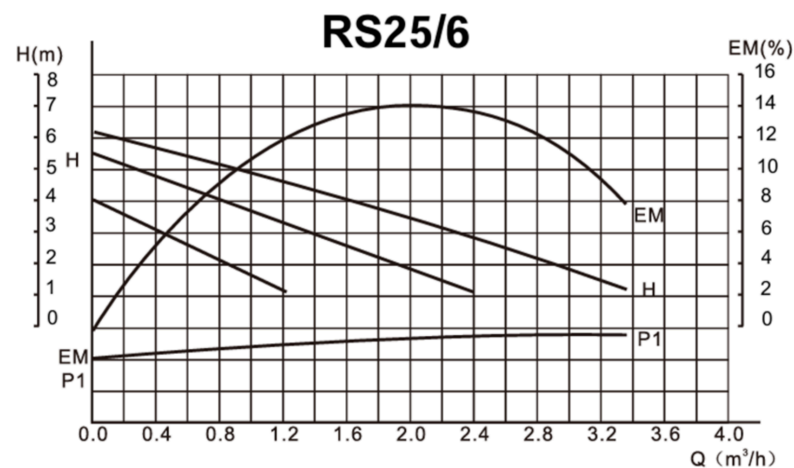


Figure 33. Manufacturer pump curve—RS 25/6 [21].

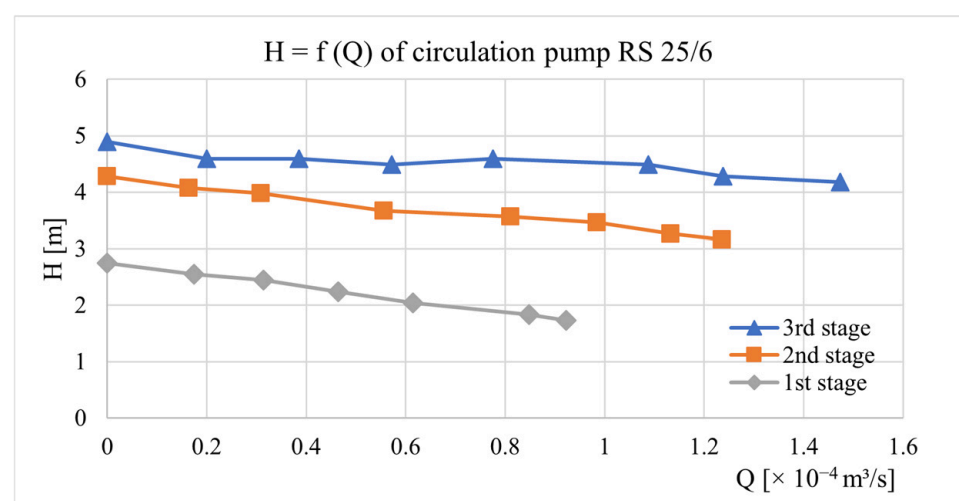


Figure 34. Experimental pump curve— $H = f(Q)$.

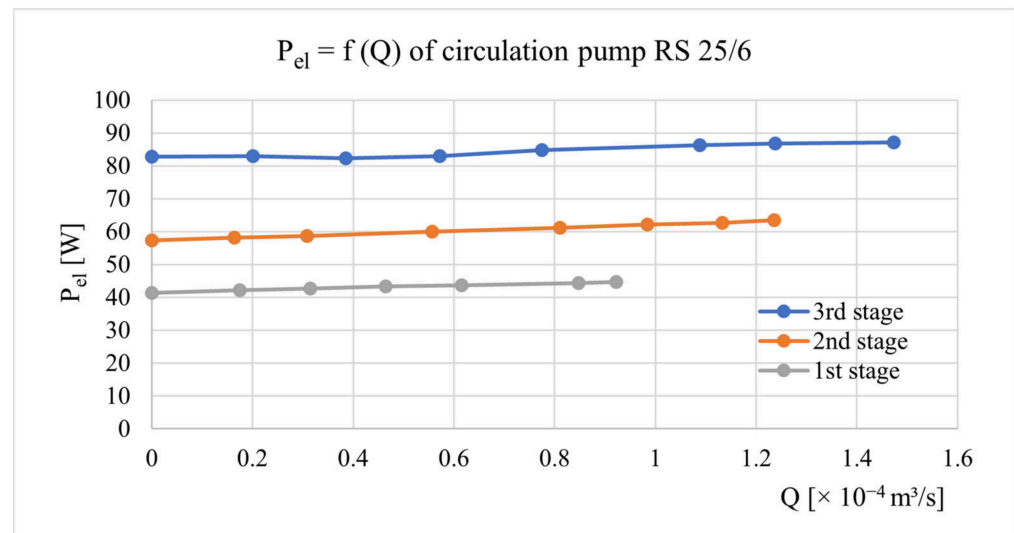


Figure 35. Experimental electrical power curve— $P_{el} = f(Q)$.

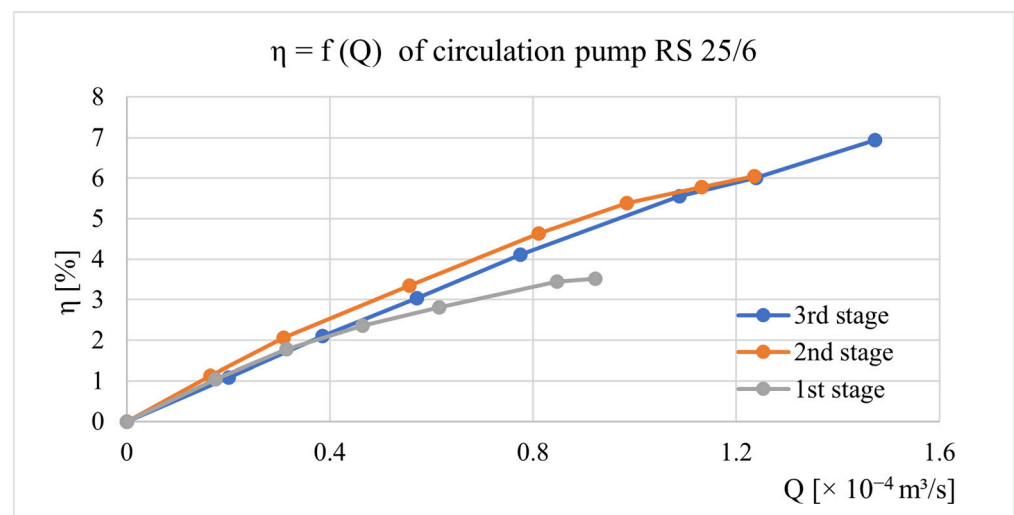


Figure 36. Experimental hydraulic efficiency curve— $\eta = f(Q)$.

The head curve (Figure 34) shows the typical performance of a circulation pump where the head steadily declines with an increase in flow rate for all three speed stages. Head is lowest in the first stage (up to 2.8 m at low flow rates, declining to 1.8 m), intermediate in the second stage (from 4.2 m to 3.2 m) and highest in the third stage (up to 4.9 m, declining to 4.2 m). The well-separated position of the three curves proves the appropriateness of the selected speeds and proper hydraulic operation. The entire shape and values of the curves perfectly match the nominal range of the manufacturer, which proves that the pump can provide the required head.

Input power (Figure 35) increases steadily with an increase in the flow rate due to the increased hydraulic loading of the circulation pump. It can be observed that the first stage consumes the least amount of power, the second stage consumes moderate amounts of power and the third stage consumes the maximum amount of power. The increasing nature of the data shows a stable power supply and correct motor functioning. The values of the power measured are close to the data specified by the manufacturer within $\pm 3\text{--}5\%$. This indicates the proper functioning of the pump from the perspective of its electrical properties. Hydraulic efficiency (Figure 36) increases with an increase in the flow rate for

all three speed stages. Maximum efficiency is attained at a peak near the normal operating range of the pump.

4. Discussion

The absence of any discrepancies in the shape of the efficiency curves suggests that the pump operation is stable in the operating range of tests without any occurrence of cavitation or mechanical instabilities during the experiments. The observed efficiency rates of 5–7% are typical for the operating mode of the small wet rotor circulation pumps under investigation, which work in the low power range. Experimental dependencies $H(Q)$, $P_{el}(Q)$ and $\eta(Q)$ demonstrated smooth and consistent physical behavior in all three speed modes of the pump operation. The experimental results of the head, the electrical power consumed by the pump and hydraulic efficiency were consistent with manufacturer data within about 3–5%. These results confirm that the circulation pump creates stable hydraulic conditions for conducting the steady-state and transient thermohydraulic experiments. Validation of the electrical power measurement chain related to the heater module (B-001) was accomplished through carrying out of the V4 validation experiment. Accurate measurement of electrical power is necessary since the heater serves as the main source of thermal energy for the hydraulic circuit and the nominal values of the powers of 500, 1000 and 1500 W provide the reference points for performing calculation of the steady-state thermal energy power balance, transient studies and evaluation of radiator heat output based on EN 442 methodology. Correctness in terms of measuring electrical input is crucial for carrying out the next steps of the thermohydraulic calculations. The validation process was carried out in accordance with the workflow presented in Table 8. During the validation, the isothermal operation of the hydraulic circuit was carried out with continuous circulation of the fluid. However, the measured electrical power revealed some minor discrepancies between the nominal heater settings and values acquired using the D69-2049 digital panel meter, AT-001 module and Tuya Smart socket. For the 500 W nominal setting, the discrepancy in readings of the measurement devices amounted to approximately 10–20 W; that is, approximately 2–4%, relatively. For the 1000 W setting, the reading discrepancy was around 30–40 W, or approximately 3–4%. For the 1500 W setting, the discrepancy slightly increased to 35–50 W, or approximately 2–3%, relatively. Such discrepancies were caused by the cumulative effect of heater power tolerance, switching/regulation properties and accuracy/resolution of each of the measurement devices. All considered, the readings of the AT-001 measurement device were consistently aligned with the reference measurement procedure at all tested powers, thus allowing its integration into HeatLab. Results of the performed validation procedures confirm that all key measuring channels are within acceptable deviation ranges. Temperature measurements deviated by no more than ± 0.2 – 0.5 K from reference values, whereas deviations in the flow meter calibration were in range of 0.35–4.07%. Deviations in pump operation from its specified characteristics were found to be within the range of 3–5%. Deviations in heater power consumption were about 2–4% compared with nominal values. It can be concluded that the measurement chain has enough precision to conduct thermohydraulic calculation in the current research. This means that discrepancies between measured and calculated thermal quantities can be regarded as being caused by system behavior or model uncertainties. The steady-state experiments confirmed physically consistent dependencies between flow rate, temperature difference and thermal output. Higher flow rates corresponded to lower temperature differences and higher convective heat transport rates. This is also confirmed by the change in the Reynolds and Nusselt numbers. Close correspondence between the electrical energy input and the experimentally obtained thermal output was confirmed by

the results of the energy balance analysis, which indicates a steady-state energy balance deviation in the order of approximately $\pm 2.8\%$.

The steady-state operating points for the S-series cover a wide thermohydraulic range, with the Reynolds number spanning 1800 to 6860, mass flow rates between 7.88×10^{-3} and 3.14×10^{-2} kg/s, temperature differences from 1.21 to 14.04 K and heat transfer coefficient U varying from 7.21 to 29.69 W/m²K, depending on the hydraulic configuration and heater power. These values represent stabilized, time-averaged conditions under which the flow and temperature fields have reached a steady state. In contrast, the higher Reynolds numbers reported for S2 (≈ 5000) and for D2 (approaching 6000) originate from the full instantaneous sweep. The dynamic operating points (D1–D4) exhibit transient behavior, with Reynolds numbers ranging from ~ 2730 to 4460, mass flow rates between 1.83×10^{-2} and 2.84×10^{-2} kg/s and corresponding variations in U and ΔT driven by thermal inertia, pump speed changes or valve restriction. These dynamic values characterize the broader hydraulic response of the system and are not used for EN 442 steady-state evaluation. To consolidate these regimes, Table 11 reports the mean values and uncertainties of Re , U , $\dot{m}$ and ΔT for all S-series and D-series experiments, which correspond to the experimental goals shown in Tables 5–7.

The resulting behavior of the Nusselt number corresponds to the expected change in the convective heat transfer coefficient in the investigated range of flows and serves as a base for comparison with the chosen [20,29,30] correlations. The investigated range of Re numbers includes the transition region; hence, the mentioned correlations have to be treated more as reference correlations rather than as universal ones. EN 442 analysis has revealed a stable correlation between the radiator's heat power generation and related temperature difference variable in log–log space. The corresponding regression implies that the radiator exhibits the anticipated power law dynamics within the considered operating range. The lack of pronounced oscillatory behavior or numerical discontinuity in the steady-state values calculated is also indicative of the ability of the browser-native computation engine to carry out required averaging and parameter calculation without producing noticeable numerical artifacts. The D-series of tests supplied extra data regarding the transient thermohydraulic behavior of the system. The step change in heating power led to instantaneous change in electrical input and then there was a gradual rise in measured thermal output. The delayed thermal response is due to the thermal capacity of the radiator, the thermal capacity of the water volume and the transport delay time of the fluid. The measured thermal time constant was about 110–130 s and it depended on hydraulic operating conditions. The lack of overshoot in the measured thermal response confirms the validity of the application of the first-order lumped capacity approximation under the studied conditions. It is important not to regard this result as proof that the lumped model describes correctly all thermal processes taking place inside the system. The effect of the hydraulic transient resulted in rapid and steady changes in flow rate and Re and Nu numbers, whereas the thermohydraulic transient showed how thermal load affects convective heat transport. Oscillations and instabilities were not detected in any of the transient experiments conducted. The deviation in the energy balance of the experiment during transient operation stayed within approximately $\pm 3.2\%$, which shows that the measured values could be integrated in real time quite stably. The browser-based computations also agreed with the reference ones with an error margin of $\pm 2.5\%$. That means that reduced-order thermohydraulic computations can be done in the browser without losing necessary accuracy.

Table 11. Summary of mean values for all steady-state and dynamic experiments.

# [—]	<i>Re</i> (Mean) [—]	<i>U</i> W/m ² K	<i>m</i> kg/s	ΔT K	Regime [—]
<i>S-series</i>					
S1	1668 ± 268	13.81 ± 6.68	$7.88 \times 10^{-3} \pm 1.64 \times 10^{-4}$	14.04 ± 2.87	steady-state
S2	4504 ± 696	20.34 ± 33.06	$2.10 \times 10^{-2} \pm 8.78 \times 10^{-4}$	6.97 ± 1.4	steady-state
S3	6856 ± 908	20.22 ± 26.99	$3.14 \times 10^{-2} \pm 2.20 \times 10^{-3}$	4.74 ± 1.08	steady-state
S4	3858 ± 397	16.95 ± 10.81	$2.27 \times 10^{-2} \pm 4.65 \times 10^{-4}$	2.99 ± 0.58	steady-state
S5	4740 ± 752	29.69 ± 36.75	$2.07 \times 10^{-2} \pm 1.63 \times 10^{-3}$	9.49 ± 2.37	steady-state
S6	4755 ± 781	20.76 ± 16.50	$2.17 \times 10^{-2} \pm 2.97 \times 10^{-4}$	7.03 ± 1.43	steady-state
S7	5857 ± 871	19.34 ± 11.59	$2.59 \times 10^{-2} \pm 7.71 \times 10^{-4}$	6.44 ± 1.37	steady-state
S8	1827 ± 346	18.77 ± 28.99	$8.87 \times 10^{-3} \pm 1.72 \times 10^{-4}$	11.28 ± 2.86	steady-state
S9	5224 ± 1008	7.21 ± 10.51	$2.15 \times 10^{-2} \pm 1.51 \times 10^{-3}$	2.19 ± 0.61	steady-state
S10	4556 ± 800	10.25 ± 28.97	$2.27 \times 10^{-2} \pm 7.29 \times 10^{-4}$	1.21 ± 0.21	steady-state
S11	5429 ± 980	9.29 ± 12.97	$2.20 \times 10^{-2} \pm 1.73 \times 10^{-3}$	2.72 ± 0.68	steady-state
S12	4959 ± 756	19.44 ± 14.47	$2.27 \times 10^{-2} \pm 1.48 \times 10^{-3}$	5.51 ± 1.10	steady-state
S13	4712 ± 811	20.75 ± 15.13	$2.28 \times 10^{-2} \pm 4.52 \times 10^{-4}$	4.99 ± 1.41	steady-state
S14	4964 ± 838	16.54 ± 11.47	$2.23 \times 10^{-2} \pm 5.49 \times 10^{-4}$	5.29 ± 1.57	steady-state
<i>D-series</i>					
D1	3336 ± 183	210.42 ± 1161.69	$2.33 \times 10^{-2} \pm 3.07 \times 10^{-4}$	5.41 ± 1.60	dynamic
D2	4463 ± 975	54.27 ± 35.44	$2.84 \times 10^{-2} \pm 4.31 \times 10^{-3}$	3.29 ± 1.28	dynamic
D3	2726 ± 440	11.17 ± 1145.28	$1.83 \times 10^{-2} \pm 3.97 \times 10^{-3}$	4.95 ± 1.89	dynamic
D4	4259 ± 847	55.49 ± 32.06	$2.64 \times 10^{-2} \pm 2.86 \times 10^{-3}$	3.84 ± 1.66	dynamic

The main novelty and contribution of HeatLab are the creation and experimental validation of an integrated physical–digital paradigm for real-time thermohydraulic analysis of water heating systems. Novelty is not brought by the independent use of IoT sensors, cloud computing, browser computing, numeric calculations or immersive visualization, which have all been thoroughly studied. On the contrary, HeatLab creates an experimental link between the physical system, real-time measurements, real-time browser-based thermohydraulic calculations and real-time digital visualization. The framework relates the values of temperature, flow rate and electrical power to the computations of thermal power, energy balance, thermophysical properties and dimensionless numbers in real time. Some physical elements of the system, such as the heater and circulation pump, can also be controlled through the digital domain, thus establishing a limited bidirectional link between the physical and digital domains. Verification tests of the V-series validate this chain of measurements and computations. Both the browser interface and the VR interface have different purposes and do not constitute redundant visualization levels. The browser interface is used for data collection, numerical calculations, quantitative analysis and the presentation of experimental results. The VR interface gives a spatial visualization of the physical system, which makes it possible to inspect the system’s components and their interactions, visualize the current state of the thermohydraulic system and interact with certain components that can be controlled by the user. In the case of the real-time experimental scenario, the measured parameters are constantly transmitted to the virtual model, which makes it possible for the displayed system’s state and associated numerical values to reflect the state of the physical experiment. The current design cannot be regarded as an autonomous digital twin of the complete heating system. Two-way interaction currently allows the heater and the circulation pump to switch on and off, while other hydraulic states of operation still have to be configured manually. For that reason, the virtual reality

element of the proposed framework can be seen as interactive visualization and control with partial digital twin capability rather than as a closed loop digital twin.

There are certain restrictions to the current implementation of HeatLab. First, thermohydraulic parameters are determined with the help of sensors whose accuracy is ± 0.5 K in the case of DS18B20 temperature sensors and that do not possess multipoint traceable calibration, but rather software offset correction. Moreover, the accuracy of the turbine flow meter decreases when measuring very small flow rates due to lower pulse frequencies and quantization effects. Although the measurement accuracy of the individual sensing subsystems is assessed through their specifications, calibration procedures and validation experiments, comprehensive uncertainty propagation through all derived thermohydraulic quantities is not performed in the present study. Such an analysis would require dedicated treatment of individual sensor uncertainty distributions, calibration uncertainties and possible correlations between input measurements. This represents a limitation of the current work and is reserved for a subsequent study focused on the metrological characterization of the HeatLab framework. Secondly, the thermal model used a reduced-order lumped capacitance model for use in real time. While correct when $Bi \ll 0.1$, it cannot resolve local temperature gradients, fin conduction, differences in temperatures from panel to panel, or airside convection and therefore cannot replace CFD (computational fluid dynamics) or distributed thermal models. In the same way, micro cavitation, air entrainment and pump hysteresis and other local hydraulic issues are not modeled. Thirdly, remote control is contingent upon reliable Internet connection and the functionality of the Firebase system itself. A data rate of 1 Hz data is sufficient for the thermal dynamics that are being studied, although it restricts the ability to capture faster processes within the hydraulic dynamics and network lag might influence real-time visualization. Fourth, computing on the browser restricts the complexity of models which can be computed in real time. Higher sampling rate, more sensors, or more complex models require higher amounts of computing and communication. The present architecture is best suited for computing reduced models in real time, while more computational tasks like CFD, multiphysics simulations and optimization can be carried out using dedicated numerics. Lastly, the VR environment has additional requirements in terms of hardware and graphics rendering and does not necessarily enhance accuracy in measurements or computations. Traditional 2D plotting remains more efficient for numeric and analytical purposes. Yet, the VR technology offers capabilities that go beyond traditional visualization, in that it allows for a spatial visualization of the physical system, a linking of real-time measurements into the virtual representation, the capability of designing and simulating scenarios manually, as well as some degree of interaction with the physical system. These limitations determine the working range of the current platform and do not negate the experimental findings. The described values of sensor errors, flow meter testing, pump testing, power metering testing and energy balance give an established framework for evaluating the correctness of the performed measurements and calculations.

5. Conclusions

The experimental study carried out on the HeatLab platform allows for thorough testing of the thermohydraulic characteristics of a miniaturized heating system under both steady-state and transient operation conditions. The overall findings of the S-, D- and V-series of the experiments confirm the ability of the browser-based computational model to collect, analyze, compute and display values of the thermohydraulic parameters in real time, yielding physically valid and reproducible outcomes. The performed V-series validation tests provided the stability of the measurement chain to within the limits of precision of the used measuring equipment. The DS18B20 temperature sensors operated inside their specified error limits, which ensured the measurement of inlet, outlet, surface

and ambient temperatures. Validation of the flow meter gave errors not exceeding 5% in the studied range of operation, whereas validation of the pump showed good correlation between experimentally obtained and manufacturer data. Measurements of electrical power stayed within about 2–4% of nominal heater power, which gave an opportunity to perform further calculations of thermal power. The deviation in the total energy balance did not exceed 3.2% for steady-state experiments. The time constant of the transient response was about 110–130 s, and the calculation made by the browser gave good correlation with the reference calculations, within 2.5%. From the analysis of the S-series tests, physically plausible correlations between flow rate, temperature difference and heat generation were found. As the flow rate was increased, the temperature difference for water decreased and the values of Re and Nu increased. The balance of thermal power showed consistent results, i.e., there was equality between electrical energy input and measured heat output. Log–log regression of EN 442 showed the consistent behavior of the radiator as a function of temperature difference. It can be concluded that there are no noticeable numerical instabilities in the browser-based calculation engine. The D-series of tests highlighted the capabilities of the HeatLab platform in terms of capturing the transient response of the system to variations in the thermal and hydraulic operating conditions. Step changes in heater power were shown to elicit a distinct thermal response, with the inlet temperatures responding before downstream temperatures due to the time lag in water transport and thermal inertia of the system. The hydraulic transient resulted in a change in the flow rate and in the Re and Nu numbers calculated. Transients involving both thermal and hydraulic inputs further highlighted the effect of thermal input on heat transfer by convection.

One of the significant advantages of HeatLab is the incorporation of experimental data collection, computation directly in the browser and visual representation in the VR model of the physical system. The VR model does not merely represent static information. In real-time mode, the measured temperatures, flow rates and calculated values can be implemented into the virtual model, so the model itself and its visualization will correspond to the current state of the physical system. Furthermore, the environment allows for the manual setup of the hydraulic connection schemes, power of the heater, flow conditions, as well as simulations that are not dependent on the physical experiment. Currently, at the level of development that has been reached, the interaction of VR with the physical system is only limited to the elementary control of the heater and circulation pump (ON/OFF), while other hydraulic conditions are manually set up. Thus, the current realization of the application can be considered as an example of a framework for real-time experimental and VR representation with limited interaction between the two systems. In summary, the findings confirm that HeatLab provides stable, real-time acquisition, browser-based thermohydraulic computation, quantitative visualization and immersive virtual reality representation within a unified experimental platform, enabling partial digital twin functionality. Thus, HeatLab can be applied to radiator testing, thermohydraulic experiments, real-time monitoring and engineering education. However, while the VR element expands numerical visualization with respect to the interaction and context of system components, no increase in the academic performance of students can be stated in this case as the semester has not yet begun. A number of features would contribute to expanding the functionality of HeatLab. Traceable multipoint or temperature-based calibration would help to diminish uncertainties in measurements, whereas better flow measurement at low flow rates would lead to improved calculation accuracy for the dimensionless numbers. Comprehensive pump characterization under controlled throttling would help to cover a greater part of the hydraulic operating region. Valve modulation and multiple heating profiles and disturbance cases would allow for a wider investigation of transient dynamics and control performance. Using reduced-order or data-driven predictive models would

help to enhance further possible predictions and control. Last but not least, automation of reporting, advanced visualization features and interactive EN 442 analyses would enhance the applicability of the platform with respect to both scientific purposes and educational needs. All these developments would pave the way toward future implementation of full digital twin systems without losing browser-native and experimentally validated platform architecture, as presented in the current study.

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Abbreviations

The following abbreviations are used in this manuscript:

Symbol	Definition	Unit
2D	Two-dimensional	-
3D	Three-dimensional	-
A	Heat transfer area	m ²
ADC	Analog to digital converter	-
AD-001	Automatic deaerator	-
AR	Augmented reality	-
ARTTMDTrack	ART tracking interface	-
AT-001	Autotransformer	-
BB	Bottom–bottom connection	-
Bi	Biot number	-
BNC	Browser-native computation	-
BTD	Bottom–top diagonal connection	-
BTU	Bottom–top unilateral connection	-
CAVE	Cave automatic virtual environment	-
CFD	Computational fluid dynamics	-
COLLADA	Collaborative design activity	-
CP-001	Control panel	-
CV-001/008	Control valves	-
c_p	Specific heat capacity of water	J/kg·K

DAQ	Data acquisition	-
DT	Digital twin	-
DWG	Drawing file format	-
DXF	Drawing exchange format	-
E57	ASTM E57 3D imaging data format	-
E_{el}	Electrical energy	J
ε	Surface emissivity	-
E_{th}	Thermal energy	J
e_{abs}	Absolute error	-
e_{rel}	Relative error	-
EV	Experimental validation	-
EV-001	Expansion vessel	-
FM-001	Flow meter	-
g	Gravitational acceleration	m/s ²
glTF	GL Transmission Format	-
Gr	Grashof number	-
h	Heat transfer coefficient	W/m ² ·K
H	Pump head	m
HE-001	Heat exchanger	-
HMD	Head-mounted display	-
HTTP	Hypertext transfer protocol	-
IFC	Industry Foundation Classes	-
IMI	Institute for Information Management in Engineering	-
IoT	Internet of Things	-
JSON	JavaScript Object Notation	-
k_{steel}	Thermal conductivity of steel	W/m·K
K_m	Modulus/characteristic coefficient of radiator	-
KIT	Karlsruhe Institute of Technology	-
L_c	Characteristic length	m
LMTD	Logarithmic mean temperature difference	K
M-001/002	Manometers	-
$\dot{m}$	Mass flow rate	kg/s
n	Exponent of the EN 442 radiator characteristic equation	-
N_{el}	Electrical power supplied to the heater from the electrical network	W
Nu	Nusselt number	-
OBJ	Wavefront OBJ format	-
OpenGL	Open Graphics Library	-
OpenSG	Open Scene Graph	-
PE	Physical experiment	-
P_{el}	Pump electrical power	W
P_{hyd}	Hydraulic power	W
p_{in}	Inlet pressure	Pa
p_{out}	Outlet pressure	Pa
ppl	Pulse density of the flow meter	pulses/m ³
Pr	Prandtl number	-
PSI	Physical-system interaction	-
P-001	Pump	-
Q	Heat transfer rate	W
Q_{conv}	Convective heat loss	W
Q_{heater}	Heater thermal output	W
Q_{rad}	Radiator heat output	W
Re	Reynolds number	-
REFF	Reference	-
RTS	Real-time sensing	-
σ	Stefan–Boltzmann constant	W/m ² ·K ⁴

STEP	Standard for exchange of product model data	-
STL	Stereolithography format	-
SV-001	Safety valve	-
T	Absolute temperature	K
T_{in}	Inlet temperature	K
T_{out}	Outlet temperature	K
T_{room}	Room/ambient temperature	K
TBD	Top–bottom diagonal connection	-
TBU	Top–bottom unilateral connection	-
THC	Thermohydraulic computation	-
TT	Top–top connection	-
U	Overall heat transfer coefficient	W/m ² ·K
$\dot{V}$	Volumetric flow rate	m ³ /s
VR	Virtual reality	-
VRML	Virtual Reality Modeling Language	-
VRPN	Virtual Reality Peripheral Network	-
β	Volumetric thermal expansion coefficient	K ⁻¹
ΔT	Temperature difference	K
η_{pump}	Pump efficiency	-
μ	Dynamic viscosity	Pa·s
ν	Kinematic viscosity	m ² /s
ρ	Density	kg/m ³
Φ	EN 442 radiator characteristic coefficient	W

References

1. Bergman, T.L.; Lavine, A.S.; Incropera, F.P.; DeWitt, D.P. *Fundamentals of Heat and Mass Transfer*, 8th ed.; Wiley: Hoboken, NJ, USA, 2018.
2. Hristov, V.; Tsankov, P. Research of the heat transfer coefficient in different connection schemes for radiators. *AIP Conf. Proc.* **2023**, *2889*, 070002. [\[CrossRef\]](#)
3. Frede, T.A.; Weber, C.; Brockhoff, T.; Christ, T.; Ludwig, D.; Kockmann, N. Data management of microscale reaction calorimeter using a modular open-source IoT-platform. *Processes* **2023**, *11*, 279. [\[CrossRef\]](#)
4. Ménétrey, J.; Pasin, M.; Felber, P.; Schiavoni, V. WebAssembly as a common layer for the cloud-edge continuum. In *Proceedings of the 2nd Workshop on Flexible Resource and Application Management on the Edge (FRAME '22)*; ACM: New York, NY, USA, 2022; pp. 3–8. [\[CrossRef\]](#)
5. Kakati, S.; Brorsson, M. A Cross-Architecture Evaluation of WebAssembly in the Cloud-Edge Continuum. In *Proceedings of the 2024 IEEE 24th International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*, Philadelphia, PA, USA, 6–9 May 2024; pp. 337–346. [\[CrossRef\]](#)
6. Kakati, S.; Brorsson, M. WebAssembly Beyond the Web: A Review for the Edge-Cloud Continuum. In *Proceedings of the 2023 3rd International Conference on Intelligent Technologies (CONIT)*, Hubli, India, 23–25 June 2023; pp. 1–8. [\[CrossRef\]](#)
7. Haas, A.; Rossberg, A.; Schuff, D.L.; Titzer, B.L.; Holman, M.; Gohman, D.; Wagner, L.; Zakai, A.; Bastien, J. Bringing the Web up to speed with WebAssembly. In *Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation*; Association for Computing Machinery: New York, NY, USA, 2017; Volume 52, pp. 185–200. [\[CrossRef\]](#)
8. Qi, Q.; Tao, F. Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison. *IEEE Access* **2018**, *6*, 3585–3593. [\[CrossRef\]](#)
9. Tao, F.; Zhang, M. Digital Twin Shop-Floor: A new shop-floor paradigm towards smart manufacturing. *IEEE Access* **2017**, *5*, 20418–20427. [\[CrossRef\]](#)
10. Beneš, T.; Husák, M.; Mihálik, O.; Vanc, R.; Bradáč, Z. Digital twin of heat exchange station. *IFAC Pap.* **2024**, *58*, 311–316. [\[CrossRef\]](#)
11. Bilka, M.; Gritsuk, I.; Holovan, A.; Volska, O.; Honcharuk, I.; Kohutiar, M.; Krbata, M. Digital twin-based assessment and forecasting of marine plate heat exchanger performance under variable operating conditions. *Machines* **2026**, *14*, 497. [\[CrossRef\]](#)
12. Usher, W.; Pascucci, V. Interactive visualization of terascale data in the browser: Fact or fiction? In *Proceedings of the 2020 IEEE 10th Symposium on Large Data Analysis and Visualization (LDAV)*; IEEE: New York, NY, USA, 2020; pp. 27–36. [\[CrossRef\]](#)
13. Zhang, Y.; Liu, M.; Wang, H.; Ma, Y.; Huang, G.; Liu, X. Research on WebAssembly Runtimes: A Survey. *ACM Trans. Softw. Eng. Methodol.* **2025**, *34*, 1–47. [\[CrossRef\]](#)

14. Boettcher, K.; Terkowsky, C.; Schade, M.; Brandner, D.; Grünendahl, S.; Pasaliu, B. Developing a real-world scenario to foster learning and working 4.0—On using a digital twin of a jet pump experiment in process engineering laboratory education. *Eur. J. Eng. Educ.* **2023**, *48*, 949–971. [\[CrossRef\]](#)
15. Kaufhold, N.; Boettcher, K. Enhancing Chemical Engineering Education: Constructive alignment and augmented reality in experimental fluid mechanics. *PAMM* **2026**, *26*, e70179. [\[CrossRef\]](#)
16. Xu, X.; Wang, F. Engineering Lab in Immersive VR—An Embodied Approach to training wafer Preparation. *J. Educ. Comput. Res.* **2021**, *60*, 455–480. [\[CrossRef\]](#)
17. Wilkerson, M.; Maldonado, V.; Sivaraman, S.; Rao, R.R.; Elsaadany, M. Incorporating immersive learning into biomedical engineering laboratories using virtual reality. *J. Biol. Eng.* **2022**, *16*, 20. [\[CrossRef\]](#) [\[PubMed\]](#)
18. BS EN 442-1:2014; Radiators and Convectors—Part 1: Technical Specifications and Requirements. Bulgarian Institute for Standardization: Sofia, Bulgaria, 2015.
19. BS EN 442-2:2014; Radiators and Convectors—Part 2: Test Methods and Rating. Bulgarian Institute for Standardization: Sofia, Bulgaria, 2015.
20. Shah, R.K.; Sekulić, D.P. *Fundamentals of Heat Exchanger Design*; Wiley: Hoboken, NJ, USA, 2003.
21. NORWIK POWER. RS25-6-180: Circulation Pump. Available online: <https://norwikpower.com/en/products/pumps/circulation/rs25-6-180/> (accessed on 17 July 2026).
22. Firebase. Firebase, Google LLC, Mountain View, CA, USA. Available online: <https://firebase.google.com/> (accessed on 7 February 2026).
23. Häfner, V. PolyVR—A virtual reality authoring system. In Proceedings of the Conference and Exhibition of the European Association of Virtual and Augmented Reality, Bremen, Germany, 8–10 December 2014. [\[CrossRef\]](#)
24. Victor-Haefner. *PolyVR—A Shortcut to Virtual Reality PolyVR GitHub Repository*; GitHub: San Francisco, CA, USA.
25. Cruz-Neira, C.; Sandin, D.J.; DeFanti, T.A.; Kenyon, R.V.; Hart, J.C. The CAVE: Audio visual experience automatic 1070 virtual environment. *Commun. ACM* **1992**, *35*, 64–72. [\[CrossRef\]](#)
26. Ngrok, Inc. Ngrok (Version 3.x), San Francisco, CA, USA [Computer Software] (2013–2026). Available online: <https://ngrok.com> (accessed on 1 February 2026).
27. International Association for the Properties of Water and Steam. *Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use (IAPWS R6-95(2018))*; International Association for the Properties of Water and Steam: Erie, CO, USA, 2018. Available online: <https://iapws.org/relguide/IAPWS95-2018.pdf> (accessed on 11 August 2026).
28. Vogel, H. Das Temperaturabhängigkeitsgesetz der Viskosität von Flüssigkeiten. *Phys. Z.* **1921**, *22*, 645–646.
29. Dittus, F.W.; Boelter, L.M.K. Heat transfer in automobile radiators of the tubular type. *Univ. Calif. Publ. Eng.* **1930**, *2*, 443–461.
30. Sieder, E.N.; Tate, G.E. Heat transfer and pressure drop of liquids in tubes. *Ind. Eng. Chem.* **1936**, *28*, 1429–1435. [\[CrossRef\]](#)
31. Testo SE & Co. KGaA. *Testo IRSofT*, Version 5.2. [Computer Software]. Testo SE & Co. KGaA: Titisee-Neustadt, Germany, 2024.

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