CLIMA 2022
Eye on 2030 | Towards digitalized, healthy, circular and energy efficient HVAC

REHVA 14th HVAC World Congress
22nd – 25th May, Rotterdam, The Netherlands

Control device for pumping one-pipe hydronic systems

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Abstract. The article presents the development and algorithms behind an active control device for pumping one-pipe (or primary-secondary pumping) systems. The main feature of such a system is the series connection of thermal loads/sources and a small pump by each load/source, as opposed to classical two-pipe systems with a parallel connection and throttling valves. Our main contribution is an integration of all necessary components into one device and the ability to infer mass flow in a secondary circuit without a flowmeter. By also measuring a temperature drop, we can estimate and control a heat flow and provide remote thermal and hydraulic diagnostics of a connected heat terminal via the device. It is powered and communicates through the Ethernet and contains a wet-rotor BLDC pump controlled by the field-oriented control method. A Kalman filter provides a mass flow estimate, and a robust distributed parameter system controller regulates the heat flow.

Keywords. One-pipe, single-pipe, primary-secondary pumping, heat flow control, iQ-pump
DOI: https://doi.org/10.34641/clima.2022.349

1. Introduction

This article focuses on one-pipe hydronic networks, also called single-pipe or referred to as primary-secondary pumping systems. Nowadays, however, mostly two-pipe hydronic heating systems are used. The most widespread is quantitative regulation, where varying hydraulic resistance in a branch regulates flow through a heat terminal. The easiest quantitative regulation actuator is a manual valve; however, nowadays, legislative norms (e.g. [1] in Czech Rep.) no longer allow its use – at least automatic thermostatic valves have to be utilised. A thermostatic valve controls its opening mechanically, depending on the room temperature. A more up-to-date solution is the use of Pressure Independent

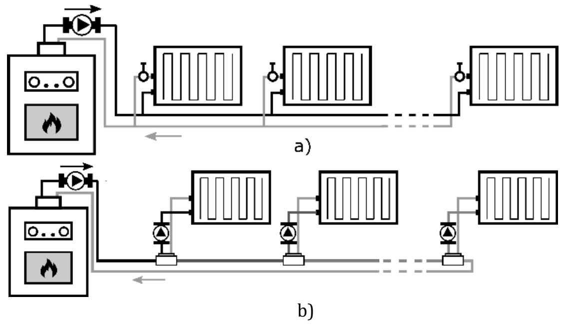

Fig. 1 – Hydronic system topologies: a) two-pipe throttling system, b) pumping one-pipe system.

Control Valves (PICV, [1]), which are utilised mostly in fan-coil unit (FCU) applications. A PICV contains a spring mechanism for maintaining a constant pressure drop across an adjacent control valve; the flow, therefore, depends only on the valve opening and not on any pressure variations [1].

Another way to control a hydronic system is to pump heat transfer liquid where needed instead of throttling it where not required. This solution is already available on the market [2,3] and uses a small pump for each heat terminal. Let us call systems with throttling valves "passive" or "throttling" and systems using the pumps "active" or "pumping". Wilo AG has also established a terminology where throttling systems are called "supply oriented" and those with pumps "demand oriented". It is possible to meet also the term "centralised" for systems with a central pump and "decentralised" for decentralised pumping systems.

Although there is also a two-pipe variant of a decentralised pumping system [2,4], this article expands only on the one-pipe pumping hydronic network and the control device designated.

The article will present the one-pipe network, the control device development, and algorithms, finished by its real-life validation.

1.1 Pumping one-pipe hydronic network

Pumping one-pipe systems, also referred to as "primary-secondary pumping" [5], are mostly used to connect heat sources, but can also be utilised on the load side. In short, from the main pipe in the circuit branch out two closely-spaced T-fitting, where a secondary (the "small") pump with a heat source/terminal is looped around. The heat sources/terminals are connected in series on the main (primary) piping, that loops back to the main circulator and a heat load/source side, respectively. See Fig. 1 for a schematic depiction.

The advantages of the pumping one-pipe hydronic system are:

- the system generally contains only two pipe diameters (primary and secondary),
- time and material savings (fewer pipes, connections, valves and plumber's work),
- one type of pump in the secondary loop can control a wide range of load capacities; i.e. the system is robust against design inaccuracies/changes,
- the amount of the overall dissipated pumping energy is the lowest of all possible topologies,
- one-pipe system contains less heat transfer liquid (water, glycol) than a comparable two-pipe system.

The disadvantages are:

- practitioners hold on the impression that one-pipe systems are inefficient and problematic. This is based on the long-surpassed throttling one-pipe heating variant with its real higher operational cost and low comfort [5]. It harms, beforehand, the reputation of the pumping one-pipe systems,
- temperature relations among secondary loops shall be considered during system design. However, there is a one-pipe network design and validation tool [8,9] available,
- this solution became feasible only recently as canned wet rotor pumps, and electronically commutated motor became available. There are not many installations proving the performance of this system. However, dozens of pumping one-pipe systems are in service in the US, e.g. [3].

For more hydronic network topologies details and a one-pipe network design tool description, resort to [6].

2. One-pipe control pump device

The thermal power of a heat terminal in a pumping one-pipe network is controlled by the speed of the secondary pump impeller. And as there is no variable hydraulic resistance in the secondary circuit, the secondary flow is governed solely by the pump speed.

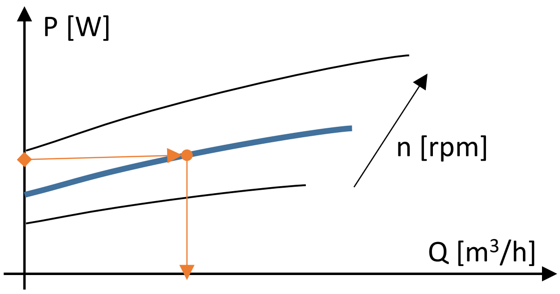

Fig. 2 – The basic principle of inferring flow from a pump electrical power reading.

This scenario makes it possible to infer flow from pump power readings, as Fig. 2 suggests. Knowing the pump speed, power, and power-flow characteristics is enough to estimate the absolute volumetric/mass flow through the pump and consequently through the whole secondary circuit. A heating/cooling power can be calculated by adding a pair of temperature sensors on a supply and return line.

Our patented invention [7,8], with the business name iQ-pump (IQP), bundles the two closely-spaced T-fittings, a pump housing, check-valve and a pair of temperature sensors together into one device. Such a device connects a heat source/terminal directly to the main pipe. See Fig. 3 for schematic depiction.

Note: Although the same principles generally apply to heat sources, the one-pipe control pump devices will only be depicted in the heat distribution to the heat terminals. Also, even though only heating will be addressed further, similar principles apply to the distribution of cooling power.

2.1 Design and Manufacturing

The EU directive [9] recommends designing heat sources for a typical building load (instead of a maximal load), with a complimentary heat source for extreme conditions. Applying the same principle to heat distribution, the main pipe has been chosen DN32 with G5/4 threads, which renders an economic pressure drop [10] for supplying one floor of 75% of commercial buildings in the EU [11]. The other 25% of establishments with higher loads shall, but only for 6% of operation time [12], experience higher main pipe velocities than 1.2 m/s and higher pressure losses.

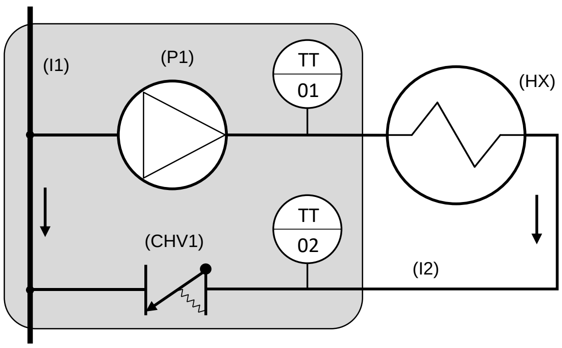

Fig. 3 – One-pipe control pump device scheme. HX – heat exchanger, CHV – check-valve, I – pipe, P – pump, TT – temperature sensor.

The device's secondary pipe and pump are sized for a load of 10 kW with an average weighted hydraulic conductivity of 0.8 bar/m³/h. The secondary ports are DN15 with G1/2 threads, the standard connection for most heat terminals. See Fig. 4 for results from the research on typical design operation conditions (normalised using EN 442-1:1995) and typical loads.

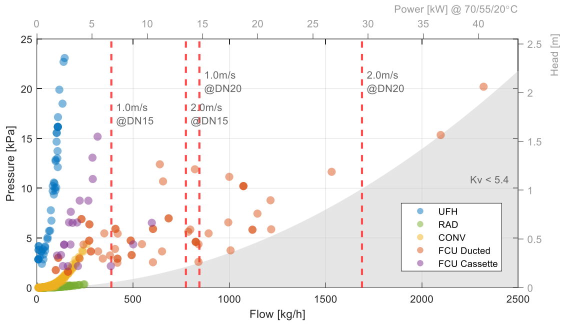

Fig. 4 – Typical design operation conditions for underfloor heating (UHF), radiators (RAD), convectors (CONV) and fan-coil units (FCU). All datasheet values normalised to conditions 70/55/20°C using the norm EN 442-1:1995

A D5-sized pump [13] (used in solar-thermic installation) serves as the secondary pump. It is a spherical-shaped wet-rotor electronically commutated pump with four rotor poles and six stator coils on a magnetic core ring.

The IQP body (Fig. 5) consists of the main pipe, from which a pump housing extends with its suction hole. The pump outlet directs perpendicularly away from the main pipe axis. The secondary outlet port houses a spring check valve and a secondary supply temperature sensor. From the same direction comes the secondary inlet, where the secondary return temperature sensor is housed and which connects back to the main pipe.

The IQP body was made as symmetrical as possible from the primary-pipe point of view to enable directing the secondary ports to the right or left regardless of the flow direction in the main pipe. I.e. the direction of flow in the main pipe does not alter hydraulic conditions in the secondary piping.

The first prototypes were manufactured using additive 3D printing from ABS and were waterproofed by curing in a solvent. This technique sufficed for all tests not involving elevated temperatures (> 50°C). Later prototypes were manufactured by selective laser sintering using high-temperature resins. These prototypes were waterproof from the beginning but were found to be very brittle and had to be later reinforced with a polymer resin armour. Later prototypes were manufactured using selective heat sintering using PA12 nylon material. These prototypes were found indestructible for all our relevant tests. The final prototypes were cast from brass using ceramic moulds (created on top of 3D printed masters). The final design is brass-castable and machinable by standard industrial methods.

The electronics cover is designed to be injection-moulded without special cores. It is designed to comply with IP44 and cable-pull protection.

3. Electronics and software

The first electronics prototype was built on the Arduino platform, mainly as a relay between the peripheries and Matlab. Afterwards, a custom-built PCB empowered by a Raspberry Pi 3 Compute Module was used. In-line motor phase measurements were performed using shunt resistors. Several Raspbian kernel modules operating the ADC over SPI were built to quickly and precisely sample the phase voltages and currents and calculate power from the asymmetric readings. Reliable measurement of the phase between voltage and current, however, remained a problem, which only was solved by a power acquisition directly by a microchip later on. The EC motor was driven by a 6-step control on-chip driver TI DRV10987.

The final electronics utilises an NXP i.MX-RT microcontroller with built-in motor control features. The pump speed control and electrical power acquisition are performed by vector control methods (FOC) [14], allowing for efficient device control in the whole range from zero to maximal flow.

The powerful ARM Cortex-M7 processor, running FreeRTOS, also allows for broadband communication, temperature readings and heat estimation and control computations.

Fig. 5 – One-pipe control pump device. Early design at the top (3D print manufacturing); brass-casted and machined final design with injection-mould-manufacturable electronics cover on the bottom.

2.2 Mass flow estimation

Mass flow estimation is the key component of the one-pipe control pump device. Being able to determine flow without the use of a flow meter enables cost-effective implementation of the following features:

- Heat flow estimation
- Heat flow control
- Heat metering
- Thermal diagnostics

Looking at the schematic of the secondary circuit (Fig. 3), there are three main features from the hydraulic point of view: the double T-fitting (connection to the primary circuit), the pump body with a check-valve and the hydraulic load, i.e. the heat terminal with its piping. The T-fittings are spaced closely together to not to create a pressure source for the secondary circuit. Changes in the primary flow do not influence the secondary flow (verified by measurement, variation less than 5 l/h per 1000 l/h change in the primary flow) – hence the two circuits are hydraulically separated. It simplifies the secondary hydraulic circuit to just two components: the pump and the load.

The IQP device sizes neither up nor down with the capacity of the load; the control authority is always full, as we control the flow directly. Precision speed control of the pump means sufficient flow control precision for any load capacity. Therefore, the IQP body with its pump housing, check-valve and ports is of a fixed size and can be described precisely by its head-flow (HQ) and power-flow (PQ) characteristics. Fig. 6 presents the measured data and their fitted polynomial model. Fitting in L1 norm under shape constraints [15] was used.

The hydraulic conductivity of the load is considered fixed but unknown.

A dynamical model of the pump (Fig. 7) will be described now. The inputs to the model are: speed reference S_{REF}[rpm], volumetric flow Q [l/h] and inlet water temperature T_{wi}[°C]. The dynamic states are: pump speed S [rpm] and coil temperature T_c[°C].

The model's outputs are: pump head H [m], pump electrical power P [W] and pump speed

$$\begin{aligned} u &= [S_{REF}, Q, T_{wi}]^T, \\ x &= [S, T_c]^T, \\ y &= [H, P, S], \theta = [\tau_S, C_c, h_c]^T. \end{aligned} \tag{1}$$

The state equation for speed is governed mainly by the speed controller, impeller inertia and flow, but the dynamics are fast enough to enable coarse approximation by first-order dynamics

$$\begin{aligned} \dot{S} &= \tau_S^{-1}(S_{REF} - S) \\ \dot{T_c} &= C_c^{-1}\left(h_c(T_{wi} - T_c) + \mathrm{pol}_{PQ}(Q, S)\right), \end{aligned} \tag{2}$$

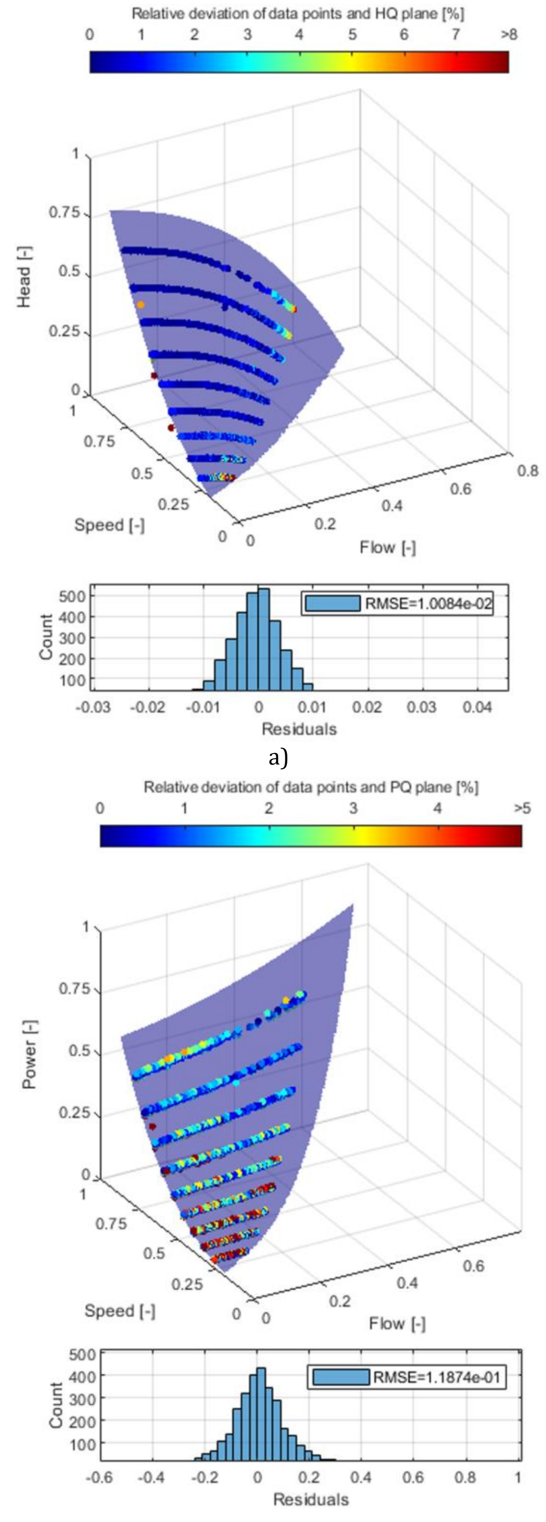

Fig. 6 – IQP device characteristics fitting: a) HQ plane, b) PQ plane.

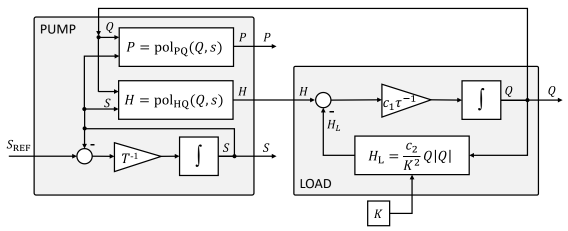

Fig. 7 – Simplified scheme of the dynamical model used for mass flow estimation.

where τ_S [s] is a time constant. The coil temperature has been identified to affect the power consumption. There is a heat transfer to the pumped water of the supply temperature, where the heat transfer coefficient is h_c[W/K] and the electrical power is represented by a polynomial model (eq. (3)). The heat capacity of the coil is denoted C_c [J/kg · K].

The outputs are defined by the steady-state polynomial maps (Fig. 6)

$$\begin{aligned} H &= \mathrm{pol}_{HQ}(Q,S) = \\ &= a_3Q^3 + a_2Q^2 + a_1Q + c_{11}Qs + \\ &\quad + b_2s^2 + b_1s + a_0 \\ P &= \mathrm{pol}_{PQ}(Q,S) = \\ &= \bar{c}_{13}Qs^3 + \bar{c}_{12}Qs^2 + \bar{a}_1Q + \bar{c}_{11}Qs + \\ &\quad + \bar{b}_3s^3 + \bar{b}_2s^2 + \bar{b}_1s + \bar{a}_0, \end{aligned} \tag{3}$$

with coefficients $a, b, c, \bar{a}, \bar{b}, \bar{c}$ fitted to measured data.

A dynamical model of the load (Fig. 7) has three inputs: head difference across the load H [m], inlet water temperature T_{wi}[°C], outlet water temperature T_{wo}[°C]. The only dynamical state is the flow Q [l/h], which is also the only output. The parameters θ are described below

$$\begin{aligned} u &= [H, T_{wi}, T_{wo}]^T, \\ x &= Q, \\ y &= Q, \\ \theta &= [K, \tau]^T. \end{aligned} \tag{4}$$

The dynamical flow model is derived from an inertance model, where the difference between input head H and load head H_L [m] is the change driving potential,

$$\dot{Q} = 3.6 \cdot 10^6 \cdot g \cdot \tau \cdot (H - H_L). \tag{5}$$

The load head follows from the Darcy-Weisbach law, where K [bar → m^3/h] is the hydraulic conductivity factor of the load, gravity is denoted g [m/s^2],

$$H_L = \frac{10^{-4}}{K^2 g} Q|Q|. \tag{6}$$

Inertial constant τ[m] is the ratio of the pipe cross-section A_c[m^2] and total pipe length L [m],

$$\tau = \frac{A_c}{L}. \tag{7}$$

The hydraulic conductivity is mildly dependent on mean water temperature by a multiplication factor k_K. The hydraulic conductance at nominal temperature $K_{nom} = K|_{T=T_{nom}}$ is a parameter estimated by a Kalman filter,

$$K = K_{nom} + k_K\left(T_{nom} - \frac{T_{wi} + T_{wo}}{2}\right). \tag{8}$$

The dynamical model is non-linear, with one parameter to be estimated. The states of the system – pump speed S [rpm] and most importantly the flow Q [l/h] – all together with the hyd. conductance of the load K_{nom} are estimated by an extended Kalman filter (EKF). The resulting flow estimate Q is denoted $\widehat{m_w}$.

2.3 Heat flow control

A heat terminal, e.g. FCU, is generally a distributed parameter, distributed time-delay system governed, when simplified, by a one-dimensional hyperbolic PDE [16]. Additionally, temperature measurements are situated at the IQP device, so there is also a, possibly significant, transport delay present due to secondary piping lenght.

Standard PID feedback control is not suitable for such systems. But a controller by Sandoval [17] is specifically designed for robust velocity control of convective spatially distributed systems, e.g. heat terminals.

The control problem statement is to find a controller of a form

$$\begin{aligned} \dot{\zeta} &= g(\zeta, e) \\ u(t) &= \phi(\zeta, \mathrm{e}), \end{aligned} \tag{9}$$

where $u(t)$ is the manipulated variable (the pump speed reference S_{REF} in our case), $e = y - r$ is the control error (heat flow error in our case) and ζ is the integrator state of the controller. The goal is to find functions g, ϕ such that the control error vanishes in time. Let the function $\phi(\zeta, e) = \zeta + \theta\psi(e)$ be such that $e\psi(e) > 0$ with $\theta = \mathrm{sign}(L_f h) = \mathrm{const.}$ being the sign of the Lie derivative of the problem (either 1 or -1). Then for an input function

$$u = u(t - \tau) + \theta\psi(e), \tag{10}$$

the error dynamics is asymptotically stable [17].

The stabilising control law is defined exactly as

$$\begin{aligned} \dot{\zeta} &= k_I \mathrm{sg}(e)\theta(|(u - \zeta)\zeta| + |\dot{e}|) \\ u &= \zeta + \theta\psi(e), \end{aligned} \tag{11}$$

where $\psi(e) = k_P e$ and $\mathrm{sg}(e) = 1$ for $e \geq 0$ and -1 otherwise.

The two constants k_P and k_I are tuning parameters for proportional and integral action, respectively. The controller can be considered a PI controller with a variable integral gain. An anti-windup clamping modification has been utilised to prevent wind-up situations.

In our scenario, the controlled output is a calculated heat output of the heat terminal

$$\begin{aligned} y &= \hat{Q}_H = \widehat{m_w} c_\mathrm{p}(T_{wi} - T_{wo}) \\ r &= Q_{REF}, \end{aligned} \tag{12}$$

where c_p[J/kg/K] is the specific heat capacity of the heat transport fluid (assumed water, a statistical test for the presence of water can be performed), T_{wi}, T_{wo} [°C] are supply and return temperature measurements in the IQP device. Heat flow reference

Q_{REF} [W] is given by a supervisory temperature controller – a wall module or a zone temperature MPC [18].

3. Validation

The development of the IQP device would not be possible without a precise and multifunction measurement and validation testbed. Flow estimation and heat control precision will be presented in this section.

3.1 Testbed

A hydronic testbed for temperature feedback hydronic control devices (Fig. 8) contains three main circuits: the main hydronic circuit starting with the main pump, passing through a hot-water tank, the IQP device, set of PT1000 temp. sensors and electromagnetic flowmeter back to the primary pump. The secondary circuit starts at the IQP device, passes through an actuated valve, a Coriolis flowmeter, a set of PT1000 temp. sensors to a water-to-air heat exchanger and back to the IQP device. A precise differential pressure sensor can be connected to IQP device ports on the secondary and the primary side. The airstream starts with a straight duct with a Wilson grid flowmeter, continues through a controlled fan and a set of PT1000 temp. sensors into the heat exchanger, from where it leaves the testbed.

The testbed also contains a small (cold) tank to realise sharp temperature changes. The cold tank is connected to the main-primary circuit using a one-pipe connection via an old IQP prototype. The heating tank is controlled by an ADRC controller, airflow and primary water flow by regular PI controllers. All controllers are embedded from Matlab into the main Unipi Neuron PLC. See Fig. 8 for a depiction of the testbed.

Two-pipe throttling actuators with temperature feedback may also be developed and tested on the testbed.

3.2 Results

Fig. 9 presents flow estimation precision. The data were obtained by ramping the pump speed up and down, preceded by three load steps, where identification (by the KF) of the hydraulic load occurred. The actuated valve connected to the secondary circuit was set to a random position to represent an unknown hydraulic load. The standard deviation in the whole range for the actual hydraulic load is 3.91 l/h; however, the estimation in the low-flow region is inaccurate due to the lack of feedback from the pump's electrical power reading; the PQ characteristics is flat here.

Fig. 10 presents results on the heat flow control of the water-to-air heat exchanger present at the testbed. The results were obtained by slowly ramping up and down the absolute heat reference value. The standard deviation over the whole range

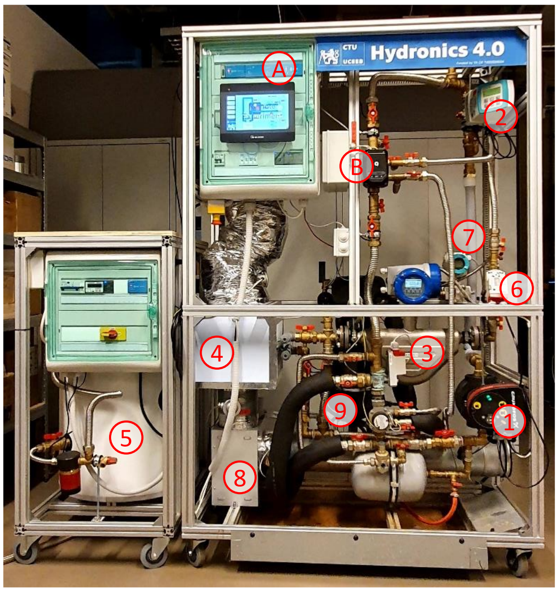

Fig. 8 - Hydronic Testbed. A) Testbed controller, B) One-pipe control pump device, 1) Primary pump, 2) Primary induction flowmeter, 3) Secondary Coriolis flowmeter, 4) Water-to-air heat exchanger, 5) Main tank, 6) Actuated valve, 7) Differential pressure sensor, 8) Controlled fan, 9) Second tank for sudden temperature steps.

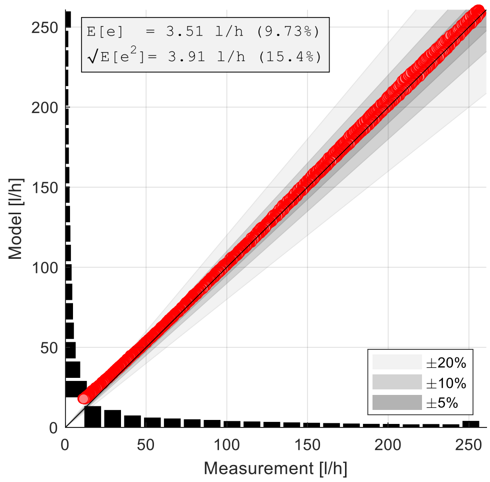

Fig. 9 – Flow estimation precision for a random fixed position of the actuated valve in the secondary circuit.

of the heat terminal was 158 W. However, the tracking precision at low heat flows is unsatisfactory due to multiple factors. First and foremost, the error in mass flow estimation is to be blamed; secondary, the delivered (real) heat is calculated from the wet water temperature sensors positioned directly on the heat exchanger inlet and outlet, whereas the estimated power is calculated from the temperature sensors on-board the IQP device, and there is a good portion of uninsulated piping between them. Note that the heat flow controller tracks the heat reference closely without any error, but the estimated power differs from the real one. Therefore, the power control error is likely accountable to the heat dissipated by secondary piping (not well insulated) and other errors in temperature measurements, but the flow estimation error also participates.

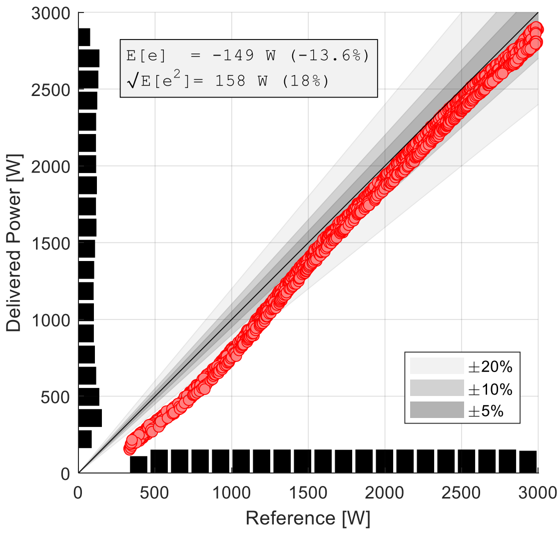

Fig. 10 – Steady-state heat flow control precision for the heat terminal present at the hydronic testbed.

4. Conclusion

This paper presents the results of a three-year-long development of the one-pipe control pump device (iQ-pump). We have built a well working testbed suitable for developing temperature feedback hydronic actuators (valves, pumps) and have designed and built the IQP device according to the patented ideas. The paper presents the mechanical development process and the core working principle from the estimation and control point of view. Measurements validate the method to be sound, although there is still room for improvement in details. Future development will be directed towards thermal diagnostics, mainly detecting diminishing heat transfer due to dust build-up in an FCU.

Acknowledgement

This research was funded by the Technology Agency of the Czech Republic, grant number TK01020024.

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