Quest Journals
Journal of Architecture and Civil Engineering
Volume 6 ~ Issue 1 (2021) pp: 35-46
www.questjournals.org

Research Paper

Experimental Verification and Optimization of Heat Pump Operation in Cooling Mode

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ABSTRACT: *This paper describes the results of experimental measurements for different variants of heat pump connection in cooling mode with refrigerant tank and cooling system. The paper compares different situations where there are differences in the volume of the tank, the volume flow of the working substance and in the direction of filling the tank. The aim of the measurements was to optimize the number of start-up cycles of the heat pump by storing energy in water tanks. By reducing the number of pump starts, the service life of the mechanical parts of the heat pump, the compressor, is extended.*

KEYWORDS: *progressive technologies, renewable energy sources, mobile laboratory, simulator and optimizer of energy systems, optimization of operation of energy systems, heat pumps, refrigerant storage tanks*

Received 15 Jan, 2021; Revised: 28 Jan, 2021; Accepted 31 Jan, 2021 © The author(s) 2021.
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I. INTRODUCTION

Progressive technologies and materials for the application of renewable energy sources in buildings consist of the following basic components [1], [2], [3]:

- Solar collectors (can be combined with solar roofs).
- Long-term liquid-based heat storage units (heat transfer by coil to liquid), solids (heat transfer to eg soil through a pipe register) or phase change (coil transfer eg to paraffin).
- Short-term heat storage tanks based on liquid or phase change.
- Cooling system, which is based on a pipe register located in the non-freezing depth of the soil (may be supplemented by an external cooler and a coolant accumulator).
- A recuperative heating / ventilation system based on a recuperation air-handling unit with preheating or air cooling in single- or dual-pipe counterflow heat exchangers located at the non-freezing depth of the soil. The final heat treatment of the ventilation air is by means of liquid, gaseous or electric heat exchangers (heaters, coolers) integrated in HVAC units or external located in the HVAC distribution system. This system can be complemented by low-temperature heating and high-temperature cooling systems used to temper the interior of the building.
- Of building structures (roof and external walls) with internal energy source - active thermal protection consisting of a pipe system provided with a distribution layer (plaster, thermally conductive foil, thermally conductive coating or spraying) placed between the load-bearing part of building structures and thermal insulation layer.
- Peak (standby) heat source (electric coil in short-term storage tank, electric boiler, gas boiler, heat pump, fireplace, other heat source and combination of multiple heat sources)
- Controller software (measurement and control), which controls all actuators and components of the combined building and energy system of the building.

II. DESCRIPTION OF THE RESEARCH AND TECHNICAL INNOVATION SOLUTIONS

Energy systems built into some building structures, which serve to capture solar energy, geothermical energy and external energy, or have the function of end elements of the heating, cooling and ventilation system, are generally called combined energy systems of buildings. We include solar roofs among the combined building and energy systems with built-in tube absorbers, building structures with active thermal protection

(ATP) - active control of heat transfer, which have a multifunctional purpose - thermal barrier, low-temperature heating, high-temperature cooling, heat recovery and storage, solar energy and outdoor energy, energy storage, large-capacity storage heat exchangers (underground heat accumulators as part of the foundation structure of a building) or heat exchangers used for recuperative ventilation of buildings built into foundation slabs and wall structures, [10].

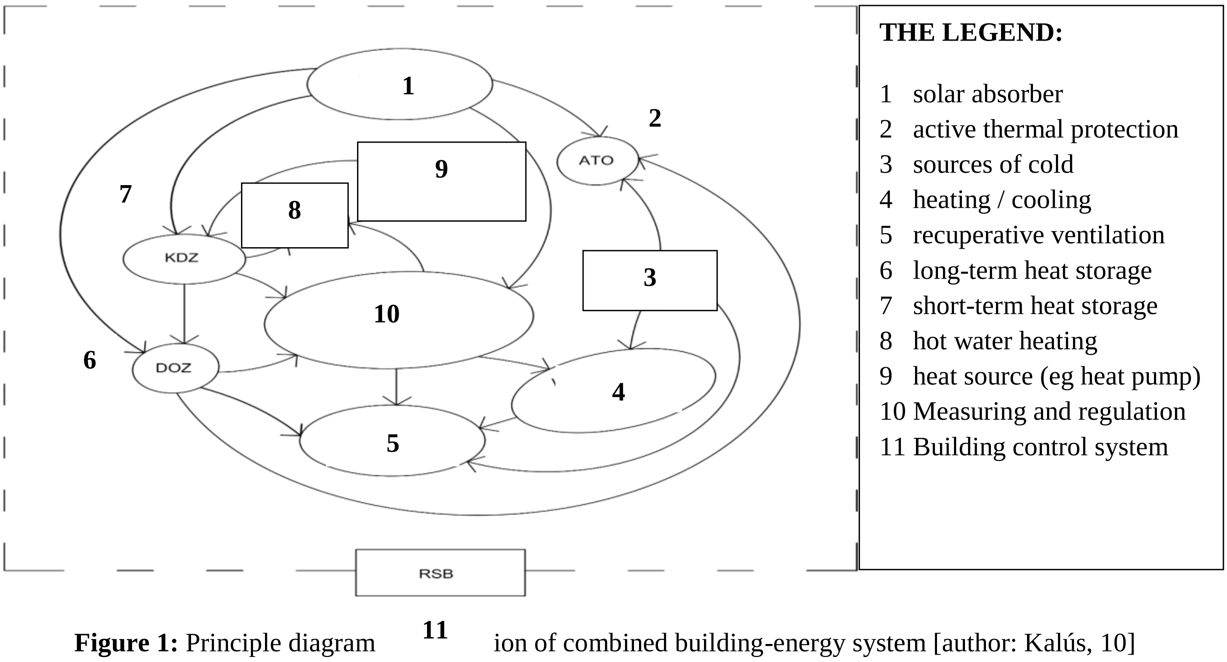


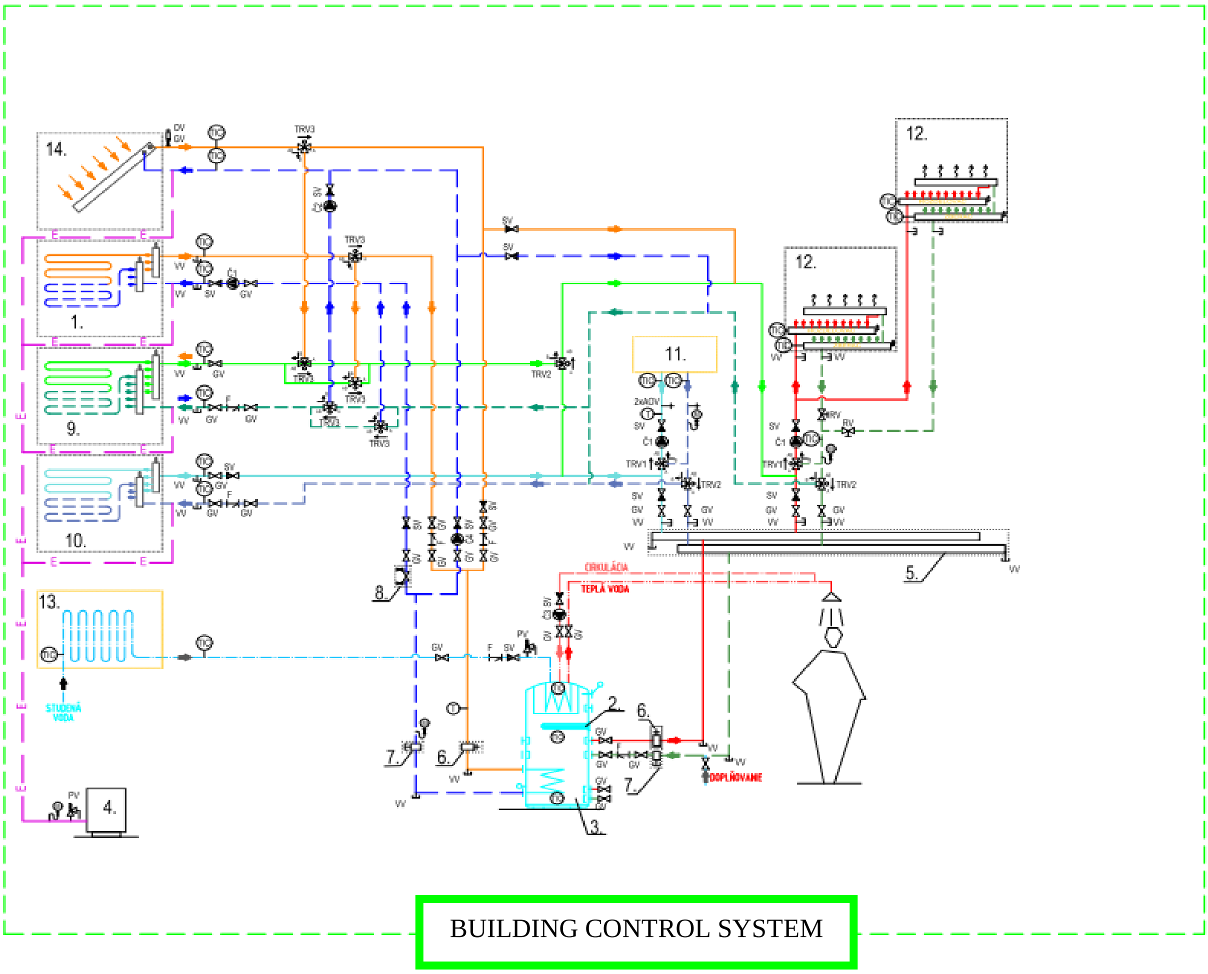
Figure 1: Principle diagram ion of combined building-energy system [author: Kalús, 10]

Based on utility model no. 5749 a series of mathematical, physical and construction models and a working laboratory have been developed for the operation of the combined building and energy system of buildings and equipment registered in Banská Bystrica, Slovak Republic in April 2011, [10]. The nature of the operation of the combined building and energy system of buildings based on the exchange and / or conversion of energy according to the invention consists in the fact that the complex creation of the indoor environment of the buildings with regard to the seasonal or immediate requirements is accomplished by a combination of controlled processes. These processes include heat absorption, heat production, cold, heat accumulation, use of active heat protection, low temperature, hot air heating, cooling, water heating. With the help of a building control system that actively regulates the temperature of the heating medium and with the help of a heat source, a cold source and a short-term heat reservoir and a short-term cold storage tank, we create the appropriate properties of the indoor environment.

In accordance with Directive EU 2018/844 (2010/31/EU), [6], on nearly zero energy buildings, the requirement to achieve energy class A0 of the primary energy of the building, the requirement for quality building envelope buildings with target thermal resistance in accordance with STN EN 73 0540, RES were developed technical solutions, which are presented:

a) **Utility Model No. 5749**: OPERATION OF COMBINED BUILDING-ENERGY SYSTEM OF BUILDINGS AND EQUIPMENT, registered in Banská Bystrica, Slovak republic, in April 2011, (author: Kalús) [10].
b) **EUROPEAN PATENT EP 2 572 057 B1:** *Heat insulating panel with active regulation of heat transition.* Date of publication and mention of the grant of the patent: 15.10.2014 In: Bullettin 2014/42 European Patent Office, interantional application number: PCT/SK2011/000004, international publication number: WO 2011/146025 (24.11.2011 Gazette 2011/47), 67 p., (author: Kalús) [7].

When creating mathematical-physical models, we focus on variants of connection with devices offered on the Slovak and Austrian markets. From the variants of research and development involvement we choose the ones that are currently most used in individual housing development. One possible variant is shown in Figure 2, where the mathematical-physical model includes an alternative energy source (solar water heating, PV cells and others), a peak source (heat pump, electric boiler, biomass boiler), two short-term storage tanks, self-heating hot water tank, heat recovery unit, cooling circuit.



VARIANT 21.01.02: ENERGY SYSTEM OF THE BUILDING IN MODIFICATION WITH SOLAR ROOF AND SOLAR COLLECTORS, THE TOP SOURCE IS AN ELECTRIC SPIRAL IN THE COMBINED STORAGE TANK, HEATING IS CARRIED OUT BY UNDERFLOOR HEATING, LONG-TERM STORAGE IS A GROUND STORAGE TANK BELOW THE BUILDING

Figure 2: Mathematical-physical model - variant 21.01.02 [Kubica, Kalús, 10]

Our research is focused on the development of compact heating / cooling units using renewable energy sources, wiring diagrams, method of measurement and regulation, possible production process and their future applications. One interesting innovation will be the performance diagnostics of the entire system connected to the compact station - which will bring better control accuracy and it will be possible to integrate this invention into existing heating / cooling systems.

The laboratory includes vacuum solar collectors, photovoltaic panels, an air-to-water heat pump with the option of producing heat or cold, and a heat recovery ventilation unit and a DHW tank with electric heating. Remote access allows you to monitor and set actual and desired quantities according to the needs of the measurements performed. The software records measured states at five minutes intervals. The software can create various time graphs with temperature, humidity, consumption or battery charge status. If necessary, we can export all values to another calculation program.

Figure 3: Mobile laboratory - photovoltaic and solar thermal panels, meteorological station [Photo source: authors]

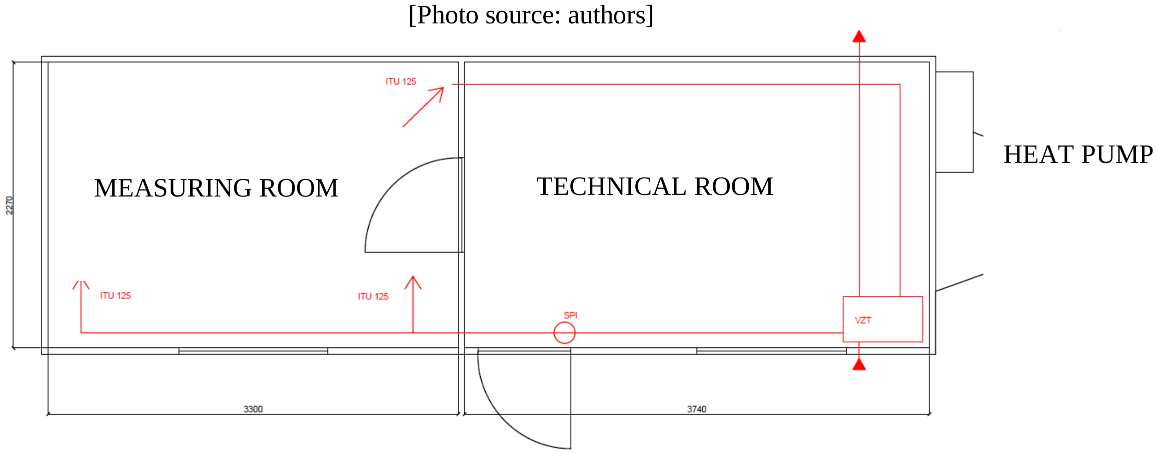


Figure 4: Floor plan of a mobile laboratory [REGULATHERM]

Figure 5: View of the heat source - heat pump and the possibility of connecting a mobile laboratory to an external heat source [Photo source: authors]

Figure 6: View at the equipment of technical and measuring micromobility of a mobile laboratory
[Photo source: authors]

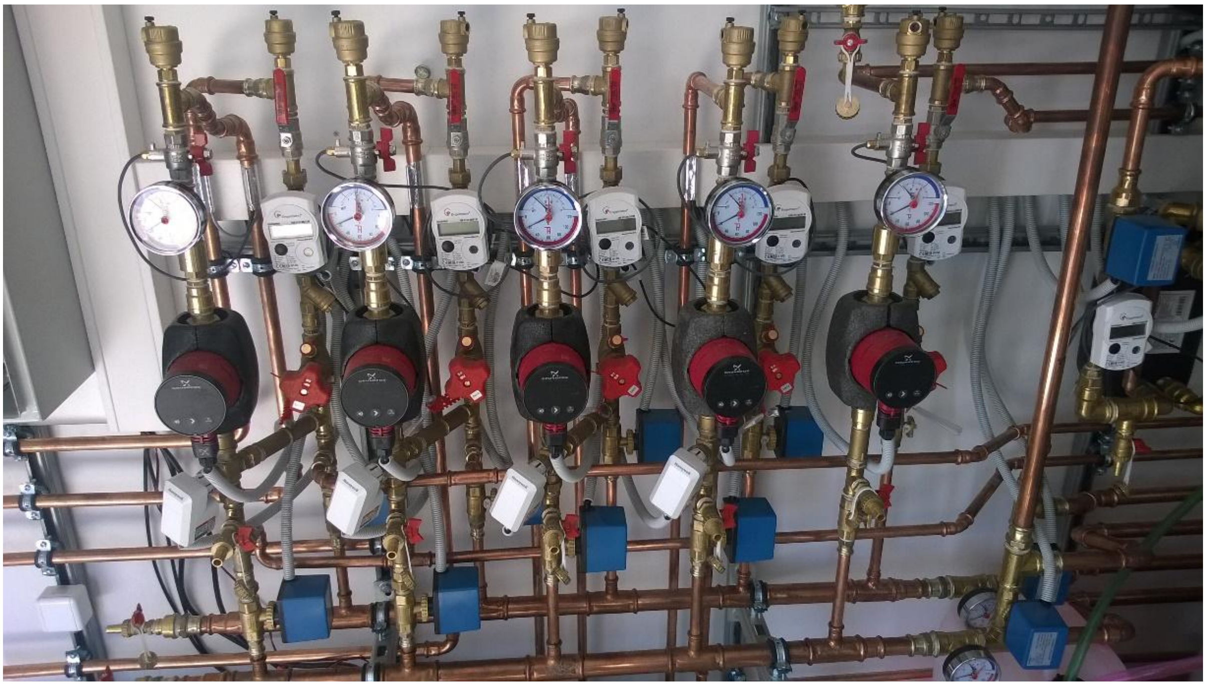


Figure 7: Distributor and collector with measuring instruments on the heat transfer side
[Photo source: authors]

Figure 8: View of the recuperation ventilation unit and air ductwork in the measuring room [Photo source: authors]

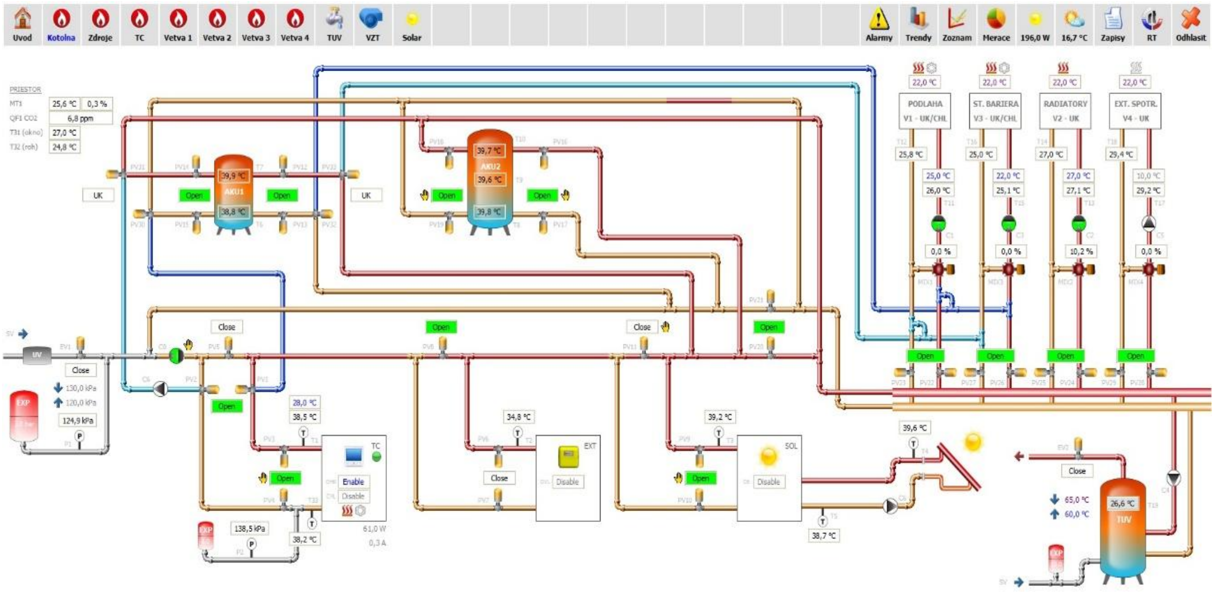


Figure 10: Visualization of a mobile laboratory in software [Kubica]

III. THE METHODOLOGY OF EXPERIMENTAL MEASUREMENTS

At present, all known cold water systems for cooling buildings are considering the accumulation of cold water. Cold water can be accumulated in tanks, pipelines or can be stored in other types of reservoirs that use the storage capacity of other working substances such as concrete structures or soil. The most commonly used variant of cold accumulation is the water tank [3].

For the production of cold is used in most cases, refrigeration equipment and heat pumps, which use the principle of compressor device. A compressor is a mechanical part of such a device that expires after a certain number of switching cycles and must be replaced. It is by using cold accumulation that we can protect

Measurements are performed in a mobile laboratory (simulator and optimizer of energy systems), designed and manufactured by REGULTHERM, s.r.o. – Slovak Republic on the basis of utility model no. 5749 Method of operation of a combined building and energy system of buildings and equipment, author Kalús, [7], [10]. We have been actively involved in the design and implementation of this mobile laboratory to prax and are continuing our continuous research and experimental measurements. Based on the following measurements, we verified the operation of the heat pump in cooling mode.

The measurements used the knowledge from the ISO 52000-1 standard and from the standards Production - heat pumps EN 15316-4-2 (M3-8-2-) and Accumulation EN 15316-5 (M3-7). The amount of accumulated energy is assessed by method B and we confirm the principles increasing the efficiency of cooling systems, where the source of cold is a heat pump using accumulation through a water tank. Some optimization steps are not shown in the operating diagram, but are implemented via the software settings of the operating modes described in the text. The comparative measurements took place at a mobile laboratory located near the town of Modra, Slovak Republic, during the summer months. Measurements were performed on 5 operating schemes, which are described in more detail in the measurement methodology [1], [2].

The methodology is divided into the following sections:

- methodology in terms of pipe schemes and operating modes,
- methodology in terms of instruments and equipment,
- methodology in terms of time and space,
- methodology in terms of physical quantities.

3.1 Methodology in terms of pipe schemes and operating modes

Experimental measurements were performed on the following 3 pipe schemes. Pipe scheme A with connection of a 100 liter storage tank with a heat pump in a top-down filling design (see Fig.11). This is a standard connection of storage tanks as used in the latest connections.

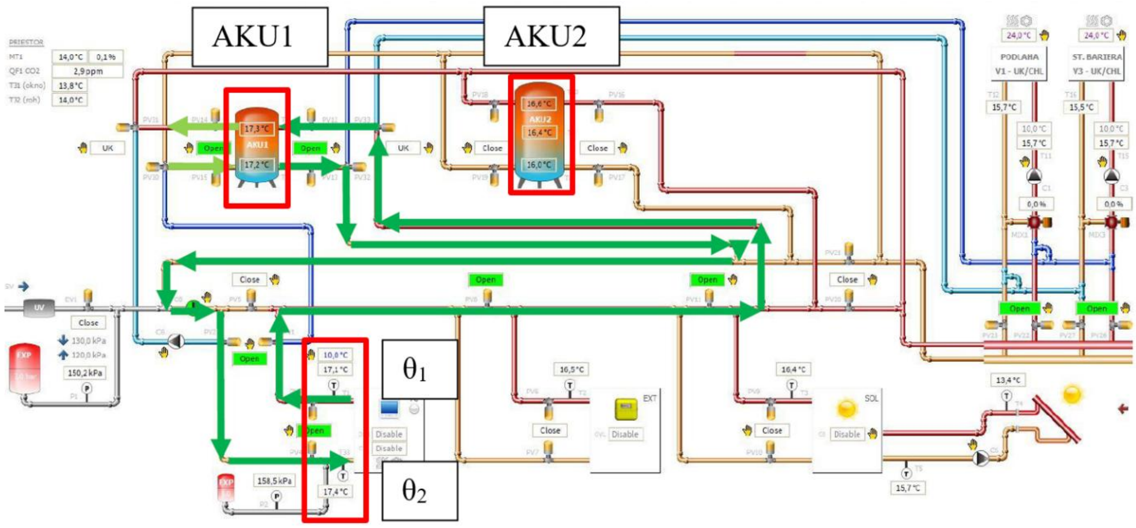


Figure 11: Pipe scheme A with connection of a 100 liters storage tank in the filling design from top to bottom [Kubica].

Pipe scheme B with connection of a 100 liters storage tank with a heat pump in a bottom-up filling design (see Fig. 12). In this connection, the gradual stratification of the prepared cold water and the elimination of mixing of hot water with cold during the start of the heat pump is considered.

Pipe scheme C with connection of a 300 liters storage tank with a heat pump in a top-down filling design (see Fig. 13). This is an alternative to Scheme A with a larger storage tank volume.

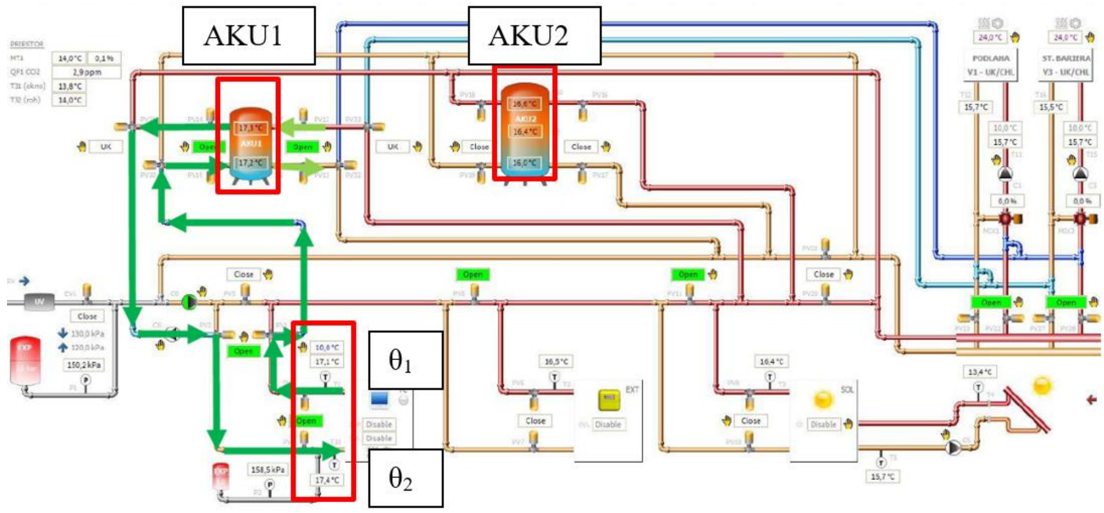


Figure 12: Pipe scheme B with connection of a 100 liters storage tank in the bottom-up filling design [Kubica].

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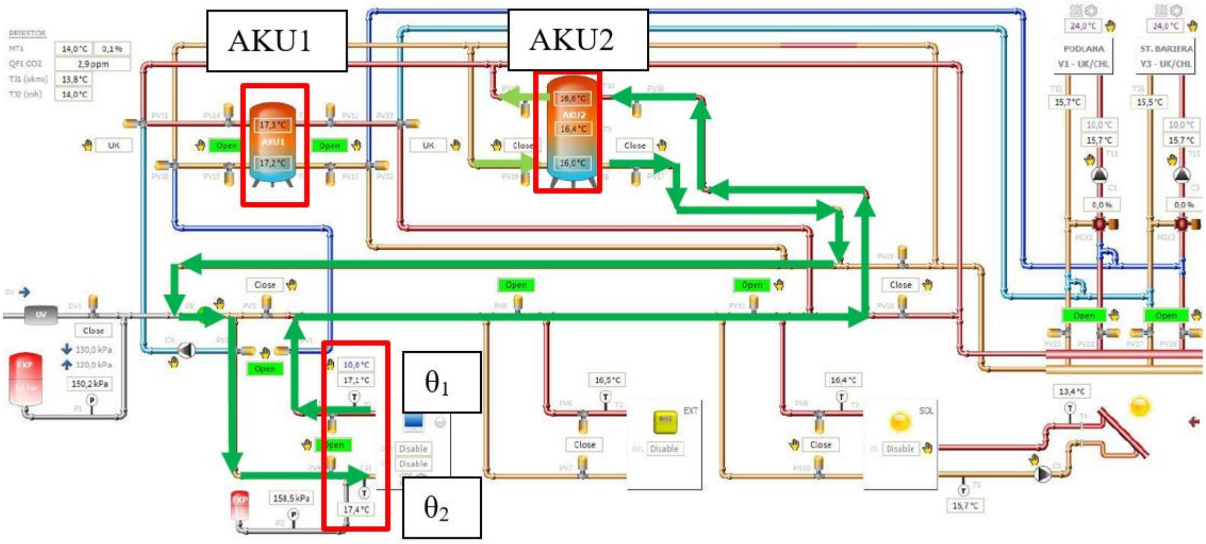

Figure 13: Pipe scheme C with connection of a 300 liters storage tank in the filling version from top to bottom [Kubica].

The differences in the operating modes of the mobile laboratory were as follows:

- How to fill the tank from top to bottom or from bottom to top.
- By adjusting the volume flow in the mode Q_1 = 745 l/h and Q_2 = 915 l/h in the cooling circuit that connects the heat pump and the storage tank.
- By changing the volume of the storage tank in the mode V_1 = 100 l and V_2 = 300 l.
- Mode 0 is a connection where the system does not use a storage tank. Mode 0 uses only the volume of the pipeline and the volume of the end element for accumulation.

A detailed description of the laboratory's operating modes is shown in Tab. 1.

Tab. 1 Overview of operating modes of experimental measurements [Kubica].

Mode no.	Pipe Scheme	Tank Volume V (l)	Volume flow Q (l/h)	Fill direction	Note
0	A	100	745	Top to bottom	No storage
1	A	100	745	Top to bottom	
2	B	100	915	Bottom to top	
3	A	300	915	Top to bottom	
4	C	300	745	Top to bottom	
5	A	100	915	Top to bottom	

The boundary conditions for starting the heat pump were identical for each mode, with:

- The heat pump started at 18 °C at the outlet of the heat pump's heat exchanger.
- The heat pump stopped at 10 °C at the outlet of the heat pump's heat exchanger.
- Accumulated energy in the form of cold was released by natural heat conduction of the storage tank.

3.2 Methodology in terms of instruments and equipment

The measurements were performed on devices and equipment installed in the mobile laboratory. The following were used for the measurement:

- Heat meter - Engelmann SensoStar2 [5], which:
  - the minimum volume flow is 6 l / h,
  - the maximum volume flow is 3 m3 / h,
  - the temperature range is 1 to 105 °C,
  - recording frequency 4 to 60 seconds,
  - The accuracy of measuring heat consumption is 1 kWh.

The heat meter contains an attached temperature sensor LF20-3B54 with a temperature range of 40 to 110 °C.

- Circulation pumps-GRUNDFOS ALPHA2 15-60 130, where the power curves of the 2nd and 3rd stage were used to maintain stable values of volume flows in the heating system
- Storage tank
  - with volume V_1 = 100 l and V_2 = 300 l,
  - AKU1 tank with a volume V_1 = 100 l has the possibility to store cold / heat in ascending and descending way,
  - The AKU2 tank with a volume of V_2 = 300 l has the option of storing cold / heat in a descending manner.

Heat pump-Mitsubishi air / water, model PUHZ-SW40VHA with a heat output of 1.7 to 4 kW with software modified output to 50% of its output. The heat pump has a factory-set algorithm for changing the compressor frequency.

3.3 Methodology in terms of time and space

Measurements took place during the summer months from August 2020 to the end of September 2020. The laboratory was located at an altitude of 438 m.n.m. on a forest clear with direct incident light in the Modra area (Slovak Rerpublic). The individual operating modes of the laboratory were switched at intervals of 2 days to 2 weeks, as follows according to Tab 2.

Tab. 2 Time division of operating modes [Kubica].

Mode no.	Since	To
R0	*10. 8.*	*12. 8.*
R1	*12. 8.*	*28. 8.*
R2	*28. 8.*	*14. 9.*
R3	*14. 9.*	*20. 9.*
R4	*20. 9.*	*25. 9.*
R5	*25. 9.*	*5. 10.*

3.4 Methodology in terms of physical quantities

All quantities are recorded at 5 minute intervals. The volume flows were constant during the individual modes and were monitored via Sensostar2 heat meters with an accuracy of 6 l / h. Temperatures were measured in ° C to the nearest 0.1 ° C. The measured quantities include the following:

- outlet temperature from the heat pump exchanger θ_1 (°C),
- inlet temperature from heat pump exchanger θ_2 (°C),
- temperature in the upper position of the storage tank AKU1 (°C),
- temperature in the lower position of the storage tank AKU1 (°C),
- temperature in the upper position of the storage tank AKU2 (°C),
- temperature in the middle position of the storage tank AKU2 (°C),
- temperature in the lower position of the AKU2 storage tank (°C) (see Fig. 12).

Additional variables that have been observed are:

- exterior air temperature θ_e (°C),
- air temperature in the measuring room θ_i (°C).

These quantities were monitored and taken for evaluation in order to more easily rule out extreme deviations of the main measurements. The number of trigger cycles was read manually.

IV. RESULTS

Due to the different boundary conditions of the outdoor temperature, it was possible to compare the results partially and on selected sections. The selected sections are the individual heat pump start cycles. The start of the heat pump is monitored by a temperature sensor located at the outlet of the heat pump exchanger. Figure 14 plots and explains the temperature profile at the outlet of the heat pump exchanger during one start-up cycle.

The comparison based on the temperature at the outlet from the heat pump of individual modes is shown in Graph No.2, Figure 15. Temperatures in individual modes are plotted with the median of the measured values.

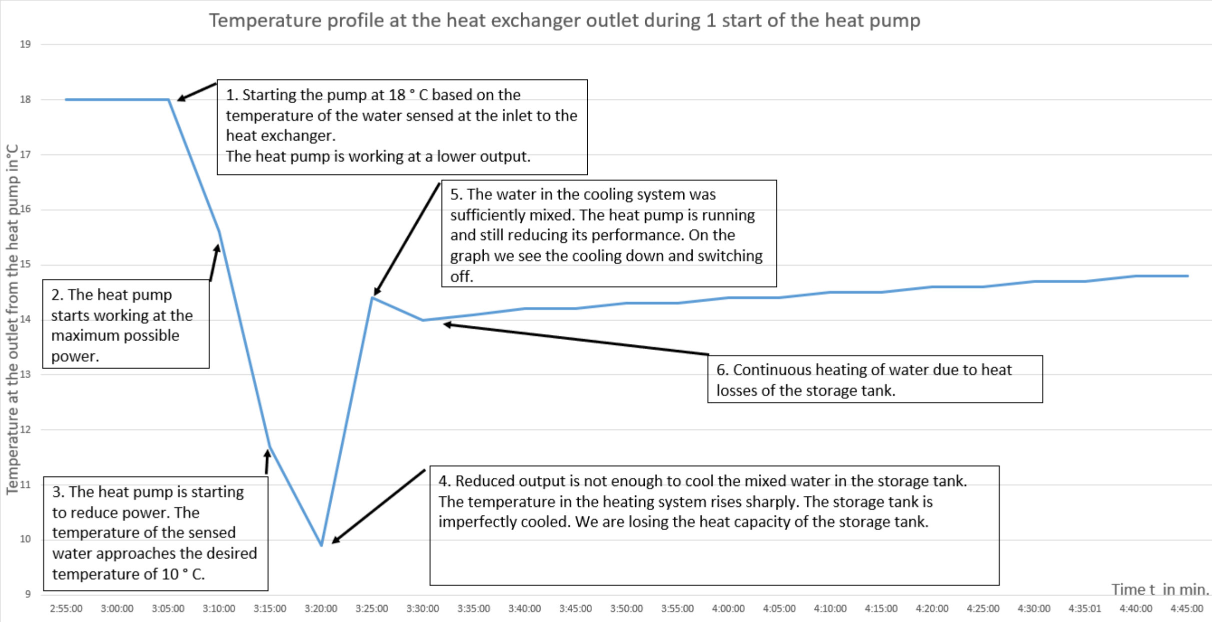

Figure 14: Temperature profile at the heat exchanger outlet during heat pump start-up.

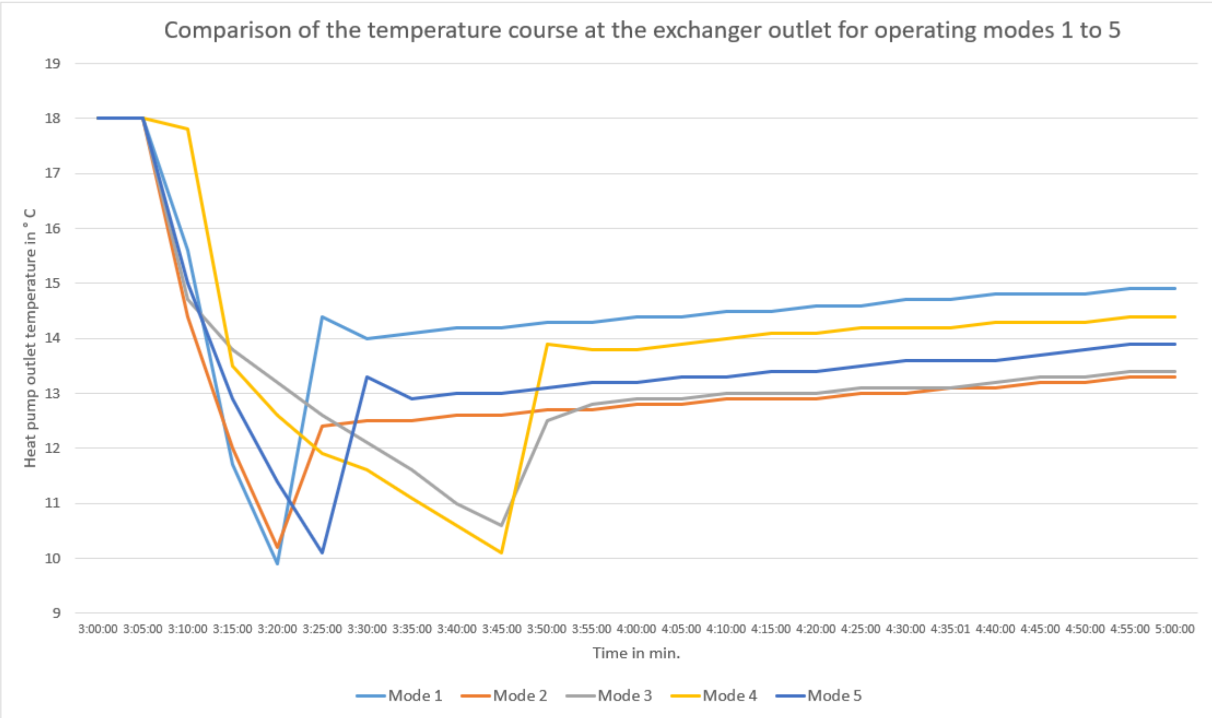

Figure 15: Comparison of temperature course for operating modes 1 to 5.

Based on the analysis of measured values we can confirm:

- Figure 14 shows that after switching off the heat pump, the temperature at its outlet rose sharply. The sharp increase is caused by additional dilution of hot and cold water. The heat pump was switched off prematurely by an incorrectly positioned temperature sensor. This defect occurs with each mode.
- Using a cold storage tank when comparing mode 0 and mode 1 has resulted in a reduction in the number of heat pump start cycles from 20 starts to 2 starts in 12 hours.
- When comparing mode 2 and mode 5, where the filling of the storage tank is different, it was found that filling the storage tank from top to bottom increases the capacity utilization of the water storage tank and the start time of the heat pump is shorter.

- When comparing mode 1 and mode 5 and when comparing mode 3 and mode 4, it was found that increasing the volume flow of the working fluid increases the capacity utilization of the water tank and the start time of the heat pump is shorter.
- A comparison of Mode 1 and Mode 4 confirmed that increasing the volume of the water tank reduces the number of start-up cycles over time
- Based on measurements, the best choice is to fill the tank from top to bottom, with a higher volume flow of the working substance and the use of a larger tank

V. DISCUSION

In the production of cold, the volume flow in the primary circuit between the heat pump and the storage tank AKU1 and AKU2 has a significant effect. By reducing the volume flow, in addition to the inversely proportional effect on the cooling time, it also had an effect on the correct shutdown moment of the heat pump. This paradox arises due to the poor distribution of cold by the working substance. When the production of cold by the heat pump is started, the piping at the temperature sensor, which controls the heat pump, cools down and the heat pump is switched off prematurely.

The main measure to prevent imperfect storage use will be software intervention. By software intervention through the shift of the temperature difference on the heat sensor controlling the operation of the heat pump, we would achieve the maximum proposed capacity of the storage tank. The temperature difference would be set based on a retrospective analysis of the temperature profile in the trend of the temperature sensor that controls the heat pump. The software solution will not increase the investment costs of the connection in any way. The automatic adjustment procedure would be in next three steps:

- automatic notification of the temperature difference between the set temperature and the actual temperature on the heat sensor that controls the heat pump after its end of the cycle,
- calculating the difference of temperature,
- shift of the required temperature on the sensor by the detected difference.

The comparison based on the temperature at the outlet from the heat pump of individual modes is shown in Fig. 5. Temperatures in individual modes are plotted with the median of the measured values.

VI. CONLUSION

The measurements proved the principles that are applied in the accumulation of heat or cold. We can influence the accumulation efficiency and the reduction of the number of start-up cycles of the heat pump by changing the volume flow of the working substance, changing the volume of the water tank, sweeping the water tank but also the correct placement of the temperature sensor.

By reducing the volume flow, in addition to the inversely proportional effect on the cooling time, it also had an effect on the correct shutdown moment of the heat pump. This paradox arises due to the poor distribution of cold by the working substance. When the production of cold by the heat pump is started, the piping at the temperature sensor, which controls the heat pump, cools down and the heat pump is switched off prematurely.

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